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Mode I delamination testing of REBCO coated conductors via climbing drum peel test

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Introduction

The transverse strength of coated conductors (CC) is a key issue in the formation of coils for high field magnets and rotating machines. Differential thermal contraction in particular is known to cause failure. While a number of studies have investigated this problem, and possible remedies, the amount of fundamental work on the mechanical properties has been limited.

Here we measure the mode I interface fracture energy, G_{IC}, using a test which is well known in the adhesives industry – the Climbing Drum Peel (CDP) test.

It is the goal of the work presented here to argue that the CDP test has the required traits to investigate the fundamental connections between REBCO CC design and final mechanical performance.

In particular we would like to test the hypothesis of Lane (M. Lane, *et al*, J. Mater. Res, vol. 15, no. 12, p. 27582769, 2000) that the G_{IC} of an interface increases strongly with the thickness of adjacent layers which can plastically deform.

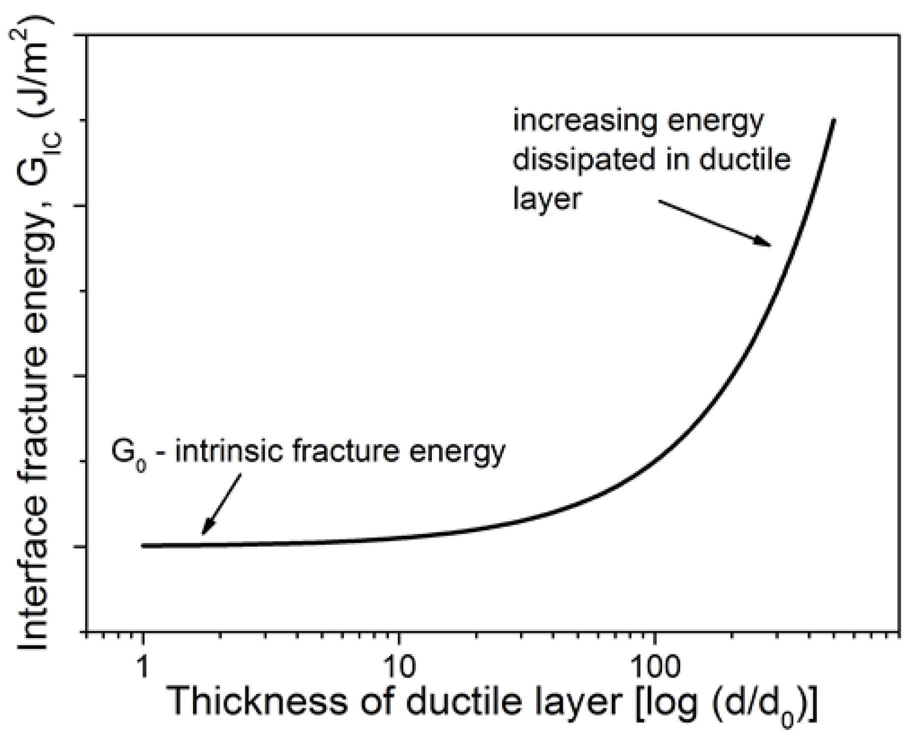

Figure 1. An illustration of the hypothesis of Lane. At small coating thickness we should measure a value of G_{IC} close to the intrinsic interface energy, G_0. With an increasing thickness of ductile material adjacent to the interface, energy is dissipated in this layer increasing G_{IC}.

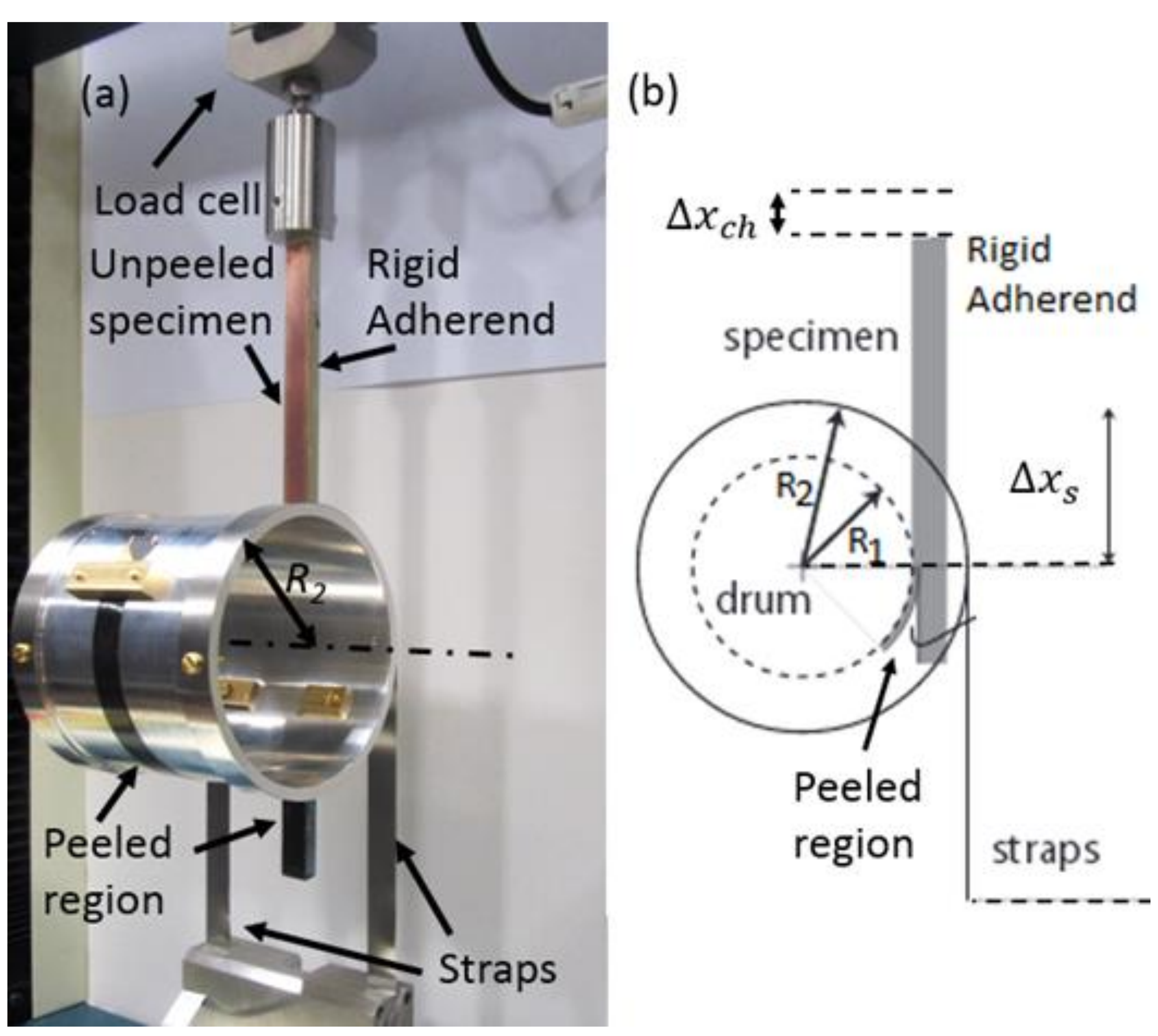

Figure 2. (a) Image of the climbing drum as it operates, note R_2 is given off the central axis of the drum. Drum is driven inside a Tinius Olsen universal testing machine. (b) Schematic of the climbing drum

Experiment method

The samples are glued to a rigid adherend, made of mild steel. The REBCO CC is glued HTS side down. This leaves the substrate of the material available to be peeled away, leaving the other materials behind, depending on what layer the fracture occurs.

The drum itself has 3 key attributes, its weight, and its two radii. The sample is attached to the inner radius R_1 and the drum is held in place by two straps on its flanges, with radius R_2 as illustrated in Fig. 2. While the drum can be understood in terms of the forces, tensions, or torques applied by the sample, straps and gravity, it is faster to consider the apparatus in terms of the work done during a test. In this point of view, the effect of the choice of radii is encapsulated in the ratio β, where

$$\beta = \frac{R_1}{R_2 - R_1}$$

The gearing ratio can be selected to provide analogue amplification of the apparent force, where the intrinsic peel force is multiplied by β as seen by the load cell. Here it was chosen to have β = 20. Setting R_1 to be sufficiently large as not to cause the substrate to be deformed plastically, sets R_1 = 44 mm and R_2 = 46.2 mm.

Sample preparation

Samples were acquired from several manufacturers, and are given in Table 1. Effort was made to acquire multiple architectures from each manufacturer in order to investigate the effects of variations in stabilizer type and thickness. Any samples with edge surround stabilizer had those edges removed by razor blade.

Mild steel rigid adherends were used to provide the required rigidity to the samples. The samples were lightly abraded to increase surface area, then cleaned with ethyl alcohol. 3M DP460EG two part epoxy was used to adhere the REBCO CC down to the adherend. The epoxy was cured over night at room temperature, and then fully cross linked at 120 °C over several hours. Fully crosslinking the epoxy is required to insure that it is prone to glassy fracture, rather than plastic deformation, which would artificially improve the toughness of the tested material.

Analysis

If we consider the work done in raising the drum and the additional work in breaking the interface, we calculate as follows.

$$\Delta W(x_{ch}) = F_{ic}\,\Delta x_{ch} = \left[\left(mg + F_p\right)\beta\right]\Delta x_{ch}$$

$$\frac{dx_s}{dx_{ch}} = \frac{R_1}{R_2 - R_1} = \beta$$

$$G_{IC}(x_s) = \frac{\left(\Delta W_p(x_s) - \Delta W_{BL}(x_s)\right)}{w} = \frac{\left(\Delta W_p(x_{ch}) - \Delta W_{BL}(x_{ch})\right)}{\beta \times w}$$

Results and discussion

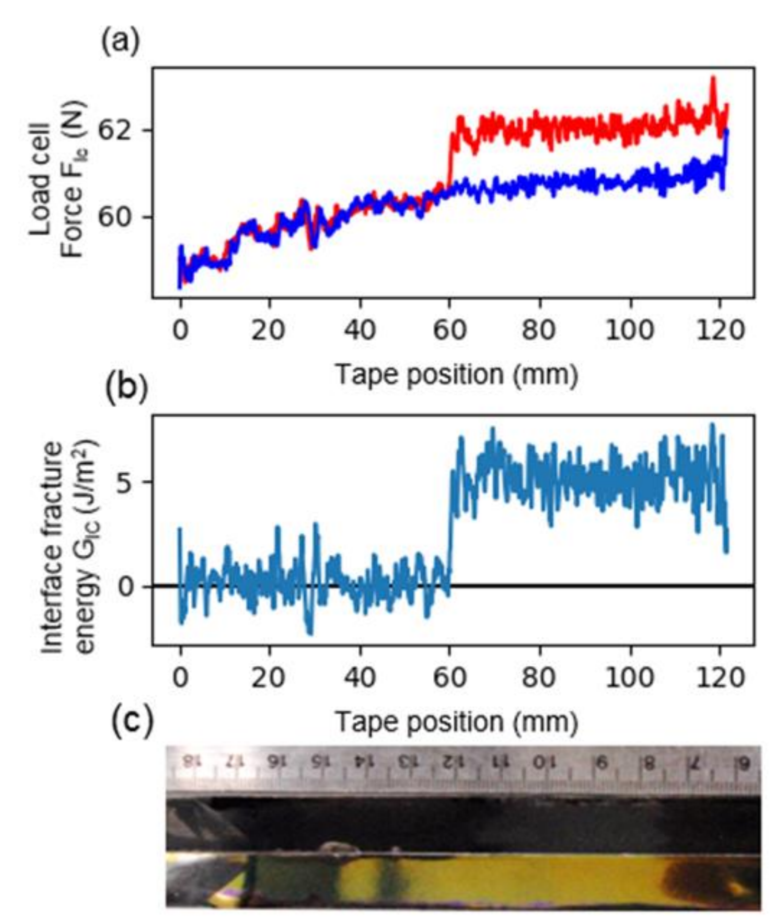

Figure 3. (a) Force as measured by 10 kN load cell, plotted against position along tape. Red curve includes force required to peel sample, the blue curve is acquired by repeating the same motion with the sample already peeled. (b) Curves from (a) are subtracted from each other, the resulting curve is then adjusted for sample width, w = 12 mm, and the gearing ratio β, to give G_{IC}. For this data, the final value is quoted as the mean of the peeled region between 60 and 120 mm, G_{IC} = 5.17 ± 0.94 J/m². (c) Peeled sample laid next to itself, with the substrate in the lower 3rd of the image, the HTS and attached rigid adherend in the middle 3rd.

Table I: MODE I TOUGHNESS, VARIOUS SUPPLIERS

Material Name	Fracture Location	Stabilizer thickness (µm)	Toughness (J/m²)	Length analyzed (mm)
AMSC Ag	Buffer stack	1	11.64 ± 4.2	765.27
Fujikura Ag	Buffer stack	20	7.22 ± 1.36	957.06
Fujikura Cu laminated	Buffer stack	107	11.4 ± 2.41	506.54
Fujikura Cu laminated	HTS layer	107	19.26 ± 2.64	331.28
Theva Cu laminated	Substrate-buffer	110	8.93 ± 1.72	852.06
Theva Cu	Substrate-buffer	30	9.17 ± 1.51	204.73
Theva Cu + Solder	Substrate-buffer	40	11.45 ± 1.36	313.02
Shanghai Ag	Buffer stack	3	5.17 ± 1.05	204.73
STI Ag-Cu[a]	Buffer stack	1	4.59 ± 1.72	911.34
SuNAM Ag	Buffer stack	1	5.9 ± 1.13	273.59
Superpower Ag	Buffer stack	1	3.56 ± 0.76	675.45
Superpower Cu	Buffer stack	20	5.14 ± 0.99	772.48

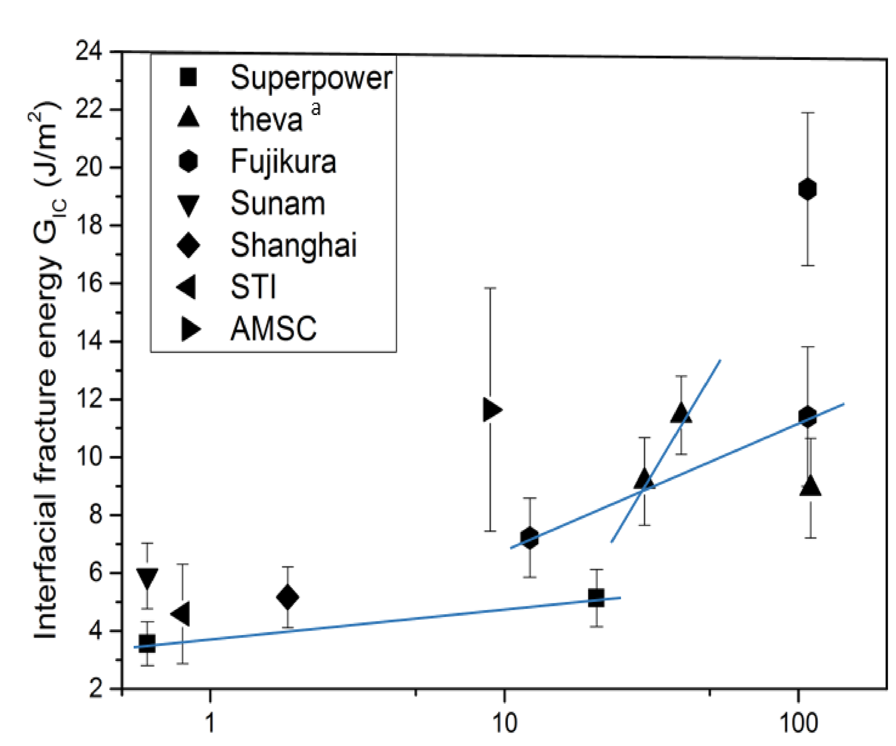

Figure 4. Mean interface fracture energy data presented for various suppliers. G_{IC} is plotted vs normalised stabiliser thickness, where the yield strength of silver relative to that of copper is used to scale the Ag thickness to an equivalent copper thickness. Trend lines given where the only variation is normalised stabiliser thickness. AMSC Ag has been positioned by considering its substrate as a source of plastic deformation and normalising by yield strength.

Conclusions

- We conclude that the CDP test is an effective test for investigating G_{IC} as well as the Griffith strain energy release rate G_0 for various REBCO CCs.
- At low stabiliser thickness we believe we see values which are appropriate for G_0 values in a ceramic layer, G_0 ~ 3-6 J/m².
- The uncertainty of this implementation of the technique has been quantified to be on the order of 1 J/m², as determined by the repeatability of measurements not including a peel force. And that the remaining uncertainty of measurements lies in the variation of fracture location and material consistency over length.
- The toughening effect of plastic deformation in proximate layers of ductile material, namely the stabilizer, has been detected. And finally the unambiguous difference in fracture energy of different layers in an REBCO CC stack has been identified by inspection of results from Fujikura copper laminated material.

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