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Three-dimensional simulation of magnetic flux dynamics and temperature rise in HTSC bulk during pulsed field magnetization

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Abstract

We have performed a three-dimensional (3D) numerical simulation of the dynamical motion of the magnetic flux and the heat propagation in the superconducting bulk after applying a pulsed magnetic field. An inhomogeneous J_c distribution was supposed in the bulk; the J_c in the growth sector boundary (GSB) is four times higher than that in the growth sector region (GSR). For lower applied pulsed field, magnetic flux was penetrated and trapped in the GSR, and for higher applied pulsed field, the magnetic flux was trapped more preferentially in the GSB. These results of the simulation reproduce the experimental ones and are valuable for the understanding the flux dynamics in the bulk during pulsed field magnetization.

Keywords; pulsed field magnetization; inhomogeneous J_c distribution; flux dynamics; heat propagation; numerical simulation

1. Introduction

RE-Ba-Cu-O superconducting bulk (RE: rare earth element or Y) can trap higher magnetic field, B_z, using a pulsed field magnetization (PFM). The B_z value by PFM is, however, pretty smaller than that by field-cooled magnetization (FCM) because of a large heat generation due to the rapid magnetic flux motion. We have investigated experimentally the enhancement of B_z by PFM based on the results of temperature rise and flux movement [1, 2]. To explore the desired research direction to the enhancement of B_z, it is necessary to analyze both the flux dynamics and the heat propagation numerically. We

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constructed a framework of the two-dimensional (2D) numerical simulation in the bulk with homogeneous critical current density J_c distribution during PFM, and simulated the time and spatial dependence of local field $B_z(t, r)$ and temperature $T(t, r)$ for a single magnetic pulse application [3, 4] and for a multi-pulse field application [5], all of which reproduced the experimental results qualitatively. However, an inhomogeneous J_c distribution exists in the actual bulk because of the characteristic crystal growth mechanism, and the inhomogeneous flux motion and heat propagation were measured experimentally. In this study, we constructed and performed a three-dimensional (3D) numerical simulation of the dynamical motion of the magnetic flux and the temperature rise in the superconducting bulk with an inhomogeneous J_c distribution after applying a pulsed magnetic field.

2. Numerical model and simulation

Based on the procedures and results of the axi-symmetric simulation [6], a framework of the 3D numerical simulation was constructed using the finite element method (FEM). A superconducting bulk disk 46 mm in diameter and 15 mm in thickness was cooled from the bottom surface. The spacing plate with the thermal conductivity, κ_{cont} (=0.5 $Wm^{-1}K^{-1}$), between the bulk and the cold stage (T_s=40 K) with 1 mm in thickness was set, which imaginarily represented both the cooling power of the refrigerator and the thermal contact of the bulk to the cold stage. The upper and side surfaces of the bulk were supposed to be adiabatic. For the numerical analysis, one forth of the superconducting bulk disk was considered, which was equally divided into 9 elements along the circumferential direction, into 6 elements along the radial direction and into 6 elements along the thickness direction, respectively, as shown in Fig. 1. The pulsed field $B_{ex}(t)$ with a rise time of τ=0.01 s and with a pulse duration of 0.1 s was applied to the bulk using a solenoid coil (82 mm I.D., 116 mm O.D., and 50 mm height). Commercial software, Photo-Eddy^{TM}, combined with Photo-Thermo^{TM} (Photon Ltd, Japan) was adopted for the analysis using a personal computer.

The power-n model (n=8) was used to describe the nonlinear E-J characteristic in superconducting bulk. The temperature and magnetic field dependence of the critical current density $J_c(T, B)$ was described as,

$$J_c(T,B) = \alpha\left\{1-\left(\frac{T}{T_c}\right)^2\right\}^{\frac{3}{2}} \frac{B_0}{|B|+B_0}, \qquad (1)$$

where T_c (=92 K) is the critical temperature at B=0, and B_0 (=1.3 T) is constant. An inhomogeneous J_c distribution was supposed in the bulk; one segment of the bulk shown in Fig. 1 was regarded as the GSB and the other 8 segments were regarded as the GSRs. In Eq. (1), the α values of 1.83 x 10^9 for GSB and 0.46 x 10^9 for GSR were adopted, which corresponded to the J_c(40 K, 0 T) values of 1.33 x 10^9 A/m^2 and 0.33 x 10^9 A/m^2, respectively. The anisotropic thermal conductivities κ_{ab}=20 $Wm^{-1}K^{-1}$ in the ab-plane and κ_c=4 $Wm^{-1}K^{-1}$ along the c-axis are adopted. For comparison, the numerical simulations for homogeneous J_c distribution with J_c(40 K, 0 T)=0.33 x 10^9 A/m^2 and 1.33 x 10^9 A/m^2 were performed.

3. Results and discussion

3.1. Time dependence of the flux penetration and temperature rise

Examples of the time and position dependence of the local field B_z and temperature T are shown in Fig. 1 for B_{ex}=6 T. At the beginning stage of the magnetic pulse application, *i.e.*, at t=0.002 and 0.006 s shown

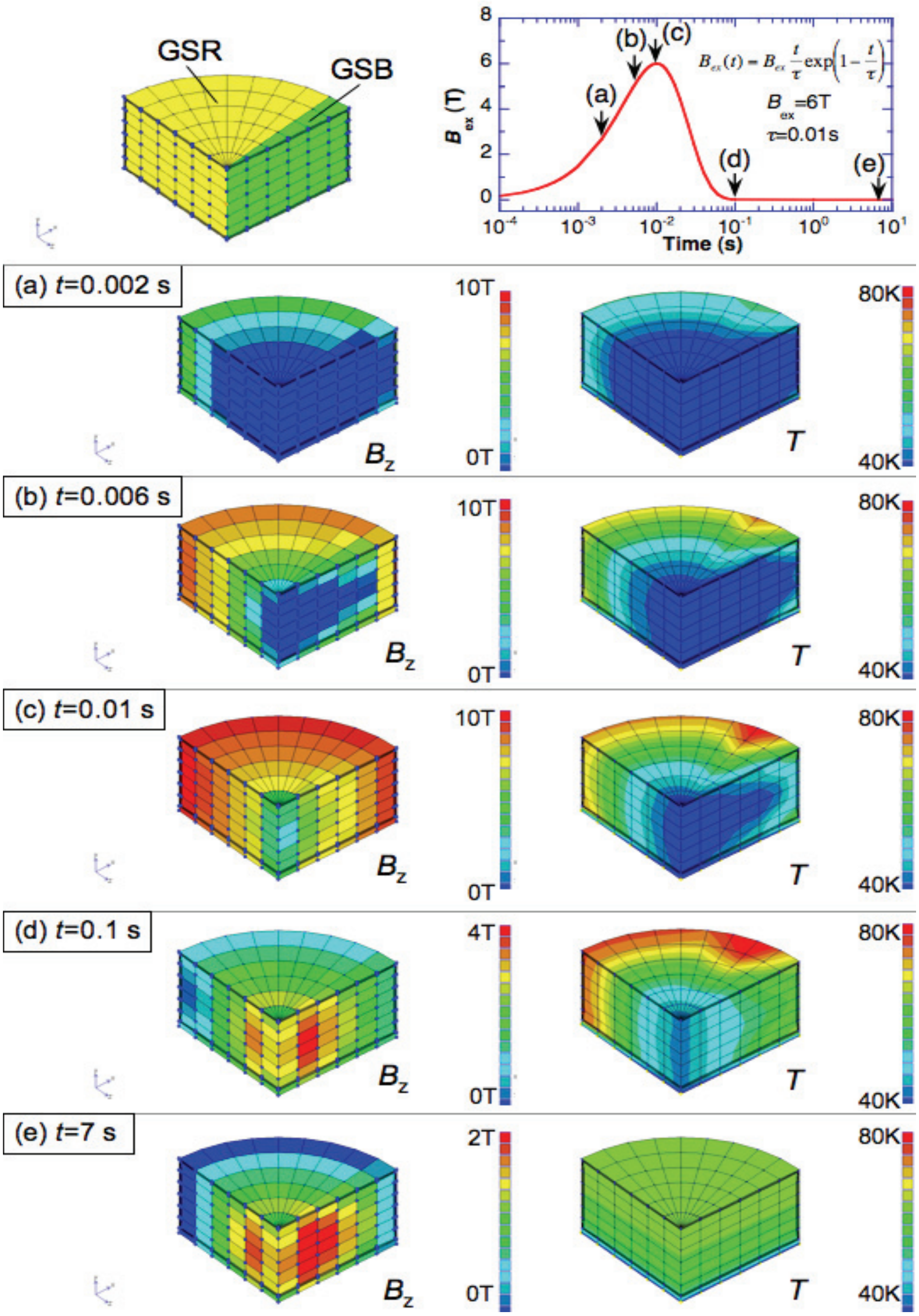

Fig. 1. The time and spatial dependences of the local field B_z and temperature T for the bulk after applying the pulsed field of 6 T at (a) t=0.002 s, (b) 0.006 s, (c) 0.01 s, (d) 0.1 s and (e) 7 s. The model of the simulation and the time dependence of the pulsed field $B_{ex}(t)$ are also shown.

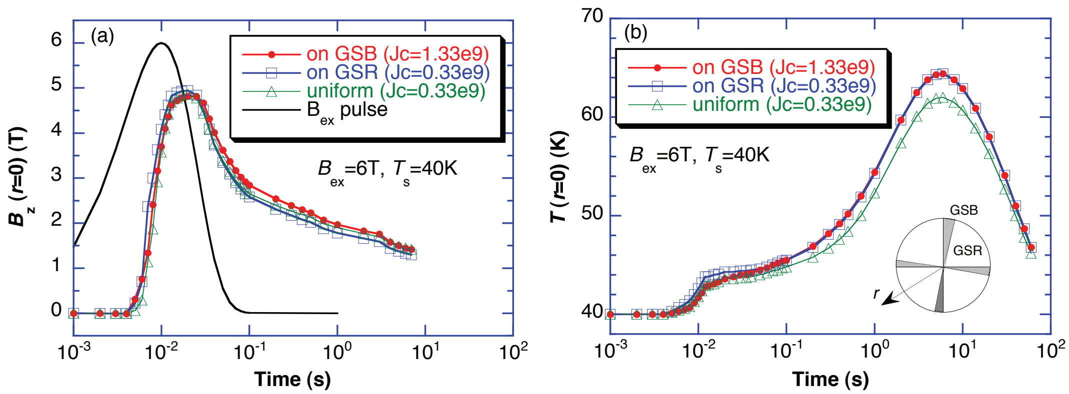

Fig. 2. The time evolution of the local field B_z and temperature T at the center of the bulk surface after applying the magnetic pulse of B_{ex}=6 T. The

in Figs. 1(a) and 1(b), the magnetic flux mainly intrudes into the bulk along the GSR. Because of the flux movement (viscous loss, Q_v) and the flux trap (pinning loss, Q_p), the temperature rise took place mainly at the GSRs. At the peak of t=0.01 s shown in Fig. 1(c), the magnetic flux intrudes also into the GSB, but the temperature rise in the GSB was delayed because of the lower thermal conductivity κ_{ab}. Thereafter, a large amount of the intruded magnetic flux was escaped from the bulk periphery as shown in Fig. 1(d), and the final trapped field in the GSB became larger than that in the GSR as shown in Fig. 1(e). The generated heat around the bulk periphery diffused in the bulk with increasing time and was exhausted from the cold stage.

Figures 2(a) and 2(b) show the time evolution of the local field and temperature at the center (r=0) of the bulk surface, respectively, after applying the magnetic pulse of B_{ex}=6 T. The results for the uniform J_c distribution are also shown. $B_z(r=0)$ takes a maximum at t=0.02 s and $T(r=0)$ takes a maximum at t=7 s, and then decreasing with time. Both results are almost independent of the J_c distribution in the bulk.

3.2. Trapped field in a steady state

Figure 3(a) shows the applied field dependence of the trapped field $B_z(r=0)$ around the center of the bulk surface on the GSB and GSR. The results for the uniform J_c distribution were also shown. For lower applied field ($B_{ex}\leq 3$ T), the magnetic flux was not trapped around the bulk center, but at the bulk periphery. For higher applied field ($B_{ex}\geq 4$ T), the magnetic flux was intruded into the center and the $B_z(r=0)$ takes a maximum at B_{ex}=5 T and then decreases with further increase in B_{ex} because of the heat generation. The difference of B_z between on the GSB and on the GSR was small. However, B_z on the GSR was larger for lower B_{ex}, but that on the GSB was larger for higher B_{ex}. For the uniform J_c distribution of J_c=0.33 x 10^9 A/m^2, the B_z vs. B_{ex} curve is an intermediate character of that on GSB and on GSR. However, for the higher and uniform J_c distribution of J_c=1.33 x 10^9 A/m^2, the magnetic flux starts to intrude and trap at B_{ex}=7 T and B_z takes a maximum at 9 T.

Figures 3(b) and 3(c) show the angular dependence of the trapped field B_z for each radius of the bulk surface for B_{ex}=3 T and 6 T, respectively. Figures 4(a) and 4(b) show respectively, the trapped field B_z on the GSB and GSR of the bulk surface, as a function of radius r at B_{ex}=3 T and 6 T. For lower applied field of B_{ex}=3 T, the magnetic flux is preferably trapped on GSR. However, for the higher B_{ex} of 6 T, the trapped field on the GSB is higher than that on the GSR. These results well reproduced the experimental ones reported by Yanagi [7] and Fujishiro [8].

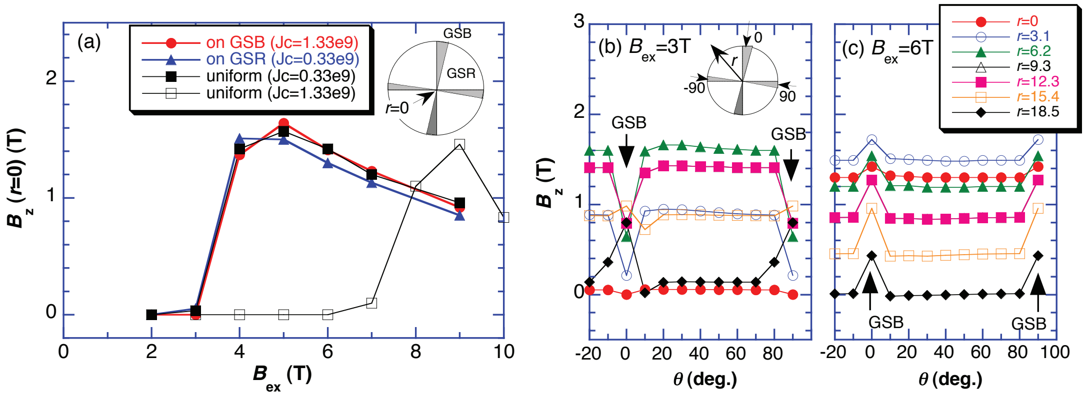

Fig. 3. (a) The applied field dependence of the trapped field $B_z(r=0)$ on the GSB and GSR. Those for the uniform J_c distribution are also shown. Angular and radius dependences of the trapped field B_z on the bulk surface for (b) B_{ex}=3 T and (c) B_{ex}=6 T.

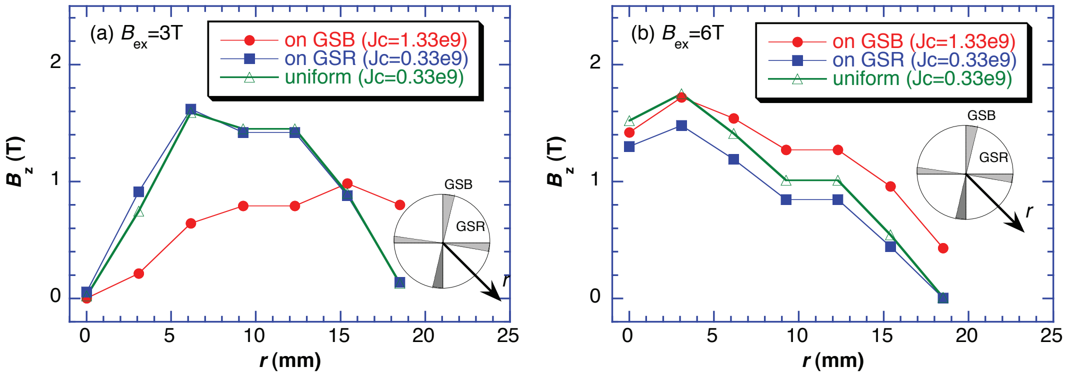

Fig. 4. The trapped field B_z on the GSB and GSR of the bulk surface, as a function of radius r at (a) B_{ex}=3 T and (b) 6 T. The results for the uniform J_c distribution are also shown.

4. Summary

We have performed a three-dimensional (3D) numerical simulation of the dynamical motion of the magnetic flux and the temperature rise for the superconducting bulk after applying a pulsed magnetic field. An inhomogeneous J_c distribution was supposed in the bulk; the J_c of the growth sector boundaries (GSBs) is four times higher than that of the growth sector regions (GSRs). For lower applied pulsed field, magnetic flux was penetrated and trapped on the GSRs, and for higher applied field, the magnetic flux was trapped more preferentially on the GSBs. These results of the simulation reproduce the experimental ones and are valuable for the understanding the flux dynamics in the bulk.

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