Distribution of Critical Current Density in a Superconducting Bi-2223 Tape Wire

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ABSTRACT

The distribution of pinning strength is estimated from measured current-voltage curves using the Weibull function for a Bi-2223 silver-sheathed tape wire under a magnetic field parallel to the c-axis. The obtained result is compared with a simple distribution function assumed in the analysis of the scaling of current-voltage curves using the flux creep-flow model. It is found that the simple distribution function describes well. The wide distribution seems to be caused by percolating current paths due to weak lines.

KEYWORDS: Bi-2223 tape wire, scaling of current-voltage curve, distribution of pinning strength, Weibull function

INTRODUCTION

The scaling of the current-voltage curves of high-temperature superconductor was predicted by the mechanism of vortex glass-liquid transition [1] and the scaling was examined for a Y-123 thin film [2]. On the other hand, not only the scaling but also the transition line and the two critical indices were explained for Bi-based superconductors by the flux creep-flow model in which the distribution of the pinning strength was taken into account [3, 4]. Such a scaling is attributed to a divergence of the correlation length of pinning at the transition point similarly to that assumed in the vortex glass-liquid transition theory. This means that this transition is not a phase transition inherent to flux lines in layered superconductors but seems to be the one governed by the flux pinning.

At the same time, it was found that the distribution of pinning strength was much wider than in metallic superconductors. This seems to be caused by percolating current paths due to weak links. It is necessary to confirm the reasonable of such a wide distribution. It is known that the distribution of pinning strength can be expressed well using the Weibull function [5]. In this study, the Weibull function is estimated for a Bi-2223 tape specimen from the current-voltage curves under the magnetic field parallel to the c-axis. The result is compared with the simple distribution function assumed in the analysis of the scaling using the flux creep-flow model.

EXPERIMENTS

The specimen used in this study was a silver-sheathed Bi-2223 superconducting tape prepared by the powder-in-tube method. The width and thickness of the superconducting region were about 3.4 mm and 50 μm, respectively, and the c-axis was directed normal to the flat surface of the specimen. The critical temperature, T_c, was 108.1 K. The current-voltage curves were measured by the four probe method under the magnetic field parallel to the c-axis. A pulsed transport current with a period of 1 s was applied to the specimen to reduce the joule heat at

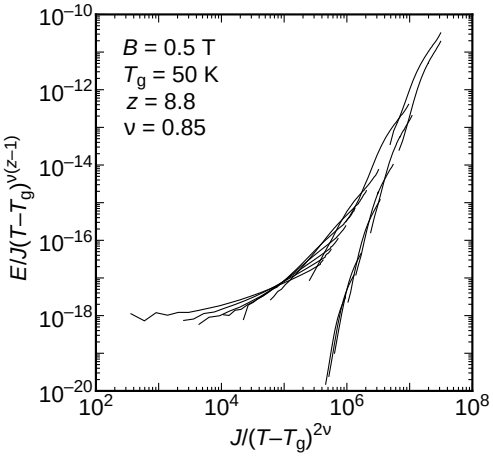

Fig. 1. Scaled current-voltage curves at $B = 0.5$ T.

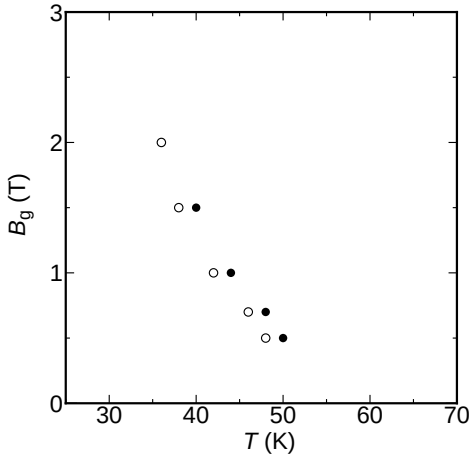

Fig. 2. Experimental (●) and theoretical results (○) of transition line.

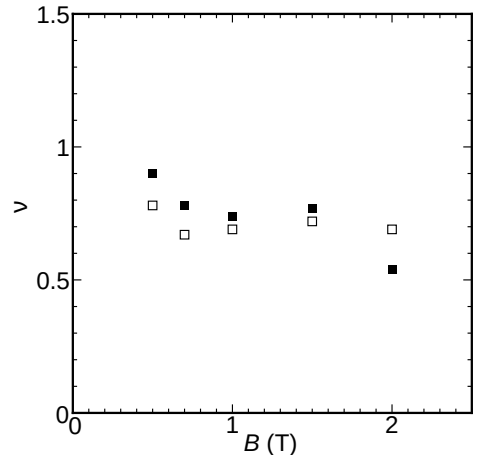

Fig. 3. Experimental (■) and theoretical results (□) of static critical index, ν.

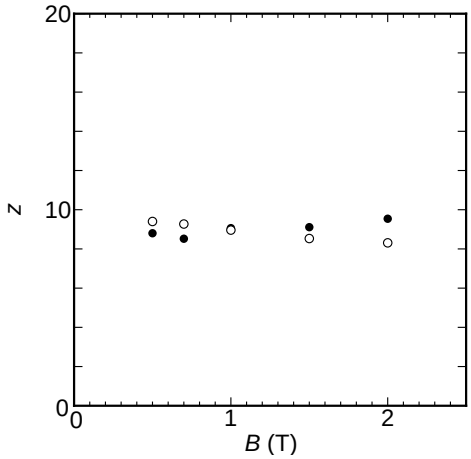

Fig. 4. Experimental (●) and theoretical results (○) of dynamic critical index, z.

current leads. The voltage was measured across the voltage terminals separated by 1.0 cm. The critical current density was defined using the offset method from the E-J curve at the point of $E = 1.0 \times 10^{-4}$ V/m.

RESULTS AND DISCUSSION

Figure 1 shows the result of scaled current-voltage curves at $B = 0.5$ T. The obtained transition temperature, static and dynamic critical indices are $T_g = 50$ K, $\nu = 0.85$ and $z = 8.8$, respectively. The magnetic field dependence of these scaling parameters are represented in Figs. 2, 3 and 4, respectively. Figure 5 shows the magnetic field dependence of the critical current density at various temperatures.

This result is compared with the theoretical analysis using the flux creep-flow model [6]. According to the model, the current-voltage curves can be calculated using the pinning potential which is expressed in terms of the virtual critical current density, J_{c0}, in the creep-free case. We assume the following temperature and magnetic field dependence of J_{c0}:

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

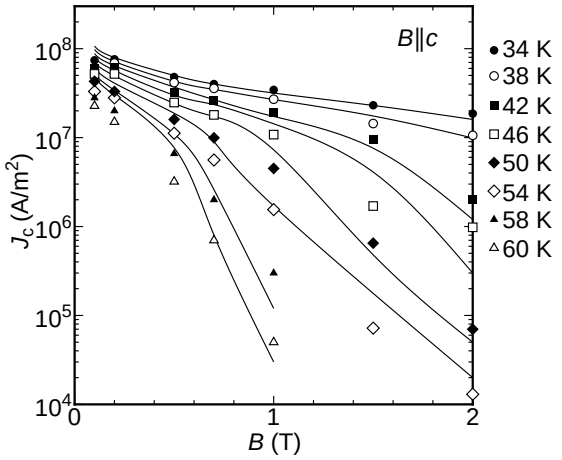

Fig. 5. Experimental (solid symbols) and theoretical results (lines) of critical current density.

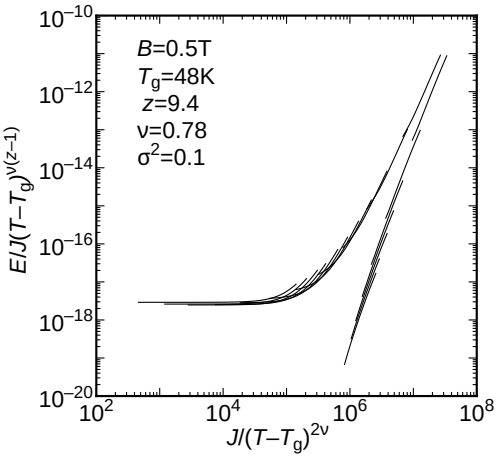

Fig. 6. Calculated scaled curves at $B = 0.5$ T.

where A, m, γ and δ are the pinning parameters. It is considered that the flux pinning strength is distributed in practical superconductors. For simplicity, we assume that only A in Eq. (1) is distributed in the form:

$$f(A) = K \exp\left[-\frac{(\log A - \log A_{\rm m})^2}{2\sigma^2}\right], \tag{2}$$

where K is a constant determined by the condition of normalization, $A_{\rm m}$ is the most probable value and σ^2 is a constant representing the degree of distribution width. The details of the theoretical analysis are described in Ref. [6].

The parameters used in the numerical calculation are ; $T_{\rm c} = 108.1$ K, $B_{\rm c2}(0) = 50.0$ T, $\rho_{\rm n}(T_{\rm c}) = 100$ $\mu\Omega$m, $A_{\rm m} = 1.08 \times 10^9$, $\sigma^2 = 0.10$, $m = 3.9$, $\gamma = 0.70$, $\delta = 2.0$. In addition, the number of flux lines in the flux bundle, g^2, is estimated as 1.0 at $T = 60$ K and $B = 1.0$ T and this value is used in the entire regions of temperature and magnetic field for simplicity. $A_{\rm m}$, σ^2, m and γ are determined so that a good fit is obtained between the experimental and theoretical $J_{\rm c}$s. The agreement of the experimental and theoretical $J_{\rm c}$s is good as shown in Fig. 5. Hence, the numerical analysis is carried out using the above parameters.

Figure 6 shows the result of scaling of numerically calculated current-voltage curves. The obtained scaling parameters are $T_g = 48$ K, $\nu = 0.78$ and $z = 9.4$. The obtained transition line, static and dynamic critical indices are compared with the experimental results in Figs. 2, 3 and 4, respectively. The agreement is good for the scaling curve and the transition line.

It is known that the distribution of the pinning strength can be described using the Weibull function [5]. This function is expressed as

$$f'(A) = \frac{m'}{\Delta}\left(\frac{A - A_0}{\Delta}\right)^{m'-1} \exp\left[-\left(\frac{A - A_0}{\Delta}\right)^{m'}\right], \tag{3}$$

where A_0 is the minimum value of A, Δ is a parameter representing the width of the distribution and m' is a parameter determining the shape of the distribution. The Weibull parameters determined from a measured current-voltage characteristic at $T = 54$ K and $B = 0.2$ T are $A_0 = 5.2 \times 10^7$, $\Delta = 7.0 \times 10^8$ and $m' = 1.7$. The resultant Weibull function is shown in Fig. 7.

σ^2 is determined so that a good fit is obtained between the simple distribution function, $f(A)$, and the Weibull function, $f'(A)$. The two distribution functions are compared in Fig. 7. The obtained

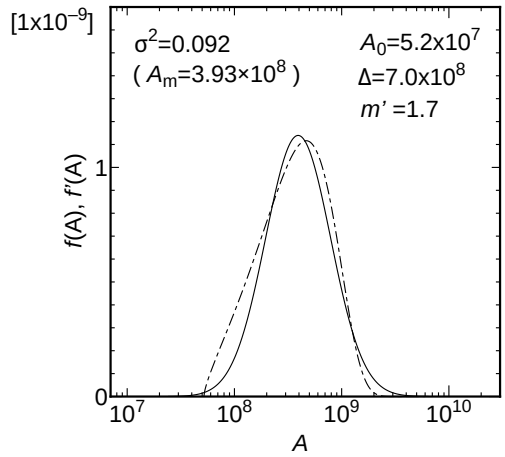

Fig. 7. Comparison of two distribution functions of critical current density. Solid and chained lines represent Eqs. (2) and (3).

result is $\sigma^2 = 0.092$, where $A_{\rm m}$ is changed to 3.93×10^8 to get a better agreement. σ^2 obtained similarly at 46 K and 60 K is 0.093 and 0.095, respectively. These results are close to the originally assumed value, $\sigma^2 = 0.10$. This agreement is consistent with the fact that the experimental results of the static and dynamic critical indices are well explained by the theory with the assumption of the constant σ^2. It is found that the assumption of the very wide distribution width of pinning strength over an order of magnitude is reasonable and the previous assumption of σ^2 on Bi-based superconducting tapes is proved. It is considered that such a wide distribution width is mainly brought about by percolating paths of current due to weak lines of grain boundaries.

CONCLUSION

The distribution of the flux pinning strength is analyzed using the Weibull function from measured current-voltage curves under a magnetic field parallel to the c-axis for a Bi-2223 silver-sheathed tape wire. The obtained result is compared with the expression of a simple distribution function estimated from the analysis using the flux creep-flow model. The following results are obtained:

1. The transition line and the two critical indices are explained fairly well by the theoretical model of flux creep and flow in which a very wide distribution is assumed.
2. A simple distribution function assumed in the analysis is compared with the Weibull function estimated from the measured current-voltage curves up to a high level of electric field. The two distributions agree well and the wide distribution width seems to be caused by weak links.

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