Biaxial Strain Measurements of $J_C$ on a (RE)BCO Coated Conductor

Jack R. Greenwood, Elizabeth Surrey and Damian P. Hampshire

For several years it has been possible to measure the uniaxial strain dependence of the critical current density $J_C(\varepsilon)$ of (RE)BCO coated conductors ((RE)BCO tapes) and a parabolic strain dependence of $J_C(\varepsilon)$ has been observed. To improve our understanding of how strain affects the electrical and mechanical properties of a SuperPower APC SCS4050 (RE)BCO tape, we have created a biaxial sample holder which can apply arbitrary strains along both the x- and y-axes of a (RE)BCO tape simultaneously. It can be used to measure $J_C$ for applied x and y strains ranging from $-0.50\% \leq \varepsilon_x \leq 0.30\%$ and $-0.15\% \leq \varepsilon_y \leq 0.20\%$ respectively, at 77 K. We present the results of $J_C$ measurements over this strain range at 77 K in magnetic fields of up to 0.7 T. We show that we obtain the standard parabolic relationship for $J_C(\varepsilon)$, with a peak in $J_C$ occurring at $\varepsilon_{x,y} \approx -0.01\%$. We also show that when we apply an additional y strain of $\varepsilon_y = -0.05\%$ the peak in $J_C$ moves to $\varepsilon_{x,y} = 0.4\%$, which cannot be explained by considering the differential strains produced by non-superconducting components of the tape and sample holder. In addition, the value of $J_C$ at the peak increases considerably, by 11%.

Index Terms—Critical current, strain measurement, 2G HTS conductors, cuprates.

I. INTRODUCTION

U}nderstanding the mechanisms responsible for the strain dependence of the critical current density ($J_C$) of 2nd generation, high temperature (RE)BCO coated conductors (often referred to as (RE)BCO tapes) allows tape manufacturers to optimize their fabrication processes and engineers to optimize systems in which the tapes are used. Over the last few years, experimental methods have been developed which allow these tapes to be strained uniaxially along the direction of current flow, so $J_C$ can be measured as a function of applied uniaxial strain ($\varepsilon$). One of the most popular methods is to use a bending beam apparatus, as it allows both compressive and tensile strains to be applied to a tape [1, 2].

It is well established that there is a parabolic relationship between $J_C$ and applied uniaxial strain [3, 4]. The peak in $J_C$ may occur at either a tensile or compressive strain [5]. Differential thermal contraction between the component parts of the (RE)BCO tape (as well as the sample holder) can cause the (RE)BCO layer to have a non-zero strain even when no external strain has been applied. The complex microtwinned structure of the (RE)BCO layer in a tape also affects its mechanical and superconducting properties [5, 6]. In this paper we have measured SuperPower APC SCS4050 (RE)BCO tapes. The superconducting layer consists of a series of A or B domains which have their a- or b-axes aligned with the direction of current flow respectively. Single crystal measurements have shown that the strain dependence of the critical temperature ($T_C$) along the a-axis is opposite to that along the b-axes [7]. From these measurements, a 1-dimensional chain model has been proposed which explains the location of the peak in $J_C$ by considering the total fractions of A and B domains in the (RE)BCO layer and the strain dependence of $T_C$ in single crystals [8].

To improve our understanding of how the microstructure of the (RE)BCO layer affects the strain dependence of $J_C$, we have designed and commissioned a new biaxial sample holder known as the ‘crossboard’. This sample holder can be used to investigate the strain dependence of $J_C$ for arbitrary applied x and y strains. The key features of the crossboard and the experimental procedure for performing biaxial strain dependent $J_C$ measurements are outlined in Section II. Section III presents results for the temperature dependence of the applied strains, as the strains are applied at room temperature, but $J_C$ measurements are made at 77 K. Section III also presents results for the biaxial strain dependence of $J_C$ at 77 K, for magnetic fields up to 0.7 T. The biaxial strain dependent $J_C$ data are discussed in further detail in Section IV and the capabilities of the crossboard are also discussed. Some conclusions are presented in Section V.

II. SAMPLE HOLDER & EXPERIMENTAL METHOD

A. Sample Holder Geometry & Assembly

The geometry of the crossboard is shown in Fig. 1. The crossboard is manufactured from Berylco® 25. Stainless steel grippers constrain the crossboard in the z direction and prevent z strains from being generated at the center of the crossboard.

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Fig. 1. (a) A CAD model of the crossboard. (b) A CAD model of the assembly used to apply x or y strains on the top side of the crossboard. The combination of nuts and bolts shown allows strains to be applied in the y direction.

Fig. 2. (a) The x strain distribution on the surface of the crossboard when an 1800 N force is applied at the positions of the arrows at room temperature. (b) The corresponding y strain distribution.

Tightening the nuts and bolts cause the wings of the crossboard to bend around the teeth of the steel grippers, which generates x or y strains at the center of the crossboard. Both tensile and compressive strains can be generated.

B. Strain Homogeneity

Finite element simulations have been performed on the crossboard to evaluate its strain homogeneity. The results of a simulation are depicted in Fig. 2. In this simulation, 4 loads of 1800 N each have been applied at the positions of the arrows. The x and y strains at the center of the crossboard are

\[ \varepsilon_x = 0.48\% \quad \text{and} \quad \varepsilon_y = -0.48\% \] respectively. The variations in x and y strain in the central 7 mm of the crossboard along its x-axis are \( \Delta \varepsilon_x = 0.025\% \) and \( \Delta \varepsilon_y = 0.002\% \) respectively. The strain variation is influenced by the magnitudes of the applied loads. The value of \( \frac{\partial \varepsilon_x}{\partial \varepsilon_y} \) at the center of the crossboard when strain is applied along one axis is \( \sim 0.42 \).

C. Experimental Method

\( J_c(B, \theta, \varepsilon_x, \varepsilon_y) \) d.c. current transport measurements have been performed on tapes at 77 K, using the crossboard sample holder and the standard four-terminal technique. A tape with a length of 24 mm and a width of 4 mm was soldered with its substrate side facing downwards onto the center of the crossboard using 60/40 Sn/Pb solder. The tape was aligned so the direction of current flow was along the x-axis of the crossboard. Current leads were attached to the ends of the tape and two pairs of voltage taps were attached around the center of the tape with separations of \( \sim 7.0 \) mm and \( \sim 10.0 \) mm. A HBM XY91-1.5/120 T rosette strain gauge containing two sensors was attached to the center of the tape, such that strain could be measured parallel and orthogonal to the current flow [9]. The sensitive area of the strain gauge is \( \sim 1 \) mm².

TABLE I

<table>
<thead>
<tr>
<th>Applied Strain Type</th>
<th>Temperature (K)</th>
<th>( \frac{\partial \varepsilon_y}{\partial \varepsilon_x} )</th>
<th>( \varepsilon_x(\varepsilon_y = 0) ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied ( \varepsilon_x )</td>
<td>300</td>
<td>-0.34</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>77</td>
<td>-0.33</td>
<td>0.024</td>
</tr>
<tr>
<td>Applied ( \varepsilon_y )</td>
<td>300</td>
<td>-0.574</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>77</td>
<td>-0.574</td>
<td>0.027</td>
</tr>
<tr>
<td>Applied ( \varepsilon_x ) &amp; ( \varepsilon_y )</td>
<td>300</td>
<td>-0.349</td>
<td>-0.097</td>
</tr>
<tr>
<td></td>
<td>77</td>
<td>-0.34</td>
<td>-0.068</td>
</tr>
</tbody>
</table>
The crossboard and grippers are attached to a probe which can be placed in an open liquid nitrogen Dewar. At room temperature, the nuts and bolts are adjusted to set the strain. The crossboard is then cooled to 77 K and the strain re-measured. The probe is connected to a 120 A power supply. A 0.7 T horizontal magnet system is used to apply a magnetic field to the tape. The magnet system can be rotated 360° around the x-axis of the crossboard, allowing variable field and variable angle measurements to be made.

III. RESULTS
A. Temperature Dependence of Strain Coordinates
Three different combinations of strain have been applied to the (RE)BCO tape. Strains have been applied along the x direction only, the y direction only and along both the x and y directions. Fig. 3 shows the effect of temperature on the applied strains and Table I lists the values of the linear fits shown in Fig. 3. The change in temperature changes the values of $\varepsilon_x(\varepsilon_x = 0)$ by ~ 0.03% but doesn’t change the gradients and the values of $x$ and $y$ strain at 77 K are reasonably reproducible. We chose to make the 2 gradients for data where both $x$ and $y$ strains were changed to be similar to that obtained when strain was applied along the $x$-direction. The values of $\partial \varepsilon_y / \partial \varepsilon_x$ will be discussed in greater detail in the Section IV.

B. $E - J$ Characteristics
In this paper, to calculate the values of $J$ and $J_C$, we have assumed the (RE)BCO layer has a thickness of 1.0 μm. Fig. 4 shows $E - J$ plots for different values of $x$ and $y$ strain. The strains correspond to a subset of the applied $\varepsilon_x$ and $\varepsilon_y$ (blue) strain coordinates in Fig. 3. $J_C$ is determined at $E = 100 \, \mu \text{V m}^{-1}$. The values of $J_C$ increase monotonically with increasing tension along the $x$-axis. There is no sign of a peak in $J_C$ over the range of $x$ and $y$ strains measured.

C. Biaxial Strain Dependence of $J_C$
The parabolic fits shown in Fig. 5, Fig. 6 and Fig. 7 for $J_C(\varepsilon_y)$ are fitted using the equation...
Further improvements could be made to the crossboard to improve its strain range and shorten the time taken to perform measurements. The main limitation of the crossboard is that the strains must be applied at room temperature. Although we have shown that we can predict the strain state of the (RE)BCO tape at 77 K from the tape’s strain state at room temperature, it would be advantageous to change strains while remaining at 77 K. Of course ideally we would like to be able to change strain in all three directions independently.

V. CONCLUSION

We have designed and commissioned a new biaxial sample holder, known as the ‘crossboard’, which can be used to measure \( J_C \) for arbitrary strains along the \( x \)- and \( y \)-axes of a (RE)BCO coated conductor in the ranges of \( -0.50\% < \varepsilon_x < 0.30\% \) and \( -0.15\% < \varepsilon_y < 0.20\% \), at 77 K. \( J_C \) measurements have been made at 77 K in fields up to \( B = 0.7 \) T and the standard parabolic relationship between applied \( x \) strains and \( J_C \) has been observed. We have shown that by applying an additional compressive \( y \) strain of \(-0.08\% \) at 77 K, the peak in \( J_C(\varepsilon_y) \) moves from a compressive \( x \) strain of \( \varepsilon_x = -0.01\% \) to a tensile strain of 0.4%. The value of \( J_C \) at the peak also increases considerably, by 11%. The movement of the strain peak position cannot be explained by considering the strains exerted on the (RE)BCO layer from the other materials in the tape or sample holder. Having the ability to apply biaxial strains to a (RE)BCO coated conductor opens exciting new possibilities to study both the mechanical and electrical properties of these tapes in two dimensions.

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