Inhomogeneous Distribution of Flux Pinning Strength and Its Effect on Irreversibility Line and Vortex Glass-Liquid Transition Line in Bi-2212 Tapes

Masaru Kiuchi[1] and Teruo Matsushita[1,2]
[1]Graduate School of Information Science and Electrical Engineering, Kyushu University, 6–10–1 Hakozaki,
Higashi-ku Fukuoka 812–8581, Japan
Yoshinori Nakayama[2,a] and Natsuko Takase[2,b]
[2]Department of Computer Science and Electronics, Kyushu Institute of Technology 680–4 Kawazu, Iizuka 820, Japan

Abstract— **The irreversibility line and the vortex glass-liquid transition line under a magnetic field parallel to the *c*-axis are investigated for silver-sheathed and dip-coated Bi-2212 tape wires. It is found that the two characteristic lines for silver-sheathed tape is well explained by the flux creep-flow model assuming the distribution of pinning strength with a single peak. On the other hand, general agreements are obtained for these characteristic lines and the critical current density between experiments and theory only when two peaks are assumed in the distribution of flux pinning strength for the dip-coated tape. The causative structure in the dip-coated tape for the peak at small strength in the distribution is discussed.**

I. INTRODUCTION

It is known that the irreversibility line and the vortex glass-liquid transition line of high-T_c superconductors depend on both the flux pinning strength and the dimensionality of the superconductor. These lines are usually used as characteristic lines showing the upper limit of applicable range of superconductor in the temperature vs magnetic field plane. However, the difference between the two lines is appreciable. This comes from the difference of the definition. That is, the irreversibility line, $B_i(T)$, is determined by the temperature at which the critical current density defined using some criterion decreases to a given level. The vortex glass-liquid transition line, $B_g(T)$, is determined by the temperature at which the curvature of the logarithmically plotted current-voltage curve varies from concave to convex [1], [2]. From the engineering viewpoint, it is desirable to use easily determined and reliable upper limit for the application. It is necessary, therefore, to clarify the relationship between the irreversibility line and the vortex glass-liquid transition line.

It is also known that the two characteristic lines are appreciably influenced by inhomogeneous distribution of flux pinning strength. In this paper, the distribution of flux pinning strength and its effect on the irreversibility line and the glass-liquid transition line are investigated for silver-sheathed and dip-coated Bi-2212 tapes. The obtained results are compared with the theoretical analysis based on the flux creep-flow model in which the distribution of the flux pinning strength is taken into account [3]–[5]. Discussion is given on the relation between the distribution of flux pinning strength and the two characteristic lines.

II. EXPERIMENTAL

The measured specimens in this study were Bi-2212 superconducting tapes prepared by a silver-sheathing technique and a dip-coat process. The *c*-axis of the specimen was approximately oriented normal to the flat tape surface. The critical temperature, T_c, measured using a SQUID magnetometer and the size of the specimens are given in Table I. The transition curve of susceptibility is broader for the dip-coated specimen, and hence, it is considered that the distribution of flux pinning strength is wider in this specimen.

The current-voltage curves were measured using the four probes method under a magnetic field parallel to the *c*-axis. The pulsed transport current with a width of 1 s was applied to the specimen to reduce the joule heat at the current leads. The voltage was measured across the voltage terminals separated by 1.0 cm. After the measurement of the current-voltage curves of the specimen, the superconducting layer was broken and the resistivity of the silver layer only was measured. This was needed for the evaluation of the current-voltage characteristics only of the superconducting region [5]. The critical current density, J_c, was determined by the off-set method from a level of electric field of $E = 1.0 \times 10^{-4}$ V/m. The irreversibility line was defined by the temperature at which the critical current density is reduced to 1.0×10^5 A/m^2. The transition line was determined by the temperature at which the curvature of the current-voltage curve changes from concave to convex.

The crirical current density of silver-sheathed and dip-

TABLE I
Critical temperature and sizes of two Bi-2212 tape specimens.

specimen	T_c (K)	width (mm)	thickness of superconducting layer, D (μm)
dip-coated	84.9	5.02	~ 10
silver-sheathed	86.0	4.41	~ 5

Manuscript received September 15, 1998.

M. Kiuchi, tel +81–92–642–3893, fax +81–92–642–3963
E-mail: kiuchi@sc.kyushu-u.ac.jp
[a] Present address: Komatu Ltd., 4–20–1 Kamata, Ohta-ku, Tokyo 144–0052, Japan.
[b] Present address: Denso corporation, 1–1 showa-cho, kriya-shi, Aichi-ken 448–8661, Japan.

1051-8223/99$10.00

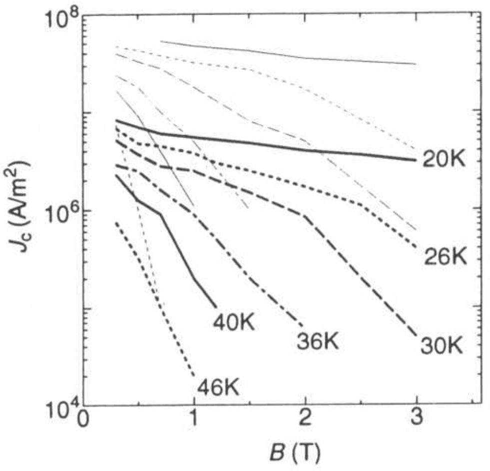

Fig. 1. Critical current density of silver-sheathed and dip-coted tapes. Thin and thick lines represent critical current desity of silver-sheathed and dip-coted tapes, respectively.

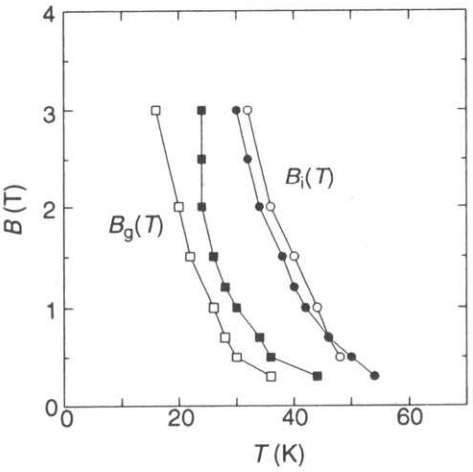

Fig. 2. Irreversibility line and transition line of silver-sheathed (open symbol) and dip-coated (solid symbol) tapes.

coated tapes is shown in Fig. 1. It is seen that the critical current density of the silver-sheathed tape is one order of magnitude larger than the dip-coated tape. The irreversibility line and the transition line of the two tapes are shown in Fig. 2. It turns out that the irreversibility line of the silver-sheathed tape with the higher J_c is higher. The obtained transition temperature and critical indices at $B = 0.5$ T are $T_g = 30$ K, $z = 11.5$ and $\nu = 0.80$ for the silver-sheathed tape [6] and $T_g = 36$ K, $z = 3.4$ and $\nu = 4.1$ for the dip-coated tape. For the dip-coated tape, the quite low z value suggests that the pinning strength is very widely distributed. It should be noted that the transition temperature of the silver-sheathed tape is lower. This seems to contradict the prediction of the flux creep theory [7].

III. DISCUSSION

These observed results are compared with the theoretical analysis using the flux-flow creep model [5]. Acoding to this 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 dependences of J_{c0}:

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

where A, m, γ and δ are the pinning parameters.

It is considered that the flux pinning strength is widely distributed in practical high-T_c superconductors. For simplicity, we assume that only A in (1) is distributed. The distribution function of the form:

$$f(A) = K\exp\left[-\frac{(\log A - \log A_m)^2}{2\sigma^2}\right] \qquad (2)$$

is assumed, where A_m is the most probable value, σ^2 is a constant representing the degree of deviation and K is a constant determined by the condition of normalization. It was found that (2) expresses approximately the distribution observed in a Bi-2223 tape [8]. $\delta = 2$ is assumed and A_m, σ^2, m and γ is are determined so that a good fit is obtained between the experimental and theoretical values of the critical current density in the whole range of magnetic field and temperature. The details of the numerical analysis are described in [4] and [5].

The parameters of silver-sheathed tape used in the numerical calculation are given in Table II. The number of fluxoids in the flux bundle, g^2, estimated at 42 K and 1.5 T on the irreversibility line was 0.8 [9]. Since the minimum value of g^2 is 1, we used this value in the calculation. Figure 3 shows the distribution of A assumed here. The obtained numerical analysis of the two characteristic lines for the silver sheathed tape is also shown in Fig. 4. The agreement is fairly good for the critical current density and the both lines. In addition, the dynamic and static indices obtained from numerical calculation agreed well with the observed results. For example, these numbers are $z = 11.5$ and $\nu = 0.80$ in experiments as abovementioned and $z = 10.0$ and $\nu = 1.10$ in calculation at $B = 0.5$ T. Thus, it can be said that the theory explains the experiment fairly well. Hence, the distribution of A assumed here seems to be correct.

The numerical analysis for the dip-coated tape is also carried out by the same method. However, a good agreement for the transition line and the critical indices are

TABLE II
Superconducting and pinning parameters of silver-sheathed tape used in the numerical calculation.

T_c (K)	$B_{c2\parallel}(0)$ (T)	$\rho_n(T_c)$ ($\mu\Omega$m)	A_m	σ^2
86.0	34.5	100	1.7×10^9	0.10
D (μm)	m	γ	δ	g^2
5.0	3.9	0.9	2.0	1.0

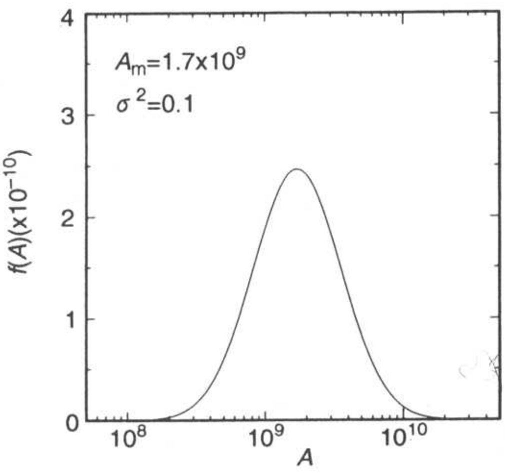

Fig. 3. Assumed distribution of A for silver-sheathed tape.

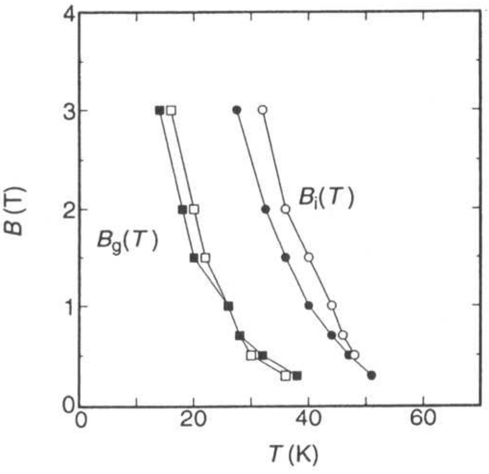

Fig. 4. Experimental (open symbols) and numerical (solid symbols) results of irreversibility line and transition line for silver-sheathed tape.

not obtained. Then, if the parameters are chosen so as to get a good fit for the transition line, a good agreement is not obtained for the critical current density. As for this reason, it is speculated that the distribution of flux pinning strength is different from that with a single peak assumed in (2). In fact, it was reported that the distribution function estimated from the second derivative of voltage with respect to current has two peaks for the dip-coated tape [10].

Hence, we assume the distribution as:

$$f(A) = K_\mathrm{p}\left\{M\exp\left[-\frac{(\log A-\log A_\mathrm{ms})^2}{2\sigma_\mathrm{s}^2}\right]\right.$$
$$\left.+\exp\left[-\frac{(\log A-\log A_\mathrm{ml})^2}{2\sigma_\mathrm{l}^2}\right]\right\}, \quad (3)$$

where A_ms and A_ml are the most probable values, σ_s^2 and σ_l^2 represent the degree of distribution width, and K_p and M are constants. In the above, the subscripts, "s" and

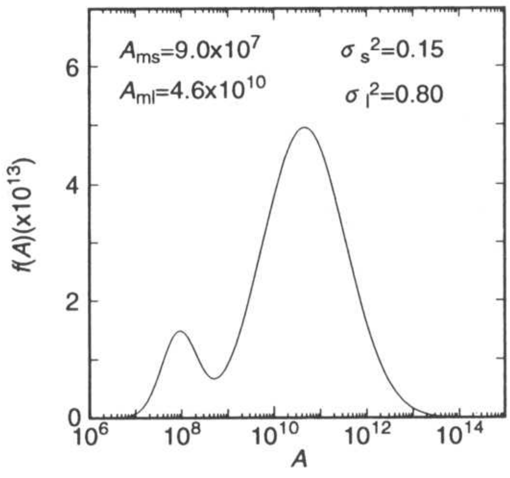

Fig. 5. Assumed distribution of A for dip-coated tape.

"l", correspond to the peaks at small strength and large strength, respectively.

The pinning parameters and the distribution parameters are determined so that a good fit is obtained for the critical current density between the experiment and the theory. The parameters for the dip-coated tape used in the numerical calculation are shown in Table III. Figure 5 shows the distribution of A assumed here.

The scaled result of experimental current-voltage curves and that of calculated ones at B = 0.5 T for the dip-coated tape are shown in Figs. 6 and 7, respectively. The scaling parameters obtained from the numerical analysis are T_g = 34 K, ν = 5.0 and z = 2.8, while those from experimental results are T_g = 36 K, ν = 4.1 and z = 3.4. Thus, the scaling parameters are similar, although the scaling curve is slightly different as seen from comparison of Figs. 6 and 7. Hence, it can be said from these results that the agreements for the both characteristic lines are better than the numerical analysis assuming the single peak [10].

Such a peak at small strength seems to be caused by regions with poor pinning property in the dip-coated tape. For example, the pressing process is not employed during the fabrication of dip-coated tapes. Hence, it is considered that the alignment of Bi-2212 grains especially at regions far from the silver layer is worse than in the silver-sheathed tape. Such regions may have quite weak flux

TABLE III
Superconducting and pinning parameters for dip-coated tape used in the numerical calculation.

T_c (K)	$B_{\mathrm{c}2\parallel}(0)$ (T)	$\rho_\mathrm{n}(T_\mathrm{c})$ ($\mu\Omega$m)	σ_s^2	σ_l^2
84.9	34.5	100	0.15	0.80
A_ms	A_ml	M	D (μm)	m
9.0×10^7	4.6×10^{10}	0.29	10	10
γ	δ	g^2		
0.9	2.0	1.0		

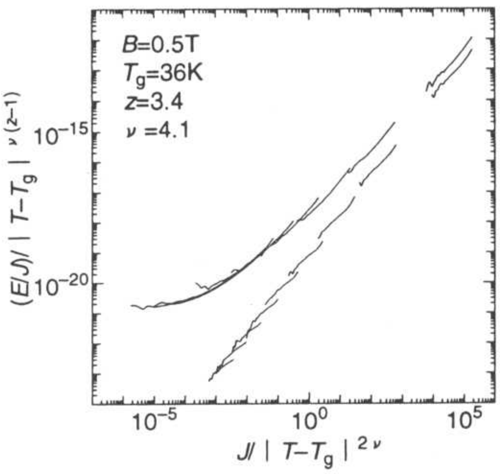

Fig. 6. Scaling of observed current-voltage curves for dip-coated tape at $B = 0.5$ T.

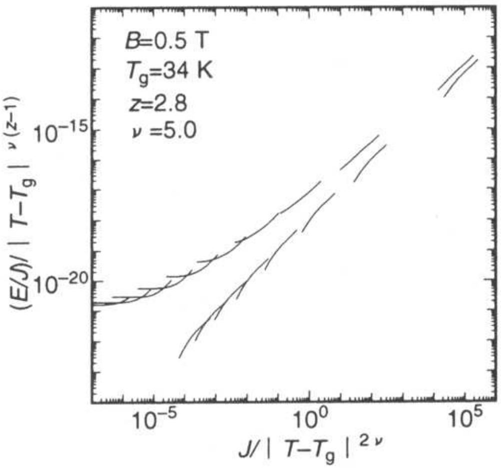

Fig. 7. Scaling of calculated current-voltage curves for dip-coated tape at $B = 0.5$ T.

pinning strength. In fact, the present calculation shows that the low critical current density in the dip-coated tape is determined by this peak at small strength. Therefore, the improvement of the grain alignment in the whole region of the tape is necessary in oder to improve the critical current density.

On the other hand, the glass-liquid transition line for the dip-coated tape can be also derived from the theoretical analysis assuming a single peak. Therefore, it is speculated that the transition line is determined by the peak at large strength. This is consistent with the experimental result that the transition line is higher of the dip-coated tape which has larger A_{ml} than A_{m} in the silver-sheathed tape.

IV. Summary

The distribution of flux pinning strength and its effect on the irreversibility line and the vortex glass-liquid transition line are investigated for the silver-sheathed and the dip-coated Bi-2212 tapes. The following results are obtained:

1. The two characteristic lines and the two critical indices for the silver-sheathed tape are explained well by the flux creep-flow model assuming a single peak in the distribution of pinning strength. Similar agreements are obtained for the dip-coated tape when two peaks are assumed in the distribution of flux pinning strength.
2. It is found that the critical current density is determined by the peak at small strength in the distribution for the dip-coated tape, while the transition line is determined by the peak at large strength.

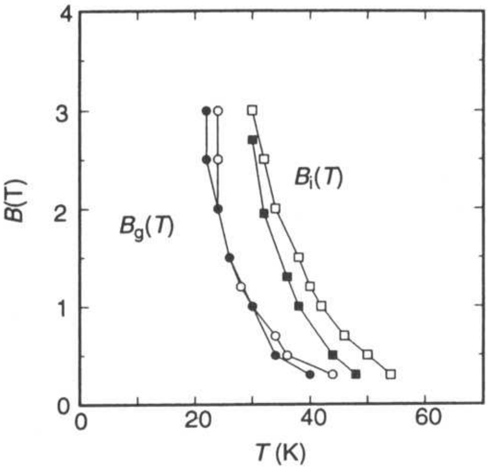

Fig. 8. Theoretical (solid symbols) and experimental (open symbols) results of glass-liquid transition line and irreversibility line for dip-coated tape.

V. Acknowledgment

The authors acknowledge Dr. T. Hasegawa of Showa Electric Wire & Cable Co. Ltd. for providing the specimens for the measurement.

References

[1] M. P. A. Fisher, *Phys. Rev. Lett.*, vol. 62, p. 1415, 1989.
[2] D. S. Fisher, M. P. A. Fisher and D. A. Huse, *Phys. Rev. B*, vol. 43, p. 130, 1991.
[3] T. Matsushita and N. Ihara, *Proc. 7th Int. Workshop on Critical Currents in Superconductors* (World Scientific, Singapore, 1994) p. 169.
[4] T. Matsushita, T. Tohdoh and N. Ihara, *Physica C*, vol. 259, p. 321, 1996.
[5] M. Kiuchi, K. Noguchi, T. Matsushita, T. Kato, T. Hikata and K. Sato, *Physica C*, vol. 278, p. 62, 1997.
[6] T. Matsushita, M. Tagomori, K. Noguchi, M. Kiuchi and T. Hasegawa, *Adv. Cryog. Eng. Mater.* (Plenum, New York, 1998) vol. 44, to be published.
[7] T. Matsushita, T. Fujiyoshi, K. Toko and K Yamafuji, *Appl. Phys. Lett.*, vol. 56, p. 2039, 1990.
[8] M. Kiuchi *et al.*, *Physica C*, to be published, 1998.
[9] T. Matsushita, *Physica C*, vol. 217, p. 461, 1993.
[10] Y. Nakayama *et al.*, *Physica C*, to be published, 1998.