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Physics Procedia 36 (2012) 1609 – 1613

Physics Procedia

Superconductivity Centennial Conference

Specific heat and thermal diffusivity of YBCO coated conductors

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Abstract

We have measured the temperature dependence of specific heat, $C(T)$, for Ag deposited YBCO coated conductor (YCC), YCC reinforced by a thin Cu tape (YCC-Cu), and the Hastelloy substrate with buffer layer. $C(T)$ of Hastelloy C-276 with buffer layer agrees well with the reported one of Hastelloy C-276, indicating that the contribution of the buffer layer to the measured $C(T)$ is negligibly small. $C(T)$ of both YCC and YCC-Cu tapes was successfully reproduced by the simple sum rule using the $C(T)$ values reported for Hastelloy, Ag and Cu. The results demonstrate that $C(T)$ of various YCC tapes can be estimated using the reported $C(T)$ of constitutional materials. The estimated thermal diffusivity, $\alpha = \kappa/C$, at 300 K of YCC, which was estimated using the thermal conductivity, κ, did not agree with the reported α of Ag. This result was inconsistent with the fact that the applied heat flew through the Ag layer, suggesting that a relation of $\alpha = \kappa/C$ for homogeneous material cannot be applicable for the layered material such as YCC.

Keywords: Keywords: YBCO coated conductor, specific heat, thermal diffusivity

1. Introduction

Since the degradation of the critical current density, J_c, in $YBa_2Cu_3O_{7-\delta}$ (YBCO) is not as large even at 77 K in a high magnetic field as that of Bi-based compounds, YBCO is a promising material for the high temperature and high magnetic field applications. In past decade, YBCO coated conductor (YCC) tapes, which consists of metal substrate, buffer and cap layers, YBCO film, and stabilizing Ag layer, has been developed for the power applications such as power cables, motors,transformers, and fault current limiters [1].

Thermal properties such as the thermal conductivity, $\kappa(T)$, thermal diffusivity, $\alpha(T)$, and the specific heat, $C(T)$, are very important to evaluate the thermal stability of the superconducting materials. The heat intrusion or exhaust, Q, through the tape is shown by the following relation,

$$Q = \frac{S}{L}\int_{T_1}^{T_2} \kappa(T)dT.$$

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doi:10.1016/j.phpro.2012.06.316

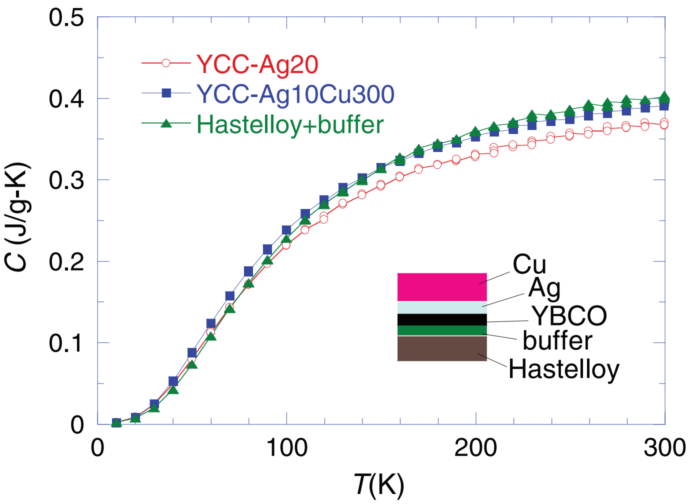

Fig. 1. Temperature dependence of the specific heat, $C(T)$, of YCC-Ag20, YCC-Ag10Cu300 and Hastelloy+buffer tapes.

Here, T_1 and T_2 are the temperatures of the terminals of the tape, S the cross section, and L the length of the tape.

We have measured $\kappa(T)$ of various YCC tapes and found that the applied heat mainly flew through the high thermal conductive layer such as stabilizing Ag and the reinforcing Cu using an equivalent heat current circuit with simple sum rule [2, 3]. In this paper, we report the temperature dependence of the specific heat, $C(T)$, of the Ag deposited YCC tape and a YCC tape reinforced by thin Cu tape. The contribution of each constitutional material of the YCC tape to $C(T)$ is discussed by simple sum rule using the $C(T)$ values from the literature. Thermal diffusivity was estimated by the relation of $\alpha = \kappa/C$ which was approved in homogeneous materials. The validity of this relation in a layered material such as YCC tape is also discussed.

2. Experimental procedure

YCC tapes were fabricated by an ion beam assisted deposition (IBAD) and a pulsed laser deposition (PLD) method. The details of fabrication technique have been described elsewhere [4]. Hastelloy C-276 (5 mm wide and 100 μm thick) was used as a substrate. $Gd_2Zr_2O_7$ (GZO) (about 1 μm thick) and CeO_2 (0.7 μm thick) films were deposited on the Hastelloy as a buffer layer by the IBAD and PLD method, respectively. YBCO film (about 1.5 μm thick) were grown by the PLD method. Finally, Ag (10-20 μm thick) was deposited on YBCO/CeO_2/GZO/Hastelloy as a thermal stabilizer. YCC tape reinforced by Cu tape (300 μm thick) and the Hastelloy with the buffer layer, named YCC-Ag10Cu300 and Hastelloy+buffer, respectively, were also prepared.

Specific heat, $C(T)$, was measured by a relaxation technique using the Physical Properties Measurement System (PPMS, Quantum Design Inc.) from 10 K to 300 K.

3. Results and Discussion

3.1. Specific heat

Figure 1 shows the temperature dependence of the specific heat of YCC-Ag20, YCC-Ag10Cu300 and Hastelloy+buffer. $C(T)$ of all the samples decreases monotonically with decreasing temperature. Absolute values of $C(T)$ at 300 K are about 0.37, 0.39 and 0.40 J/g-K for YCC-Ag20, YCC-Ag10Cu300 and Hastelloy+buffer, respectively.

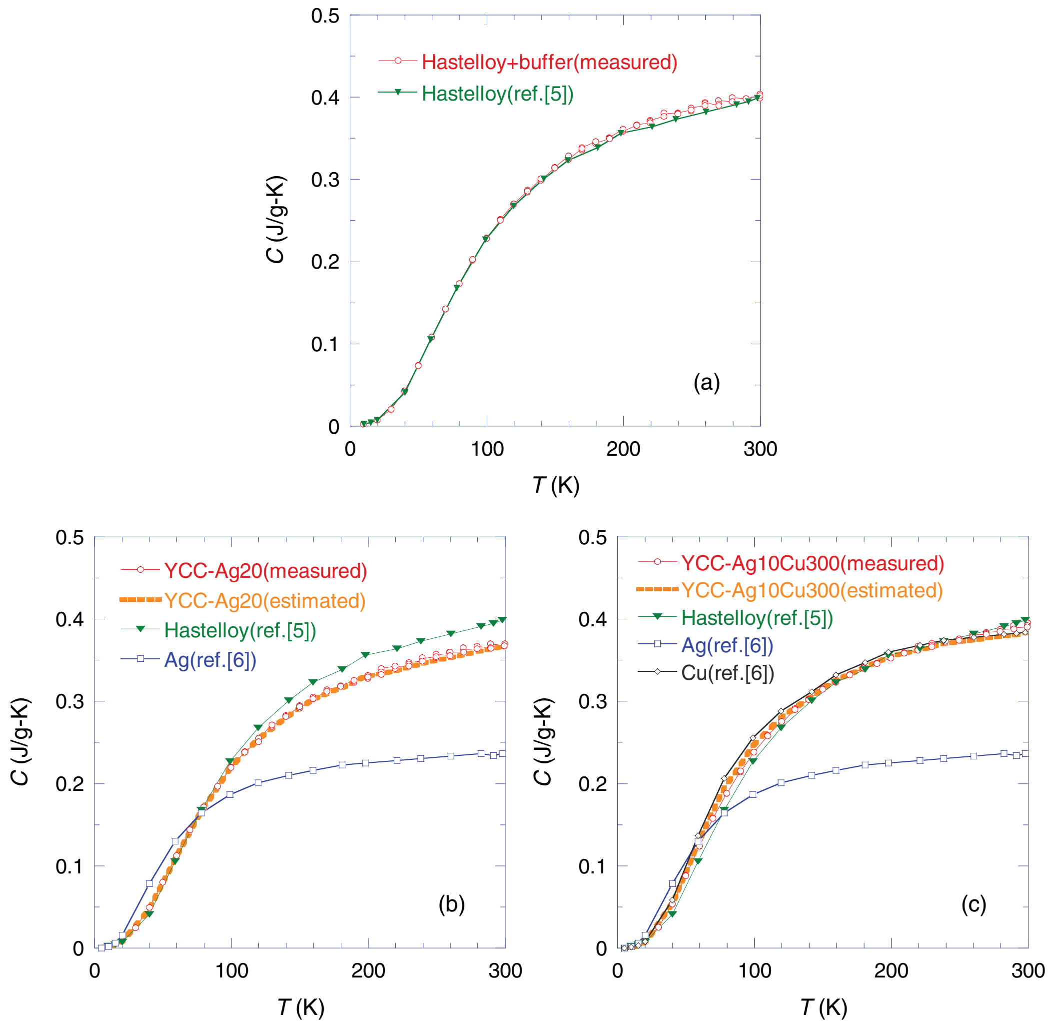

Fig. 2. (a) Temperature dependence of the specific heat, $C(T)$, of Hastelloy+buffer and the reported $C(T)$ of Hastelloy. (b) and (c) show the measured and estimated $C(T)$ of YCC-Ag20 and YCC-Ag10Cu300, respectively. The reported $C(T)$ of Hastelloy, Ag and Cu is also plotted.

Figure 2(a) shows the measured $C(T)$ of Hastelloy+buffer and the reported one of Hastelloy C-276 [5]. The measured $C(T)$ coincides well with the reported one, meaning that the contribution of the buffer layer is negligibly small because of a very small volume fraction of the buffer layer.

We estimate the $C(T)$ for YCC-Ag20 and YCC-Ag10Cu300 using the reported $C(T)$ of Hastelloy [5], Ag [6] and Cu [6]. In a composite material which consists of n kinds of materials, the total quantity of heat, Q^{tot}, is given by the sum of that of each constitutional material as follows:

$$Q^{tot} = \sum_{i=1}^{n} Q^{i},$$

where, Q^i is the quantity of heat of the i-th part. When the specific heat per unit weight, C^i, is known, Q^i is given as $C^i \times (V^i \times d^i)$. Here, V^i and d^i are the volume and density of the i-th part, respectively. Consequently,

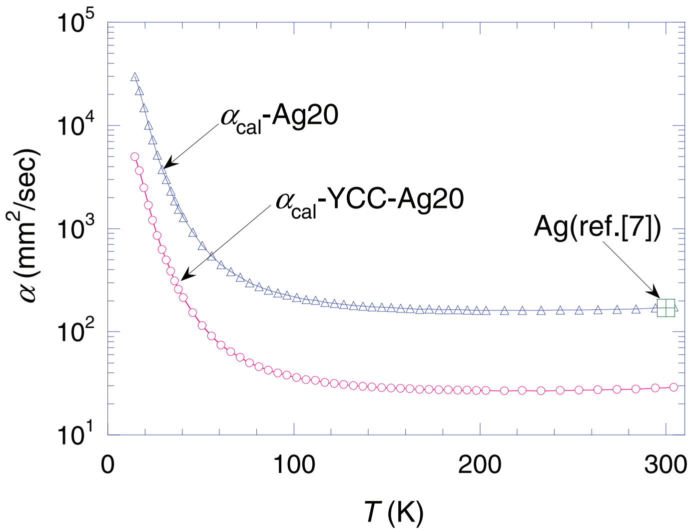

Fig. 3. Temperature dependence of the estimated thermal diffusivity, $\alpha(T)$, of YCC-Ag20 tape and Ag20. The reported $\alpha(300\ K)$ at 300 K of Ag is also plotted.

the total specific heat C^{tot} per unit weight can be estimated by the following relation:

$$C^{tot} = \frac{\sum_{i=1}^{n}(C^i \times V^i \times d^i)}{\sum_{i=1}^{n}(V^i \times d^i)}$$

Figures 2(b) and 2(c) show the temperature dependence of the measured and estimated $C(T)$ for YCC-Ag20 and YCC-Ag10Cu300, respectively. Here, the densities of Hastelloy, Ag and Cu are 8.89, 8.96 and 10.49 g/cm^3, respectively. We ignore the contribution of the YBCO layer, because it is negligibly thin in comparison with those of other metallic parts. For both tapes, the measured $C(T)$ is well reproduced by the estimated one, indicating that the $C(T)$ of the composite samples with various thickness and species of each layered material can be estimated from the known $C(T)$ of each part using the simple sum rule.

3.2. Thermal diffusivity

Figure 3 shows the temperature dependence of the thermal diffusivity, α_{cal}-YCC-Ag20 of YCC-Ag20 tape, which is estimated from the measured $C(T)$ shown in Fig. 1 and the $\kappa(T)$ reported by us [2]. α_{cal}-YCC-Ag20 increased gradually with decreasing temperature and steeply upturned at lower temperatures. The $\alpha(T)$ behavior is a usual manner for ordinary materials. However, the absolute value of $\alpha(T)$ should be noted. In the analysis of $\kappa(T)$ for YCC tapes, the heat mainly flows in the stabilizing Ag layer, regardless of the very thin thickness [2]. For the α value, which is closely related with the transient heat propagation, it must be taken into consideration that the heat flux preferentially flows in the Ag layer. We estimated the revised thermal diffusivity, α_{cal}-Ag20, as shown in Fig. 3, where the heat flux is supposed to propagate only through the high-thermal conductive Ag layer 20 μm in thickness in the YCC tape. The α_{cal}-Ag20 was calculated using $\kappa_{Ag}/C_{Ag} = \kappa_{tot}/((S_{Ag}+S_{tot})/C_{Ag})$, where κ_{tot} is the thermal conductivity of the Ag stabilized YCC tape, κ_{Ag} is that of stabilizing Ag layer, S_{Ag} and S_{tot} are the cross section of the Ag layer and total YCC tape, and C_{Ag} is the specific heat of Ag. The α_{cal}-Ag20 value is about one order of magnitude larger than α_{cal}-YCC-Ag20. It should be noted that the α_{cal}-Ag20 value at 300 K is quite reasonable agreement with that of the reported Ag [7]. These results suggest that the heat flux flows in the Ag layer of the layered superconducting tapes. The relation, $\alpha = \kappa/C$, is applicable only for the homogeneous materials.

Finally, we comment on the use of the thermal diffusivity value for the thermal stabilizing design for the superconducting apparatus. If we use the α_{cal}-YCC-Ag20 value as the thermal diffusivity of the tape, the amount of the heat flow is underestimated. In this case, the additional thermal stabilizing materials must be taken in consideration. In fact, the heat should propagate faster and no stabilizing materials such as Cu inserting tape may be added. The measurement and application of the thermal parameters of the layered structural system must be performed cautiously.

4. Summary

We have measured the temperature dependence of the specific heat, $C(T)$, of Ag deposited YBCO coated conductor (YCC) tape, YCC reinforced by a thin Cu tape (YCC-Cu) and Hastelloy substrate with the buffer layer. $C(T)$ of Hastelloy with the buffer layer almost coincided with that of Hastelloy C-276 reported previously. This means the negligibly small contribution of the buffer layer to the measured $C(T)$. $C(T)$ of both YCC and YCC-Cu tapes was well reproduced by the reported $C(T)$ of Hastelloy, Ag and Cu using a simple sum rule. Thus, if we know the $C(T)$ values of all component of the YCC tape, whose unknown $C(T)$ can be obtained by the calculation without a direct measurement. Thermal diffusivity, $\alpha(T)$, of the YCC tape was estimated from the measured $C(T)$ and $\kappa(T)$ using the relation of $\alpha = \kappa/C$, where κ is thermal conductivity. Since the main heat pass of the YCC tape is the stabilizing Ag layer, $\alpha(T)$ of the stabilizing Ag layer was also estimated. The magnitude of $\alpha(T)$ of the stabilizing Ag layer was one order of magnitude larger than that of the YCC tape and nearly corresponded to that of the reported Ag at 300 K, which suggested that the heat flux propagated in the Ag layer of the YCC tape and that the obtained $\alpha(T)$ of the YCC tape was underestimated. We can conclude that the relation of $\alpha = \kappa/C$ for homogeneous system cannot be applicable for the layered system such as the YCC tapes.

Acknowledgement

This work was supported by the New Energy and Industrial Technology Development Organization (NEDO).

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