Irreversibility Field in Hg-1223 Grain Aligned Powders

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ABSTRACT

The crystal axis of Hg-1223 powders was aligned in epoxy resin under a high magnetic field and the irreversibility field, $B_{\rm i}$, was estimated from the onset of the temperature dependence of the fundamental and third harmonic AC susceptibilities under a magnetic field parallel to the c-axis. When the temperature dependence of $B_{\rm i}$ is expressed as $[1-(T/T_{\rm c})^2]^n$, n was large at low temperatures and reduced to 1.5 at high temperatures. This behavior is the same as other oxide superconductors and indicates that two kinds of pinning centers work collectively. The flux creep theory with assuming two kinds of pinning centers successfully explains the temperature dependence of $B_{\rm i}$. Comparing the present result with the pinning force density dependence of $B_{\rm i}$ in various oxide superconductors, the dimensionality of Hg-1223 was found to be close to that of Bi-2223 and Hg-1212.

KEYWORDS: Hg-1223, irreversibility line, pinning potential, flux creep, grain aligned powder, dimensionality of superconductor

INTRODUCTION

Hg-1223 superconductor has the highest transition temperature in Hg-series superconductors (Hg-1201, Hg-1212, Hg-1223, Hg-1234) which are less anisotropic [1]. It was found by Shimoyama *et al.* [2] that the synthesis of Hg-based superconductor was stabilized by doping Re instead of using high pressure synthesis. However, it has not yet succeeded to prepare axis-oriented bulk materials. On the other hand, it is possible to align the crystal axis of powders of this material under a relatively high DC magnetic field [3]. From the viewpoint of application, it is important to estimate the irreversibility field where the critical current density reaches zero due to the flux creep. It is known that the irreversibility field of Hg-1223 reaches several T at 77.3 K [4]. This is partly ascribed to its high critical temperature but also to its higher dimensionality than Bi-2212 superconductor. However, the dimensionality of Hg-1223 has not yet been clarified quantitatively. In this study the irreversibility field of Hg-1223 powder with aligned grains in a DC magnetic field is estimated using AC susceptibility measurements, and the result is analyzed using the flux creep theory. Discussion is given on the dimensionality of the Hg-1223 superconductor and the potential of this material for applications.

EXPERIMENTS

The investigated specimen was prepared in the program-controlled high pressure chamber. Starting materials were mixed in a gold capsule and placed in the reaction cell between the profiled anvils and the pressure was raised to 2–4 GPa at 700–1000℃. The oxygen doping of specimen is controlled by changing oxygen content in starting materials and is in the optimum condition. Further details of the synthesis were reported in elsewhere [5]. The average powder size is 10 μm. The alignment of grain was carried out in stycast epoxy resin by applying a DC magnetic field of 9 T at 300 K.

During the process the magnetization was observed and found to decrease with time, suggesting the alignment of the c-axis of grains parallel to the magnetic field. The temperature dependence of the fundamental and the third harmonic AC susceptibilities was measured under various DC magnetic fields and the irreversibility field was estimated. The AC magnetic field amplitude and the frequency were 1.0 mT and 1.0 kHz, respectively. A DC magnetization hysteresis was also measured at various temperatures for estimation of the critical current density. All measurements were carried out using a commercial magnetometer (PPMS, Quantum Design) under the magnetic field parallel to the c-axis. The critical temperature estimated from onset of the fundamental AC susceptibility was 132.5 K.

RESULTS AND DISCUSSION

Figure 1 shows the result of the irreversibility field, $B_{\rm i}$, estimated from fundamental and third harmonic AC susceptibilities (χ_1'', χ_3', χ_3'') as a function of temperature. The criterion of AC susceptibilities for χ_1 and χ_3 are 1.0×10^{-4} (SI) and -6.0×10^{-6} (SI), respectively. The results from the three methods agree well, indicating that the viscous force on flux lines is not appreciable at this frequency. When the temperature dependence of the irreversibility field is expressed as $B_{\rm i} \propto [1 - (T/T_{\rm c})^2]^n$, n is large at low temperatures, while n gradually reduces to 1.5 at high temperatures. This behavior is known in other oxide superconductors (Y-123, Bi-2212, Bi-2223), and it is speculated that plural kinds of pinning centers act collectively, resulting in different pinning properties in different temperature regions [6]. Namely at high temperatures, relatively larger pinning centers than the flux line spacing such as non-superconducting particles are considered to be dominant, resulting in $n = 1.5$ as predicted by the pinning and the flux creep theories. Therefore, similar pinning centers are also expected in Hg-1223.

The DC magnetic field dependence of the critical current density, $J_{\rm c}$, at various temperatures estimated from the hysteresis of DC magnetization is shown in Fig. 2. The accurate estimation of $J_{\rm c}$ is difficult due to the distribution of the grain size. For simplicity we use the mean value, $d = 10$ μm. At high temperatures $J_{\rm c}$ decreases drastically according to increasing DC magnetic field due to the flux creep.

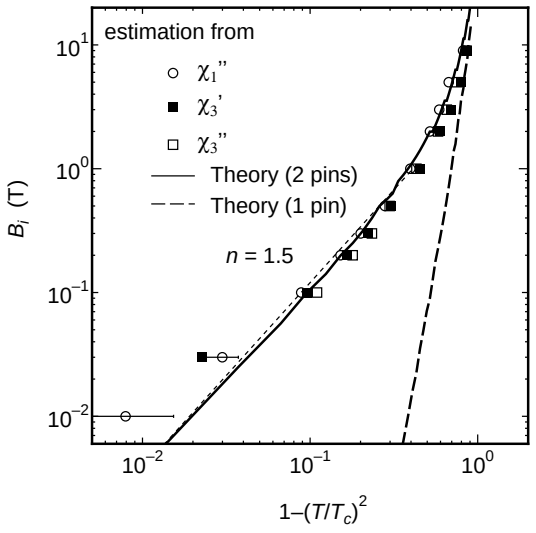

Fig. 1. Temperature dependence of irreversibility field in Hg-1223. Lines denote theoretical predictions based on the flux creep theory.

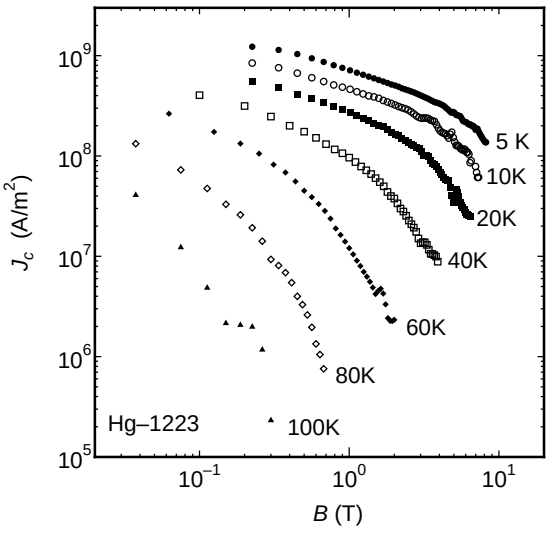

Fig. 2. Magnetic field dependence of the critical current density estimated from DC magnetization hysteresis at various temperatures.

According to the flux creep theory, the electric field, E, is induced by the thermally activated motion of the flux bundle trapped in the pinning potential well. Therefore, $B_{\rm i}$ is strongly related to the pinning potential. The pinning potential is described in terms of the virtual critical current density, $J_{\rm c0}$, in the creep-free case, which represents the flux pinning strength [6]. The dependences of $J_{\rm c0}$ on temperature and magnetic field are given as

$$J_{\rm c0} = \frac{F_{\rm p0}}{B} = A\left[1-\left(\frac{T}{T_{\rm c}}\right)^2\right]^m B^{\gamma-1}\left(1-\frac{B}{B_{\rm c2}}\right)^\delta, \tag{1}$$

where A, γ and δ are pinning parameters. From the result of $J_{\rm c}$ at low temperatures, where the effect of flux creep is not significant, these pinning parameters can be determined. The irreversibility field is predicted to be given by

$$B_{\rm i}^{(3-2\gamma)/2} = \left(\frac{K}{T}\right)\left[1-\left(\frac{T}{T_{\rm c}}\right)^2\right]^m \left(1-\frac{B}{B_{\rm i}}\right)^\delta \tag{2}$$

in the flux creep theory [6]. In the above, K is approximately a constant value given by

$$K = \frac{0.835 g^2 A^{1/2}}{\zeta \ln(B a_{\rm f} \nu / E_{\rm c})}, \tag{3}$$

where g^2 is the number of flux lines inside the flux bundle, ζ is a constant dependent on the kind of pinning centers, $a_{\rm f}$ is the flux line spacing, ν is the damping oscillation frequency and $E_{\rm c}$ is the criteria of the electric field where $J_{\rm c}$ is determined. g is theoretically expressed as $g = (C_{66}/\zeta J_{\rm c0} B a_{\rm f})^{1/2}$, where C_{66} is the shear modulus of the flux line lattice. It is to be noted that the value of C_{66} depends on the state of the flux line lattice and cannot be derived deterministically. Therefore, C_{66} and g are obtained only from the thermodynamic principle that the critical current density under flux creep takes the maximum value. If the value of g when the flux line lattice is a perfect triangle lattice is denoted by $g_{\rm e}$, g is theoretically derived as a function of $g_{\rm e}$ [7].

Here we assume that two kinds of pinning centers work collectively. One of them is considered to be dominant at low temperatures and responsible for the measured $J_{\rm c}$. Point-like defects seem to be this kind of pinning centers. The other pinning centers may be particles of non-superconducting phases which are found in other superconductors [6]. These pinning centers are known to work effectively at high temperatures. Here we assume that the size and the volume fraction of normal particles are 2 μm and 5 %, respectively. In this case $J_{\rm c0}$ is theoretically calculated and the values of A, m and γ are given [6]. Table 1 shows the pinning and other material parameters such as the normal resistivity, ρ_n [1].

In Fig. 1 the lines show the numerically calculated results of the irreversibility field in the cases of two kinds of pinning centers and one kind of pinning centers. Details of the calculation are described in reference [6]. The theoretical result for the two kinds of pinning centers agrees well with the experimental result. Therefore, it is speculated that two kinds of pinning centers act collectively. This result indicates that an introduction of pinning centers such as non-superconducting particles is necessary to increase the pinning force as well as the irreversibility field.

Finally a discussion is given for the dimensionality of the Hg-1223 superconductor. Figure 3 shows the relation between $B_{\rm i}$ and the pinning force density in creep-free case, $F_{\rm p0}$, at 4.2 K, 1 T for various oxide superconductors with optimum doping. The lines in the figure show the relation $B_{\rm i} \propto F_{\rm p0}^{1/3}$ predicted by the flux creep theory when $\gamma = 0.5$. The result for Hg-1223 is located near the lines for Bi-2223 and Hg-1212 between the three-dimensional Y-123 and the two-dimensional Bi-2212. Thus, it is concluded that the dimensionality of Hg-1223 is similar to that of Bi-2223. That is, $B_{\rm i}$s in Hg-1223 and Bi-2223 are similar at the same $T/T_{\rm c}$, if the flux pinning strength is same as seen in Fig 3. However, $B_{\rm i}$ of Hg-1223 at 77 K is larger than that of Bi-2223, since $T_{\rm c}$

Table 1: Pinning and material parameters of Hg-1223 specimen.

pinning center	type 1	type 2
$\rho_n(T_c)$ [1]	4.0×10^{-5} Ωm	
T_c	132.5 K	
$B_{c2}(0)$	100 T	
E_c	1.0×10^{-7} V/m	
A	1.0×10^9	8.0×10^8
γ	0.43	0.5
m	7.6	1.5
ζ	6.28	4.0
g^2	5.3	2.6
g_e^2	310	130

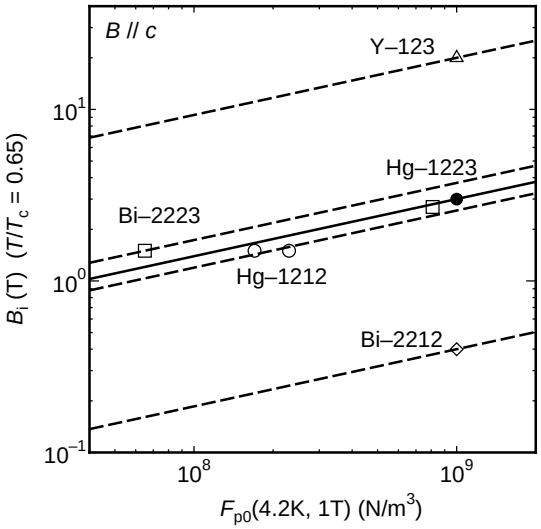

Fig. 3. Irreversibility field along the c-axis at $T/T_c = 0.65$ vs pinning strength for various superconductors.

of Hg-1223 is higher. Therefore, the potential of Hg-1223 for applications is higher than that of Bi-2223. It is required to search a condition of optimum doping and methods to introduce strong pinning centers and to improve crystal structure for application of this material.

SUMMARY

In this study, the irreversibility field of the grain-aligned Hg-1223 along the c-axis was investigated and compared with the prediction of the flux creep theory. Following results are obtained:

1. The temperature dependence of the irreversibility field is large at low temperatures and small at high temperatures. This behavior is the same as other oxide superconductors and indicates that two kinds of pinning centers act collectively. The flux creep theory can explain quantitatively the irreversibility field well with the assumption that non-superconducting particles work as pinning centers.
2. The dimensionality of Hg-1223 is similar to that of Bi-2223 and Hg-1212 from the comparison of the irreversibility field and the pinning strength. From the viewpoint of application at 77 K, Hg-1223 has higher potential than Bi-2223 because of higher critical temperature.

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