Determination of irreversibility field variations in mono- and multifilamentary $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ tapes by transport current methods

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The irreversibility field, H^*, has been measured for a variety of mono- and multifilamentary $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (2223) tapes using two different transport current techniques. It is common to characterize the quality of 2223 tapes by their zero-field, 77 K critical current density [J_c(0 T, 77 K)], even though this ignores the fact that significant self-fields depress J_c(0 T, 77 K) and the possibility that the in-field $J_c(B)$ characteristics may be optimized independently of the J_c(0 T, 77 K) value. To provide more useful information, we propose a second characterization, that of the irreversibility field, H^*. Having both H^* and J_c(0 T, 77 K) information helps in separating the two independent contributions that better connectivity and stronger flux pinning can make to the J_c of a tape. We illustrate this point with results from a variety of mono- and multifilamentary Bi-2223/Ag tapes in damaged and undamaged conditions, which show that H^* (77 K) can vary from ~100 to ~200 mT and not directly correlate with J_c(0 T, 77 K). The two proposed protocols for H^* measurement are robust and compatible with common transport measurement procedures.
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Both the zero-field, $J_c(0)$, and the in-field, $J_c(B)$, critical current densities of $(Bi,Pb)_2Sr_2Ca_2Cu_3O_x$ (2223) tapes must be improved to make applications economically feasible. J_c is defined experimentally as $J_c = I_c/A$ where I_c is the critical current and A is the area of the whole ceramic cross section. However, this averaged, overall J_c is most certainly an understatement of the maximum local J_c because the current percolates through only a fraction of the cross-sectional area, A_{active}. $J_c(0)$ contains significant contributions from current paths that include weakly linked grain boundaries, which are decoupled by small magnetic fields, and it is thus at least partially limited by self-fields generated by the transport current. However, $J_c(B)$ is strongly influenced by the strength of the flux pinning. At high fields, either *intra*granular[1–6] or *inter*granular[7,8] flux pinning becomes the main J_c-limiting mechanism. Because different mechanisms determine $J_c(0)$ and $J_c(B)$, this leads us to believe that $J_c(B)$ may be optimized independently of $J_c(0)$. The irreversibility field, H^*, is an increasingly common parameter used to measure flux pinning because it is strongly influenced by flux pinning. H^* can be measured by several magnetization and transport current techniques. Previous work[8–10] has shown that individual composites often show a direct correlation between H^* and $J_c(0)$. However, as we have accumulated a larger database of H^* and $J_c(0)$ characterizations, we have found that there is no universal correlation and we, therefore, conclude that it is vital to characterize both the flux pinning *and* zero-field properties, if the highest performance is to be developed in BSCCO-2223 tapes.

When H^* is measured by magnetization, the magnetization signal is averaged over the whole volume of the sample. However, the transport current properties preferentially sample the continuous current-carrying sections of the tape, and for an inhomogeneous material such as BSCCO, the transport current should also be the preferred method for determining H^*. In this work, we compare two methods of measuring H^* (77 K) using transport current, hoping to encourage the widespread adoption of H^* as a standard characterization of BSCCO-2223 tapes.

Silver-sheathed monofilamentary 2223 tapes were produced using techniques described previously.[11,12] Each tape received different thermomechanical treatments so as to create samples with different $J_c(0)$ values. Tapes Mono1 and Mono2 were not quite fully reacted (only two heat treatments). Tapes Mono3 and Mono4 were both fully reacted, but other aspects of their processing were changed in order to produce different critical current densities. Multifilamentary 2223 tapes with 19 and 85 filaments and a range of $J_c(0)$ values were also characterized.

H^* was measured using two different transport current techniques in magnetic fields applied perpendicular to the broad tape surface (i.e., with B approximately $\parallel c$ axis). In method 1 (the $E-J$ curvature method), extended electric-field (E)–current-density (J) characteristics were measured and each extended log(E)–log(J) curve was fit to a quadratic equation. H^* was then defined as the field at which the curvature changes from negative to positive,[1,8–10,13,14] as shown in Fig. 1. This method is appropriate for either glass–liquid transition[15] or collective creep models.[16,17] A less model-dependent characterization can be obtained by a second method (the resistance method), in which the field dependence of the resistance in the limit of a small current density is measured. At the onset of flux flow, whatever the cause, the resistance will increase sharply. To implement this method we used a bipolar power supply to measure both positive and negative currents at electric fields less than 50 nV/cm (the bipolar supply is not essential, but it does expand

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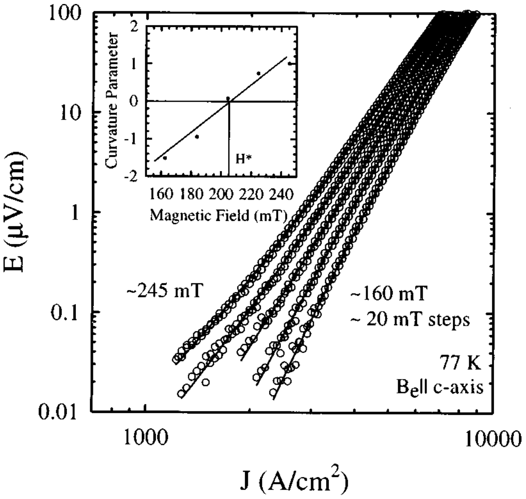

FIG. 1. Extended $E-J$ characteristics of monofilament sample Mono4. The open circles are the actual data and the lines are quadratic fits to the data. H^* is defined as the field at which the curvature parameter of the quadratic fit changes sign (inset).

the range of the measurement). Examples of two of these $E-J$ curves are shown in Fig. 2. A linear regression fit to the base line of each linear-scale $E-J$ curve defined the resistance. H^* was then defined as the field at which there is an abrupt change in the resistance versus magnetic-field plot, as shown in Fig. 3. The voltage was measured for both methods using a Keithley 2001 multimeter fed by a Keithley 1801 nanovolt preamplifier. To keep thermoelectric noise at a minimum, continuous Cu leads were used from the voltage contacts on the sample to the inputs of the nanovolt preamplifier. It has been shown previously[8,9,14] that there is some current sharing by the silver sheath in electric fields greater than 1 μV/cm. Therefore, in method 1, to correct for this sharing, we subtracted the effect of the silver using a method described in an earlier work.[9]

The H^* results for the monofilament tapes are shown in Table I. Tape Mono1 [$J_c(0)=5$ kA/cm^2] had $\mu_0 H^*$ values of 160 and 180 mT by the curvature and resistance methods, respectively. Tape Mono2 [$J_c(0)=13$ kA/cm^2] had $\mu_0 H^*$ values of 170 mT (method 1) and 140 mT (method 2). Tape Mono3 [$J_c(0)=17$ kA/cm^2] also shows a discrepancy, with a $\mu_0 H^*$ of $\sim$205 mT as measured by method 1 and a $\mu_0 H^*$ of 180 mT as measured by method 2. For tape Mono4 [$J_c(0)=23$ kA/cm^2], there is very good agreement between the two techniques, which both result in the same $\mu_0 H^*$ of $\sim$205+/−5 mT. It should be noted that all monofilament tapes are rather inhomogeneous with the current being carried preferentially near the Ag sheath,[18–20] particularly when not fully converted to the 2223 phase.

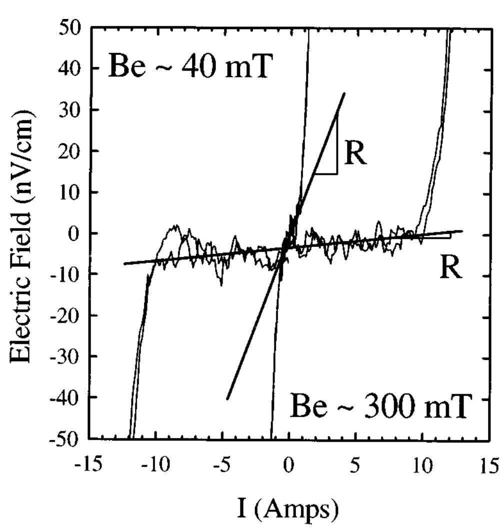

FIG. 2. $E-J$ characteristics of sample Mono4 in linear space at 40 mT and at $\sim$300 mT.

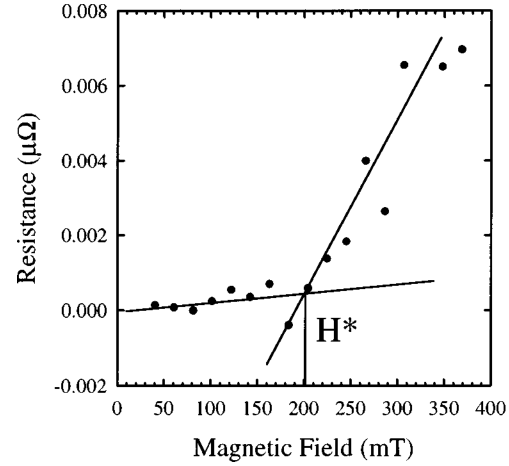

FIG. 3. Resistance vs magnetic-field plot for sample Mono4. H^* is defined as the field of the intersection of the two best fits to the data.

The results for the multifilamentary tapes show excellent agreement (Table I) as might be expected from their thinner filament dimensions and greater uniformity. Tape Multi1 had the extended $E-J$ characteristics shown in Fig. 4, which we have often seen in samples that have been damaged in some manner. These extended $E-J$ characteristics are not at all quadratic in nature, which therefore, makes the determination of $\mu_0 H^*$ by method 1 impossible. We found that $E-J$ characteristics such as these are produced by ohmic resistance, which results from current transfer around damaged regions into the silver sheath.[21] However, when this sample was measured by the resistance method, $\mu_0 H^*$ was quite clearly defined as 155 mT, as shown in the inset to Fig. 4. Tapes Multi2 and Multi3 each had a $J_c(0)\sim 40$ kA/cm^2 and $\mu_0 H^*$ of $\sim$120 mT when measured by both techniques. Similarly, tape Multi4 [$J_c(0)\sim 53$ kA/cm^2] also showed good agreement with a $\mu_0 H^*$ of $\sim$100 mT when measured using both techniques.

TABLE I. Comparison of the irreversibility field, H^*, as measured on various mono- and multifilamentary tapes

Sample I.D.	J_c(0 T,77 K) (kA/cm^2)	Method 1 $\mu_0 H^*$ (mT)	Method 2 $\mu_0 H^*$ (mT)
Mono1	5	160+/−5	180
Mono2	13	170+/−5	140
Mono3	17	205+/−5	180
Mono4	23	205+/−5	200
Multi1	~50	indeterminate	155
Multi2	~40	120+/−5	120
Multi3	~40	115+/−10	120
Multi4	~53	110+/−10	100

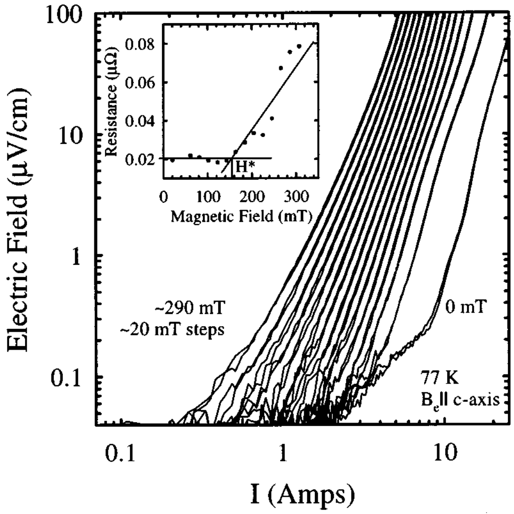

FIG. 4. Extended $E-J$ characteristics of sample Multi1. Determination of H^* by method 1 is impossible due to the nonquadratic shape of these curves. The ohmic component of these characteristics is due to the partial shunting of current into the silver sheath around damaged regions. This produces a finite, constant resistance seen below the value of $\mu_0 H^*$ $\sim$155 mT (inset).

The results in Table I show that H^* and $J_c(0)$ can vary independently, as evidenced by a lower $J_c(\sim 23\ \mathrm{kA/cm^2})$ monofilamentary tape having a higher $\mu_0 H^*(\sim 200\ \mathrm{mT})$ than a higher $J_c(\sim 53\ \mathrm{kA/cm^2})$ multifilamentary tape with a lower $\mu_0 H^*(\sim 100\ \mathrm{mT})$. The tapes that have a J_c below 20 kA/cm^2 (Mono1, Mono2, and Mono3) all exhibit a measurable discrepancy between the two measurement techniques. However, tapes with $J_c > 20\ \mathrm{kA/cm^2}$, whether mono- or multifilamentary, showed very good agreement between the two measurement techniques. We believe that disagreements for lower J_c, monofilament tapes are the result of their more significant inhomogeneity; the low J_c monofilaments are relatively thick (50–60 μm), and are more inhomogeneous than the thinner ($\sim$5 μm) filaments within the multifilamentary tapes. Therefore, it is not surprising that these two techniques do not always agree, because H^* is determined from an equally weighted average over five decades of electric field in the $E-J$ curvature method (method 1), while H^* is determined from an average of only one decade of electric field in the resistive method (method 2).

In summary, we measured H^* with transport current using two different techniques. When measuring inhomogeneous monofilament samples with low $J_c(< 20\ \mathrm{kA/cm^2})$, these two techniques did not yield the same value, but in more homogeneous, higher $J_c(> 20\ \mathrm{kA/cm^2})$ samples, the two techniques showed good agreement. In addition, the resistance method provides useful information about H^* for even grossly damaged samples, when the $E-J$ curvature method fails. Our measurements showed that J_c(0 T, 77 K) and H^* (77 K) can vary independently, emphasizing the value of measuring both properties as a tool for understanding the optimization of BSCCO-2223 composites.

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