Estimation of generated heat in pulse field magnetizing for SmBaCuO bulk superconductor

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Abstract

The generated heat \( Q \) during the pulse field magnetizing (PFM) has been estimated for a cryo-cooled SmBaCuO bulk superconductor based on the maximum temperature rise \( \Delta T_{\text{max}} \) and specific heat \( C(T) \). Five successive magnetic pulses with a fixed amplitude \( (B_{\text{ex}} = 3.01 \text{T} \sim 5.42 \text{T}) \) are applied and \( \Delta T_{\text{max}} \) are measured for the various initial temperature \( T_i \) between 40 and 70 K. \( Q \) has shown characteristic dependences on \( T_i \), \( B_{\text{ex}} \) and the pulse number of the successive pulses. The pinning loss \( (Q_p) \) and viscous loss \( (Q_v) \) have been separated and estimated as a function of \( T_i \) and \( B_{\text{ex}} \).

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1. Introduction

The pulse field magnetizing (PFM) method for the melt-processed REBaCuO bulk superconductors (RE: rare earth ions) has been recently recognized to have a promising potential and intensively studied to magnetize the bulk system. However, at present, the trapped magnetic field \( B_{\text{T}} \) by PFM is lower than that by the static field-cooled magnetizing (FCM) [1–3]. The reason has been attributed to the temperature rise \( \Delta T \) due to the magnetic flux motion, which reduces the pinning force \( F_p \). We studied the time evolution and spatial distribution of \( \Delta T(t) \) at the surface of the cryo-cooled YBaCuO [4] and SmBaCuO [5,6] bulk superconductors after PFM. The \( \Delta T(t) \) behavior changed depending on the initial stage temperature \( T_i \) the applied pulse field \( B_{\text{ex}} \) and the distribution of \( B_{\text{T}} \) before applying the pulse field. The measurement on the spatial distribution of \( \Delta T(t) \) enabled us to locate the easy path, through which the fluxes preferably intrude into the bulk. In order to elucidate the magnetizing mechanism by PFM and to enhance \( B_{\text{T}} \) it is necessary to estimate the generated heat \( Q \) for various \( T_i \) and \( B_{\text{ex}} \) because the...
\( Q \) value may offer more exact information than \( \Delta T \).

In this paper, we estimate the \( Q \) values for the SmBaCuO bulk superconductor after applying \( B_{ex} \) iteratively by use of the measured specific heat \( C(T) \) and the maximum temperature rise \( \Delta T_{\text{max}} \). We investigate the \( T_s, B_{ex} \) and the pulse number dependences of \( Q \) to discuss the mechanisms of the heat generation from the viewpoint of the pinning and viscous power losses.

2. Experimental

A highly \( c \)-axis oriented SmBaCuO bulk superconductor of disk shape with 46 mm in diameter and 15 mm in thickness was used, which was composed of SmBa\(_2\)CuO\(_y\) (Sm123) and Sm\(_2\)BaCuO\(_5\) (Sm211) with the molar ratio of Sm123:Sm211 = 1.0:0.3, 15.0 wt.% Ag\(_2\)O powder and 0.5 wt.% Pt powder [6]. The bulk was tightly stuck on the cold stage of a Gifford McMahone cycle helium refrigerator, which was evacuated below \( \sim 10^{-5} \) Torr. The initial stage temperature \( T_s \) was changed from 40 to 70 K. The time evolution of temperature \( T_0(t) \) at the center of the bulk (P0) was recorded about seven times just after applying the pulse field using chromel–constantan thermocouple adhered to the bulk surface. The bulk was magnetized using a pulse coil \( (L = 1.08 \text{ mH}) \) dipped in liquid \( N_2 \). The rise time of the pulse field \( B_{ex} \) was about \( \sim 10 \) ms. Five successive pulse fields with a fixed amplitude of \( B_{ex} = 3.01, 3.84, 4.64 \) or 5.42 T were applied to the bulk for each \( T_s \). Hereafter we abbreviate the five pulses as Nos. 1–5. \( B_T^p \) just upon the bulk surface was measured by the Hall sensor (F.W. Bell, model BHT 921) adhered to a position 2.5 mm apart from P0. After a set of \( T_0(t) \) and \( B_T^p \) measurements completed for Nos. 1–5 pulses at \( T_s \) the bulk was heated up to 120 K in order to eliminate the trapped fluxes completely and then again was cooled down below the superconducting transition temperature \( T_c(= 93 \text{ K}) \). The specific heat \( C(T) \) was measured from 4.2 to 300 K by the commercial PPMS system (Quantum Design Co., Ltd.) using a sample with the same composition as the bulk crystal.

3. Results and discussion

Fig. 1 shows examples of \( T_0(t) \) after applying the Nos. 1 and 5 pulses of \( B_{ex} = 3.01 \) and 4.64 T at (a) \( T_s = 40 \) K and (b) \( T_s = 60 \) K, respectively. In the inset of Fig. 1(b), the pulse number dependence of the maximum temperature rise \( \Delta T_{0,\text{max}} \) is presented. In all the cases, \( \Delta T_{0,\text{max}} \) is the largest for the No. 1 pulse and decreases with increasing pulse number, approaching a fixed ultimate value after the No. 3 pulse. This behavior is reasonable because the largest amount of the flux penetrates into the virgin state bulk during the No. 1 pulse and is trapped in the bulk.

Fig. 2 shows \( \Delta T_{0,\text{max}} \) for the (a) No. 1 and (b) No. 5 pulse applications as a function of \( T_s \). With increasing \( T_s, T_0 \) values on the first pulse...
application only slightly increase for $B_{\text{ex}} = 3.01$ T, while those for $B_{\text{ex}} \geq 3.84$ T clearly decrease. In order to discuss the heat generation mechanisms on PFM, however, we must know the exact amount of generated heat.

Fig. 3 presents the temperature dependence of the specific heat $C(T)$ (J/cm$^3$ K) of the bulk. Since the bulk is a composite material with about 65% volume fraction of the superconductive Sm123 phase [7], only a faint cusp in $C$ is observable at $T_c = 93$ K as seen in the inset. The generated heat $Q$ due to the pulse field application can be estimated using the following equation:

$$Q = \int_{T_s}^{T_s + \Delta T_{0\text{max}}} C(T) V \, dT,$$

where $V$ is the volume of the bulk disk. In the present case, we can assume that the heat generation occurs under the adiabatic condition because the heat generation is completed within the pulse duration ($\sim 20$ ms) and the $Q$ is exhausted in 10–20 min through the bottom surface of the bulk in vacuum atmosphere. The hatched region in Fig. 3 shows an example of the calculation of $Q$ per unit volume for $B_{\text{ex}} = 4.64$ T at $T_s = 40$ K ($\Delta T_{0\text{max}} = 28$ K). The estimated $Q$ values using $\Delta T_{0\text{max}}$ may be underestimated because the heat generation occurs in the peripheral region and the $\Delta T_{0\text{max}}$ value is usually the smallest on the bulk surface [4–6]. Fig. 4 shows the results of the $Q$ values for each $B_{\text{ex}}$ as a function of $T_s$. It can be seen that the $T_s$ dependence of $Q$ in Fig. 4 and $\Delta T_{0\text{max}}$ in Fig. 2 are different. In Fig. 4(a) for the No. 1 pulse, $Q$ for $B_{\text{ex}} \leq 4.64$ T increases with increasing $T_s$ takes a maximum and decreases with the further increase in $T_s$. On the other hand, $Q$ for $B_{\text{ex}} = 5.42$ T monotonically decreases with increasing $T_s$. In Fig. 4(b) for the No. 5 pulse, $Q$ for $B_{\text{ex}} \leq 3.84$ T monotonically increases with increasing $T_s$ while $Q$ for $B_{\text{ex}} \geq 4.64$ T takes a maximum at around 60 K. The $Q$ (or $T_{0\text{max}}$) value was confirmed to be very small above $T_c$ possibly because of the disappearance of $F_p$.
The heat generation during PFM is caused by the pinning loss \( Q_p \) and viscous flow loss \( Q_v \) as expressed by the following equation [1]:

\[
Q = Q_p + Q_v = (F_p + F_v)v t_p
\]

\[
= \left( J_c B_{ex} v + \frac{B_{ex}^2 v^2}{\phi_0} \right) t_p,
\]

where \( F_p \) is the pinning force, \( F_v \) the viscous force, \( v \) the flux velocity, \( \eta \) the viscosity coefficient, \( \phi_0 \) a fluxoid quantum, \( J_c \) the critical current and \( t_p \) is the pulse duration. \( \eta \) is given by

\[
\eta(B_{ex}, T) = \frac{B_{c2}(T) \phi_0}{\rho_n(T)} \left( 1 + \frac{B_{ex}}{2B_{c2}(T)} \right),
\]

where \( B_{c2}(T) \) is the upper critical field and \( \rho_n(T) \) is the resistivity in the normal state. Similarly to \( \Delta T_{0max} \) (or \( Q \)) shown in the inset of Fig. 1(b), the \( B_{c2}^p \) value was also found to almost saturate after the No. 3 pulse. Accordingly, no additional flux trapping takes place during the No. 5 pulse and the pinning power loss \( Q_p \) may be negligible. Then \( Q(\text{No. 5}) \) for the No. 5 pulse shown in Fig. 4(b) can be regarded as almost due to the viscous loss \( Q_v \). If we assume that \( Q_v \) is not much different for each pulse, the difference \( \Delta Q = Q(\text{No. 1}) - Q(\text{No. 5}) \) may roughly stand for \( Q_p \) for the No. 1 pulse. The \( \Delta Q \) values as a function of \( T_s \) are displayed in Fig. 5(a) for each \( B_{ex} \) and Fig. 5(b) presents \( B_{c2}^p \) for the No. 1 pulse. Comparing Fig. 5(a) and (b), we notice that \( \Delta Q \) and \( B_{c2}^p \) have much similar \( T_s \) dependences, i.e., when \( \Delta Q \) is large, \( B_{c2}^p \) is also large. This fact supports our assumption that \( \Delta Q \) can be roughly regarded as \( Q_p \).

In Fig. 5(a), \( \Delta Q \approx Q_p \) exhibits the negative \( T_s \) dependence as a whole, which is reasonable on the basis of Eq. (2) because \( F_p \) or \( J_c \) should decrease with increasing \( T \). The \( dQ_p/dT_s \) values, however, take positive values for \( B_{ex} = 3.01 \) and 3.84 T below 60 and 50 K, respectively. This may be caused by the strong pinning centers in the peripheral region which obstruct the intrusion of the flux into the bulk. The existence of the strong pinning centers in the peripheral region was confirmed for this sample in the previous papers [4,5]. In Fig. 4(b), overall \( T_s \) dependence of \( Q_s (= Q \text{ (No. 5)}) \) is positive. This fact is somewhat puzzling because \( \eta \) is expected to decrease with increasing \( T \) owing to the reduction in \( B_{c2}(T) \) in Eq. (3). The existence of the strong pinning centers in the peripheral region can also be an origin of the positive \( dQ_v/dT \). The strong pinning in the peripheral region obstructs the free intrusion of the flux and suppresses the amount of the flux flow in the bulk. With increasing temperature, the peripheral pinning is weakened and a larger amount of the flux can freely penetrate into the bulk, resulting in the larger viscous loss \( Q_v \). The another possibility may be the increase in the effective flux velocity \( v \) in Eq. (2). If the critical state is realized during PFM, \( v \) should be inversely proportional to the pulse duration \( t_p \) and should be temperature independent for a fixed \( B_{ex} \). If the critical state is not attained because of too short \( t_p \), \( v \) may increase with \( T \) owing to the reduced \( F_p \), which may result in the increase in \( Q_v \) because \( Q_v \) is proportional to \( v^2 \) in Eq. (2).

In summary, the generated heat \( Q \) after applying the pulse magnetic field has been estimated for the SmBaCuO bulk superconductor using the maximum temperature rise \( \Delta T_{0max} \) and the measured specific heat \( C(T) \). Analyzing the pulse number dependence of \( Q \) for the five successive pulse applications with a fixed amplitude \( B_{ex} \), the contributions of the pinning power loss \( Q_p \) and the viscous flow power loss \( Q_v \) to the total \( Q \) have been roughly separated. \( Q_p \) decreases with increasing initial stage temperature \( T_s \) because of the reduction in the pinning force \( F_p \) with increasing \( T \). It has been confirmed that \( Q_p \), which is approximately
by $Q^p \cong \Delta Q = Q(\text{No. 1}) - Q(\text{No. 5})$, is closely correlated with the trapped magnetic field $B_T^p \cdot \text{d}Q_v/\text{d}T_s$ has been found predominantly to be positive, somewhat in contradiction with the theoretical expectation. The strong pinning centers in the peripheral region, which suppress the free intrusion of the flux may provide a plausible origin for the positive $\text{d}Q_v/\text{d}T_s$. Another possibility for $\text{d}Q_v/\text{d}T_s > 0$ may be the deviation from the critical state model, permitting the increase in the flux velocity $v$ and, resultantly, $Q_v$ with increasing $T$.

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