Thermal conductivity and dilatation of a Bi-2223/Ag (DI-BSCCO) superconducting wire laminated with various thin alloy tapes

Tomoyuki Naito, Hiroyuki Fujishiro, Yuichi Yamada

***Abstract*—A Bi-2223/Ag wire laminated with Ni-alloy tapes offered the high critical tensile strength over 400 MPa with high critical current of about 200 A, which has just started to be equipped in high-field facilities. To design such a practical superconducting apparatus, we must know the heat leakage through the wires and the elasticity among the constitutional materials. In this paper, we report on the thermal conductivity and dilatation of this new Bi-2223/Ag/Ni-alloy tape, compared to those of other Bi-2223/Ag tapes, and discuss the contribution of lamination alloy to the thermal properties.**

***Index Terms*—Bi-2223/Ag tape, thermal conductivity, thermal dilatation**

I. INTRODUCTION

A first generation superconducting tape, (Bi, Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_{10+x}$ sheathed with Ag (Bi-2223/Ag), has been strenuously studied by many researchers and companies [1]. The controlled overpressure (CT-OP) sintering technique enables us to fabricate the high quality Bi-2223/Ag tape with low porosity, high Young's modulus and high critical current, I_c, over 200 A [2], [3]. Since the critical current was degraded by the tensile/compressive stress [4], the Bi-2223/Ag tapes are often reinforced by the lamination of various alloys to obtain the high yield stress. Although the stainless steel lamination offered the critical tensile strength of about 270 MPa at 77 K, a high-field superconducting magnet over 23.5 T, which corresponds to the 1 GHz-NMR frequency, requires the higher strength of the tapes. Recently, the critical tensile strength of 400 MPa was realized for a Bi-2223/Ag tape by laminating Ni alloy tapes [5]. The Bi-2223/Ag tapes have already been used in the practical superconducting applications such as AC [6] and DC [7] cables, high-field magnets [8], [9] and current leads [10], [11].

In addition to the critical current and mechanical strength, the heat intrusion, $Q_{\rm in}$, is also an important parameter for the thermal stability of the practical superconducting applications [11]. The thermal conductivity, $\kappa(T)$, allows us to estimate correctly the heat intrusion in the materials between a low and high temperature sides, $T_{\rm L}$ and $T_{\rm H}$, in the following relation,

$$Q_{\rm in} = \frac{S}{l}\int_{T_{\rm L}}^{T_{\rm H}} \kappa(T)dT, \qquad (1)$$

where l the length and S the cross section of the material. On the other hand, the thermal dilatation is also the important physical property, because the different change in the length among the constitutional materials in a device would give a mechanical stress which suppresses the superconducting properties. In this paper, we report the temperature dependence of the thermal conductivity, $\kappa(T)$, and thermal dilatation for the new Bi-2223/Ag tape laminated by Ni alloy tapes.

II. EXPERIMENTAL

A. Fabrication of Bi-2223/Ag tapes

Bi-2223/Ag tapes were fabricated by the powder in tube (PIT) method with the CT-OP sintering technique [2]. Table I summarizes the specifications of five Bi-2223/Ag tapes studied here. Type H is a standard silver sheathed tape. Three type HT tapes with high yield stress were prepared, in which the type H tape was laminated from both surfaces by thin alloy (nickel alloy (NX), stainless steel (SS), copper alloy (CA)) tapes. To achieve higher yield stress against for the hoop stress in the extremely high magnetic field over 23.5 T, the 'pre-tension' process was applied for the type HT-NX tape. The Ni alloy (NX) tapes were expanded and soldered to the type H tape to apply the residual compressive stress to the type H tape. The stainless steel (SS) and copper alloy (CA) tapes were soldered without the pre-tension, because both type HT-SS and HT-CA tapes are often used for the low-field magnets. We also prepared the low thermal conductive Bi-2223/Ag tape sheathed with an Ag-5.4wt%Au alloy, which was type G.

B. Method of measurements

Thermal conductivity, $\kappa(T)$, along the rolling direction, i.e., parallel to the ab-planes of Bi-2223 filaments, was measured by a steady-state heat flow method [12]. One end of the tape was soldered to the copper-block (sample stage). A small metal chip resistor of 1 kΩ as a heater was adhered to the other end of the tape by GE7031 varnish. κ is obtained by the relation,

$$\kappa = \frac{Q_{\rm app}}{\Delta T}\cdot\frac{\ell}{S}, \qquad (2)$$

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TABLE I
SPECIFICATIONS OF THE BI2223/AG TAPES

Type	sheath and lamination materials	cross section (mm^2)	width (w) (mm)	total thickness (t) (mm)	thickness of lamination (mm)
H	Ag + no lamination	0.99	4.3	0.23	–
HT-NX	Ag + nickel alloy	1.4	4.5	0.31*	0.03
HT-SS	Ag + stainless steel	1.3	4.5	0.29*	0.02
HT-CA	Ag + copper alloy	1.5	4.5	0.34*	0.05
G	Ag-5.4wt%Au + no lamination	1.0	4.3	0.24	–

* including the thickness of lamination tapes and solder layers (N.A.).

where Q_{app} is the applied heat flow, ΔT is the temperature difference and ℓ is the distance between two chromel-constantan thermocouples, and S is the cross sectional area of tape. ΔT was maintained to be 0.5–0.7 K by controlling the heater power. Thermal dilatation normalized by the sample length, L, at 300 K,

$$\frac{dL(T)}{L(300\ \mathrm{K})} = \frac{(L(T) - L(300\ \mathrm{K}))}{L(300\ \mathrm{K})}, \tag{3}$$

was measured by a standard strain-gauge method using a commercial strain-gauge (CFLA-1-350-11[the gauge length was 1 mm, the gauge resistance was 350 Ω, and the gauge factor was 2.09]; Tokyo Sokki Kenkyujo Co., Ltd.). Electrical resistivity, $\rho(T)$, was measured by a conventional dc four-probe method with a typical current density of about 3 A/cm^2. The temperature of sample stage was controlled between 6 and 300 K using a Gifford-McMahon cycle helium refrigerator and 30 W heater. To minimize a radiation loss, $\kappa(T)$ was measured below 200 K. $dL(T)/L(300\ \mathrm{K})$ was measured above 20 K owing to the sensitivity of strain gauge.

III. RESULTS AND DISCUSSION

A. Thermal properties of the Bi-2223/Ag tapes laminated by various alloys

Fig. 1 shows the temperature dependence of the thermal conductivity, $\kappa(T)$, of various Bi-2223/Ag tapes. $\kappa(T)$ of type H tape decreased quite moderately with decreasing temperature from 300 K down to 100 K and showed a gentle increase below 100 K. Subsequently, it began to increase rapidly below 60 K and took a maximum of about 780 W m^{-1} K^{-1} at 14 K. The low-temperature peak of $\kappa(T)$ is often observed in high-purity metals and insulators, and can be explained by the relation of $\kappa = (1/3)C_{\mathrm{th}}v_{\mathrm{th}}l_{\mathrm{th}}$, where C_{th}, v_{th} and l_{th}, respectively, are the specific heat, the velocity and the mean free path of thermal carriers [13]. The lattice vibration suppressed at low temperatures causes the steep increase of l_{th}; the l_{th} finally reaches to the sample size. On the other hand, the specific heat decreases monotonically with decreasing temperature. The competition between the increase (and saturation) of $l_{\mathrm{th}}(T)$ and the decrease of $C_{\mathrm{th}}(T)$ results in the $\kappa(T)$-peak. The $\kappa(T)$ of the type HT-NX, HT-SS and HT-CA tapes showed the similar shape, but smaller absolute value, compared to $\kappa(T)$ of the type H tape. The $\kappa(T)$ of the type H, HT-SS, and HT-CA tapes is almost the same as the reported previously [12], [14]. We estimated the contribution of electrons to the total thermal conductivity, κ_{e}, from the electrical resistivity, $\rho(T)$, using the Wiedemann-Franz law, κ_{e}=L_0T/ρ. Here, L_0 is the Lorenz number. Fig. 2 shows the temperature dependence of the electrical resistivity for various Bi-2223/Ag tapes. All the tapes showed the sharp superconducting transition at the critical temperature, T_{c}, of 111 K and demonstrated a good T-linear dependence in the normal state. The κ_{e} values were estimated to be approximately 245, 167, 179, and 226 W m^{-1} K^{-1} for the type H, HT-NX, HT-SS, and HT-CA tapes, respectively, which are nearly comparable to the measured $\kappa(T)$ above T_{c}. The absolute value of $\rho(T)$ of the sheath metal and lamination alloy is generally rather smaller than that of Bi-2223 filaments in the normal state, suggesting that the applied heat mainly flows through both sheath and lamination alloys. Therefore, the small $\kappa(T)$ of the type HT-NX tape seems to originate from the poor thermal conductive lamination alloy, as found in the inset of Fig. 1, in which the measured $\kappa(T)$ curves for the solder, SS and Ni alloy and the reported for the typical Cu alloy, bronze (Cu:Sn=9:1) [15] are shown. The absolute value of $\kappa(T)$ of the Ni alloy was approximately one to two orders of magnitude smaller than

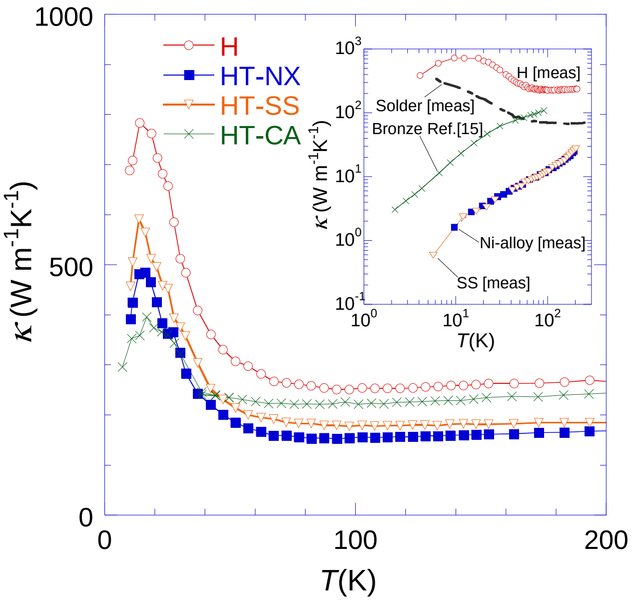

Fig. 1. Temperature dependence of the thermal conductivity, $\kappa(T)$, for various Bi-2223/Ag tapes. Inset shows the $\kappa(T)$ curves for the solder and various lamination alloys.

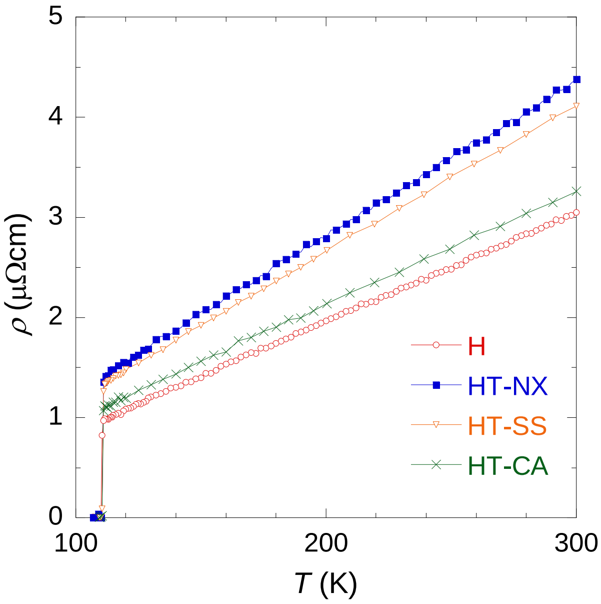

Fig. 2. Temperature dependence of the electrical resistivity, $\rho(T)$, for various Bi-2223/Ag tapes.

that of the type H tape. The $\kappa(T)$ value of the HT-NX tape is somewhat smaller than that of the HT-SS tape, although the absolute $\kappa(T)$ values of SS and Ni alloy were nearly identical. This might originate from the difference in the laminating process, as described in Sec. II-A. The large compressive stress due to the pre-tension process for the type HT-NX tape causes the lattice distortion in the Ag sheath, which should create the dislocations. The dislocations are known to scatter the mobile electrons as well as the phonons, which suppresses naturally the thermal conductivity [13]. The absolute value $\kappa(T)$ of the type HT-CA tape was comparable with that of the type H tape in the normal state, however the low-temperature peak was strongly suppressed. This suggests that the unignorable amount of applied heat flows through the Cu alloy lamination [14].

Fig. 3 shows the temperature dependence of the thermal dilatation, $dL(T)/L$(300 K), for various Bi-2223/Ag tapes. $dL(T)/L$(300 K) of all the samples showed a similar temperature dependence. $dL(T)/L$(300 K) decreased monotonically with decreasing temperature from 300 K to 25 K, and subsequently showed almost constant value below 25 K. The $dL(T)/L$(300 K) of about -0.25% at 20 K for the type HT-NX tape was about -0.04% smaller than that of the type H tape (-0.29%), in contrast to both type HT-SS (-0.3%) and HT-CA (-0.31%) tapes. Inset of Fig. 3 shows the $dL(T)/L$(300 K) of the typical Ni-based alloy (Hastelloy C) and stainless steel. The small $dL(T)/L$(300 K) of the Hastelloy C compared to that of the stainless steel prevented from shrinking the type H tape embedded in the HT-NX tape.

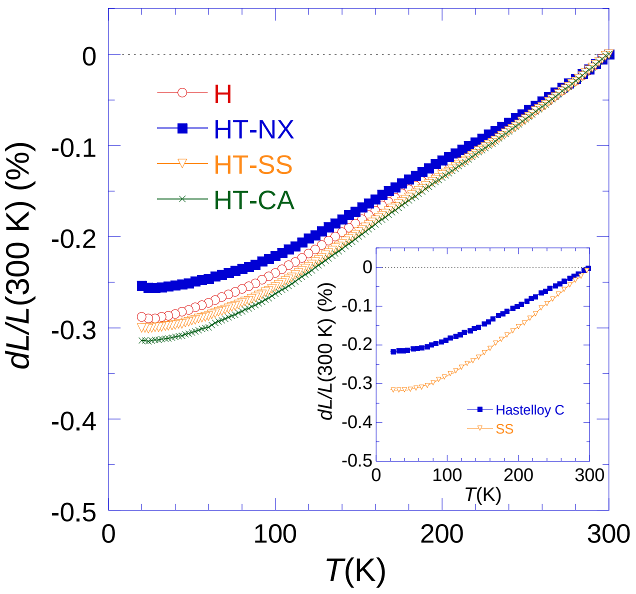

Fig. 3. Temperature dependence of the thermal dilatation, $dL(T)/L$(300 K), for various Bi-2223/Ag tapes. Inset shows the $dL(T)/L$(300 K) curves for the Ni-based alloy (Hastelloy C) and stainless steel (SS).

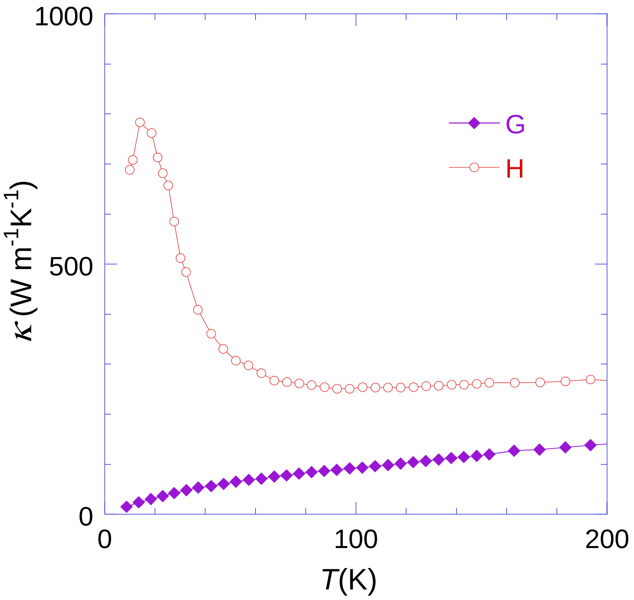

Fig. 4. Temperature dependence of the thermal conductivity, $\kappa(T)$, for the Bi-2223/Ag tape sheathed with Ag-5.4wt%Au alloy; the $\kappa(T)$ of the type H tape is also shown as a reference.

B. Thermal conductivity of the Bi-2223/Ag tapes sheathed with Ag-Au alloy

Fig. 4 shows the temperature dependence of the thermal conductivity, $\kappa(T)$, for the Bi-2223/Ag tape sheathed with Ag-5.4wt%Au alloy, type G tape. The $\kappa(T)$ decreased monotonically with decreasing temperature. The absolute value of $\kappa(T)$

was quite smaller than that of the type H tape, and the low-temperature peak was fully suppressed. The $\kappa(T)$ of the type G tape resembles to that of low-purity metals and alloys, in which the electrons are scattered by the substituted impurity atoms. The obtained result agreed well with the reported data [12], and will be used to estimate the heat leakage through the current leads for ITER.

IV. SUMMARY

We have measured the thermal conductivity, $\kappa(T)$, and dilatation, $dL(T)/L(300\text{ K})$, of a new type Bi-2223/Ag tape laminated with the Ni alloy (NX), Bi-2223/Ag-NX. The measured $\kappa(T)$of the Bi-2223/Ag-NX tape was smaller than the estimated from those of the constitutional components, such as the bare Bi-2223/Ag and NX tapes. We considered that residual compression stress in the tape, which was introduced during the lamination process, deteriorated the thermal conductivity. The $dL(T)/L(300\text{ K})$ of the Bi-2223/Ag-NX tape was found to be about -0.04% smaller than that of the bare Bi-2223/Ag tape, which is contrast to other Bi-2223/Ag tapes laminated by the stainless steel and copper alloy. This can be explained by the small $dL(T)/L(300\text{ K})$ of the Ni alloy. We believe that the obtained results are useful information for designing a practical superconducting application. The $\kappa(T)$ was also measured for a Bi-2223/Ag tape sheathed with Ag-5.4wt%Au alloy and the quite low $\kappa(T)$ was confirmed. The heat leakage through the current leads consisting of the stacked tapes can be estimated correctly by using the $\kappa(T)$ measured here.

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