CRITICAL CURRENT DENSITY, IRREVERSIBILITY LINE, AND FLUX CREEP ACTIVATION ENERGY IN SILVER-SHEATHED $Bi_2Sr_2Ca_2Cu_3O_x$ SUPERCONDUCTING TAPES

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Abstract--Transport data, magnetic hysteresis and flux creep activation energy experimental results are presented for silver-sheathed high-T_c $Bi_2Sr_2Ca_2Cu_3O_x$ superconducting tapes. The 110 K superconducting phase was formed by lead doping in a Bi-Sr-Ca-Cu-O system. The transport critical current density was measured at 4.0 K to be 0.7 x 10^5 A/cm^2 (the corresponding critical current is 74 A) at zero field and 1.6 x 10^4 A/cm^2 at 12 T for H||ab. Excellent grain alignment in the a-b plane was achieved by a short-melting method, which considerably improved the critical current density and irreversibility line. Flux creep activation energy as a function of current is obtained based on the magnetic relaxation measurements.

I. INTRODUCTION

Large-scale application of high-T_c superconductivity depends on the successful production of long wires with high current-carrying capability, mechanical flexibility, and chemical stability. The metal-sheathed powder-in-tube technique has proved successful for making long high-T_c superconductor wires that can carry high critical current densities [1-5]. Specifically, Bi-based superconducting tapes that can carry critical current densities greater than 1 x 10^5 A/cm^2 in high magnetic field (> 20 T) at 4.2 K have been developed [5]. In this paper, we report on the critical current density and irreversibility data for silver-sheathed Bi-Pb-Sr-Ca-Cu-O tapes processed by a novel method. We discuss the possible relationship between the critical current and the microstructure of the tapes.

II. EXPERIMENTAL PROCEDURE

The processing method for making the silver-sheathed Bi-Pb-Sr-Ca-Cu-O tapes was previously reported by Dou et al. [1]. The superconducting powders were made by a freeze-drying technique [1]. The solution of Bi_2O_3 in nitric acid was mixed with $Pb(NO_3)_2$, $Ca(NO_3)_2 \cdot 4H_2O$, $Sr(NO_3)_2$, and $Cu(NO_3)_2.3H_2O$ in distilled water in the ratios Bi : Pb : Sr : Ca : Cu = 1.6 : 0.4 : 1.6 : 2 : 3. The solutions were then quickly frozen by spraying into a liquid nitrogen bath. The frozen mixtures of the nitrates were placed in a freeze drier and dried under vacuum for 48 h. The dried powders were calcined in air at 830°C for 10 h. The calcined powders were then pressed into pellets and sintered at 850°C for 20 h. The sintered pellets were powdered and poured into a silver tube of 10 mm outside diameter and 8 mm inside diameter. The silver tube was then rolled into tapes 0.1 mm thick and ~2-3 mm wide. Two types of heat treatment were used in this study. Sample 1 was heat treated at ~820°C for 150 h in a mixture of oxygen and nitrogen with varying O_2 partial pressure; the heat treatment was repeated twice to optimize the grain alignment. Sample 2 was heat treated at ~ 830°C for 70 h in a similar atmosphere; in addition, it underwent a partial melting at 860°C for 20-30 min. The detailed processing procedure for partial melting of Sample 2 can be found elsewhere [2].

The transport critical current density, J_c, of the silver-sheathed tapes was measured at 4.0 K up to 12 T and 76 K up to 1 T. The measurements were performed by using a standard four-probe method with a voltage criterion of 1 μV/cm. The direction of the transport current was perpendicular to the applied field. For comparison, we also measured magnetization critical current density in a wide temperature regime using a vibrating sample magnetometer. By applying the Bean critical state model [6] we calculated the magnetization J_c(A/cm^2) using the formula $\Delta M = a_2 J_c(1-a_2/3a_1)/20$, where ΔM is the magnetic hysteresis difference in emu/cm^3, and $2a_1 x 2a_2$ is the cross-sectional area of the sample ($a_1 > a_2$).

III. RESULTS AND DISCUSSION

In agreement with most of the previously reported transport data, the high J_c value of Sample 1 remained approximately the same (> 1 X 10^4 A/cm^2) as the field reached 12 T at 4.0 K for both H||ab and H||c (Fig. 1). However, the J_c (H||ab) was about 20% higher than the J_c (H||c) at 12 T and T = 4.0 K. It should be pointed out that the total critical current at 4.0 K and zero field reached a maximum value of 74 A [3].

We found that the texturing in the silver-sheathed tapes was greatly enhanced by the short-melting process. As can be

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seen in Fig. 2, Sample 2 has a higher degree of texture compared with the previously obtained microstructure [3]. Although some degree of texturing can be obtained by extended sintering (150 h at 820°C), the short-melting process at partial melting temperature is required to further improve the grain alignment for achieving an optimized critical current density.

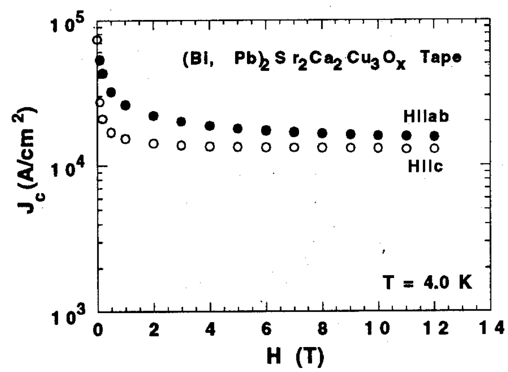

Fig. 1. Transport J_c vs. H at at 4.0 K for sample 1.

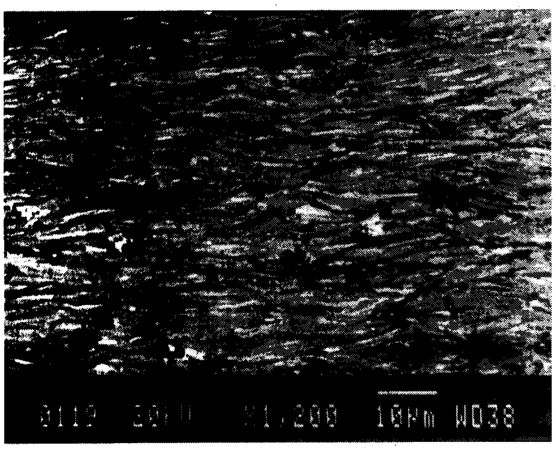

Fig. 2. Scanning electron microscopy photograph showing highly c axis-oriented grains in a tape processed by short-melting method.

The magnetic hysteresis curves were obtained from 4.2 K to 90 K for the applied fields up to 5 T for H||c. Figure 3 shows the temperature dependence of the J_c at 0.5 T for Samples 1 and 2. As can be seen, the J_c of sample 2 is considerably increased relative to that of sample 1 with increasing temperature, particularly in the high temperature range. However, in the temperature range below 50 K, the J_c value of sample 2 is lower than that of sample 1.

It has been well reported that flux-creep effects are strong in the bismuth-based system and that the "irreversibility line" lies in the low regions of temperature and field compared with those of the $YBa_2Cu_3O_x$ compound.

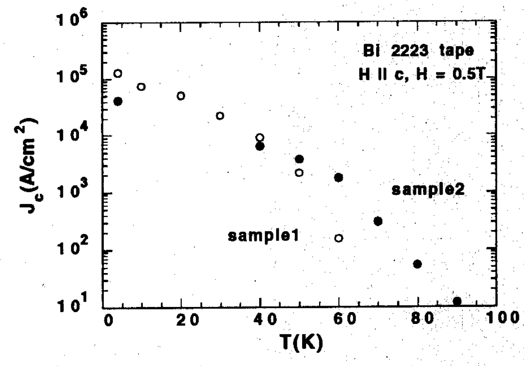

Fig. 3. Magnetization J_c vs. temperature, T, at 0.5 T for sample 1 and 2.

Figure 4 shows the irreversibility lines of samples 1 and 2. We have defined the irreversibility line as the point where the hysteresis loop closes. A similar effect to the temperature dependence of J_c shown in Fig. 3 is observed. It has been found that partial melting generates a high density of dislocations in the superconducting phase and that these dislocations can act as pinning centers [2]. Moreover, as with J_c, the shift of the irreversibility line in sample 2 is more pronounced at high temperatures. Below 10 K and at high fields, the irreversibility lines of samples 1 and 2 are located in the nearby regions.

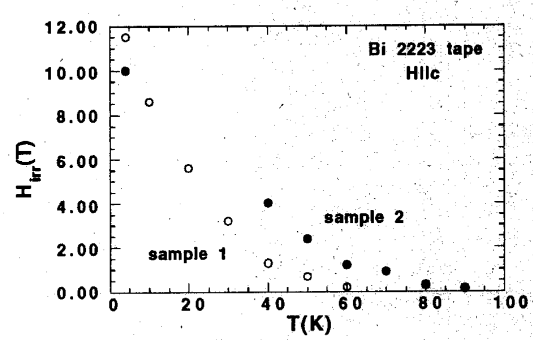

Fig. 4. Irreversibility lines determined based on the magnetic hysteresis data for samples 1 and 2.

It is not clear why, at high temperatures, the J_c's and the irreversibility line for sample 2 is higher than sample 1. A possible interpretation is that the flux pinning increases with temperature as a result of the short-melting method, although the pinning mechanism is still to be identified. On the other hand, the difference in anisotropy of J_c at 4.0 K and 77 K suggests that pinning by Cu-O planes is not important at low temperatures, where the superconducting system is more uniform. As observed in Ref. 3 and shown in Fig. 1, the J_c is not much different for both H||c and H||ab, while a large difference in J_c is observed at 77 K for these configurations.

We consider here that the effective activation energy, U, is a function of J, which is temperature and field dependent [7]. We expand the effective activation energy U(J) about some current J_0 at time t_0 to obtain

$$U(J) = U(J_0) + [\partial U/\partial J]_0(J - J_0) + (1/2)[\partial^2 U/\partial J^2]_0(J - J_0)^2 + ...$$
$$\sim U(J_0) + \alpha (J - J_0) + (1/2)\beta (J - J_0)^2 + ... \quad (1)$$

where $\alpha = [\partial U/\partial J]_0$ and $\beta = [\partial^2 U/\partial J^2]_0$.

Considering the second-order term and assuming that the preexponential factor A is constant in the temperature range considered, one obtains that

$$J(t) = J_0 + (kT/\alpha) \ln(t/t_0) - (k^2T^2 \beta/2\alpha^3) \ln^2(t/t_0). \quad (2)$$

Using Bean's model, one can rewrite above equation as

$$M(t) = M_0 + a\ln(t/t_0) + b\ln^2(t/t_0), \quad (3)$$

where $a = (kT)[\partial M/\partial U]_0$ and $b = -(k^2T^2/2)[\partial^2 U/\partial M^2]_0 [\partial M/\partial U]_0^3$. Experimentally, one can determine the constants a and b from the magnetic relaxation measurements and use them to calculate α and β. Substituting α and β into Equation (1), a smooth U-J curve can be obtained. This method is equivalent to that developed by Maley et al. [8]. Figure 5 shows the U-J relationship for sample 1. As can be seen, at large driving force, U varies gradually while a rapid increase is observed as J is reduced to a small level. We found that this behavior is typical for most of the type-II superconductors including A-15 Nb_3Sn.

In conclusion, we have found that the J_c and the irreversibility line are considerably enhanced in silver-sheathed Bi-based superconducting tapes by employing a short-melting method developed previously. The flux-pinning strength has been found to increase with temperature, resulting in more pronounced enhancement of J_c in the partially melted tape at high temperatures. The pinning mechanism associated with the enhancement of the J_c and the irreversibility line in sample 2 is under investigation. We have obtained the flux-creep activation energy of the silver-sheathed tape based on magnetic relaxation data.

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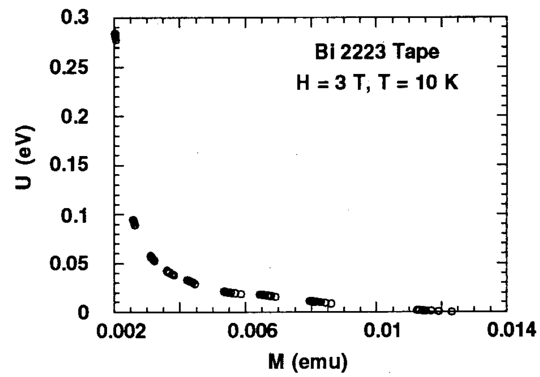

Fig. 5. U vs. M curve for Sample 1.

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