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Physica C 412–414 (2004) 646–650
PHYSICA C
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Estimation of generated heat in pulse field magnetizing for SmBaCuO bulk superconductor

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Received 29 October 2003; accepted 19 January 2004
Available online 7 May 2004

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 ΔT_{max} and specific heat $C(T)$. Five successive magnetic pulses with a fixed amplitude ($B_{ex} = 3.01\ T \sim 5.42$ T) are applied and ΔT_{max} are measured for the various initial temperature T_s between 40 and 70 K. Q has shown characteristic dependences on T_s, B_{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_s and B_{ex}.

PACS: 74.25.Bt; 74.80.Bj; 74.60.Ge
Keywords: Pulse field magnetizing; Heat generation; Specific heat; Pinning and viscous loss; SmBaCuO

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_T^P by PFM is lower than that by the static field-cooled magnetizing (FCM) [1–3]. The reason has been attributed to the temperature rise ΔT 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_s the applied pulse field B_{ex} and the distribution of B_T^P 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_T^P it is necessary to estimate the generated heat Q for various T_s and B_{ex} because the

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doi:10.1016/j.physc.2004.01.083

Q value may offer more exact information than ΔT.

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 ΔT_{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 $SmBa_2Cu_3O_y$ (Sm123) and Sm_2BaCuO_5 (Sm211) with the molar ratio of Sm123:Sm211 = 1.0:0.3, 15.0 wt.% Ag_2O powder and 0.5 wt.% Pt powder [6]. The bulk was tightly stuck on the cold stage of a Gifford McMahon 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 $T0(t)$ 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 ($L = 1.08$ 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 $T0(t)$ 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 $T_c(= 93$ 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 $T0(t)$ 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 $\Delta T0_{max}$ is presented. In all the cases, $\Delta T0_{max}$ 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 $\Delta T0_{max}$ for the (a) No. 1 and (b) No. 5 pulse applications as a function of T_s. With increasing T_s, $T0_{max}$ values on the first pulse

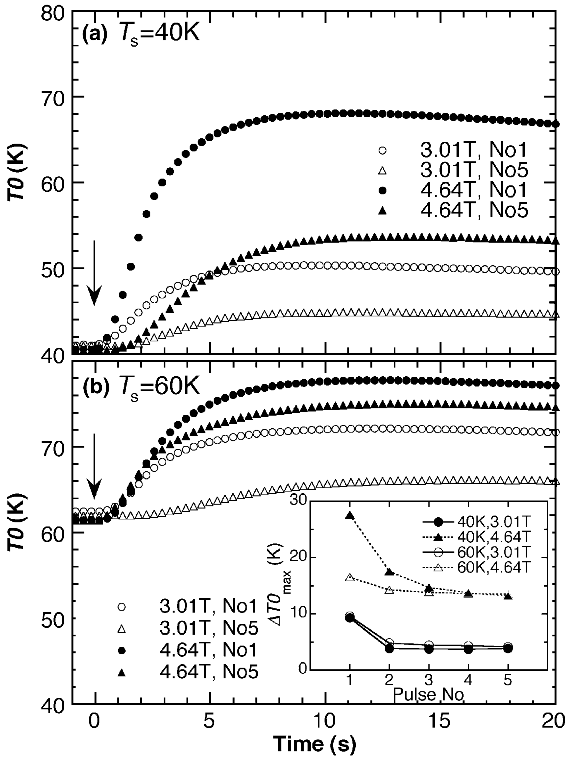

Fig. 1. Examples of the time evolution of temperature $T0(t)$ after applying the Nos. 1 and 5 pulse field of $B_{ex} = 3.01$ and 4.64 T at (a) $T_s = 40$ K and (b) $T_s = 60$ K. The pulse number dependence of the maximum temperature rise $\Delta T0_{max}$ is shown in the inset of (b).

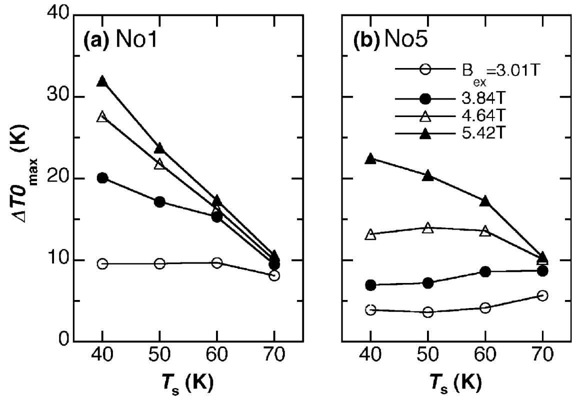

Fig. 2. The maximum temperature rise $\Delta T0_{max}$ for the (a) No. 1 and (b) No. 5 pulse application as a function of the initial stage temperature T_s.

application only slightly increase for $B_{ex} = 3.01$ T, while those for $B_{ex} \geqslant 3.84$ 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:

$$Q = \int_{T_s}^{T_s+\Delta T0_{max}} C(T)V\,dT, \quad (1)$$

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 (~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 $B_{ex} = 4.64$ T at $T_s = 40$ K ($\Delta T0_{max} = 28$ K). The estimated Q values using $\Delta T0_{max}$ may be underestimated because the heat generation occurs in the peripheral region and the $\Delta T0_{max}$ value is usually the smallest on the bulk surface [4–6]. Fig. 4 shows the results of the Q values for each B_{ex} as a function of T_s. It can be seen that the T_s dependences of Q in Fig. 4 and $\Delta T0_{max}$ in Fig. 2 are different. In Fig. 4(a) for the No. 1 pulse, Q for $B_{ex} \leqslant 4.64$ T increases with increasing T_s takes a maximum and decreases with the further increase in T_s On the other hand, Q for $B_{ex} = 5.42$ T monotonically decreases with increasing T_s. In Fig. 4(b) for the No. 5 pulse, Q for $B_{ex} \leqslant 3.84$ T monotonically increases with increasing T_s while Q for $B_{ex} \geqslant 4.64$ T takes a maximum at around 60 K. The Q (or $T0_{max}$) value was confirmed to be very small above T_c possibly because of the disappearance of F_p.

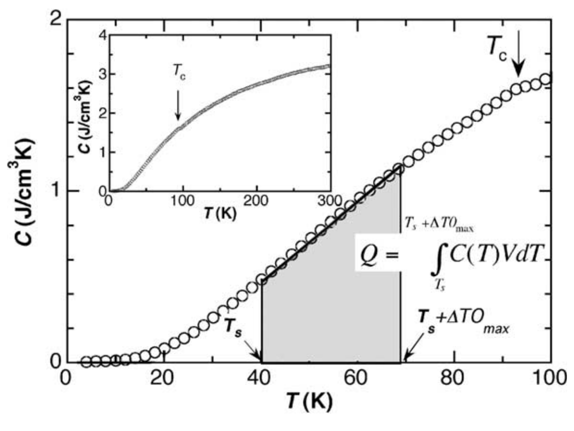

Fig. 3. The temperature dependence of the specific heat $C(T)$ of the SmBaCuO bulk.

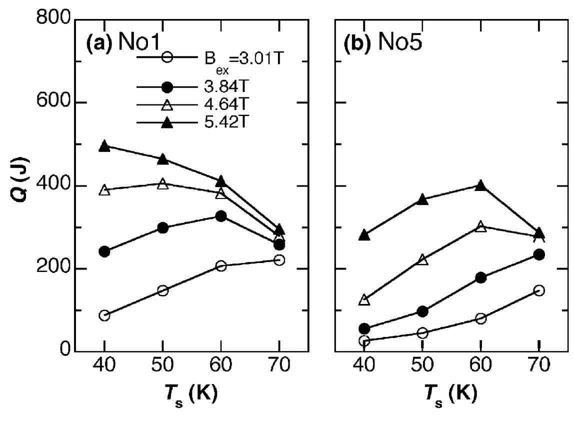

Fig. 4. The estimated Q values for each B_{ex} as a function of T_s after the (a) No. 1 and (b) No. 5 pulse application, respectively.

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]:

$$Q = Q_p + Q_v = (F_p + F_v)vt_p = \left(J_c B_{ex} v + \eta \frac{B_{ex}}{\phi_0} v^2\right) t_p, \quad (2)$$

where F_p is the pinning force, F_v the viscous force, v the flux velocity, η the viscosity coefficient, ϕ_0 a fluxoid quantum, J_c the critical current and t_p is the pulse duration. η is given by

$$\eta(B_{ex}, T) = \frac{B_{c2}(T)\phi_0}{\rho_n(T)} \left(1 + \frac{B_{ex}}{2B_{c2}(T)}\right), \quad (3)$$

where $B_{c2}(T)$ is the upper critical field and $\rho_n(T)$ is the resistivity in the normal state. Similarly to $\Delta T0_{max}$ (or Q) shown in the inset of Fig. 1(b), the B_T^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(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 ΔQ values as a function of T_s are displayed in Fig. 5(a) for each B_{ex} and Fig. 5(b) presents B_T^P for the No. 1 pulse. Comparing Fig. 5(a) and (b), we notice that ΔQ and B_T^P have much similar T_s dependences, i.e., when ΔQ is large, B_T^P is also large. This fact supports our assumption that ΔQ can be roughly regarded as Q_p.

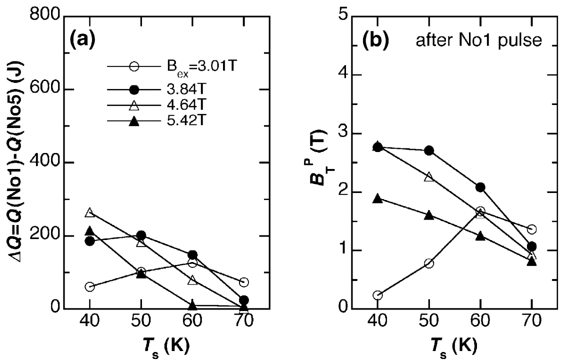

Fig. 5. (a) $\Delta Q(= Q(\text{No. 1}) - Q(\text{No. 5}))$ and (b) B_T^P for each B_{ex} as a function of T_s.

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 $Q_v(= Q$ (No. 5)) is positive. This fact is somewhat puzzling because η 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_s 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 $\Delta T0_{max}$ 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 $B_T^P \cdot dQ_v/dT_s$ 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 dQ_v/dT_s. Another possibility for $dQ_v/dT_s > 0$ may be the deviation from the critical state model, permitting the increase in the flux velocity v and, resultantly, Q_v with increasing T.

Acknowledgements

The authors greatly thank Prof. M. Ikebe of Iwate University for valuable suggestions and Dr. J. Hejetmanek of Institute of Physics, Academy Science of Czech Republic for the specific heat measurement. This work is partially supported by Japan Science and Technology Corporation under the Joint-research Project for Regional Intensive in the Iwate Prefecture on "Development of practical applications of magnetic field technology for use in the region and in everyday living".

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