# Characterization of Critical Current Density in Silver-Sheathed Bi-2223 Tape

Teruo Matsushita, Yoshiko Himeda, Masaru Kiuchi, Jun Fujikami, and Kazuhiko Hayashi

***Abstract*—The critical current property of a superconducting Bi-2223 tape produced by the over pressure processing at the final heat treatment was investigated. The critical current density increased by a factor of 1.6–1.8 at 77.3 K in comparison with the tape produced by the usual process. Thus, the critical current increased in spite of a reduction in the filament thickness. It was also found that the irreversibility field increased by a factor of 1.34 at 77.3 K by the new process. As a result, the enhancement of the critical current density at higher fields is remarkable. These results suggest that the over pressure process not only enriches the mass concentration of the superconducting phase but also contributes to the $c$-axis alignment. This is supported directly by the reduction of FWHM of rocking curve and indirectly by an enhancement the $n$ value. The critical current property at lower temperatures is also investigated and the possibility of the further improvement of the property is discussed.**

***Index Terms*—Bi-2223 tape, critical current density, irreversibility field, $n$ value, over pressure processing.**

## I. Introduction

SUPERCONDUCTING Bi-2223 tapes have a high potential for application, since the fairly high critical current has been achieved and very long wires with a high homogeneity has been constantly fabricated. However, we still need further development of the critical current as well as the reduction of the AC losses to increase the potential of Bi-2223 tapes for practical use. In fact, the enhancement of the critical current seems to be feasible, since a quite high critical current density has been found locally by a magneto-optical observation [1] and the analysis of $E - J$ curves which clarifies the distribution of the local critical current density also supports this result [2].

One of the important factors which determine the critical current density is the densification of the superconducting Bi-2223 phase as well as the $c$-axis orientation. For this purpose the application of high pressure has been investigated in detail [3]. Recently we have developed an over pressure process and a high isostatic pressure over 20 MPa is applied to the tape during the final heat treatment in a new furnace [4]. In this paper, the critical current property of a superconducting tape fabricated by the over pressure processing will be investigated in detail. Discussion will be given on the feasibility of further development of the critical current density.

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T. Matsushita, Y. Himeda, and M. Kiuchi are with the Faculty of Computer Science and Systems Engineering, Kyushu Institute of Technology, Iizuka 820-8502, Japan (e-mail: matusita@cse.kyutech.ac.jp; himeda@aquarius10.cse.kyutech.ac.jp; kiuchi@cse.kyutech.ac.jp).

J. Fujikami and K. Hayashi are with the HTS R&D Department, Sumitomo Electric Industries, Ltd., Osaka 554-0024, Japan (e-mail: fujikami-jun@sei.co.jp; hayashi-kazuhiko@sei.co.jp).

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## II. Experiments

Specimen #1 used in the investigation is a Bi-2223 tape fabricated by the over pressure processing. The silver ratio of the tape is 1.5 and the critical temperature measured by a DC magnetization is 107 K. For reference a usual tape specimen #2 fabricated in an ambient pressure was also investigated.

The microscopic observation of the cross section revealed that the average of filament thickness defined at the center of each filament was reduced to a factor of 0.84, suggesting that the superconducting phase is densified. This is consistent with the increase in the mass concentration by 12%. At the same time the standard deviation of the filament thickness was reduced to a factor of 0.78. Hence, it is found that this new process not only densifies the filament but also increases the uniformity of the filament thickness.

The critical current density of the tape specimens was measured resistively at 77.3 K in a magnetic field with different angles from to the tape surface. The $n$ value was estimated from the $E - J$ curve. Magnetization measurement was also done using a SQUID magnetometer in the temperature region of 10 to 77.3 K, and the critical current density was estimated by extended Bean's model.

## III. Results and Discussion

Fig. 1 shows the critical current density of the two specimens in a magnetic field parallel ($\theta = 0°$) and normal ($\theta = 90°$) to the tape at 77.3 K. It is found that the critical current density is enhanced by a factor of 1.6–1.8 in the both field directions by the introduction of the over pressure processing. This explains the enhancement of the critical current in spite of the reduction of the cross-sectional area of the superconducting region.

Fig. 2 shows the field angle dependence of specimen #1. When the critical current density is replotted versus the normal magnetic field component to the tape as in Fig. 3 with $\theta$ denoting a field angle from the tape surface, a master curve is obtained: From a point at which the critical current is saturated, the misorientation angle is estimated to be in the range of 7 to 10°. A FWHM of a rocking curve of a similar specimen prepared by the over pressure processing is 9.7°, which is improved from that of 10.3° for the usual tape.

Fig. 4 shows the $n$ value of the two specimens in a magnetic field normal to the tape surface. The $n$ value of specimen #1 is higher than that of specimen #2, and exceeds 20 in the absence of magnetic field. Although the enhancement of the $n$ value is limited in the low field region, this suggests that the

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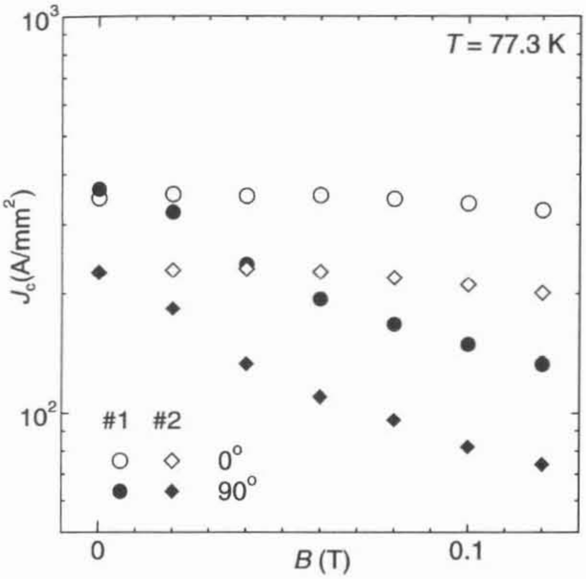


Fig. 1. Transport critical current density of specimens #1 and #2 in a magnetic field parallel and normal to the tape surface at 77.3 K.

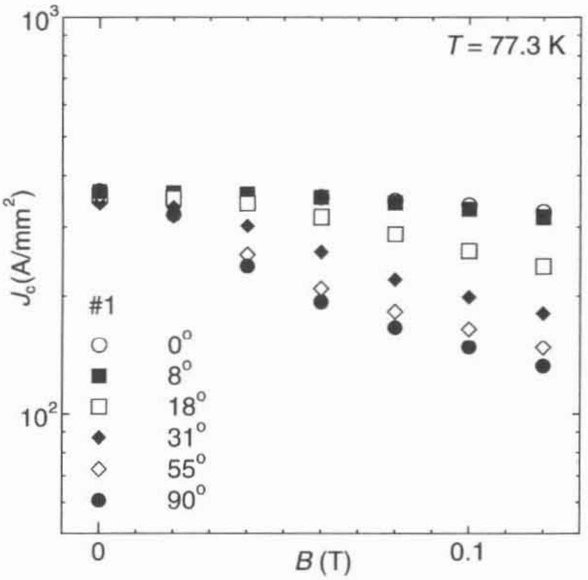


Fig. 2. Transport critical current density of specimen #1 in a magnetic field of various directions at 77.3 K.

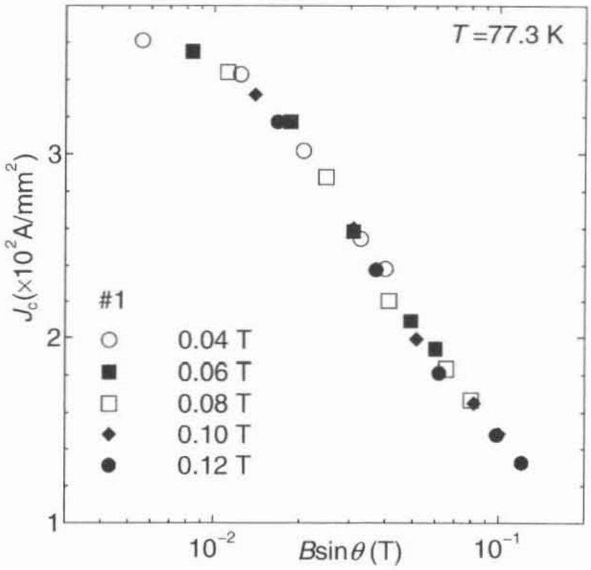


Fig. 3. Transport critical current density of specimen #1 versus a magnetic field component normal to the tape surface at 77.3 K.

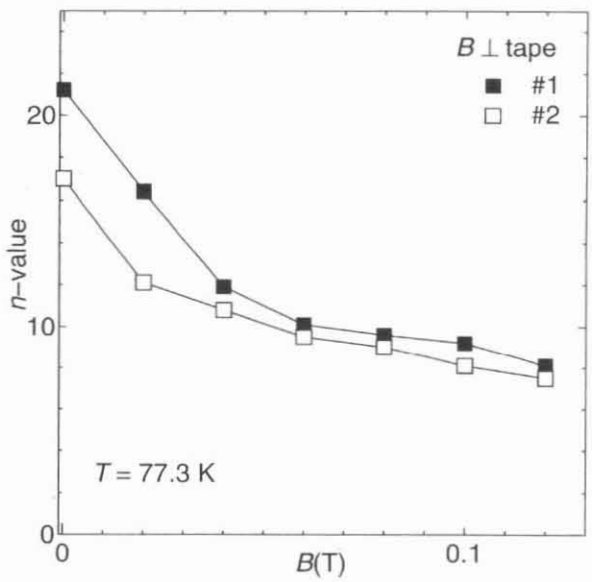


Fig. 4. $n$ value of specimens #1 and #2 in a magnetic field normal to the tape surface.

uniformity of the local critical current density is improved by the new process.

Fig. 5 shows the critical current density measured from a DC magnetization at 77.3 K. This value is lower, especially at high magnetic fields, than the value obtained by the resistive measurement in Fig. 1. This is due to the difference of the electric field criterion [5]: it is of the order of $1.5 \times 10^{-10}$ V/m in the magnetization measurement, while it is $1.0 \times 10^{-4}$ V/m in the resistive measurement.

The magnetic critical current density in the low electric field region can be estimated with the $n$ value. In specimen #2, $n = 8.1$ and the transport $J_c = 82\ \mathrm{A/mm^2}$ at $B = 0.10$ T normal to the tape surface lead to the magnetic $J_c$ of 16 $\mathrm{A/mm^2}$, which is slightly larger than the observed value of 15 $\mathrm{A/mm^2}$ as shown in Fig. 6. This means that the effective $n$ value decreases slightly at very low electric fields: if the average $n$ value is defined in the region of $10^{-10} - 10^{-4}$ V/m, it amounts to 7.7. On the other hand, the similar analysis with $n = 9.2$ and the transport $J_c = 1.5 \times 10^2\ \mathrm{A/mm^2}$ lead to 34 $\mathrm{A/mm^2}$ for specimen #1 at the same magnetic field. This value is slightly smaller than the observed value of 38 $\mathrm{A/mm^2}$, indicating that the effective $n$ value is increased to 9.9. Thus, the improvement of the $n$ value is remarkable in the low electric field region.

This difference is explained by the fact that the state of flux lines is close to the liquid state in specimen #2, while it is close to the glass state in specimen #1. For this reason the enhancement of the critical current density becomes larger at a higher magnetic field. In other words, the irreversibility field is increased by the new process. In fact, if the irreversibility field is defined by the current density criterion of 1.0 $\mathrm{A/mm^2}$, it is enhanced by

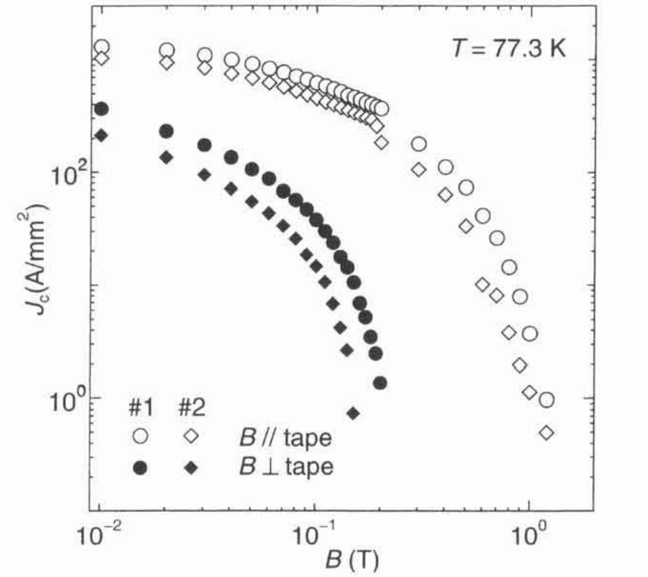


Fig. 5. Magnetic critical current density of specimens #1 and #2 in a magnetic field parallel and normal to the tape surface at 77.3 K.

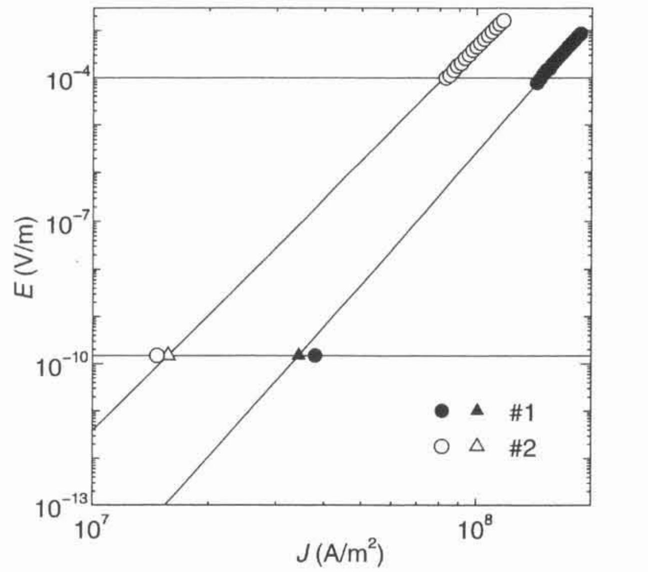


Fig. 6. Estimation of magnetization critical current density by extrapolating the $E - J$ curve of resistive measurements. Triangular symbols show the estimated values. Observed magnetization critical current density is also shown for comparison.

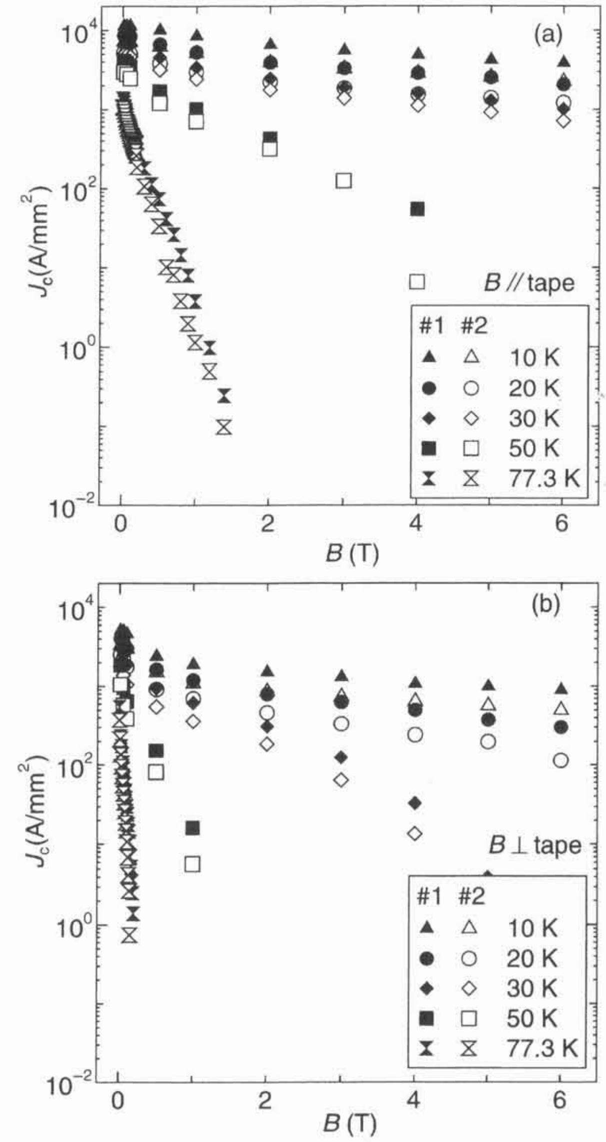


Fig. 7. Magnetization critical current density at various temperatures in magnetic fields (a) parallel to the tape and (b) normal to the tape.

a factor of 1.34 and 1.20 for a magnetic field normal and parallel to the tape surface.

Fig. 7(a) and (7b) show the magnetization critical current density of the two specimens in magnetic fields parallel and normal to the tape surface, respectively. The over pressure processed specimen shows better performance in the whole temperature range of measurement. Fig. 8 shows the factor of improvement of the magnetization critical current density. It is seen that the factor is almost the same between the two field orientations at low temperatures, while it is larger for the field normal to the tape surface at high temperatures. The drastic improvement near the irreversibility field is caused by the improvement of the irreversibility field.

It is concluded from the above results that the over pressure processing can densify the mass concentration and this directly contributes to the enhancement of the critical current density. However, the enhancement factor of 1.6–1.8 is too large to be explained only by the enhancement of the mass concentration by 12%. The enhancement of the $n$ value suggests that the quality is also improved. The misorientation of the $c$-axis is reduced by this process as above-mentioned. This is considered to be caused by a change of the laminar structure into a flat shape due to the disappearance of voids and thick regions of filaments by the high pressure. In addition, the connectivity of grains also seems to be improved. These factors contribute to the improvement of the critical current density and the irreversibility field. Hence, this process is quite effective to produce superconducting tapes showing a good performance.

One of the differences between the results of Figs. 1 and 5 is that the anisotropy of the critical current density with respect to the field orientation is much larger in the magnetic measurement. In specimen #1, for example, the ratio of $J_c(\theta = 0^\circ)/J_c(\theta = 90^\circ)$ is 16.4 for the magnetic measurement at $B = 0.10$ T, while that is 2.3 for the resistive measurement. In

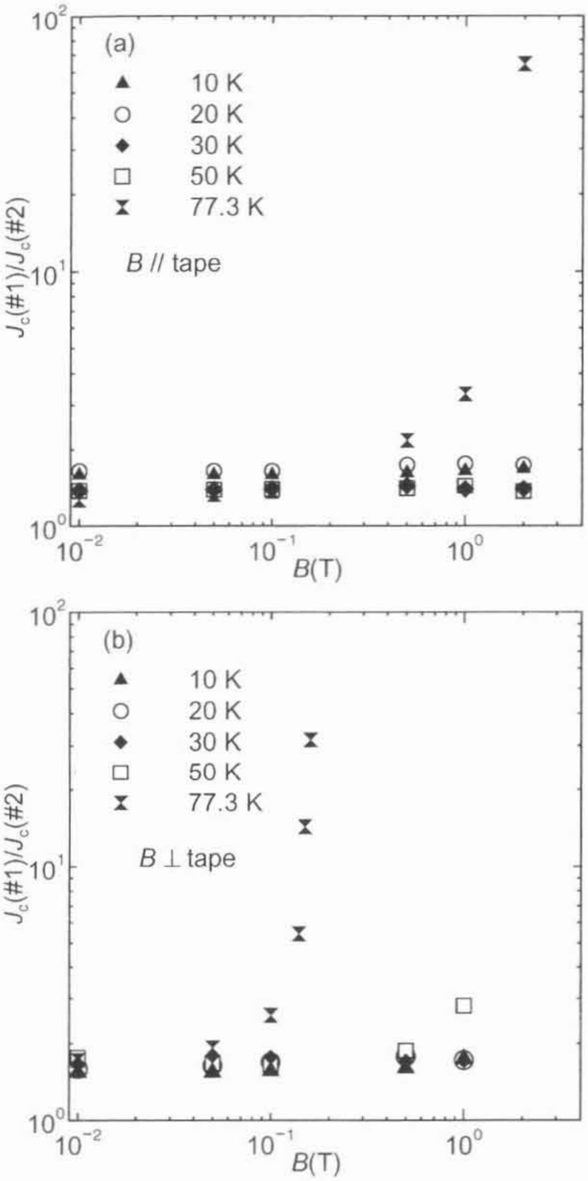


Fig. 8. Factor of improvement of magnetization critical current density by the over pressure processing for a magnetic field (a) parallel and (b) normal to the tape surface.

a magnetic field parallel to the tape surface, some grains have a large current capacity. All of them can contribute to the magnetization $J_c$ even if these grains are isolated, while only a few grains can contribute to the transport $J_c$ due to a percolation problem. The rather low anisotropy in the transport $J_c$ in the over pressure processed tape suggests that there is a large room for a further improvement of the critical current density by improving the present technique. This will be effectively realized by the improvement of the crystal alignment.

## IV. Summary

The critical current density of the Bi-2223 tape prepared by the over pressure processing is investigated in detail. It is found that the critical current density is drastically improved, which can not be attributed only to the enhancement of mass concentration of the superconducting phase. This is considered to be caused by the improvement of grain connectivity and crystal alignment. The observed improvement of the $n$ value supports this hypothesis. As a result, the irreversibility field is also increased and this brings about the good critical current performance at high fields. For these reasons, the over pressure processing is promising for the improvement of the critical current property of Bi-2223 tapes and a further improvement is expected by optimization of the process conditions.

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