The Biaxial Strain Dependence of the Critical Current Density of a (RE)BCO Coated Conductor at 77 K

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Introduction

We have recently designed and commissioned a 2D sample holder known as a 'Crossboard' [1], which has been used to apply biaxial stresses in-plane to a (RE)BCO SuperPower SCS4050 APC tape [2] and measure the effect on the critical current density (J_C). Data are presented for magnetic fields up to 0.7 T at 77 K. We also present a theoretical model that is used to describe the experimental data taken using the Crossboard. We show that the in-field, biaxial strain dependence of the tape's critical current density $J_{CT}(B, \varepsilon_{xx}, \varepsilon_{yy})$ is governed by the J_C's of the A- and B-domains in the (RE)BCO layer, which have their crystallographic a- or b-axes (respectively) aligned along the tape length, with twin boundaries lying along the [110] direction. The experimental results and the parameterisation show that the tape has roughly equal populations of A- and B-domains ($f = 0.49$) and that the strain sensitivity of the critical temperature along the a-axis is 1.8 K%$^{-1}$ and along the b-axis is -1.3 K%$^{-1}$, in both domains. Applications that are subjected to multiaxial loads during their manufacturing process and operation that can be described using the formalism given in this work, include CORC® and Roebel cables [3,4].

The Biaxial Strain Model for J_C (BSJ)

- The (RE)BCO layer is treated as a 1D chain of A- and B-domains that have their a- and b-axes aligned along the length of the tape. The J_C of the whole tape (J_{CT}) has contributions from the J_C's of the A- and B-domains (J_{CA} and J_{CB} respectively) [5]

$$J_{CT} = \left[f J_{CA}{}^{-N} + (1-f) J_{CB}{}^{-N}\right]^{-1/N}, \quad (1)$$

where f and $1-f$ are the fractions of A- and B-domains and N is the tape's quality index.

- The J_C of domain type i is calculated using the engineering scaling law [5]:

$$J_{Ci} = A[B_{c2i}]^{n-3} b^{p-1} (1-b)^q T_{Ci}^2 \left(1 - \left(\frac{T}{T_{Ci}}\right)^2\right)^2, \quad (2)$$

where i = A or B, A, p and q are fitting constants, n is fixed at 2.5, B_{c2i} and T_{Ci} are the upper critical magnetic field and critical temperature of the domain respectively and b is the reduced field B/B_{c2i}.

- The T_C's of the A- and B-domains are taken to be linear functions of x- and y-strain (ε_{xx} and ε_{yy}):

$$T_{CA}(\varepsilon_{xx}, \varepsilon_{yy}) = T_C(0,0)\left(1 + \left(\frac{\partial T_{CA}}{\partial \varepsilon_{xx}}\right)_{\varepsilon_{yy}=0}(\varepsilon_{xx} - \varepsilon_{xx0}) + \left(\frac{\partial T_{CB}}{\partial \varepsilon_{xx}}\right)_{\varepsilon_{yy}=0}(\varepsilon_{yy} - \varepsilon_{yy0})\right), \quad (3a)$$

$$T_{CB}(\varepsilon_{xx}, \varepsilon_{yy}) = T_C(0,0)\left(1 + \left(\frac{\partial T_{CB}}{\partial \varepsilon_{xx}}\right)_{\varepsilon_{yy}=0}(\varepsilon_{xx} - \varepsilon_{xx0}) + \left(\frac{\partial T_{CA}}{\partial \varepsilon_{xx}}\right)_{\varepsilon_{yy}=0}(\varepsilon_{yy} - \varepsilon_{yy0})\right), \quad (3b)$$

where $T_C(0,0)$ is the critical temperature of an A- or B-domain at zero net strain and ε_{xx0} and ε_{yy0} are pre-strains along x and y respectively, caused by the tape's manufacturing process and cool-down. $(\partial T_{CA}/\partial \varepsilon_{xx})_{\varepsilon_{yy}=0}$ and $(\partial T_{CB}/\partial \varepsilon_{xx})_{\varepsilon_{yy}=0}$ are the strain sensitivities of T_C of a (RE)BCO single crystal along it's a- and b-axes respectively [6].

- The B_{c2}'s of the A- and B-domains are related to their respective T_C's using a power law. [5,7]

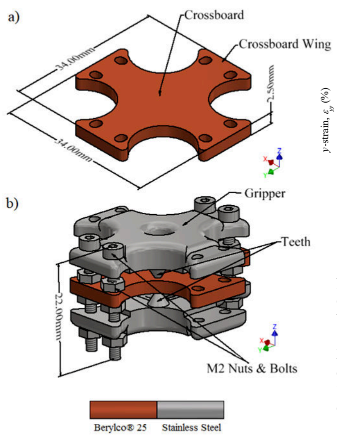
Experimental Setup

- SuperPower® SCS4050 APC tapes [2] were soldered substrate-side down onto a Crossboard (see Fig 1a) [1].

- The length of the tape is aligned with the x-axis of the Crossboard.

- Applying stresses along the x- and y-axes of the tape using the grippers, nuts and bolts (see Fig. 1b) fixes the x- and y-strain state of the tape.

- J_C is measured at the strains represented by closed symbols in Fig. 2 using a 4-terminal strain gauge in magnetic fields up to 0.7 T for $B \| c$-axis ($\theta = 90°$) and $B \| ab$-plane ($\theta = 0°$) at 77 K.



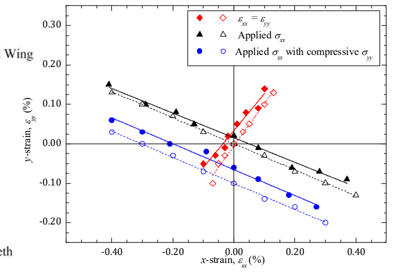


Fig. 1 (Left) a) A CAD model of the Crossboard. b) A CAD model of the Crossboard with the grippers, nuts and bolts used to apply stresses [1].

Fig. 2 (Top) The strains at which J_C was measured. The closed data points and solid lines correspond to strains at 77 K and the open data points and dashed lines correspond to the strains at 300 K.

Experimental Results & Their Parameterisation

- The data were fitted with $\varepsilon_{xx0} = \varepsilon_{yy0} = 0\%$

- $J_C(B, \varepsilon_{xx}, \varepsilon_{yy})$ is parabolic with respect to x-strain near $\varepsilon_{xx} = 0\%$ for the 'applied σ_{xx}' and 'applied σ_{xx} with compressive σ_{yy}' data and is linear for the '$\varepsilon_{xx} = \varepsilon_{yy}$' data.

- The (RE)BCO layer has $f = 0.49$, so the populations of A- and B-domains are roughly equal.

- $\left(\frac{\partial T_C}{\partial \varepsilon_{xx}}\right)_{\varepsilon_{yy}=0}$ is 1.8 K%$^{-1}$ along the a-axis and -1.3 K%$^{-1}$ along the b-axis, in both domains.

Table 1: Free parameters derived from fitting the J_C data with the BSJ, at the strains shown in Fig. 2 in fields up to 0.7 T at $\theta = 90°$ and $\theta = 0°$.

Field Angle (°)	Parameter f	$\left(\frac{\partial T_{C,A}}{\partial \varepsilon_{xx}}\right)_{\varepsilon_{yy}=0}$ (K%$^{-1}$)	$\left(\frac{\partial T_{C,B}}{\partial \varepsilon_{xx}}\right)_{\varepsilon_{yy}=0}$ (K%$^{-1}$)	p	q	$A_{\varepsilon_{xx}=\varepsilon_{yy}}$ (MAm^{-2}K^{-2}T$^{-0.5}$)	$A_{\sigma_{xx}}$ (MAm^{-2}K^{-2}T$^{-0.5}$)	$A_{\sigma_{xx}+\sigma_{yy}}$ (MAm^{-2}K^{-2}T$^{-0.5}$)
90	0.49	1.8	-1.3	0.706	0.0	20.0	21.5	20.5
0				0.674	5.8	23.2	23.6	23.2

N was set to be 18 from experiments. $B_{c2}(T = 0, \varepsilon_{xx} = 0, \varepsilon_{yy} = 0)$ was set at 98.7 T for $\theta = 90°$ and 185 T for $\theta = 0°$ [5, 8] and $T_C(0,0)$ was set at 90.1 K [5].

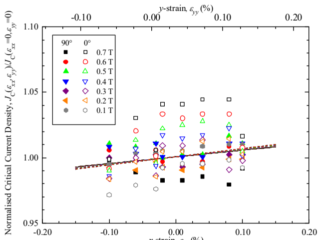


Fig. 3 The strain dependence of J_C at 77 K when the y-strains are fixed to be the same as the x-strains.

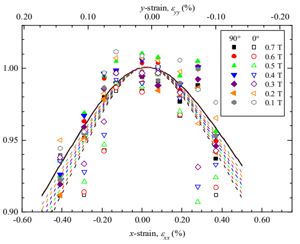


Fig. 4 The strain dependence of J_C at 77 K when stresses are applied along the x-axis of the tape.

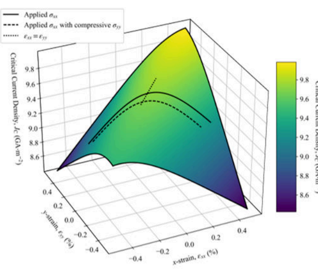


Fig. 6 The biaxial strain dependence of J_C at 77 K for B = 0.5 T and $\theta = 90°$. The surface is generated using the constants in Table I, with A = 21.5 MAm^{-2}K^{-2}T$^{-0.5}$. The three lines correspond to the solid trendlines in Fig.'s 3, 4 and 5.

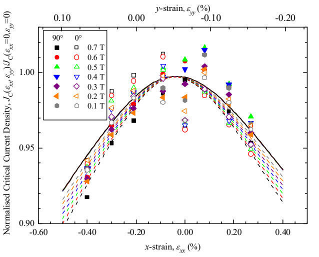


Fig. 5 The strain dependence of J_C at 77 K when stresses are applied along the x-axis of the tape and an additional compressive stress is applied along the y-axis.

Conclusions

We have:

1) Measured $J_{CT}(B, \varepsilon_{xx}, \varepsilon_{yy})$ using the Crossboard in fields up to 0.7 T at 77 K.

2) Developed a theoretical model to describe the in-plane biaxial strain dependence of J_C of a (RE)BCO tape.

The experimental data and the theoretical model show that:

1) $J_{CT}(\varepsilon_{xx}, \varepsilon_{yy})$ has a parabolic behaviour near $\varepsilon_{xx} = 0$ when we apply an x-stress to the tape, whether we add a constant y-stress or not.

2) $J_{CT}(\varepsilon_{xx}, \varepsilon_{yy})$ has a linear behaviour near $\varepsilon_{xx} = 0$ when we fix $\varepsilon_{yy} = \varepsilon_{xx}$.

3) The fractions of A- and B-domains are approximately equal.

4) $\left(\frac{\partial T_C}{\partial \varepsilon_{xx}}\right)_{\varepsilon_{yy}=0}$ is 1.8 K%$^{-1}$ along the a−axis and −1.3 K%$^{-1}$ along the b−axis, in both domains.

References & Acknowledgements

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