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Angular J_c measurements at 77 K in-field, on an ISD REBCO coated conductor using a straightforward mechanical scribing technique to reduce tape width

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Abstract.

E-J traces have been measured on an inclined substrate deposition coated conductor up to 0.7 T as a function of angle at 77 K. A large change in J_c is seen on reversal of the direction of the magnetic field, associated with different surface barriers to flux nucleation. The effect of angular hysteresis and field hysteresis on J_c has been found to be much smaller. Narrow bridges have been successfully fabricated by a simple scribing technique using a diamond-tipped scribe and a template. These bridges have been made from 1.4 mm to 4 mm width on the 12 mm width tape, which decrease I_c linearly with width. Measurements before and after the heat treatment for strain gauge glue curing at 170 °C for 120 min have been made and confirm there is no systematic decrease in J_c .

1. Introduction

Rare-Earth Barium Copper Oxide (REBCO) Coated Conductors (CCs) manufactured by Inclined Substrate Deposition (ISD) have the crystallographic *ab*-planes at relatively large angles to the tape surface. As crystal growth is slow in the *c*-direction, inclined planes allows thick films to be produced with shorter growth times by exploiting fast growth in the *ab*-directions to increase thickness [1]. The orientation of the *ab*-planes in ISD CCs changes the dependence of critical current density, J_c , on magnetic field angle, which must be known for optimum cable and magnet design.

We have measured 12 mm wide GdBa₂Cu₃O_{7- δ} ISD CCs fabricated by THEVA. During their fabrication, MgO is deposited on a Hastelloy C-276 (UNS N10276) substrate, inclined at an angle to the vapour spray to produce a faceted biaxially textured surface for REBCO growth. The crystallographic orientation of the MgO buffer layer controls the orientation of the CuO superconducting *ab*-planes, which are inclined at $\sim 30^\circ$ to the tape surface [2]. The REBCO layer is coated with silver and the whole tape coated with copper as a stabiliser. The REBCO layer thickness is $\sim 3.5 \mu\text{m}$.

In this work, we demonstrate that a straightforward mechanical scribing technique can safely be used to reduce the width of the samples without damaging them. We investigate the large change in J_c that occurs when the direction of the magnetic field is reversed, associated with the changes in surface pinning. We also demonstrate that there is no systematic decrease in J_c



associated with the extended heat treatment of these samples that is used while mounting strain gauges on them.

All data presented here are derived from electric field–current density, E - J , transport measurements. Typical data are shown in figure 1, with a noise level $< 3 \mu\text{V m}^{-1}$, well below the transition onset threshold of $10 \mu\text{V m}^{-1}$. These data are used to extract the values of the critical current, I_c , defined using an electric field criterion of $100 \mu\text{V m}^{-1}$ and the index of transition, N , calculated between $10 \mu\text{V m}^{-1}$ and $100 \mu\text{V m}^{-1}$.

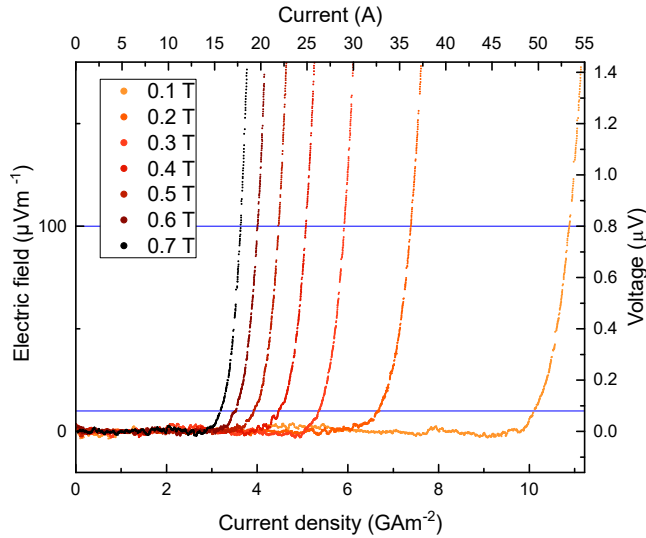


Figure 1. E - J traces at a range of fields, measured at 77 K with $B \parallel c$ and the sample width reduced to 1.4 mm. The critical current density is extracted using an electric field criterion of $100 \mu\text{V m}^{-1}$ and N values calculated between $10 \mu\text{V m}^{-1}$ and $100 \mu\text{V m}^{-1}$.

2. Mechanical scribing to reduce cross-section

Reducing the cross-section of the tape allows us to measure higher critical current densities which opens up new areas of phase-space. Bridges have been patterned on CC using chemical etching [3, 4, 5], photolithography [6, 7, 8] and laser ablation [9, 10, 11]. Mechanical scribing has also been used as a means of reducing AC losses [12].

We have used a simple scribing method to reduce I_c . The REBCO cross-section is reduced by scribing deep tracks into the tapes using a diamond-tipped scribe and a template. The bridge has an 8 mm region of constant width and curved ends to minimise crack nucleation at corners. The regions outside the bridge are heavily scored to prevent any effects of current leakage across the tracks. The bridge shown in figure 2 is 1.5 mm wide. The tracks are roughly $50 \mu\text{m}$ wide and have cut through the copper, REBCO and buffer layers to the Hastelloy substrate, as shown in figure 3. Figure 4 shows that I_c scales linearly with the bridge width over the range of fields measured, and the shape of the angular variation is preserved (figure 5). I_c is too high to make low-field measurements on the as-supplied 12 mm tape. J_c has been calculated throughout this paper using the measured bridge width and a nominal thickness of $3.5 \mu\text{m}$, with the uncertainty associated predominantly with the width of the damaged region.

3. Angular J_c measurements

The angular dependence of J_c is shown in figure 6, measured up to 0.7 T. The inclined CuO planes shift the peak in J_c away from 0° to $\sim 30^\circ$. We also observe a shoulder feature at $B \perp$ tape, which is weaker at low fields. A similar feature, a peak at $B \perp$ tape rather than a shoulder, has been seen in an ISD tape previously [3]. The data reported here are from a number of different samples with differing bridge widths, as not all measurements were made on every sample. Unmounting the sample damaged the tape, so some measurements which were

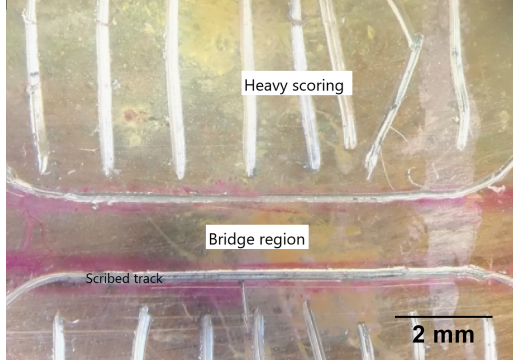


Figure 2. Image of a scribed bridge. The bridge is 8 mm×1.5 mm and simply produced with a diamond-tipped scribe and template.

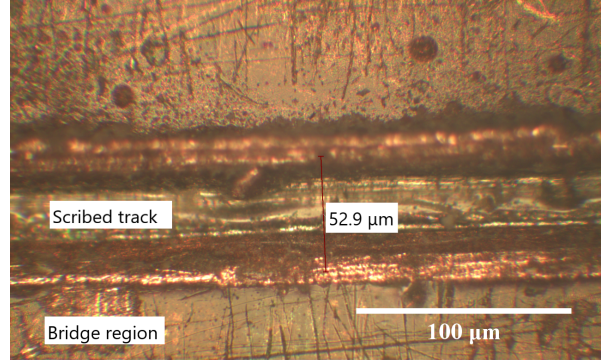


Figure 3. Magnified image of a scribed part of a bridge, showing that the material is cut down to the Hastelloy substrate.

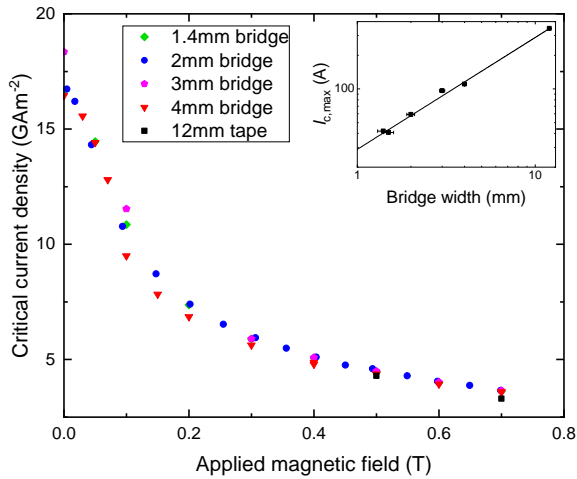


Figure 4. A comparison between the field dependence of J_c for bridges of different widths at 77 K for $B \parallel c$. The different bridge widths show good agreement across the field-range. Inset: I_c variation with bridge width when $B \parallel ab$, with a linear fit through the origin.

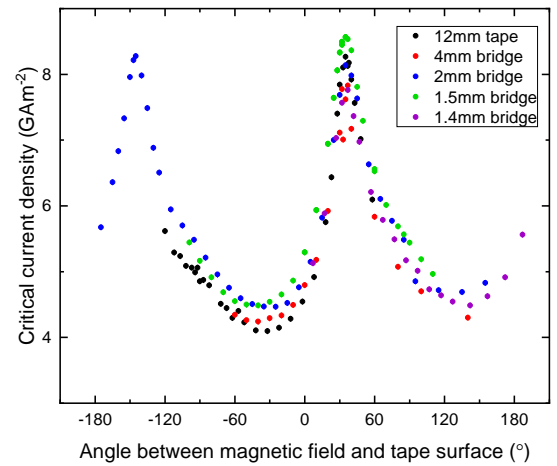


Figure 5. The angular variation of J_c for the as-supplied 12 mm tape and different bridge widths. All measurements are at 0.5 T and 77 K. The angular dependent shape is preserved to within a relatively small error in the scaling factor.

introduced later could only be performed on a limited set of the samples. We conclude that all the samples measured were broadly similar (once scaled by the bridge width), given the results of section 2.

An empirical relationship between J_c and the index of transition, N , has been found in LTS [13], with

$$N(B, T, \varepsilon) = 1 + r(T, \varepsilon)[J_c(B, T, \varepsilon)]^{s(T, \varepsilon)}. \quad (1)$$

This is observed, as shown in figure 7 for $B \parallel c$, for a sample with a 4 mm bridge. We attribute the deviations at higher currents to heating during the transition. Figure 8 shows this relation

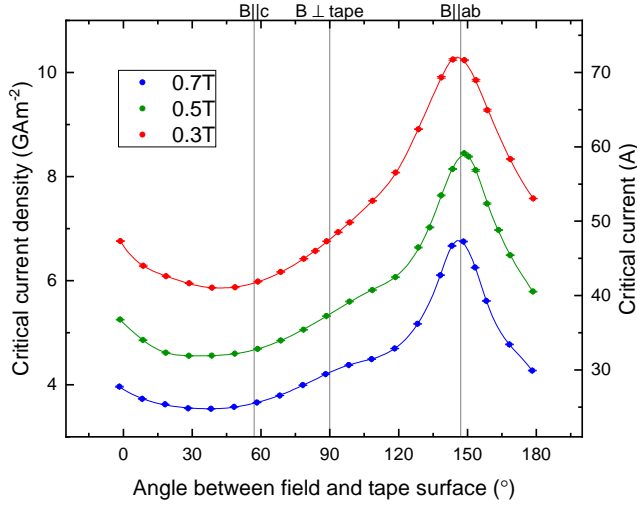


Figure 6. The angular dependence of J_c at three magnetic fields on a sample with a 2 mm bridge. The ab -peak is shifted by 30° due to the angle between the ab -planes and the tape substrate. Also apparent is a shoulder feature when $B \perp$ tape.

also applies for J_c measurements over a range of angles, with similar r and s values as shown in table 1.

The N values are comparable (≈ 20 for $B = 0.5$ T) for both the 1.4 mm and 4 mm bridge widths, suggesting that the damage region is small compared to the bridge-width. Reliable N values were not obtained on the full-width tape due to heating at the high currents. Some bridged samples also exhibited heating effects (i.e. inconsistent N values), which we attribute to the resistance of the current injection point. N values for these samples have not been reported.

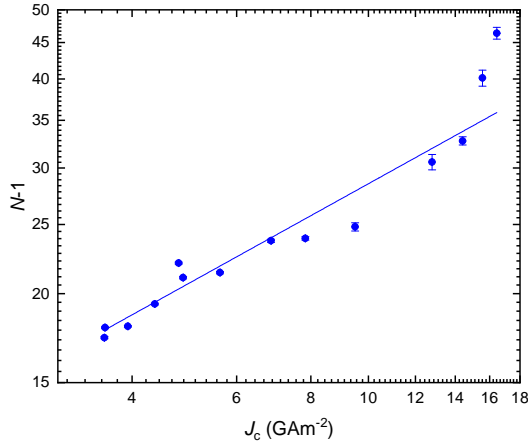


Figure 7. Index of transition versus critical current density with $B \parallel c$ for a 4 mm bridge. We attribute the non-linear behaviour at higher currents to heating during the transition.

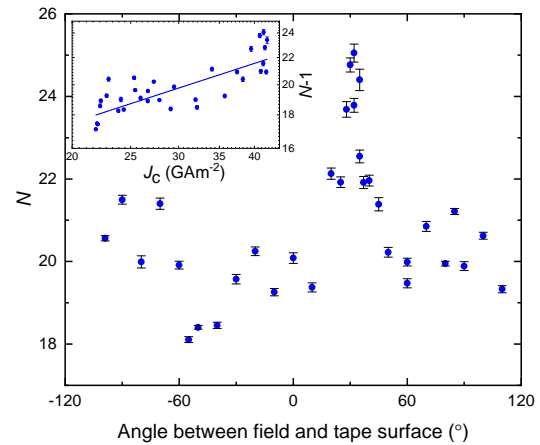


Figure 8. The angular dependence of N at 0.5 T on a sample with a 1.4 mm bridge. The peak in N occurs at 30° when J_c is at its peak value and $B \parallel ab$. Inset: data replotted as $N - 1$ vs. J_c on a logarithmic scale.

4. Asymmetry on field inversion

We have observed a marked change in J_c after rotating the sample by 180° . An asymmetry of similar magnitude has been observed previously [14, 15, 16, 17], weakly at 1 T [18], and on an ISD

Table 1. r and s values calculated using equation 1 for the data in figures 7 and 8.

	$r((\text{GA m}^{-2})^{-s})$	s
$B \parallel c$, varying field (figure 7)	9.8(3)	0.46(5)
$B = 0.5 \text{ T}$, varying angle (figure 8)	11.7(3)	0.30(4)

tape [3]. To ensure our asymmetry results are not due to magnetic history effects, a sample with a 1.5 mm bridge was measured with three different magnetic histories, as shown in figure 9. To check for hysteretic effects the magnetic field was kept constant at 0.3 T and the angle between the direction of the field and the tape surface monotonically increased during the sequence of J_c measurements, producing set 1. In set 2, the magnetic field angle was monotonically decreased. The sweep with increasing angle was extended for 360° to measure the region with opposite Lorentz force direction (set 4). Another set of hysteretic measurements (set 3) were taken, where the magnetic field was ramped to 0.7 T at the new angle before returning to 0.3 T for the measurement. The J_c data for set 1 with angle increasing (highest average J_c) is on average $0.13(8) \text{ GA m}^{-2}$ higher than the equivalent data with hysteretic field ramps taken during set 3 (lowest average J_c) with the largest difference in J_c , $0.271(10) \text{ GA m}^{-2}$, occurring at 15° . The change in J_c on field inversion is shown in the inset of figure 9, which has a maximum change of $0.89(3) \text{ GA m}^{-2}$ at 0° . This is significantly larger than any change we have seen due to magnetic field history in these samples and therefore cannot be attributed to field hysteretic effects.

This marked asymmetry is due to the difference in surface pinning between the buffer layer-superconducting layer and the silver coating-superconducting layer. The surface that the flux nucleates on is controlled by direction of flux flow, or equivalently the direction of the Lorentz force on the fluxons, or the relative direction of the applied field and the current. As the maximum in surface pinning is not aligned with maximum intrinsic pinning, the two J_c peaks are not 180° apart. In tapes where the ab -planes are parallel to the tape surface, only a change in peak height of J_c is seen with no angular shift. The effect is weaker at higher fields (see figure 10).

5. The effect of heat treatment on ISD REBCO

REBCO stability at elevated temperatures is a concern for sample preparation involving heat treatments. In particular, samples prepared for strain measurements have a strain gauge applied, which require a heat treatment for glue curing, with the recommended thermal history a gradual increase in temperature at 2 K min^{-1} from 50°C to 170°C followed by 120 min at 170°C , and may experience a degradation in J_c . Prior to any measurements (and the curing process), the sample was soldered to the strain board, requiring a couple of minutes at 200°C to 230°C . Degradation in soldering conditions has been investigated by Preuss et al. [19], who measured the change in I_c of a range of REBCO tapes (all with $c \perp$ tape) with copper stabilisers, finding an Arrhenius-like relation between I_c -decay time and temperature down to 225°C . Extrapolating their linearly temperature-dependent decay constant data down to the 170°C gives $\tau = 2.7_{-1.6}^{+3.6} \times 10^5 \text{ s}$ at 170°C in the relation

$$\frac{I_c}{I_{c0}} = \exp\left(\frac{-t}{\tau}\right), \quad (2)$$

and predicts a heat treatment of 170°C for 120 min would give a $2.6_{-1.5}^{+3.2} \%$ drop in I_c .

The Arrhenius-like relation for I_c -decay with temperature suggests the degradation is diffusion controlled. This is likely to be oxygen diffusing out of the REBCO layer, as the superconducting

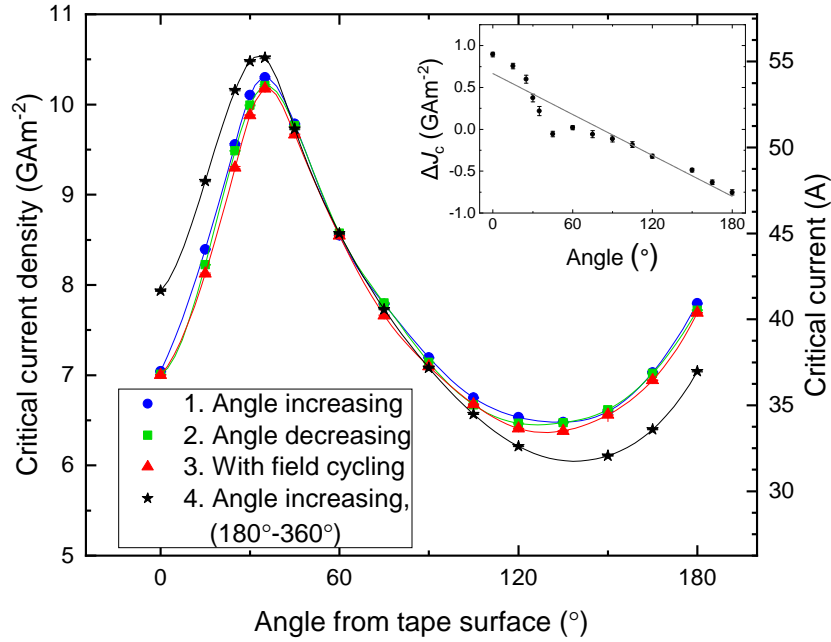


Figure 9. The angular dependence of J_c at 0.3 T for different magnetic field histories. To rule out magnetic field hysteric effects, three measurement scenarios have been used. For set 1 (●) and set 2 (■), the magnetic field was kept at 0.3 T and the sample rotated with the angle increasing or decreasing respectively. For set 3 (▲), the magnetic field was cycled to 0.7 T at the new angle before each measurement. Set 1 was extended to the full 360°, giving the data labelled as set 4 (★) which have been replotted minus 180°, so they can included here. Inset: the difference in J_c on rotating the magnetic field by 180°, derived from the data of sets 1 and 4.

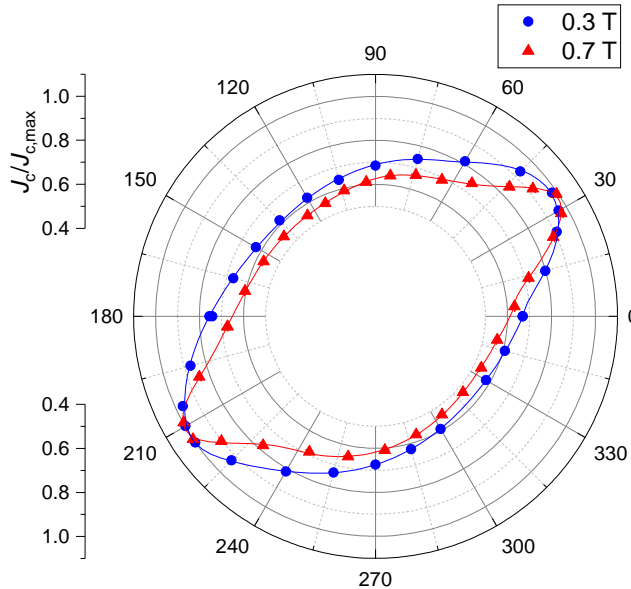


Figure 10. A normalised polar plot of J_c vs. angle for two field strengths. The sample had a bridge width of 1.5 mm. J_c is not symmetric on a 180° rotation, with the difference more pronounced at 0.3 T than at 0.7 T.

properties are strongly dependent on the oxygen content of REBCO. Ossandon et al. [20] found both a change in T_c and a large change in B_{c2} in single crystals, with a drop in B_{c2} to from 5.5 T to 0.6 T at 77 K for a change in oxygen deficiency (δ in $\text{REBa}_2\text{Cu}_3\text{O}_{7-\delta}$) from 0.06 (peak T_c) to 0.15. This would have a significant effect on the I_c measurements.

We calculate the changes in J_c as critical parameters change using a standard volume pinning force, F_p , expression [21, 22, 23]:

$$F_p = J_c B = A \frac{(B_{c2}^*)^n}{\kappa^2} \left(\frac{B}{B_{c2}^*} \right)^p \left(1 - \frac{B}{B_{c2}^*} \right)^q, \quad (3)$$

with $p = 0.5$, $q = 2$ [24], $n = 2.5$, and A is a fixed constant. The Ginzburg-Landau parameter κ is found from the thermodynamic critical field (B_c) and the two-fluid model

$$B_{c2}^*(T) = \sqrt{2}\kappa(T)B_c^*(0) \left(1 - \left(\frac{T}{T_c} \right)^2 \right). \quad (4)$$

Ossandon et al.'s data predict a change of oxygen deficiency from 0.06 to 0.11, and a commensurate $\sim 20\%$ decrease in J_c at 0.3 T and 77 K. Figure 11 shows the effect on J_c from changing the oxygen content at 77 K and 4.2 K, using Ossandon et al.'s data and the scaling law in equation 3. Note that the peak J_c is at a higher oxygen content for 4.2 K, 14 T, than for 77 K, 0.3 T, due to the peak $B_{c2}^*(0)$ being at a higher oxygen content than the peak in T_c . This implies that the optimal oxygen content for low-temperature operation does not necessarily give the maximum T_c . We assume a linear interpolation of the data in figure 11 and calculate that a change in oxygen deficiency from 0.060 to 0.064 is associated with a change in J_c of 1.5 % at 77 K and 0.3 T.

If oxygen diffusion is limited by the diffusivity through REBCO rather than through a barrier at the superconductor/silver interface, degradation is expected to be sensitive to crystallographic orientation. Oxygen diffusivity is much larger in the ab -planes than in the c -axis direction [25, 26], with Rothman et al. [26] finding $D_{ab} \geq 10^6 D_c$ at 400 °C.

In an ISD tape, the distance along the ab -plane to the nearest surface can be much shorter (the maximum distance in the samples tested is $\sim 2 \mu\text{m}$) than for other manufacturing methods. For example in an IBAD tape, the distance between the surfaces at the ends of the ab -planes is approximately the width of the tape (i.e. typically a few mm) rather than the thickness of the superconducting layer. If oxygen diffusion out of the REBCO layer is responsible for thermal degradation, the much shorter diffusion distance in ISD could in principle lead to significant I_c -decay during the heat treatment necessary to attach strain gauges to them.

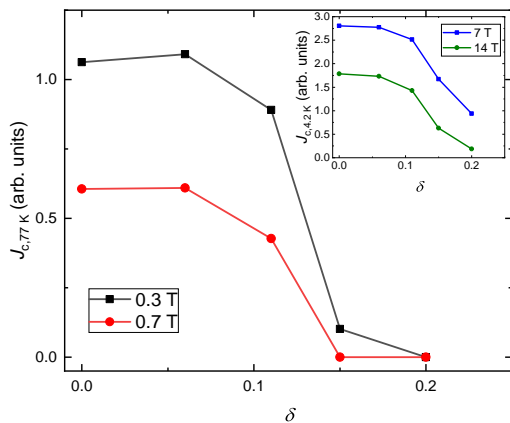


Figure 11. A calculation of J_c in-field at 77 K versus oxygen deficiency, δ , for $\text{REBa}_2\text{Cu}_3\text{O}_{7-\delta}$ tape using B_{c2}^* and T_c thermal data from [20] and the scaling law in equation 3. Inset: equivalent J_c calculations for 4.2 K.

To investigate whether significant thermal degradation is occurring in ISD CCs, two samples were measured before and after the strain gauge glue curing process, with several room temperature to 77 K cycles applied to the second sample to check whether the cryogenic thermal cycle between room temperature and 77 K could be causing any changes in J_c . The thermal histories of the two samples are summarised in table 2.

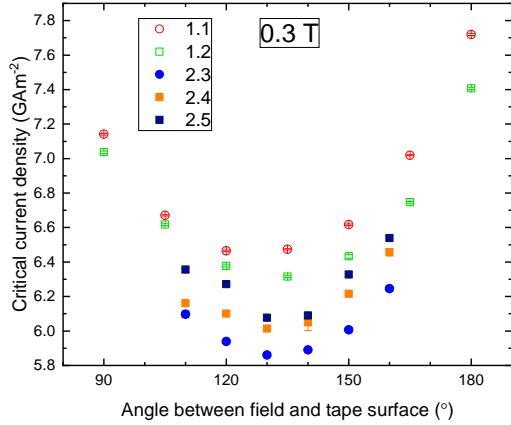


Figure 12. Angular measurements near the minimum J_c for two samples after different thermal cycles. A summary of thermal history is given in table 2. Measurements were made at $B = 0.3$ T. Open symbols are for sample 1. Closed symbols are for sample 2. Circles and squares are for pre- and post-curing respectively.

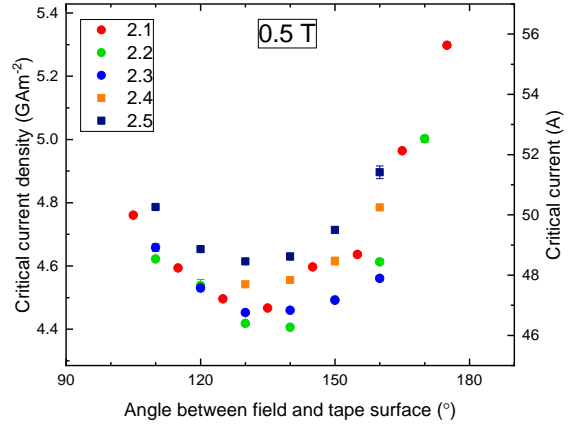


Figure 13. Measurements at 0.5 T for sample 2. The data 2.1-3 show the variation on cycling from 77 K to room temperature, and data 2.4-5 (squares) are after the heat treatment for strain gauge glue curing.

Table 2. Thermal history of the samples in figures 12 and 13. After each thermal process J_c was measured at fixed field as a function of angle.

Sample 1 1.5 mm bridge	
1.1	As-supplied
1.2	Strain gauge applied
Sample 2 3 mm bridge	
2.1	As-supplied
2.2	One room temperature - 77 K cycle
2.3	Two room temperature - 77 K cycles
2.4	Strain gauge applied
2.5	Further room temperature - 77 K cycle

Figures 12 and 13 present the data measured for the two samples before and after the curing process. We have fitted parabolas to the data and found that J_c in sample 1 decreased by 2.0(5) % and in sample 2 increased by 2.9(2) % after the curing heat treatment. These changes are similar to the change in J_c we observed on thermal cycling from 77 K to room temperature, which have a standard deviation of 1.5 %. We observed no systematic decrease in J_c , although we cannot rule out a small degradation, consistent with the lower bounds of the extrapolation from the data presented by Preuss et al. [19]. Our data show no evidence for any degradation. If it occurs, there is no evidence it is significantly greater than is expected for tapes with $c \perp$ tape, despite the much shorter diffusion distance for oxygen through REBCO in ISD CCs.

6. Conclusions

We have successfully reduced the cross-section of REBCO coated conductor tapes by patterning a current bridge with a diamond tipped scribe. We have found this patterning reduces I_c linearly with the width of the bridge over all angles and fields up to 0.7 T at 77 K. We are confident that these bridges can be used to access measurements of J_c in the low-field regions of phase space otherwise inaccessible on a full-width tape. The angular dependence of J_c has been measured using sample bridges, and the lack of 180° rotational symmetry has been shown to be stronger than can be attributed to magnetic field hysteretic effects.

We have also seen that the heat treatment used to mount a strain gauge does not systematically degrade J_c , with changes that are similar to those attributed to thermal cycling between room temperature and 77 K. We conclude that we can make and measure REBCO ISD sample bridges and use the standard strain gauge mounting process with confidence that it is not significantly affecting these samples.

Acknowledgments

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