Review of progress in electromechanical properties of REBCO coated conductors for electric device applications

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Abstract

Rare-earth barium copper oxide (REBCO) coated conductor (CC) tapes have already been commercialized but still possess some issues in terms of manufacturing cost, anisotropic in-field performance, $I_c$ response to mechanical loads such as delamination, homogeneity of current transport property, and production length. Development on improving its performance properties to meet the needs in practical device applications is underway and simplification of the tape’s architecture and manufacturing process are also being considered to enhance the performance-cost ratio. As compared to low temperature superconductors (LTS), high temperature superconductor (HTS) REBCO CC tapes provide a much wider range of operating temperature and a higher critical current density at 4.2 K making it more attractive in magnet and coil applications. The superior properties of the REBCO CC tapes under magnetic field have led to the development of superconducting magnets capable of producing field way above 23.5 T. In order to achieve its optimum performance, the electromechanical properties under different deformation modes and magnetic field should be evaluated for practical device design. This paper gives an overview of the effects of mechanical stress/strain on $I_c$ in HTS CC tapes due to uniaxial tension, bending deformation, transverse load, and including the electrical performance of a CC tape joint which were performed by our group at ANU in the last decade.

Keywords: Coated conductors, critical current, electromechanical property, delamination, CC joint

1. INTRODUCTION

Rare-earth barium copper oxide (REBCO) coated conductor (CC) tapes have shown higher critical current capability under external magnetic field and good mechanical properties. These superior properties lead to the expectations of CC tapes to be adopted in magnets, SMES, rotating machines, cables and even wide range of applications. With the achievement of a km length CC tapes with higher critical current density, $I_c$, coils for motors, accelerators, high field magnets, and other superconducting devices are already being tested and studied [1-7]. For such applications, in which coil is one of the major component technology, the electromechanical property (EMP) evaluation is one of the foremost things to do to ensure its performance during fabrication and operation. The understanding of its current transport characteristics under different stress/strain and electromagnetic force including cooling characteristics, stability etc. is important for the performance design in practical device applications.

In most of the device applications, it is expected that the CC tapes will experience different mechanical stress/strain during fabrication, cool-down and operation. In power cables, the bending stress/strain originates from tape bending when the tape are wound around a former while tensile stress/strains are applied to the HTS wires in winding, cable installation and cable cooling. In coils in particular, bending is inevitable. Differences in thermal expansion coefficient between the turns and the adjacent material can cause thermal stress/strain in the coated conductor. Coils will experience hoop stress when energized due to Lorentz force and large amount of it may cause degradation of the current carrying capacity of the CC tapes.

The strain of a magnitude can cause large degradation on the current density and when the critical strain is exceeded, the current carrying capacity is irreversibly reduced. The design process of coils therefore requires the understanding of the strain dependence of the critical current in the conductor and the ability to predict the strain state of the conductors in the coil. To ensure the performance of CC tapes in practical device application, electromechanical property evaluation is necessary prior to the devise design. This article is updated for 2G HTS device applications based on our previous review submitted to the Ceramic [8].

2. STRAIN EFFECT ON CRITICAL CURRENT, $I_c$

The CC tapes will be subjected to different types of loadings and deformations that may induce stress/strain to the REBCO superconducting film layer that may cause critical current, $I_c$, to increase or decrease reversibly or irreversibly.

2.1. Reversible strain effect on $I_c$ at self-field

A reversible strain effect on $I_c$ has been known for REBa$_2$Cu$_3$O$_{7-\delta}$ (REBCO) CC tapes. In the reversible

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region, the strain dependence of \( I_c \) obeyed the intrinsic strain effect and was well expressed by Ekin’s formula; 
\[
\frac{I_c}{I_{c_{\text{max}}}} = 1 - a \varepsilon_{\text{applied}} - b \varepsilon_{\text{peak}}
\]
where \( a \) and \( b \) are constants and the \( \varepsilon_{\text{peak}} \) is the strain corresponding to the \( I_c \) peak location. Cheggour et al. reported that the reversible variation of \( I_c \) appears below a certain limit [9] and \( I_c \) decreases rapidly with strain beyond the reversible limit. The strain limit at which \( I_c \) cannot recover anymore even after the applied strain is relieved is defined as the irreversible strain limit \( \varepsilon_{\text{irr}} \) [9, 10]. It is widely accepted that this significant irreversible degradation of \( I_c \) in CC tapes is attributed to the cracking of the superconducting film due to its innate brittleness. Hence, for engineering purposes we need to measure the maximum strain that can be applied before the superconductor breaks [11-13].

Primarily, the mechanical properties of the substrate material affect the \( \varepsilon_{\text{irr}} \) of \( I_c \) as shown in Fig. 1 [14]. Samples adopting lower yield strength Hastelloy exhibiting discontinuous yielding showed a much lower tolerance of \( I_c \) with uniaxial strain even though it has Cu stabilizer as compared with just Ag-stabilized sample having higher yield strength Hastelloy substrate.

Through the analysis of the residual strain and deformation behavior of YBCO CC tapes, Osamura et al. reported that the reversibility limit of \( I_c \) coincided with the limit of micro-yielding. Furthermore, the irreversible degradation of the \( I_c \) as a function of strain is suggested to be related to the macroscopic yielding [15, 16]. It was then suggested that the boundary between the micro- and macroscopic yielding corresponds to the irreversible strain limit for the \( I_c \). Further efforts are now being done to fully disclose the mechanism of the reversible behavior in the CC tapes. Measurements of the local strains are being done using high precision diffractometer using quantum beams. From these residual strain measurement tests, however, reports suggested that the micro twin structure is critical to understand [17]. Recently, Sugano et al. reported that there is no clear correlation between peak and residual strain even if 3D or 2D strain state is incorporated in CCs [18].

Consequently, the \( \varepsilon_{\text{irr}} \) significantly increased with an addition of stabilizer and also the improvement depends on stabilizer material adopted [19, 20]. Primarily, substrate holds the whole CC superconductor composite, thus it influences the mechanical behavior of the whole tape especially for Ag-stabilized CC tape samples [21]. The \( \varepsilon_{\text{irr}} \) of Ag-stabilized ones can be enhanced by adding a metallic stabilizer such as Cu or stainless steel. As compared with the Ag-stabilized CC sample, stainless steel foils-reinforced CC tapes exhibited doubled \( \varepsilon_{\text{irr}} \) [22]. Soldered laminate metal foils on both sides improved CC response to tension load, buckling and torsion. Enhancement of \( \varepsilon_{\text{irr}} \) and the corresponding stress for \( I_c \) due to stabilizer/laminate and its technique have been reported both in REBCO CC and BSCCO tapes [19, 22, 23]. From the start of the development of CC tapes, the incorporation of Cu stabilizer was to provide protection adding thermal and electrical stability in the whole CC tape. Consequently, as reported by Cheggour et al., the Cu also enhances the tolerance strain of CC tapes to axial strain [19]. However, the effect of Cu stabilizer on CC tapes showed that the enhancement of \( \varepsilon_{\text{irr}} \) where the onset of cracking occurs was not primarily due to the differential coefficient of thermal expansion (CTE) but rather considered as a toughening effect of stabilizer which acted as crack arrester. Some variation of this effect was observed when Cu was only soldered on one side or both sides of the CC tapes.

The uniaxial pressure dependence of the critical temperature, \( T_c \) causes a reversible effect of strain on the critical current density and flux pinning strength in many high temperature superconductors. In the case of BSCCO tapes, van der Laan et al. showed the evidence that the reversible strain effect on \( J_c \) and flux pinning is caused entirely by the pressure dependence of the \( T_c \) [24]. In the case of coated conductors, the contribution of the grain and grain boundaries to the reversible strain effect is comparable [25].

Under uniaxial tension, currently available CC tapes showed good mechanical properties and \( \varepsilon_{\text{irr}} \). Table 1 shows the irreversible limits in some coated conductors under uniaxial tension. Fig. 2 shows the uniaxial strain dependence of \( I_c \) in GdBCO CC tapes. Cu stabilized RCE-DR- and MOCVD-GdBCO CC tapes with Hastelloy substrate represented almost similar \( \varepsilon_{\text{irr}} \) of 0.55% and 0.52%, respectively as indicated by the arrows and then a rapid \( I_c \) degradation afterwards. On the other hand, RCE-DR GdBCO CC tape with stainless steel showed a critical strain limit in the range of 0.90-1.05%, and a gradual \( I_c \) degradation with strain even though it had a

**Fig. 1.** \( I_c/I_{c_{\text{irr}}} \)-tensile strain relation in SmBCO CC tapes with different yield strength of Hastelloy. Arrows indicate the irreversible strain limit, \( \varepsilon_{\text{irr}} \), in each CC tape. Stress-strain curves shown in the graph are for the Hastelloy substrates adopted by each CC tape [14].

<table>
<thead>
<tr>
<th>Substrate</th>
<th>Deposition process</th>
<th>Irreversible strain limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hastelloy</td>
<td>RCE-DR</td>
<td>0.45%, 0.55%, 0.70-0.80%</td>
</tr>
<tr>
<td></td>
<td>EDDC</td>
<td>0.50%</td>
</tr>
<tr>
<td></td>
<td>MOCVD</td>
<td>0.52%</td>
</tr>
<tr>
<td></td>
<td>PLD</td>
<td>0.44%</td>
</tr>
<tr>
<td>Stainless steel</td>
<td>RCE-DR</td>
<td>0.9-1.05%, 1.05%</td>
</tr>
</tbody>
</table>

*Ag-stabilized, Cu-stabilized, Brass-laminated
large intrinsic strain sensitivity of $I_c$ under uniaxial tension.

Higher $\epsilon_{irr}$ could be achieved when adopting stainless steel as the substrate material. This improvement was due to the pre-compressive strain in the GdBCO film as the stainless steel substrate has much higher CTE as compared to the GdBCO superconducting film. But thicker stainless steel substrate may impact the engineering critical current density, $J_e$, as compared to a thinner Hastelloy substrate. Through further improvement of strain-sensitivity, the stainless steel material can be expected to be adopted as the substrate of CC tapes. Consequently, the properties of the substrate materials affected the mechanical and subsequently the electromechanical properties of Cu-stabilized GdBCO CC.

2.2. Bending strain effect on $I_c$ at self-field

CC tapes have a great potential to be utilized in high field magnet applications due to their high current density even under strong magnetic field. During fabrication, bending is inevitable in coil winding of a superconducting magnet. Therefore the bending tolerance of CC tapes was one of the foremost fundamental electromechanical properties that have been evaluated by many groups [26-32]. Fig. 3 shows the $I_c$ response of Cu-stabilized coated conductors under bending deformation. Cu stabilized RCE-DR GdBCO CC tapes and MOCVD GdBCO tape showed reversible behavior of $I_c$ up to 12 mm bending diameter. Thin profile CC tapes showed a higher tolerance under bending deformation. $I_c$ may show a peak value either in tension or in compression side depending on the pre-strain state in the coating film but not completely determined by the amount of the residual strain. It is also suggested that the bending deformation characteristics of the coating films depended on the substrate property and the scattering on data might be due to the inhomogeneity of the CC tape including the substrate material.

By investigating the intrinsic strain effect on $I_c$ in GdBCO CC tapes, it was found out that it is independent of the fabrication process and substrate material adopted and showed almost the same strain sensitivity as shown in Fig. 4. This dependence can be described by a power law function $I_c/I_{c_{max}} = 1 - a(\epsilon_{b-\epsilon_{irr}})^2$ in which $a$ represents the strain sensitivity of $I_c$. Exponent of this function varies in some reports [33]. For GdBCO CC tapes, the strain sensitivity value obtained in the RCE-DR and MOCVD processed samples is 0.177 similarly with $a=0.199$ in PLD processed sample having the same GdBCO film crystal orientation as reported by Sugano et al [34]. For samples having Hastelloy substrate, the intrinsic strain response of $I_c/I_{c_{max}}$ under bending was well correlated with those under uniaxial tension. The intrinsic strain sensitivity of $I_c$ in GdBCO CC tapes depends on the crystal orientation of the GdBCO coating film as have been reported by Sugano et al and van der Laan et al. [34, 35]. RCE-DR and MOCVD processed GdBCO CC samples investigated have similar crystal orientation parallel to the tapes length and this might be the reason that they showed similar strain sensitivity. The intrinsic strain effect on $I_c$ under bending is independent of the fabrication process and substrate material adopted. The variation of the strain response of $I_c$ against bending curvature appeared in Fig. 2 resulted from the difference in the pre-strain state induced in the superconducting film due to CTE difference among constituent layers and geometry of the samples.
2.3. Strain effect on $I_c$ under magnetic field, $I_c(\varepsilon, B)$

These CC tapes showed a good strain tolerance of $I_c$ both at self-field and under external magnetic field [33, 36-38]. Under magnetic field, different testing apparatus or rig have been developed for the evaluation of electromechanical properties of HTS tapes which includes the Walter spring [37], CuBe bending rig [33, 39], and tension-compression bending rig as described in ref [38], [40-42]. Fig. 5 shows some EMP devices reported by different groups. Strain effects in superconducting wires/tapes have been intensively investigated by adopting these different testing procedures [33, 37, 38, 43]. Up to now, there is no standard test method yet for the EMP evaluation of HTS tapes under self-field and external magnetic field although there are already reports on the different devices used to evaluate these properties as mentioned earlier.

The magnetic field dependence of $I_c$ is highly variable from sample to sample, thus it is the first characteristic usually measured for most 2G CC tapes. The magnetic field dependence of $I_c/I_{c0}$ in differently processed REBCO CC tapes is shown in Fig. 6. The $I_c/I_{c0}$ of REBCO CC tapes degraded with increasing magnetic field up to 3 T in which EDDC-SmBCO exhibits better magnetic tolerance of $I_c$ as compared with other cases. In two differently processed SmBCO and GdBCO CC tapes, a difference in magnetic tolerance of $I_c$ can be observed. The response of $I_c$ with magnetic field not only depends on the kind of the superconducting layer but also depend on the fabrication process adopted. All the CC samples in Fig. 6 have no artificial pinning centers, and the difference of the magnetic field dependence of $I_c$ is likely due to the different microstructures and defects which act as natural pinning sites [44]. In the case of RCE-DR GdBCO CC tapes, almost similar $J_c-B$ relation was observed for both the samples with Hastelloy and stainless steel substrates [45]. The magnetic field dependence of $J_c$ in RCE-GdBCO CC tapes is independent on the substrate material adopted both in the Cu-stabilized and brass-laminated samples. It was then inferred that similar deposition conditions used in the RCE-DR process will produce similar microstructure which defines its flux pinning characteristics. In addition, in some reports, strain response of pinning force showed similar to that of the $I_c-\varepsilon$ response under magnetic field. Similarly with $F_{\text{p, max}}$, irreversibility field ($B_{\text{irr}}$) was slightly affected by strain [46]. Fig. 7 shows the $I_c/I_{c0}$ strain relation under magnetic field in SmBCO and YBCO CC tapes, respectively. In the cases of SmBCO CC tapes specifically in RCE-SmBCO, the $I_c/I_{c0}$ showed different behavior as compared with YBCO CC case [33, 38, 40]. In SmBCO CC tapes, no $I_c$ peak was observed during uniaxial tension test showing a monotonic decrease of $I_c/I_{c0}$ with strain in contrast to the case of YBCO CC [47]. On the other hand, in the case of YBCO CC tape, an interesting behavior has been observed showing shifting of the $I_c$ peak with magnetic fields as has been described in [33, 38, 40]. Some reports attributes the $J_c$ or $I_c$ behavior to the strain dependent pinning mechanisms namely the pinning of Abrikosov-Josephson vortices at grain boundaries at low magnetic field and the pinning of Abrikosov vortices at high magnetic field [48]. Since the magnetic field effect on $I_c$ depends on the characteristics of the microstructure such as grain boundary, defects, etc, strain effect on $I_c$ is also suggested to be related on these mechanisms. The existence or non-existence of $I_c$ peak in both SmBCO CC tapes could be attributed to the fabrication process of the coating film adopted. In the case of RCE-SmBCO, it experienced the transition from liquid to solid phase during coating film deposition and reaction process, but in the case of EDDC-SmBCO sample it has been processed by the epitaxial growth of textured grains in the substrate. The

![Fig. 5. EMP evaluation devices for HTS tapes under magnetic field (a) Walter spring (b) Katagiri-type tension rig (c) Cu-Be bending spring and (d) permanent magnet system developed at ANU [8].](image5.png)

![Fig. 6. Magnetic field dependence of $I_c$ in various CC tapes evaluated at 77 K under B//c-axis [8].](image6.png)
Fig. 7. Strain response of $I_c/I_c^0$ under magnetic field in Cu-stabilized (a) MOCVD-YBCO CC and (b) RCE-DR SmBCO CC tapes with Hastelloy substrate at 77 K [8].

Grain orientations in the substrate layer in EDDC-SmBCO sample are directly reflected to the superconducting layer as it is. Therefore in the EDDC-SmBCO CC tape, it can be expected that the characteristics or the density of grain boundaries were significantly developed, and phenomena like $I_c$ peak and its shift under magnetic field due to the Josephson vortices appeared. However in the case of RCE-SmBCO CC sample, a relatively weak formation of Josephson vortices resulted to a non-$I_c$ peak occurrence even by straining or under magnetic field. But with additional brass laminations, variations on the strain effect became minimal [49]. However, there are no clear evidences yet regarding this assumption and up to now, mechanisms of this unique strain response of $I_c$ under magnetic field in different CC tapes are not yet clearly understood.

2.4. Strain effect on $I_c$ at different angle under low magnetic field: $I_c(\varepsilon, \theta, B, 77 \, \text{K})$

Recently, we have developed a permanent magnet system to measure the uniaxial strain effect on $I_c$ in HTS tapes at low magnetic field with the capability to adjust the angle of orientation of the external field with respect to the tape’s surface as shown in Fig. 8 [43, 49, 50].

Fig. 9 shows the strain effect on $I_c$ at specified field angle with respect to the tape surface. The strain response of $I_c$ at $\theta = 0^\circ, 30^\circ, 60^\circ$ are almost identical with those at $\theta = 180^\circ, 150^\circ, 120^\circ$, respectively. The strain sensitivity becomes significant at $\theta = 90^\circ$ ($B//a-b$ plane), therefore the $I_c$ degradation was also significant at this condition. The strain sensitivity of $I_c$ in RCE-DR processed GdBCO CC tapes is dependent on the magnetic field intensity and angle.

In Fig. 9 (b), the result under 0.3 T for Cu-stabilized CC samples with stainless steel substrate showed a minimal increase in the strain sensitivity from $\theta = 90^\circ$ up to $0^\circ$ as compared with those tested at 0.5 T. The variations of these strain sensitivity with angle of orientation from $\theta = 0^\circ$ to $90^\circ$ becomes less at lower magnetic field and is expected to have a large variations at 1 T in which $I_c$ showed the least strain sensitivity under magnetic field from 0 to 3 T as we have reported elsewhere [45]. The strain effect on $I_c$ under different angles are dependent on the intensity of the external magnetic field. It could be found out that the strain sensitivity of $I_c$ in CC tapes is dependent upon both the magnetic field intensity and angle regardless of substrate and stabilizer materials adopted.

These results can be explained as follows; the large intrinsic pinning is observed at $\theta = 90^\circ$ ($B//a-b$ plane) wherein the Cu-O plane acts as the natural pinning sites [26]. Under $\theta = 0^\circ$ ($B//c$-axis), however the $I_c$ is significantly affected by the magnetic field. Recently, Sunwong et al. reported that the strain effect on $J_c$ in YBCO is related to its induced change in the grain boundaries properties [51]. Since the irreversibility in $I_c$ is attributed to a presence of permanent deformation or fracture in REBCO coating film such as micro cracks, these will likely affect the correlated pinning under $B//c$-axis such as grain boundary effect. Efforts to improve the current carrying capacity of the GdBCC CC tapes under $B//c$-axis by artificial pinning centers or other approach are still necessary to improve its current carrying capability and reduce anisotropic $I_c$ response under external magnetic fields.
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3. RELIABILITY OF CC TAPES IN PRACTICAL APPLICATIONS

3.1. Cyclic loading (fatigue)

For electric devices such as motors, generators and magnets, the effect of cyclic loads on $I_c$ should also be taken into account. The intensity and frequency of the stress/strain applied to the CC tapes depends on the specific performance condition of the device. In this cyclic loading, the tapes were tested up to failure and in other case up to $10^5$ cycles in order to determine the electrical fatigue limit of EDDC-SmBCO CC tapes, i.e., with the 95% $I_c$ retention [51]. From this criterion, the electrical fatigue limit was determined to be about 500 MPa ($0.8\sigma_y$) in Fig. 10. The $I_c$ response on cyclic tension loading is significantly dependent on the maximum applied stress. At both stress ratios (R), $I_c$ did not show any significant degradation although the CC tape failed at R = 0.1.

And this Cu-stabilized sample adopting low yield strength substrate just showed fatigue strength less than 500 MPa under both R = 0.1 and 0.5 as shown in Fig. 11 [52]. But increasing the value of R will result to an increase both in the mechanical and electrical fatigue limit.

Fig. 9. Strain effect on $I_c$ in RCE-DR GdBCO CC tape with stainless steel substrate; (a) brass-laminated at 0.5 T and (b) Cu-stabilized at 0.3 T and 77 K.

Fig. 10. $I_c/I_{c_{0}}$-N relation of SmBCO CC tapes obtained from fatigue test with stress ratio (a) R=0.1 and (b) R=0.5.

Fig. 11. S-N curves of SmBCO CC tapes at R=0.1 and 0.5.

3.2. Delamination behaviors of CC tapes under transverse stress

The CC tapes exhibited a much higher axial tensile stress tolerance of more than 600 MPa and bending deformation tolerance as compared with the 1G and LTS wires [3, 9], [53]. Utilizing these properties, the current density in the superconducting coils can be increased resulting to a much smaller and compact device, [54]. However, these CC tapes showed anisotropic stress tolerance exhibiting a much lower tolerance with transverse stress of about 10 MPa and
delaminated showing a significant decrease in $I_c$ [55]. In the report of Takematsu et al., they demonstrated that an epoxy impregnated YBCO CC double pancake coil showed substantial degradation in the coil performance due to CC tape delamination [56]. The CC tape delamination was explained as a consequence of excessive transverse stress. The cumulative transverse (radial) stress developed during epoxy cure and cool down exceeded the critical transverse strength and resulted in a significant $I_c$ degradation. Few reports on the delamination strength of CC tapes are highly variable [55-57] and some commercially available CC tapes had already showed a transverse strength of 40-100 MPa [53, 57, 58]. CC tapes are made by subsequent deposition of different layers, and can be modeled as an adhesive lap joint. If a layer is debonded or fractured, the CC performance is substantially degraded [56]. Stress types common to adhesive joints include tensile, shear, cleavage and peel stress. In CC tapes, cleavage and peel strength are much lower than the transverse tensile strength and therefore are undesirable and should be avoided such as in magnet coils [59-60].

Furthermore, the delamination of CC tapes can be mitigated by thermal cycling [61, 62]. In some cases, delamination of CC tapes occurred when exposed to magnetic field angle of 10° and 20° due to the electromagnetic force that a screening current and background magnetic field had generated [63].

Recently, our groups have reported the delamination behavior in GdBCO CC tapes [64-67]. A loading fixture has been designed to achieve a good alignment during transverse tensile test as shown in Fig. 12. During anvil tests under transverse tensile stress, the $I_c$ degradation in GdBCO CC tapes showed both abrupt and gradual behaviors. Moreover, a reversible $I_c$ degradation behavior similarly with the case under uniaxial tensile stress was observed. This $I_c$ degradation behavior could be explained by the observation and analysis of delamination sites. Abrupt $I_c$ degradation exhibited delamination within GdBCO coating layer and at the GdBCO/silver layer interface while gradual degradation showed delamination at the GdBCO/buffer layer interface. However, the delamination mechanism in CC tapes is not yet clear and may show cohesive, adhesive, or interlaminar delamination failure under transverse tensile stress [68].

For the transverse mechanical strength of a 12 mm wide RCE-DR GdBCO CC tape with the stainless steel substrate, a similar behavior was observed at the superconducting layer side and at the substrate side as shown in Fig. 13. Brass lamination did not bring any enhancement of the delamination strength. Wide GdBCO CC tapes with stainless steel substrate exhibited interlaminar or mixed delamination sites [67].

3.3. CC tape joints for device application

The production length of commercially available CC tapes is still insufficient for the fabrication of power cables and coil windings, thus joining is necessary for device fabrication and installation. The joining of CC tapes is required in constructing solenoid or double pancake and}

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**Fig. 12.** (a) Set-up for sample mounting, and (b) location of upper anvil in widthwise direction (above) and schematic of soldering orientation (below) [67].

![Fig. 12](image1.png)

**Fig. 13.** Mechanical delamination strength of 12 mm wide Cu-stabilized and brass laminated RCE-DR CC tapes along the width direction (center & edge) [67].

![Fig. 13](image2.png)
respectively. Using the lap and butt joint analysis, we can approximate the joint resistance in a parallel or bridge type joint and estimate the number of bridges required to design an acceptable joint resistance. For a standard CC tape with 4 mm or 10 mm width, total resistance of parallel/bridge joints can be estimated using the formula: \( R_j = \frac{(c \times R_{10lap})}{N} \), where \( R_{10lap} \) and \( N \) are the joint resistance of a 10-mm lap joint and number of bridges, respectively and \( c=5 \) for a 4 mm width and \( c=2 \) for 10 mm-width CC tapes. This formula was derived from the parallel circuit analysis of the lap joints [72].

Recently, we have reported a new joint method using ultrasonic welding (UW) [73]. This welding method is applicable in joining of metal alloys and thermoplastics through the frictional heat generated from a localized high frequency ultrasonic vibration. This is the first time that UW method was applied in joining superconductors and Cu-stabilized GdBCO CC tapes were successfully joined without \( I_c \) degradation although it showed slightly higher joint resistance as can be observed in Fig. 15 as compared with those mechanical-controlled solder jointed ones. Also, specific joint resistance is the same with varying joint lengths which indicates that similar quality of joints is achieved during the UW process. Employing the UW joint consumed lesser time to prepare a CC tapes joint as compared with other joint methods. Welding parameters should be chosen based on the specific geometry and characteristics of CC tapes as have been observed in samples having different substrate materials. Further efforts to have a lower joint resistance are needed to make the UW method more suitable in joining of CC tapes for devices such as power cables and coils.

4. CONCLUSIONS

The 2G REBCO CC tapes have shown great potentials for several electric device applications and through concerted efforts performance characteristics have been drastically improved. Further improvement on the electromechanical properties such as delamination strength will fully impact the designs of different devices such as magnets and coils. Through the development of the manufacturing process and homogeneity of \( I_c \), reliable CC tape joints are now possible with a comparable bending and uniaxial tensile stress/strain tolerance with the single tape. Further efforts in achieving a much higher quality UW CC tape joints is underway for a fast and efficient joining for practical device applications. Finally, the good characteristics of REBCO CC tapes having high critical current density and good mechanical strength make it the enabling technology for different application fields.

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