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Direct Measurement of Modified Interconductor Contact Resistance Values in Coated Conductor Stacks and Roebel Cable at Variable Temperatures

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Introduction

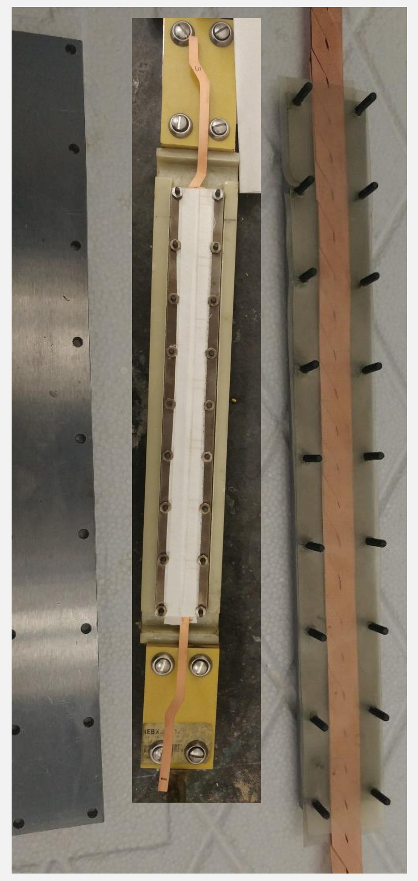
- Many next generation high-field magnets and applications have been designed to utilize REBCO coated conductor to maintain large J_e in the presence of large magnetic fields.
- Multiple REBCO cable insulation composite strategies have been fabricated to meet the demands of a high J_e while keeping AC-loss, inductance, and stored energy of large windings to a minimum.
- As wound, the interconductor contact resistance (*ICR*) of some REBCO cable designs will have negligible current sharing [1].
  - While this will decrease AC-Loss, stability and current sharing will also decrease without additional processing.
  - Similar to LTS cables, a balance needs to be pursued to find an acceptable level of *ICR*.
- REBCO cables and coils can also have excessive current sharing.
  - This can be reduced with low *RRR* resistive metal layers/coatings [2] or Metal-to-Insulator-Transitioning (MIT) "smart" layers [3,4].
- Low-temperature diffusion bonding and electrodeposited coatings have been a proven method to control *ICR* in LTS cables and this methodology has been pursued for REBCO cables by OSU [5].
- Even very thin coatings can change *ICR* drastically, introducing a means to optimize stability and current sharing with little penalty to J_e of the winding.

REBCO Roebel cable

- For this study, Roebel cable received from KIT was used. The properties of this cable are shown below.
- The 9-tape cable was pressed in a fixture over a length of 300 mm.
- Tapes 1 and 5 were revealed on both ends of the fixture to transfer current across the entire cable.
- Measurements were performed in a LN_2 bath.

Parameter	Specification
Roebel cable manufacturer	Karlsruhe Institute of Technology
REBCO tape manufacturer	SuperPower Inc.
Type of Roebel cable	9/5.6
Number of Tapes	9
Tape Width, w_{tape} (mm)	5.6
Cable Width, W_C (mm)	11.8
Tape thickness, t_{tape} (mm)	0.1
Pitch Length, L_p (mm)	126
Cross-over angle, ϕ (degrees)	30
$L_{Inter\text{-}strand\ gap}$ (mm)	0.4
$W_{Cross\text{-}over}$ (mm)	5.6
I_c @ 77 K, sum of tapes (A)	1168

Roebel Cable ICR measurement results at 77 K



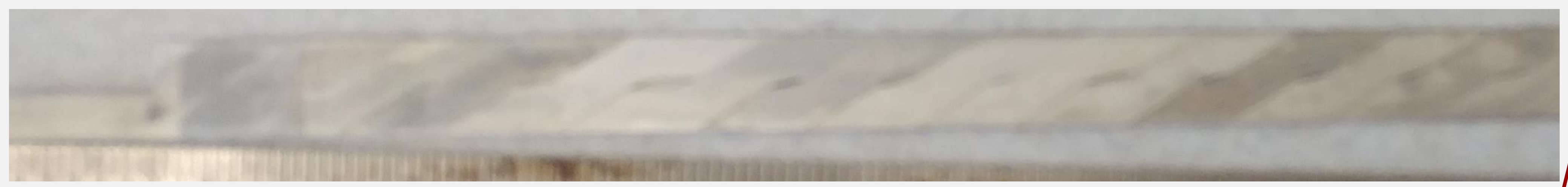
Sample processing and *ICR* results for Roebel cable pressed at 2.7 MPa in LN_2.

Roebel cable processing	*ICR* ($\mu\Omega\cdot cm^2$)
As-received	8.9
Cu-Cu 150 °C x 3 hr	8.6
Cu-Cu pO_2 240 °C x 6 hr	5.8
Chrome plated	98

*100x

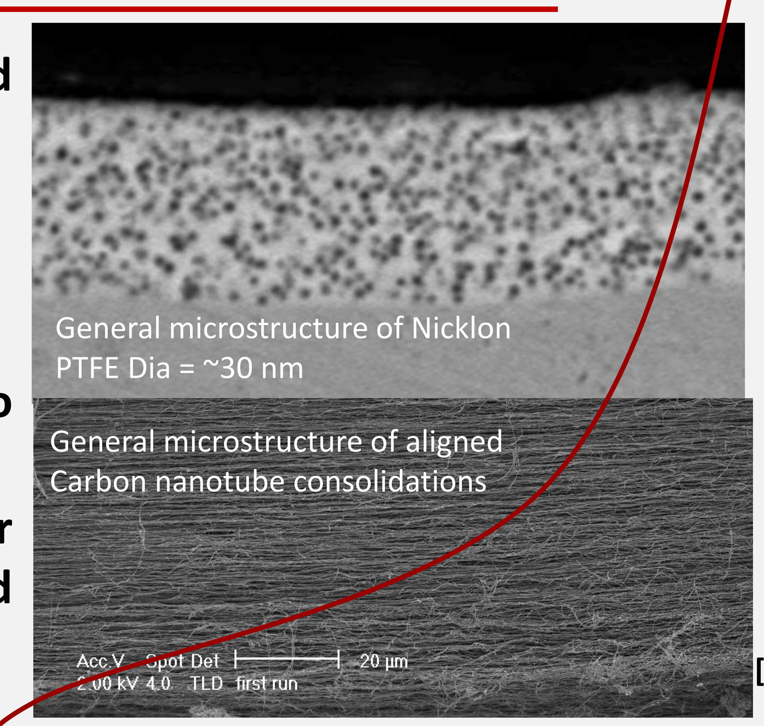
5x

- Low-T diffusion bond processing was performed on ReBCO Roebel cable.
- A small decrease in ICR was seen for processing of 150 °C x 3 hr @ 2.7 MPa and 240 °C x 6 hr under pO_2 @ 2.7 MPa.
- Cable flexibility decreases with diffusion bonding and cable precleaning and other preparation may be required for stronger bonding.
- Chromium plating increased resistance and maintained cable flexibility.
- Chromium plating needs to be performed on a disassembled Roebel cable to ensure an even electrodeposited layer.



REBCO coated conductor stacks at 77 K and 4.2-150 K

- A single lap joint was created with 14 mm wide as received SuperPower REBCO coated conductor.
- Measurements were performed at:
  - 77 K and 200 MPa
  - 4.2-300 K and 20 MPa
- Tests: Cr, Ni, Nicklon (Ni-PTFE), As-rec Cu and Ag w and w/o DexMat CNT insert (heat treated under Ar at 400 C and as-is)
- The CNT insert was investigated as a Metal-to-Insulator material (near REBCO T_c) for permitting high ramp rates and current sharing during quench.



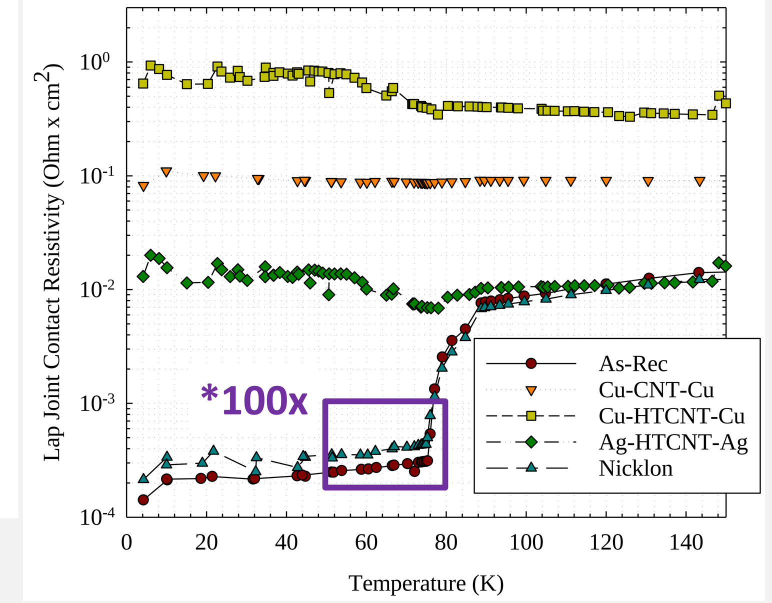
Processing and *ICR* for coated conductor lap joint at 200 MPa in LN_2.

Sample processing	*ICR* [$\mu\Omega\cdot cm^2$]
Chrome electrodeposition	564 ± 5%
Nickel electrodeposition	987 ± 5%
Silver electrodeposition	12 ± 5%
Nickel-nanoTeflon codeposition	94 ± 5%
As-received w/ CNT tape insert	300 ± 5%
Vacuum Diffusion Bond (10 MPa, 160 °C x 8 hr)	No bonding

5x

10x

ICR for coated conductor lap joint At 20 MPa in 4.2-150 K He-gas



Discussion

- The pressed (2.7 MPa) Roebel cable native copper layer had a much lower *ICR* than the pressed (20 MPa) coated conductor native copper stack. This may be due to differences in internal geometry, e.g. Roebel cable introduces shear to internal surfaces when pressed perpendicular to the cable face. Such shear stresses would break up oxide layers more effectively than a single perpendicular press in a stack.
- During variable temperature measurements, the measured 16 K transition width is 10 K broader than similar measurements performed in [6] and much broader than resistive transition measurements performed along the A-B plane of the coated conductor length [7]. Because longitudinal resistance measurements have the external REBCO surface totally in parallel with the current carrying direction, any surface *Tc* degradation would go unnoticed. For lap joints, the YBCO surface plays a strong role in the measured joint resistance because the surface is partially in series with the current carrying direction. Any small amounts of external surface REBCO *Tc* degradation due to manufacturing, stresses, or storage conditions should therefore be strongly noticed in temperature dependent contact measurements [8].
- Hard surface coatings resulting in a larger contact resistance is expected from Holm contact theory of pressed contacts [9]. This would explain the Nickel vs. Nicklon result.

Conclusions

- A small decrease in *ICR* was seen for low-temperature diffusion bonding processing with (150 C / 2.7 MPa); this shouldn't negatively degrade superconducting properties.
- Cable flexibility decreases with diffusion bonding and the bonding has low adhesion.
- Chromium and Nickel plating results in a higher *ICR* option
- Silver plating results in a very low *ICR* option, possibly useful near current injection
- Even when pressed with a 75x lower pressure than a lap joint, Roebel cable results in a significantly smaller *ICR* than the lap joint.
- Nicklon (Nickel-Teflon nanocomposite) is a low-friction, durable, chemically resistant coating that results in *ICR* values similar to as-received Cu-Cu lap joints
- CNT tape functions as a high-tensile strength, thin, easy to implement, and low-friction "smart" insulation
- For some samples, the T_c extended to 75 K. T_c degradation near 77 K can greatly increase the measured *ICR*.

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