Critical Current Density of $YBa_2Cu_3O_{7-\delta}$ Coated Conductors Under High Compression in High Fields

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***Abstract*—From an engineering standpoint, the magnetic field (B), temperature (T), and strain dependence (ε) of the critical current density (J_C) in practical superconducting wires/tapes is critical for optimizing device design using superconducting technology. The highly anisotropic and brittle nature of $YBa_2Cu_3O_{7-\delta}$ (YBCO) coated conductor tapes means a detailed investigation of the parameters that affect the critical current is a challenging experimental task to achieve within a single strain apparatus. Here we present critical current measurements as a function of strain on YBCO coated conductors made using a bending apparatus designed for use in horizontal split-pair magnet systems with a 40 mm diameter bore. The design and configuration of the apparatus allows different compressive and tensile strain between $-1.4\% < \varepsilon_{\text{applied}} < +0.5\%$ to be applied. Magnetic fields up to 0.7 T at T = 77 K, and 15 T at 4.2 K, were applied at different angles (θ) with respect to the coated conductor surface. At 77 K, J_C can be reversibly reduced by more than 85% with a $\sim -1\%$ compressive strain at 0.7 T. For high compressive strains, J_C versus strain data show convex behavior. We provide a preliminary parameterization of the scaling relation for $J_C(B,T,\varepsilon,\theta)$.**

***Index Terms*—Critical current, high-temperature superconductors, strain.**

I. Introduction

The improved quality in YBCO coated conductors has been achieved by fabricating materials with small misalignment angles between the grains, enhanced flux pinning within the grain boundaries as well as from nanoscale pinning inclusions within the grains and has yielded technologically useful critical current densities $[J_C(B,T,\varepsilon,\theta)]$. However in these optimized YBCO materials, J_C has been found to decrease reversibly by as much as ~45% in self-field at 77 K, when a uniaxial compressive strain of -1.2% is applied [1]–[3]. This large reversible decrease presents the opportunity to investigate and understand the behavior of J_C under strain which is beneficial for optimizing the use of these materials in engineering applications and for understanding the underlying fundamental physics.

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Recently, several groups have reported $J_C(\varepsilon)$ measurements using strain apparatus that can apply both tensile and compressive strains at high magnetic fields [4], [5]. We present results from a strain apparatus designed to apply compressive and tensile strains in magnetic fields over a wider strain range ($\sim -1.4\% \leq \varepsilon_{\text{applied}} \leq +0.5\%$). The sample and experimental method is outlined in Section II. Sections III and IV present the results and analysis. The conclusion is in Section V.

II. Experimental Method

Standard four-point DC voltage-current measurements were performed on the samples. The strain apparatus is loosely based on the bending beam design developed by the University of Twente [6]. It consists of a Cu-Be bending beam 78 mm in length, 15 mm in width, and 2.5 mm in thickness. The bending beam has two pairs of legs separated by ~50 mm; one pair is held by a support tube while force is applied to the second pair via a pushrod. The pushrod either increases the separation of the legs, creating a compressive strain on the top surface of the bending beam, or decreases the separation creating a tensile strain. The pushrod is manipulated by a computer controlled and monitored servomotor. This configuration yields a strain range $\sim -1.4\% \leq \varepsilon_{\text{applied}} \leq +0.5\%$ within the confines of a 40 mm diameter magnet bore (perpendicular to the surface of the beam); this is ideal for the magnet access ports of high-field horizontal split-pair magnet systems.

In our horizontal magnet system, we are able to measure the effects of strain as a function of the magnitude of the magnetic field and the angle between the field and the coated conductor surface over a full 360 degrees. The bending beam is positioned vertically within the split-pair magnet and current flow is perpendicular to the field direction for all angles (maximal Lorentz force). At 77 K, we can apply fields up to 0.7 T. The magnetic field range at 4.2 K is up to 15 T.

A Hall probe is placed on the surface of the coated conductor in order to determine the orientation of the magnetic field accurately. Strain gauges are placed on the bending beam and beside the sample. This allows us to measure whether there is twisting of the probe or bending beam deflection during high-field and high-current (i.e. high Lorentz force) measurements.

The samples used in these measurements are commercially available YBCO coated conductors consisting of $\sim 1\ \mu m$ thick superconductor deposited on Hastelloy substrates using an MOCVD deposition technique. In such tapes, the $a-b$ planes of the YBCO structure lie approximately along the direction of the surface of the tape. The strain in the superconducting layer

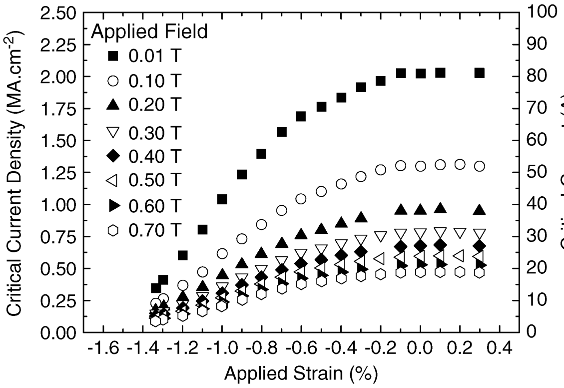

Fig. 1. Critical current density as a function of applied strain for different applied magnetic fields at 77 K. The magnetic field was applied perpendicular to the coated conductor's surface. The electric field criterion was 100 $\mu V.m^{-1}$.

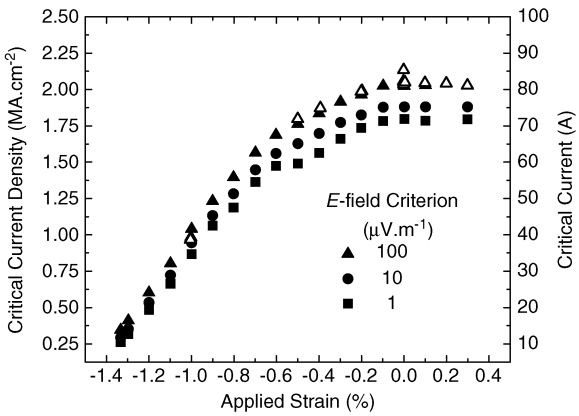

Fig. 2. Critical current density as a function of applied strain at 77 K and 0.01 T for various E-field criterion. The magnetic field was applied perpendicular to the conductor surface. Closed symbols are data taken in the direction of tensile strain towards high compressive strain. Open symbols are reversibility checks of J_C.

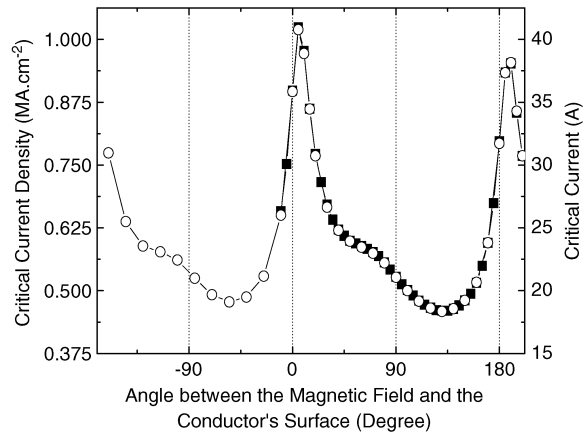

Fig. 3. Critical current density as a function of the angle between the magnetic field and the conductor surface at 77 K. The magnitude of the applied field was 0.5 T. Measurements were first performed over the range from -10 degrees to $+200$ degrees (closed symbols) and then from $+200$ degrees to -160 degrees (Open symbols).

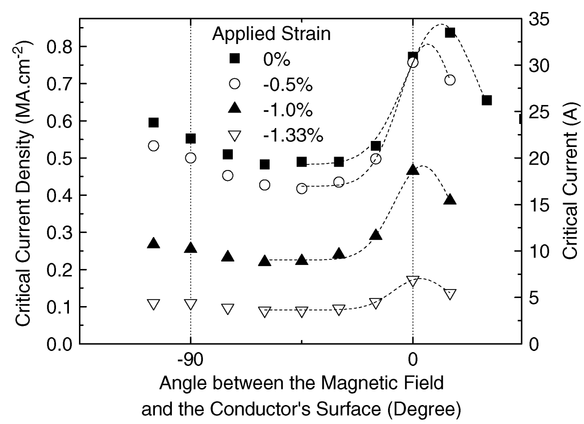

Fig. 4. Critical current density measurements as a function of the angle between the magnetic field and the conductor's surface at 77 K, 0.5 T and different applied strains. The dotted lines are a guide to the eye.

during the measurements presented in this paper is typically homogeneous to 1 part in 10^3.

III. Results

A. J_C at 77 K

Fig. 1 shows the critical current density as a function of strain at 77 K for various magnetic fields applied perpendicular to the coated conductor's surface. Similar datasets were obtained both under tension and compression as a function of angle every 15 degrees. The reversibility of the critical current (I_C) was checked for compression down to strains of -1.3% as is shown in Fig. 2 for the data taken at 0.01 T. Independent of the electric field criterion used, reversibility of I_C was confirmed to be better than 0.5 Amps for strains down to -1% strain and 1.5 Amps for strains down to -1.3%, indicating no damage.

Fig. 3 shows measurements at 0.5 T and zero applied strain. The angular J_C measurements were taken over 360 degrees by increasing the angle from -10 degrees to $+200$ degrees, and then in decreasing angles from $+200$ degrees to -160 degrees. The angles were verified using a Hall probe accurate to 0.5 degrees. The offset in the peak value of J_C from zero and 180 degrees is not due to alignment errors. A shoulder is also visible near ± 90 degrees. We attribute this shoulder to extrinsic pinning centers fabricated during the deposition process. There is no angular hysteresis in J_C.

Fig. 4 shows angular J_C data at 0.5 T and various strains at 77 K. The peak at $+12$ degrees shifts towards zero degrees and the shoulder near -90 degrees becomes less pronounced with increased compression.

B. J_C at 4.2 K

Fig. 5 shows angular J_C data at 4.2 K, 11 T, and zero applied strain. In contrast to the 77 K data, the functional form is symmetric, there is no evidence of a shoulder, and the calculated peak is within 1 degree of zero degrees. These data are consistent with intrinsic pinning from the $a-b$ planes predominantly determining J_C when $\theta = 0$ degrees.

In a 14 T magnetic field with the field applied perpendicular to the conductor surface, we investigated the reversibility of J_C under strain cycling. Two distinctly different reversible curves for $J_C(\varepsilon)$ are shown in Fig. 6. The bottom curve was obtained during the initial application of strain from 0% to $+0.3\%$ and then down to -0.8%. J_C is reversible between $+0.3\%$ and -0.6% but increases slightly for strains of -0.7% and -0.8%

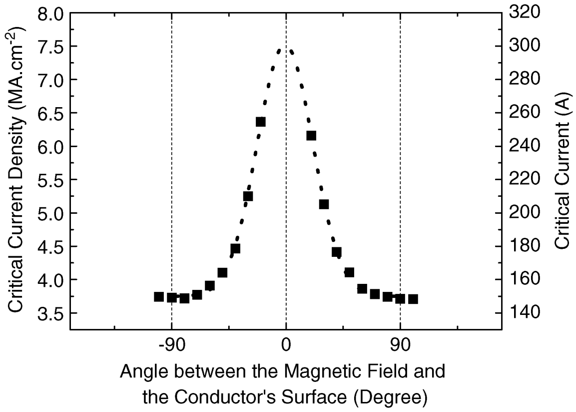

Fig. 5. Critical current density measurements at 4.2 K, 11 T and zero applied strain as a function of the angle between the magnetic field and the conductor's surface. The dotted line is a guide to the eye.

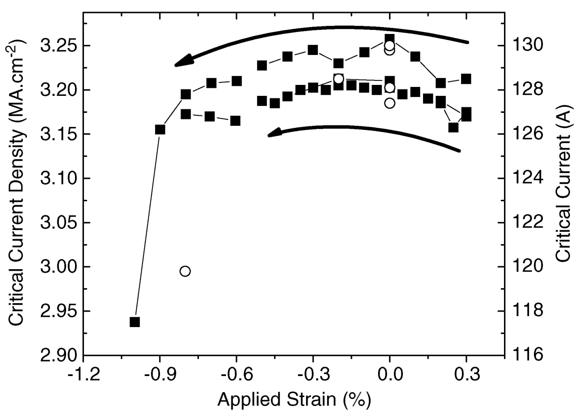

Fig. 6. Critical current density as a function of applied strain at 4.2 K and 14 T (applied perpendicular to the conductor surface). Solid symbols are applied strain from tension to compression. Open symbols are data taken upon release of the applied strain.

and then irreversibly increases by $\sim$1.5% upon release of the strain to 0%, producing the second reversible curve. The reversible strain range is increased in the second (top) curve and extends to -0.8%. Similar behavior in $J_{\rm C}$, where different reversible $J_{\rm C}(\varepsilon)$ curves are produced after strain cycling, has been observed in low temperature superconducting (LTS) $\rm Nb_3Sn$ composites and is attributed to the plastic deformation of components of the conductor composite [7]. $J_{\rm C}$ irreversibly decreases for large compressive strains beyond -0.8%, indicating damage to the conductor.

IV. Analysis and Discussion

A. Convex Strain Dependent Behavior

Fig. 7 shows the strain dependence of $J_{\rm C}$ at 77 K and 0.5 T, with the magnetic field applied perpendicular to the conductor surface, for different E-field criteria. Consistent with the low field data in Fig. 2, at low strains the data can be described using a power-law behavior from tensile to moderate compressive strains, for magnetic fields applied both perpendicular and parallel (not shown) to the conductor surface. The dashed line in Fig. 7 is a fit to a simple power-law parameterization and the free-parameters obtained are consistent with values reported in the literature for YBCO coated conductors [3]–[5], [8]. However, Fig. 7 demonstrates that the behavior at high compressive strain in high-fields becomes increasingly convex and deviates from the power-law parameterization. As with LTS materials, a series expansion can be used to describe such strain dependence if accurate parameterization alone is required [9].

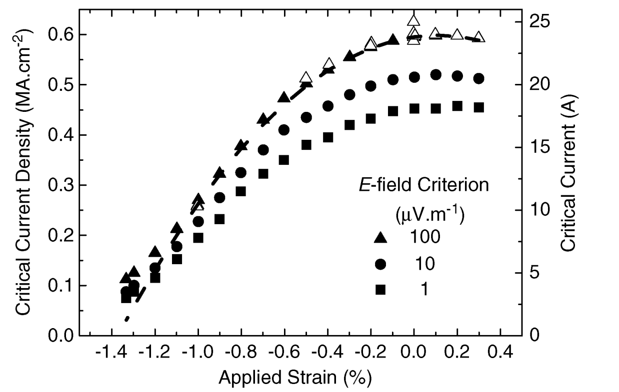

Fig. 7. Critical current density as a function of applied strain at 77 K and 0.5 T for various E-field criteria. The magnetic field was applied perpendicular to the conductor surface. Closed symbols are data taken in the direction of tensile strain towards high compressive strain. Open symbols are reversibility checks of $J_{\rm C}$. Deviations from a power-law behavior occur at high strains and are independent of the electric field criterion used to determine $J_{\rm C}$.

B. J_C Parameterization

The data in this work do not include a direct measurement of the upper critical field $(B_{\rm C2})$, hence one can only parameterize these data using a flux pinning scaling law with $\rm B_{C2}$ as an adjustable parameter [10]. We choose to use the more simple parameterization of $J_{\rm C}$ associated with granular superconducting materials which at low fields does not require direct measurements of the upper critical field.

We write the parameterization of $J_{\rm C}$ in the form [11]:

$$J_{\rm C}(B,T,\varepsilon,\theta) = \alpha(T,\varepsilon)\cdot\left(1-\frac{B}{B_{\rm C2}(T,\varepsilon)}\right)\cdot\exp\left(-\left(\frac{B}{\beta(T)}\right)^{m}\right) \quad (1)$$

where we have added the constant m to account for non-exponential behavior at low fields. The term $(1 - B/B_{\rm C2})$ describes the reduction in the order parameter within the grains; $\alpha(T,\varepsilon)$ is the depairing critical current density, and $\beta(T)$ describes the magnetic field suppression of the order parameter associated with tunneling across grain boundaries. The parameters $\alpha(T,\varepsilon)$ and $\beta(T)$ are determined at each strain by fitting $J_{\rm C}$ versus magnetic field to (1) for all the angular data assuming the applied field is very small compared to $B_{\rm C2}$. The results are shown in Fig. 8 where m was found to be 0.30. The work by Hsiang and Finnemore [12] gives $\beta(T) = \phi_0/2\sqrt{3\pi l d}$ (where l is the electron scattering length and d is the width of the grain boundary) and hence is consistent with $\beta(T)$ having no strain dependence. Fig. 8 suggests that $\beta(T)$ is a weak function of angle except when the magnetic field is parallel to the $a-b$ planes of the YBCO, and $\alpha(77\,{\rm K},\varepsilon)$ decreases with increasing compressive strain.

A more detailed investigation was made of the $J_{\rm C}$ data at 90 degrees as a function of strain using (1) by explicitly in-

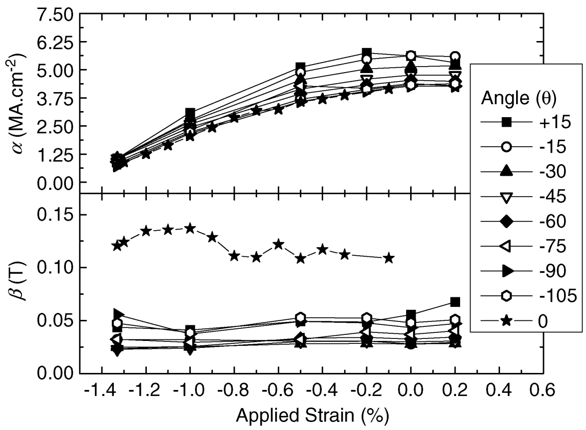

Fig. 8. Parameters $\alpha(T,\varepsilon)$ and $\beta(T)$ as determined from data fit to (1).

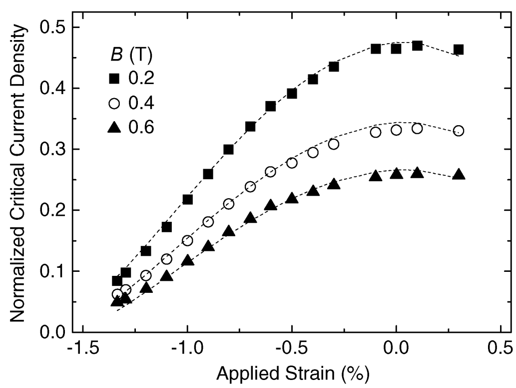

Fig. 9. Critical current density at 77 K as a function of strain for various applied magnetic fields perpendicular to the conductor surface.

cluding the term that includes B_{C2}. The relationships between T_C, $B_{C2}(T,\varepsilon)$, and strain were defined from the following relations which are successfully used with low temperature superconductors (LTS) [7], [13]:

$$\frac{B_{C2}(0,\varepsilon)}{B_{C2}(0,\varepsilon=0)} = \left(\frac{T_C(\varepsilon)}{T_C(\varepsilon=0)}\right)^w, \tag{2}$$

$$B_{C2}(T,\varepsilon) = B_{C2}(0,\varepsilon)(1-t^v), \tag{3}$$

$$\frac{B_{C2}(0,\varepsilon)}{B_{C2}(0,0)} = 1 + c_1\varepsilon + c_2\varepsilon^2 + c_3\varepsilon^3, \tag{4}$$

where $t = T/T_C(\varepsilon)$ and $w = 3$ and $\nu = 3/2$ are values taken from LTS scaling, and c_i are constants. The fixed values that we used to provide the fits were $T_C = 92\,\mathrm{K}$, $B_{C2}(0,0) = 40\,\mathrm{T}$, and the free parameters obtained were $\alpha(0,0) = 12.3\ \mathrm{MA.cm^{-2}}$, $\beta = 0.4\ \mathrm{T}$, $m = 0.52$ and c_1, c_2 and c_3 were 0.032, -0.358 and -0.141 respectively. Fig. 9 shows that the fit to the J_C data at zero degrees are accurately described using this parameterization. We conclude that, in our limited data set, the low temperature scaling law framework for describing the strain dependence of J_C may provide a useful starting point to parameterize J_C data on YBCO coated conductors.

V. Conclusion

We have presented a strain apparatus for measuring J_C over the strain range from -1.4% to $+0.5\%$ in high field horizontal magnet systems.

The strain dependence of J_C in these YBCO coated conductors is reversible from -1.33% to $+0.3\%$ at 77 K. At high compressive strain, convex behavior is found. In contrast, at 4.2 K, J_C is only reversible in the strain range from -0.6% to $+0.3\%$ and it increases by $\sim 1.5\%$ after being cycled to -0.7% strain. Below -0.8% strain, the sample shows an irreversible decrease in J_C, indicative of damage. We note that in these materials J_C versus strain exhibits just a single peak for all fields, temperatures and angles [4], [5].

The angular dependence of J_C is found to be periodic over 180 degrees (rather than 90 degrees), suggesting that at least two different mechanisms operate to determine the critical current density. The angle, at which J_C is a maximum, changes as a function of strain at a fixed field and temperature.

We have been able to parameterize $J_C(B, 77\ \mathrm{K}, \varepsilon, \theta)$ using an exponential field dependence based on a tunnelling junction model. The model incorporates scaling variables and parameters which have been successfully used in scaling the flux pinning force in practical high-field superconductors, most notably Nb_3Sn [7].

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References

[1] N. Cheggour *et al.*, "Reversible axial-strain effect and extended strain limits in Y-Ba-Cu-O coatings on deformation-textured substrates," *Appl. Physics Lett.*, vol. 83, no. 20, pp. 4223–4225, 2003.

[2] N. Cheggour *et al.*, "Reversible axial-strain effect in Y-Ba-Cu-O coated conductors," *Supercond. Sci. Technol.*, vol. 18, pp. S319–S324, 2005.

[3] D. C. van der Laan and J. W. Ekin, "Large intrinsic effect of axial strain on the critical current of high-temperature superconductors for electric power applications," *Appl. Physics Lett.*, vol. 90, p. 052506, 2007.

[4] D. C. van der Laan *et al.*, "Effect of strain, magnetic field and field angle on the critical current density of $YBa_2Cu_3O_{7-\delta}$ coated conductors," *Supercond. Sci. Technol.*, vol. 23, p. 072001, 2010.

[5] M. Sugano, K. Shikimachi, N. Hirano, and S. Nagaya, "The reversible strain effect on critical current over a wide range of temperatures and magnetic fields for YBCO coated conductors," *Supercond. Sci. Technol.*, vol. 23, p. 085013, 2010.

[6] B. ten Haken, A. Godeke, and H. H. J. ten Kate, "The strain dependence of the critical properties of Nb_3Sn conductors," *J. Appl. Physics*, vol. 85, p. 3247, 1997.

[7] D. M. J. Taylor and D. P. Hampshire, "Effect of axial strain cycling on the critical current density and n-value of ITER niobium-tin wires," *Physica C*, vol. 401, pp. 40–46, 2004.

[8] K. Osamura *et al.*, "Internal residual strain and critical current maximum of a surrounded Cu stabilized YBCO coated conductor," *Supercond. Sci. Technol.*, vol. 22, p. 065001, 2009.

[9] D. M. J. Taylor and D. P. Hampshire, "The scaling law for the strain dependence of the critical current density in Nb_3Sn superconducting wires," *Supercond. Sci. Technol.*, vol. 18, pp. S241–S252, 2005.

[10] N. Cheggour, J. W. Ekin, and C. L. H. Thieme, "Magnetic-field dependence of the reversible axial-strain effect in Y-Ba-Cu-O coated conductors," *IEEE Trans. Appl. Supercond.*, vol. 15, no. 2, pp. 3577–3580, Jun. 2005.

[11] D. P. Hampshire, "A barrier to increasing the critical current density of bulk untextured polycrystalline superconductors in high magnetic fields," *Physica C*, vol. 296, pp. 153–166, 1998.

[12] T. Y. Hsiang and D. K. Finnemore, "Superconducting critical currents for thick, clean superconductor-normal-metal-superconductor junctions," *Physical Rev. B*, vol. 22, no. 1, pp. 154–163, 1980.

[13] J. W. Ekin, "Unified scaling law for flux pinning in practical superconductors: I. Separability postulate, raw scaling data and parameterization at moderate strains," *Supercond. Sci. Technol.*, vol. 23, p. 083001, 2010.