Options for epoxy impregnation of REBCO Roebel cables

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Roebel cable - candidate for accelerator magnets

- **REBCO Roebel cables**
  - Fully transposed
  - High engineering current density
  - High mechanical flexibility in soft bending direction
  - Retain anisotropy of coated conductor

Good candidate for HTS accelerator magnets

- **EuCARD2 20 T dipole magnet**
  - 15 T LTS magnet
  - 5 T HTS insert
  - Stresses up to 110 MPa

G. Kirby et al., EuCARDII meeting
Impregnation needed to support Roebel structure

- Bare Roebel cables are weak under transverse stress due to stress concentrations

- D. Uglietti et al.:  
  - Compressive pressure of 70 MPa  
  - Up to 70% $I_c$ degradation  
  - Visible damage under the ‘bridges’

J. Fleiter et al.

D. Uglietti et al.
CC degradation due to thermal stress

- Thermal mismatch between epoxy and REBCO conductor causes $I_c$ degradation

- Proven solutions
  - Beeswax/paraffin impregnation (T. Takematsu, S. Matsumoto)
  - Cyanoacrylate resin (K. Mizuno)
  - Epoxy + polyester/polyimide barrier (U. Trociewitz, Y. Yanagisawa)
  - Silica filled epoxy resin (C. Barth)

T. Takematsu et al.
# Tested filled epoxy resins

<table>
<thead>
<tr>
<th>Filler</th>
<th>Filling ratio [wt%]</th>
<th>Product name</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electrically conductive fillers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Silver</td>
<td>60-80</td>
<td>Duralco 125</td>
</tr>
<tr>
<td>Graphite</td>
<td>50-60</td>
<td>Duralco 127</td>
</tr>
<tr>
<td>Carbon particles + CNT</td>
<td>4-8</td>
<td>Carbocond 171</td>
</tr>
<tr>
<td>Graphite + CNT</td>
<td>4-8</td>
<td>Carbocond 471</td>
</tr>
<tr>
<td><strong>Insulating fillers</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fused silica</td>
<td>50-66</td>
<td>Araldite CY5538/HY5571</td>
</tr>
<tr>
<td>Al(OH)$_3$</td>
<td>56</td>
<td>Araldite CW5730N/HY5731</td>
</tr>
</tbody>
</table>

- Measurements of:
  - Thermal expansion
  - Thermal conductivity
  - Electrical resistivity
Reduction of the thermal expansion mismatch for filled epoxy's

>50 wt % silica, alumina or graphite filler needed

Thermal expansion, $T = 300 \rightarrow 4.2\, K$

Combination of low viscosity and low thermal expansion needed

<table>
<thead>
<tr>
<th>Filler</th>
<th>Filling ratio [wt%]</th>
<th>Product name</th>
<th>Thermal expansion $T = 300 \rightarrow 420$ K</th>
<th>Viscosity [Pa s]</th>
<th>Processing temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>60-80</td>
<td>Duralco 125</td>
<td>-1.04 %</td>
<td>20</td>
<td>20 °C</td>
</tr>
<tr>
<td>Graphite</td>
<td>50-60</td>
<td>Duralco 127</td>
<td>-0.58 %</td>
<td>50</td>
<td>20 °C</td>
</tr>
<tr>
<td>Carbon particles + CNT</td>
<td>4-8</td>
<td>Carbocond 171</td>
<td>-1.18 %</td>
<td>6-8</td>
<td>20 °C</td>
</tr>
<tr>
<td>Graphite + CNT</td>
<td>4-8</td>
<td>Carbocond 471</td>
<td>-1.11 %</td>
<td>1-2</td>
<td>20 °C</td>
</tr>
<tr>
<td>Fused silica</td>
<td>50-66</td>
<td>Araldite CY5538/HY5571</td>
<td>-0.82 % -0.60 %</td>
<td>&lt; 4.5</td>
<td>80 °C</td>
</tr>
<tr>
<td>Al(OH)3</td>
<td>56</td>
<td>Araldite CW5730N/HY5731</td>
<td>-1.11 %</td>
<td>0.7</td>
<td>60 °C</td>
</tr>
</tbody>
</table>

- Araldite CY5538/HY5571 with 50 wt% fused silica is the most suitable
  - Low viscosity
  - Low thermal expansion
Impregnation adaptation for epoxy with filler

- Wet winding

- High viscosity (due to fillers) impedes epoxy flow
Successfully vacuum impregnated dummy cable

- Dummy between two stainless steel tapes, no glass fiber
- Araldite CY5538/HY5571
- 50 wt% fused silica
- $T = 80 \, ^\circ\mathrm{C}$
- $P = 0.3 \, \text{kPa}$

- Central hole is filled
- Thickness $< 1 \, \text{mm}$ → high current density
No $I_c$ degradation after impregnation

- Same cable and impregnation but with one REBCO strand
- $I_c$ measurements ($T = 77$ K)

<table>
<thead>
<tr>
<th></th>
<th>$I_c$ [A]</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before impregnation</td>
<td>171.7</td>
<td>28.1</td>
</tr>
<tr>
<td>After impregnation</td>
<td>170.2</td>
<td>26.8</td>
</tr>
<tr>
<td>(cycle 1)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After impregnation</td>
<td>170.9</td>
<td>28.5</td>
</tr>
<tr>
<td>(cycle 2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- No degradation
Transverse pressure test (UTwente)

- Samples to be tested
  1. Reference cable
  2. Impregnated cable (CY5538/HY5571 + 50 wt% silica)

- Cryogenic press (UTwente)
  - $T = 4.2$ K
  - $I_{\text{max}} = 50$ kA
  - $B_{\text{max}} = 11$ T (perpendicular)
  - $F_{\text{max}} = 260$ kN
  - U-shaped samples

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W. van de Camp et al.
“Transverse pressure dependence of $I_c$ in Nb$_3$Sn Rutherford cables”, ASC2012 Portland
Conclusion

- Roebel cables need impregnation for reinforcement

- Thermal expansion of epoxy resins can be modified by adding fillers

- A dummy cable was successfully impregnated with a 1:1 epoxy/silica mixture
  - No glass fiber
  - High curing temperature

- Dummy with one REBCO strand impregnated without $I_c$ degradation

- Transverse pressure test is planned at UTwente