CRITICAL CURRENT DENSITY, IRREVERSIBILITY LINE, AND FLUX CREEP ACTIVATION ENERGY IN SILVER-SHEATHED Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$ SUPERCONDUCTING TAPES

Donglu Shi, Z. Wang, S. Sengupta, and M. Smith
Materials Science Division, Argonne National Laboratory, Argonne, IL 60439

L. F. Goodrich
Electromagnetic Technology Division
National Institute of Standards and Technology, Boulder, CO 80303-3328

S. X. Dou, H. K. Liu, and Y. C. Guo
School of Materials Science and Engineering, University of New South Wales
P.O. Box 1, Kensington, NSW 2033, Australia

Abstract—Transport data, magnetic hysteresis and flux creep activation energy experimental results are presented for silver-sheathed high-\(T_c\) Bi$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$ 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 \(\times\) 10\(^5\) A/cm\(^2\) (the corresponding critical current is 74 A) at zero field and 1.6 \(\times\) 10\(^4\) A/cm\(^2\) at 12 T for Hilab. 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 \(\times\) 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$_2$O$_3$ in nitric acid was mixed with Pb(NO$_3$)$_2$, Ca(NO$_3$)$_2$·4H$_2$O, Sr(NO$_3$)$_2$, and Cu(NO$_3$)$_2$·3H$_2$O 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 \(\mu\)V/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 \(J_c(\Delta\mu/cm^2)\) using the formula \(\Delta\mu = a_2J_c(1-a_2/a_1)20\), where \(\Delta\mu\) is the magnetic hysteresis difference in emu/cm$^3$, and \(a_1x2a_2\) 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 \(\times\) 10\(^4\) A/cm\(^2\)) as the field reached 12 T at 4.0 K for both Hilab and Hilc (Fig. 1). However, the \(J_c\) (Hilab) was about 20% higher than the \(J_c\) (Hilc) 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
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.

![Graph](image)

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

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$_2$Cu$_3$O$_x$ compound.

![Graph](image)

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

The magnetic hysteresis curves were obtained from 4.2 K to 90 K for the applied fields up to 5 T for Hicl. 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.

![Image](image)

Fig. 2. Scanning electron microscopy photograph showing highly c axis-oriented grains in a tape processed by short-melting method.
more uniform. As observed in Ref. 3 and shown in Fig. 1, the J_c is not much different for both H1c and H1hab, 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 I_0 at time t_0 to obtain

\[ U(J) = U(I_0) + \left[ \partial U / \partial I \right]_0 (J - I_0) + \left( 1/2 \right) \left[ \partial^2 U / \partial I^2 \right]_0 (J - I_0)^2 + \ldots \]

\[ - U(I_0) + \alpha (J - I_0) + \left( 1/2 \right) \beta (J - I_0)^2 + \ldots \]  

(1)

where \( \alpha = \left[ \partial U / \partial I \right]_0 \) and \( \beta = \left[ \partial^2 U / \partial I^2 \right]_0. \)

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

\[ J(t) = I_0 + (kT / \alpha) \ln(t / t_0) - \left( kT^2 / \beta / \alpha^2 \right) \ln^2(t / t_0). \]

(2)

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

\[ M(t) = M_0 + \alpha \ln(t / t_0) + \beta \ln^2(t / t_0). \]

(3)

where \( \alpha = (kT / \partial M / \partial I) I_0 \) and \( \beta = -(kT^2 / 2) \left[ \partial^2 U / \partial M^2 \right] I_0 \left[ \partial M / \partial I \right]_0^3. \) Experimentally, one can determine the constants \( \alpha \) and \( \beta \) from the magnetic relaxation measurements and use them to calculate \( \alpha \) and \( \beta \). Substituting \( \alpha \) and \( \beta \) 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 Nb3Sn.

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.

REFERENCES


