Determination of irreversibility field variations in mono- and multifilamentary (Bi,Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$ tapes by transport current methods

J. W. Anderson, J. A. Parrell,a) M. Polak,b) and D. C. Larbalestierc)

Applied Superconductivity Center and Materials Science Program, University of Wisconsin–Madison, Madison, Wisconsin 53706

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The irreversibility field, $H^*$, has been measured for a variety of mono- and multifilamentary (Bi,Pb)$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$ (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 [$J_c(0, 0 T, 77 K)$], even though this ignores the fact that significant self-fields depress $J_c(0, 0 T, 77 K)$ and the possibility that the in-field $J_c(B)$ characteristics may be optimized independently of the $J_c(0, 0 T, 77 K)$. To provide more useful information, we propose a second characterization, that of the irreversibility field, $H^*$. Having both $H^*$ and $J_c(0, 0 T, 77 K)$ 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 $\sim$100 to $\sim$200 mT and not directly correlate with $J_c(0, 0 T, 77 K)$. 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)$_2$Sr$_2$Ca$_2$Cu$_3$O$_x$ (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 intragranular1–6 or intergranular7,8 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 work9–10 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 multifilamentary 2223 tapes were produced using techniques described previously.1,12 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 in the 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 transition15 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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a)Present address: Oxford Superconducting Technology, Carteret, NJ 07008.

b)On leave from Slovak Academy of Sciences, Bratislava, Slovakia.

c)Electronic mail: larbales@engr.wisc.edu

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Electronic mail: larbales@engr.wisc.edu

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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 $H^*$ results for the monofilament tapes are shown in Table I. Tape Mono1 [$J_c(0) = 5\,\text{kA/cm}^2$] had $\mu_0H^*$ values of $160$ and $180$ mT by the curvature and resistance methods, respectively. Tape Mono2 [$J_c(0) = 13\,\text{kA/cm}^2$] had $\mu_0H^*$ values of $170$ mT (method 1) and $140$ mT (method 2). Tape Mono3 [$J_c(0) = 17\,\text{kA/cm}^2$] also shows a discrepancy, with a $\mu_0H^*$ of $\sim 205$ mT as measured by method 1 and a $\mu_0H^*$ of $180$ mT as measured by method 2. For tape Mono4 [$J_c(0) = 23\,\text{kA/cm}^2$], there is very good agreement between the two techniques, which both result in the same $\mu_0H^*$ 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, particularly when not fully converted to the 2223 phase.

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 $\mu_0H^*$ by method 1 impossible. We found that $\mu_0H^*$ characteristics such as these are produced by ohmic resistance, which results from current transfer around damaged regions into the silver sheath. However, when this sample was measured by the resistance method, $\mu_0H^*$ was quite clearly defined as $155$ mT, as shown in the inset to Fig. 4. Tapes Multi2 and Multi3 each had a $J_c(0)\sim 40\,\text{kA/cm}^2$ and $\mu_0H^*$ of $\sim 120$ mT when measured by both techniques.

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.

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

<table>
<thead>
<tr>
<th>Sample I.D.</th>
<th>$J_e(0)$, T,77 K (kA/cm²)</th>
<th>Method 1 $\mu_0H^*$ (mT)</th>
<th>Method 2 $\mu_0H^*$ (mT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mono1</td>
<td>5</td>
<td>160 +/- 5</td>
<td>180</td>
</tr>
<tr>
<td>Mono2</td>
<td>13</td>
<td>170 +/- 5</td>
<td>140</td>
</tr>
<tr>
<td>Mono3</td>
<td>17</td>
<td>205 +/- 5</td>
<td>180</td>
</tr>
<tr>
<td>Mono4</td>
<td>23</td>
<td>205 +/- 5</td>
<td>200</td>
</tr>
<tr>
<td>Multi1</td>
<td>~ 50</td>
<td>indeterminate</td>
<td>155</td>
</tr>
<tr>
<td>Multi2</td>
<td>~ 40</td>
<td>120 +/- 5</td>
<td>120</td>
</tr>
<tr>
<td>Multi3</td>
<td>~ 40</td>
<td>115 +/- 10</td>
<td>120</td>
</tr>
<tr>
<td>Multi4</td>
<td>~ 53</td>
<td>110 +/- 10</td>
<td>100</td>
</tr>
</tbody>
</table>
The results in Table I show that $H^*$ and $J_c(0)$ can vary independently, as evidenced by a lower $J_c(\sim 23 \text{ kA/cm}^2)$ monofilamentary tape having a higher $\mu_0 H^*(\sim 200 \text{ mT})$ than a higher $J_c(\sim 53 \text{ kA/cm}^2)$ multifilamentary tape with a lower $\mu_0 H^*(\sim 100 \text{ mT})$. The tapes that have a $J_c$ below $20 \text{ kA/cm}^2$ (Mono1, Mono2, and Mono3) all exhibit a measurable discrepancy between the two measurement techniques. However, tapes with $J_c > 20 \text{ kA/cm}^2$, whether monofilar 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 ($50-60 \mu$m), and are more inhomogeneous than the thinner ($\sim 5 \mu$m) 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 $J_c(<20 \text{ kA/cm}^2)$, these two techniques did not yield the same value, but in more homogeneous, higher $J_c(>20 \text{ kA/cm}^2)$ 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 $J_c(0 \text{T, } 77 \text{ K})$ and $H^*(77 \text{ K})$ 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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17 D. Dew-Hughes, Cryogenics 28, 674 (1988).