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Processing and fabrication of high-T_c superconductors for electric power applications*

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Abstract

Recent developments in the powder-in-tube fabrication of $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ tapes include identification of high-current-transport regions of the superconductor core, optimization of conductor design and processing to take advantage of these high-current regions, optimization of superconductor powders and heat treatments, and incorporation of flux-pinning defects into the superconductor grains. These developments are briefly discussed and their implications are assessed.

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1. Introduction

High-temperature-superconductor (HTS) wires and tapes are generally fabricated by a powder-in-tube (PIT) process [1-3]. Clad $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (Bi-2223) and $Bi_2Sr_2CaCu_2O_y$ (Bi-2212) tapes both exhibit excellent promise for application, but little progress has been made for such tapes from other superconducting compounds. Ag alloys are used for the cladding because they are chemically compatible with the superconductor cores [1-4]. Critical current density (J_c) remains the most important property for practical application of HTS wires and tapes. Bi-2223 can exhibit high J_c values to temperatures of 77 K. Because of its lower T_c value, Bi-2212 will generally be used only at temperatures $< \approx 30$ K [5-7]. This paper will focus primarily on recent developments in Ag-clad Bi-2223 tapes.

Ag-clad Bi-2223 tapes have been incorporated into prototype HTS motors, transmission cables, and fault current limiters; performance has generally been acceptable. However, because high J_c in magnetic fields is generally necessary, the applicability of such tapes in large electrical equipment has been limited to temperatures <30 K [8]. Substantial effort is now focused on addressing this limitation.

Several groups have reported that the supercurrent in Ag-sheathed Bi-2223 tapes is transported through a thin region adjacent to the Ag interface [9-16]. Furthermore, the bulk of the superconductor core does not contribute substantially to the total critical current (I_c). The high–current superconducting layers are generally ≈ 2-3 μm thick and have been shown to support a transport current with a J_c value $> 10^5$ A/cm^2 at 77 K [9,17]. Transport J_c values of tapes with identical superconductor cross-sectional areas but differing Ag/Bi-2223 interfacial lengths, confirm the importance of the interfacial region [11]: I_c was shown to be proportional to the Ag/Bi-2223 area, expressed as a linear function, the interface perimeter length (IPL). These results imply that <10% of the Bi-2223 superconductor transports the vast majority of supercurrent in Ag-clad Bi-2223 tapes. Thus, J_c values can be increased by microstructural design through optimization of the IPL.

Improved conductor structure can lead directly to increased J_c values. In addition, flux pinning in Bi-2223 and Bi-2212 at temperatures >30 K must be improved. J_c as a function of applied magnetic field is highly anisotropic [5-7]. In Bi-2223 tapes with equal J_c, the effective pinning energy for fields that are perpendicular to the c axis is two orders of magnitude higher than that for fields that are parallel to the c axis [7]. Substantial effort is now focused on reducing flux motion through introduction of pinning sites [18].

Recent results on the processing and fabrication of Bi-2223 conductors and on the creation of flux-pinning sites is discussed. Progress to date has been steady, and properties are soon expected to be adequate for many applications.

2. Recent materials developments

2.1. PIT processing

Efforts to enhance J_c by increasing the Ag/Bi-2223 interfacial area continue. Fabrication of multifilamentary tapes accomplishes this goal, but in general the areal fraction of Ag increases for such tapes [19]. An alternative approach is to incorporate Ag wires into a Bi-2223 core. Initial work focused on use of a single Ag wire [20,21]. In addition to offering possibilities for improved transport J_c, significant enhancement of bend-strain tolerance with a wire-in-tube approach has been reported [21].

This duplex-core work has recently been extended to a two-step process in which many fine Ag wires are coated with Bi-2223 precursor powder and then loaded into an Ag tube. Conventional PIT working then produces a tape with a very high Ag/Bi-2223 interfacial area [22]. To date, up to 600 Ag wires, ≈76 µm in diameter, have been loaded into a single Ag tube. Despite the lower cross-sectional area of the obtained Bi-2223 superconductors, transport J_c values are now greater than those of corresponding monofilament tapes [23].

Another promising development in Bi-2223 tapes is based on the work of Parrel et al. [24]. They observed that the cooling rate from the sintering temperature had a significant effect on transport J_c and attributed the effect to partial decomposition of Bi-2223 during slow cooling. However, other changes in the Bi-2223 also arise from slow cooling, e.g., increase in oxygen content [25]. Increased oxygen content may contribute to enhanced J_c through flux pinning. Nomura et al. [26] concluded that J_c values of Bi-2223 tapes increase with an increase in oxygen content. In previous work with the University of Pittsburgh [27], we also showed that cooling rate had a pronounced effect on transport J_c. The thin layer of Bi-2223 adjacent to the Ag sheath was placed under compression during fast cooling; the compressive stress induced microcracking and, hence, a lower J_c. Slower cooling minimized the cracking.

More recently, studies of cooling rate have continued [28]. In the study reported here, the final heat treatment of Ag-clad Bi-2223 tapes in 8% O_2

consisted of heating to ≈820°C at a rate of ≈2°/min, holding for 50 h, and then cooling. The standard rate was 1-2°C/min, but slower rates were also used. Transport I_c at 77 K in self field with a 1 μV/cm criterion was measured by a conventional four-probe method. Figure 1 shows the effect of cooling rate on I_c values of tapes 1.2 m long (powder packing has also been studied, but results will be discussed elsewhere). Table I summarizes the best transport I_c values we obtained during this study of Ag-clad Bi-2223 multifilamentary tapes.

Slow cooling improved transport current properties by ≈2-3 times compared with those of the standard cooling rate. It was concluded that the thermal gradient between the Ag sheath and the Bi-2223 core exerted a compressive stress on the thin layer of Bi-2223 adjacent to the Ag. The stress affected grain alignment and connectivity In extreme cases, compression caused by a strong thermal gradient induced microcracking in the Bi-2223. Careful control of processing parameters has now resulted in consistent I_c values for long lengths of superconducting tape (Fig. 2).

In addition to the results presented above, significant effort is being expended to improve transport J_c in Bi-2223 conductors by tailoring powder compositions, morphologies, and packing, mechanical processing, heat treatment, and use of alternative sheaths [1-3,29]. Further significant improvements to J_c are likely to occur [30].

2.2. Flux-pinning centers

Enhanced flux pinning is required to enable wide-scale application of Bi-2223 tapes at temperatures that approach 77 K. Several successful approaches have been reported for Bi-2223 and Bi-2212, and an excellent review has been written by Dou et al. [18]. A few results will be summarized briefly here. We will focus on use of standard techniques that create second phases; irradiation approaches will not be discussed.

Methods to create flux-pinning defects can be broadly classified as either intrinsic or extrinsic. In intrinsic methods, compositions and heat treatments within the Bi-Pb-Sr-Ca-O system are controlled to create nanometer-scale second phases. Intrinsic methods include heat treating above and below the solidus line [18,31-33], processing powders that have been supersaturated with either Ca and Cu [34] or Pb [35], and manipulating oxygen content [26,36]. Extrinsic methods include cation substitution into the superconductor lattice [37-39] and addition of second phases such as MgO or $SrZrO_3$ [40-46]. Both methods have quite successfully increased intragranular J_c, with strong improvements obtained at temperatures <30K. In addition, transport J_c values of Ag-clad tapes have been doubled by the creation of flux-pinning defects [41,42,45,46]. In general, Bi-2212 has proved to be easier to work with than Bi-2223; thus, most J_c enhancement has been at <30 K. A typical example of J_c enhancement by addition of a second phase is shown in Fig. 3 [46].

Several research groups have now reported that engineered defects in bulk Bi-2223 increase flux pinning at temperatures >50 K. Therefore, it appears that enhanced transport J_c through improved flux pinning is attainable [18]. Substantial worldwide effort is now directed toward this goal.

3. Summary

Powder-in-tube-fabricated Bi-2223 tapes exhibit good transport J_c values, but transport at 77 K, especially in large applied magnetic fields, must be improved. Good transport of supercurrent is confined to core regions adjacent to the Ag-alloy sheath. We have succeeded in increasing J_c through improved processing and conductor design. Efforts to improve J_c in magnetic fields by creating flux-pinning defects offer promise for further advancement.

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Figures

Figure 1. Transport I_c along 1.2-m tape vs. cooling condition.

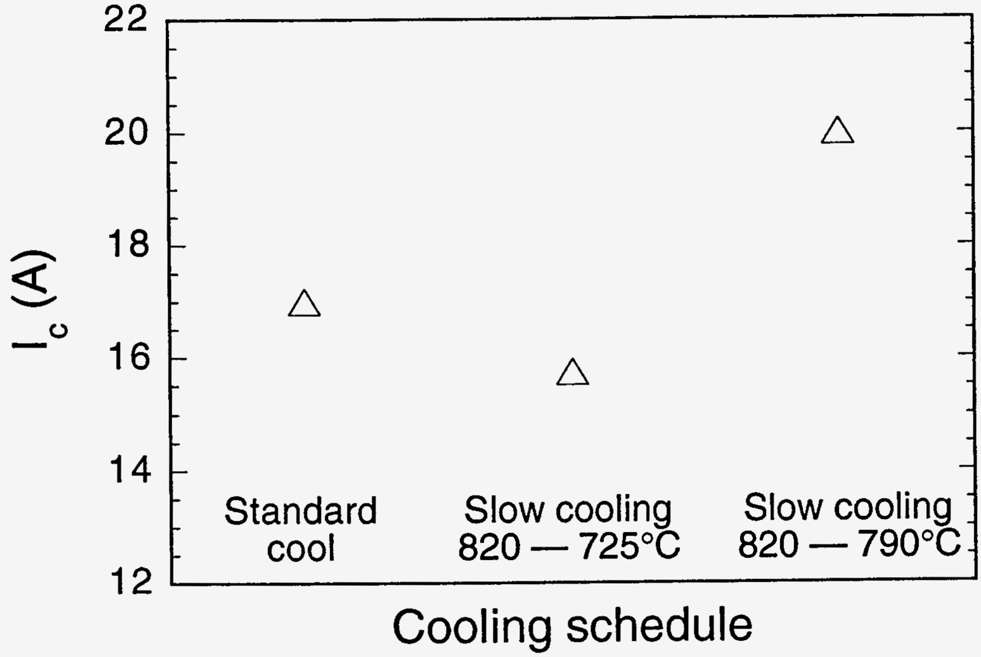
Figure 2. Distribution of I_c values for different manufacturing runs of Bi-2223 tapes 100–150 cm long.

Figure 3. Magnetic J_c in applied field (J_c(m)) normalized by zero-field value (J_c(0)) as a function of magnetic field for Bi-2212 (O) and Bi-2212 doped with nanometer-scale MgO particles (Δ) [46].

Table

Table 1. Transport I_c, engineering critical current density (J_e), and J_c of multifilamentary Bi-2223 tapes vs. conductor length.

Conductor Length (m)	I_c (A)	J_e (A/cm^2)	J_c (A/cm^2)
0.04	60	6,400	25,000
164	54	6,000	24,000
1260	18	3,500	12,000



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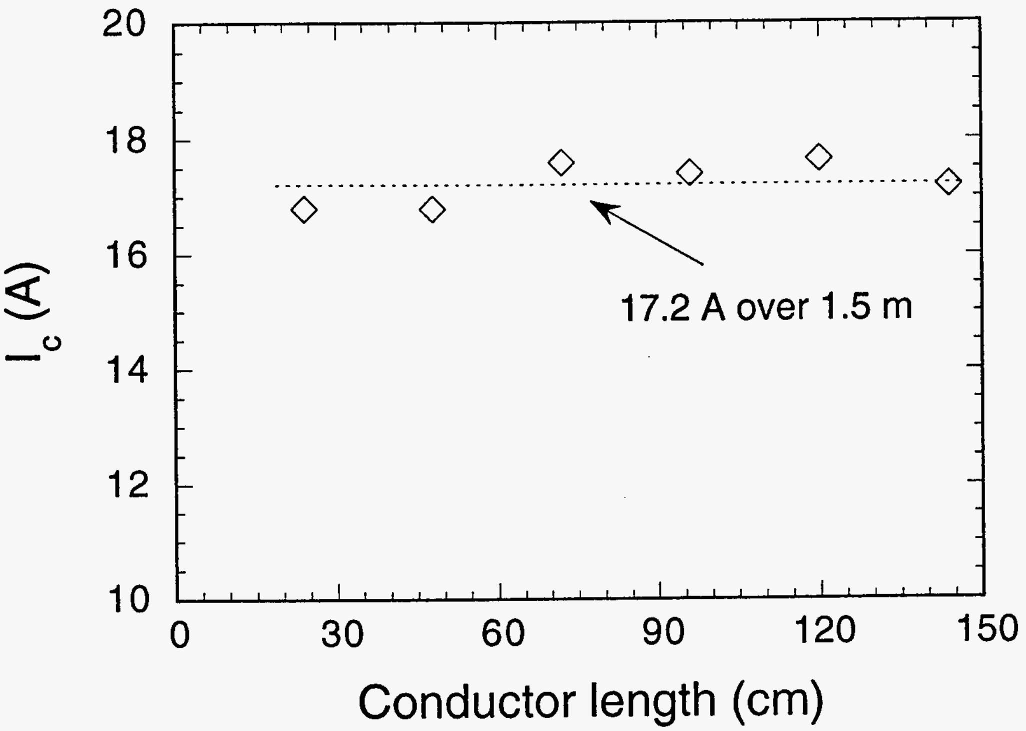
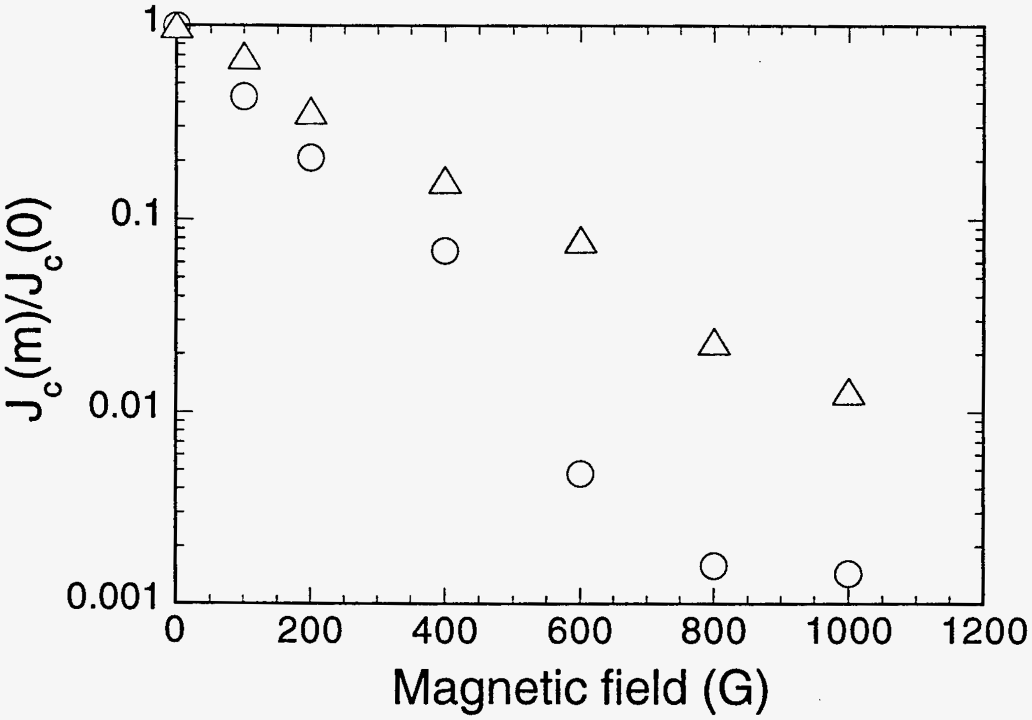
— Balachandran et al., Fig. 1 —



— Balachandran et al., Fig. 2 —



Balachandran et al., Fig. 3

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