The 3rd harmonic AC susceptibilities in the grain model of high-$T_c$ superconductors

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Abstract

AC susceptibility measurement has been widely used to investigate the magnetic properties of high-$T_c$ superconductors which is composed of the grains and their interconnecting links. Transport critical current density is low because of a grain structure. The fundamental AC susceptibility of the superconductors with the grain structure has been successfully simulated using the critical state model by Irie and Yamafuji and gave separately the critical current densities in both intra- and inter- grains. The 3rd harmonic AC susceptibilities with a real part $\chi''$ are numerically calculated in the grain model to get more clear insight of the grain-link structure. The double peaks and multi-transitions also appear in the simulated curves. The simulated results are satisfactorily compared with the measured characteristics of Sm-123 superconductors to give pinning penetration fields $B_{pg}$ and $B_{pl}$ of the grain and the link. Combining with the crystallographic investigation, the critical current densities $J_{cg}$ and $J_{cl}$ in the grain and the link can be estimated.

Keywords: grain model; AC susceptibility; 3rd harmonics; pinning penetration field; Sm-123

1. Introduction

Transport critical current densities of high-$T_c$ superconductors do not achieve the practical level because of their polycrystalline microstructures with interconnecting link regions between the grains. The grains are intrinsic superconducting region with high critical current density $J_{cg}$ and link regions exhibit weak superconductivity with low critical current density $J_{cl}$. Respective examination of each property of the multiphase is indispensable to obtain a quantitative insight and to improve the superconducting intergrain quality. In grained materials, the coupling component supports global supercurrents and has its own effective critical temperature $T_{cl}$, critical current density $J_{cl}$ and pinning penetration depth $B_{pl}$. In the weak superconducting coupling region the magnetic flux enters more freely through them compared to the grain regions. Then the interface fields of the grains are designated by the matrix superconducting phases. The field profile can be expressed as the intrinsic superconducting grains with high pinning penetration field $B_{pg}$ are distributed inside the weak matrix region with low $B_{pl}$.

Field distribution and magnetization in the grain model has been calculated by Bean model [1] in the previous report [2, 3]. Critical current densities, however, depend strongly on field and the grained Bean model could not fit well in the wide field range. In the preceding paper, the field profiles of the grain model were described by Irie-Yamafuji pinning model [4] which is known to agree well with the superconducting characteristics in the wide field region. The fundamental AC susceptibilities simulated were successfully compared with the measured curves. AC
susceptibility study of 2-phase superconductors simulated using the grain model will clarify the inter-granular characteristics of the grained superconductors. Here, the 3rd harmonic AC susceptibilities of the grain model are investigated to get more detailed characteristics of grain-link interface.

2. Grain model

The magnetic field distributions of the matrix superconductor with half width $D$ are arranged by a penetration field $B_{pt}$ and a pinning parameter $\gamma_t$, and the field at the grain surface with the penetration field $B_{pg}$ and a pinning parameter $\gamma_g$ are settled as shown in Fig. 1. The field $B_t$ outside the grain is given by $B_{pt}$ following the Irie-Yamafuji model as

$$B_t = B_o \pm B_{pt} \cdot X / D$$

where the sign is fixed by pinning effect for the fluxoid motion, and the field $B_g$ inside the grain with the size $d_g$ similarly by both $B_{pg}$ and $B_t$

$$B_g = B_o \pm B_{pg} \cdot x / d_g$$

2.1. AC susceptibility

Averaged magnetic flux density $<B> \text{ is calculated and the magnetization } M \text{ at field } B_o \text{ is given as } <B> = -B_o$.

Fourier integrals of $M$ give the $n$-th AC susceptibilities $\chi_n$ and $\chi_n''$ under an AC field $B_a \exp(i\omega t)$ as [5]

$$\chi_n = \chi'_n - i\chi_n'' = \frac{1}{\pi B_o} \int_0^\infty M(\omega t) \exp(-in\omega t) d\omega$$

Numerical integration of eq. (3) is carried out and the imaginary part of the first and third AC susceptibilities $\chi_1''$, $\chi_3''$ and the real part $\chi_1$, $\chi_3'$ are plotted in Fig. 2 as a function of the amplitude $B_a$ normalized by the link penetration field $B_{pl}$. Introduction of grains of $B_{pg} / B_{pl}$ and grain volume factor $f_g = d_g / d_v = 0.3$ yields a second peak at high field. Decrease of pinning effect of the inter-grain induced by low $\gamma_t$ ($= 0.5$) shifts the peak and transition portion to lower field region. The third harmonics of AC susceptibilities produce small but distinctive signals like double peaks in $\chi_1''$ curves.

2.2. Temperature dependence of 3rd harmonic AC susceptibility

![Fig. 1. Field distribution $B_t$ outside the grain and distribution $B_g$ inside the grain. Penetration fields are $B_{pt}$ and $B_{pg}$ for matrix and grain, respectively. The grain diameter is $2d_g$ and the distance between grains is $2d_v$.](image1)

![Fig. 2. Computed AC susceptibilities $\chi_1$ and $\chi_3$ as a function of AC field $B_a$ normalized by $B_{pl}$ at pinning parameters of $\gamma_t = 1, \gamma_t = 1$ and 0.5.](image2)
Temperature dependence of the 3rd AC susceptibilities $\chi''$ and $\chi'$ can be obtained by introducing the temperature variation of the penetration fields of $B_{pg}$ and $B_{pl}$ which have a usual parabolic dependence of the form,

$$B_{pg} = B_{pg0} \left( 1 - \left( T / T_{cg} \right)^2 \right)^{\frac{1}{2}}$$  \hspace{1cm} (4)$$

$$B_{pl} = B_{pl0} \left( 1 - \left( T / T_{ct} \right)^2 \right)^{\frac{1}{2}}$$  \hspace{1cm} (5)$$

where the pinning effect for the fluxoid motion disappears over the temperatures $T_{ct}$ and $T_{cg}$ in the link and the grain region.

2.3. Effect of link penetration field $B_{pl0}$ on 3rd harmonic AC susceptibilities

Graphs of the 3rd harmonic AC susceptibilities of $\chi''$ and $\chi'$ at $B_{pl0} / B_a = 5$, $\gamma_p = \gamma_l = 1$, $f_g = 0.5$ and $B_{pl0} / B_a = 0.5$-50 are shown in Fig. 3. At high temperatures $B_{pl}$ reduces and the flux front penetrates into the center of the superconductor through the inter-grain matrix shown as dotted to solid lines in the figure. With increasing $B_{pl0}$, the valley moves towards high $T / T_c$ and the depth of valley portion becomes deeper.

2.4. Effect of grain penetration field $B_{pg0}$ on 3rd harmonic AC susceptibilities

The 3rd harmonic susceptibilities of $\chi''$ and $\chi'$ at $B_{pg0} / B_a = 5$, $\gamma_p = \gamma_l = 1$ and $B_{pg0} / B_a = 2.5$-500 are shown in Fig. 4. Around the penetration temperature of the grain $T_{pg} = \left( 1 - \left( B_a / B_{pg0} \right)^{1 / \gamma_p} \right) / 0.894$, the valley due to the grain exists in all curves and the valley due to the link moves from low to high temperature region and merges with the grain valley. For low values of $B_{pg0} / B_a$, the link valleys are converted by the grain valley. With increasing $B_{pg0} / B_a$, the grain valleys shift to high temperature, the link valleys appear and the double valley structure is observed.

2.5. Effect of grain volume factor $f_g$ on 3rd harmonic AC susceptibilities

The 3rd harmonic AC susceptibilities at $B_{pl0} / B_a = 5$, $B_{pg0} / B_a = 50$, $\gamma_p = \gamma_l = 1$ and $f_g = 0$ to 1 are shown in Fig. 5. In the case of no grain $f_g = 0$, the curve shows typical 3rd harmonic profile. With increasing the grain content, the link valley become shallow and the grain valley is born and grows up.

3. Grain and link characteristics in Sm-123 superconductors

SmBa$_2$Cu$_3$O$_{7-\delta}$ melt-solidified bulk superconductors were melt-processed in air [6]. Sample size is 3.2×1.0×0.6 mm$^3$ and grain size is 10 μm estimated from SEM observation. AC susceptibilities of Sm-123 superconductor were measured using PPMS (Quantum Design Co.). The 3rd harmonic AC susceptibilities $\chi''$ and $\chi'$ are shown in Fig. 6 (a) at the applied DC magnetic field $B_{dc}$ of 0 to 14 T. The simulated results by the grain model are plotted in Fig. 6 (b) and parameters $B_{pg0}$, $B_{pl0}$ and $f_g$ in Fig. 7. With increasing $B_{dc}$, the valleys become shallower. Sharp decrease of $f_g$ with increasing $B_{dc}$ is caused by declining valley signal and should not be associated the reduction of the grain region. Simi-
lar decreasing property with field can be derived from the reversible motion of the fluxoid concerning the AC penetration depth $\lambda_0$ defined by Campbell [7].

The critical current densities of the grain $J_{cg}$ and the link $J_{cl}$ are estimated from $B_{pg}$ and $B_{pl}$ using $J_{cg} = \frac{2B_{pg}}{\mu_0 d_g}$ and $J_{cl} = \frac{B_{pl}}{\mu_0 D}$ at temperature 20, 40, 60 and 77 K in Fig. 8. The critical current densities estimated from the fundamental at 77 K are plotted satisfactorily as dotted line.

4. Conclusions

It has been shown that, AC susceptibility of high-$T_c$ superconductor is well accounted in the assumption of uniform grain structure, where the superconducting regions are divided into two parts; grains and interconnecting links. The magnetic flux distributions are described by Irie-Yamafuji critical state model. The real and imaginary parts of the measured susceptibilities are favourably compared with the simulated grain model. The critical current densities at the grain and the interconnecting link are successfully estimated. Most likely, the remarkable reduction of the valleys observed in $\chi'$ should be associated with the reversible motion of the fluxoids.

References