Contact resistivity between REBCO tapes coated with a thin resistive layer

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Introduction

• Turn-to-turn contact resistivity (Rc) is a key parameter for NI REBCO coil. It relates to self-protection ability, charging delay and ramp losses.

• Appropriate range of Rc, $10^2 - 10^4 \mu\Omega\cdot cm^2$ (W.D. Markiewicz and S. Noguchi)

• Reliable Rc measurement has been performed at the NHMFL (ASC 2016 and SUST 2017).

• Applying various surface coatings is one way to control Rc. Effects of different coatings and the load cycles will be presented.
Contact pressure in REBCO DP coil

Contact pressure = Winding + Thermal + Electromagnetic

Winding tension

Electromagnetic


Rc Experimental Setup 1

- Load is controlled by air pressure and calibrated with a load cell. Max pressure = 150 MPa.
- Alignment checked by a Fuji film.
• Load cycle between 2.5 and 25 MPa, up to 10 Hz frequency.
• Resistance is measured by injecting $+ / - 1$ A current.
### $R_c$ variation in uninsulated conductors (no load cycle)

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample</th>
<th>Surface</th>
<th># of samples</th>
<th>$R_c$ 1st load at 25 MPa ($\mu\Omega$-cm$^2$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SuperPower</td>
<td>As-received, no cleaning</td>
<td>3</td>
<td>45-2000</td>
</tr>
<tr>
<td>2</td>
<td>SuperPower</td>
<td>Ethanol wiped</td>
<td>13</td>
<td>16-58</td>
</tr>
<tr>
<td>3</td>
<td>SuperPower</td>
<td>Finger handled</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>SuperPower</td>
<td>Scotch-brite wiped</td>
<td>5</td>
<td>0.8-7.3</td>
</tr>
<tr>
<td>5</td>
<td>SuperPower</td>
<td>HCl etched</td>
<td>6</td>
<td>3.4-22</td>
</tr>
<tr>
<td>6</td>
<td>SuperPower</td>
<td>Ethanol wiped</td>
<td>7</td>
<td>47-180</td>
</tr>
<tr>
<td>7</td>
<td>SuNam</td>
<td>Ethanol wiped</td>
<td>2</td>
<td>5.9-7.5</td>
</tr>
</tbody>
</table>

There is two orders of magnitude variations in $R_c$, depending on surface conditions.
Rc after surface coating (no load cycle)

<table>
<thead>
<tr>
<th>No.</th>
<th>Sample</th>
<th>Surface</th>
<th># of samples</th>
<th>Rc at 24 MPa (µΩ·cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>SuperPower</td>
<td>Ni plating</td>
<td>5</td>
<td>19-580</td>
</tr>
<tr>
<td>2</td>
<td>SuperPower</td>
<td>Cr plating</td>
<td>3</td>
<td>75-1000</td>
</tr>
<tr>
<td>3</td>
<td>SuperPower</td>
<td>A stainless steel tape in between</td>
<td>3</td>
<td>28000-33000</td>
</tr>
<tr>
<td>4</td>
<td>SuNam</td>
<td>Stainless steel plating</td>
<td>2</td>
<td>180,224</td>
</tr>
<tr>
<td>5</td>
<td>SuperPower</td>
<td>Ebonol oxidized at RT</td>
<td>3</td>
<td>6-960</td>
</tr>
<tr>
<td>6</td>
<td>SuperPower</td>
<td>Graphite sprayed</td>
<td>1</td>
<td>180</td>
</tr>
</tbody>
</table>

- Rc has large variations.
- Rc of stainless steel coated seems to be more consistent.
Effect of low number of load cycles (ASC-2016)

Rc increases with load cycle. Cold-work effect?
Effect of large number of load cycles:

At the end of 10,000 cycles, $R_c \sim 5 \, \mu\Omega \cdot \text{cm}^2$. one order of magnitude smaller $R_c$. 

SuperPower SCS4050
Rc temperature dependence (ASC-2016)

- Rc increases with T, similar to behavior of copper $\rho(T)$, consistent with constriction resistance.
- The low resistivity ratio can be explained by a T independent $R_{\text{film}}$. 
At the end of 10,000 cycles, 4.2 K $R_c$ is a few times smaller than at 77 K.
Control of Rc: thin film coating

- Stainless steel coating seems to work well. But a wider range of control over Rc is desirable.
- We are searching for economical methods that can customize Rc to a wide range of values.

TWO APPROACHES

A: thin film coating on REBCO tape to increase Rc
- Pro: Eliminate the co-winding process, higher Jw
- Con: process risking REBCO
- Tested
  1. Cr plating
  2. Ni plating
  3. Ni-P plating
  4. Cu oxidation by Ebonol®

B: thin film coating on stainless steel tape to decrease Rc.
- Pro: no risk on REBCO, low R&D cost.
- Con: Co-winding, low Jw.
- Tested:
  1. Cu plating
  2. Ni plating
Electroless Ni-P plating

- Ni-P electroless plated material has up to 10% P and high resistivity.
- Commercial solution (Caswell Inc. US) consists of nickel sulfate (NiSO₄) and sodium hypophosphite (NaH₂PO₂) and hydroxyl complex acid and organic matter with carboxylic group are added to control the chemical reaction:

\[
\text{Ni}^{2+} + \text{H}_2\text{PO}_2^- + \text{H}_2\text{O} \xrightarrow{\text{Ni}} \text{Ni}^0 + \text{H}_2\text{PO}_3^- + 2\text{H}^+
\]

\[
\text{H}_2\text{PO}_2 + \text{H}_2\text{O} \xrightarrow{\text{Ni}} \text{H}_2 \uparrow + \text{H}_2\text{PO}_3^-
\]

REBCO immersed in solution at 90 C for 10 min.
5 µm layer thickness (as measured by weight gain)

<table>
<thead>
<tr>
<th>Coating thickness (µm)</th>
<th>Rc at 150 MPa (µΩ-cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>1524</td>
</tr>
<tr>
<td>2</td>
<td>1292</td>
</tr>
</tbody>
</table>

Solder splice of Ni-P plated samples has resistivity 1 µΩ-cm².
Ni-P/Ni plating

For better uniformity, 1 µm Ni layer is electroplated before Ni-P plating.

As received

2 µm Ni-P

Bare spot

1 µm Ni + 0.02 µm Ni-P

Rc at 25 MPa (µΩ·cm²)

Ni/Ni-P plated

Ni-P layer thickness (µm)
0.8 μm Ni-P/1 μm Ni plated SCS4050

At the end of 10,000 cycles, $R_c \sim 18 \ \mu\Omega\cdot\text{cm}^2$
Ebonol® C oxidation

- Ebonol C powder: NaOH : NaClO₂ = 2:1
- Concentration: Ebonol: H₂O = 18:80
- Surface treatment: HCl: H₂O = 1:10
- Oxidation temperature: 98 °C

The process is low cost, reliable and controllable.
Rc of ebonol oxidized samples

Rc increases with oxidation time, moderately decreases with load cycles
Myung-Hwan Sohn, et al., Mon-Po 1.03-07 shows similar trend
Wide range of contact resistivity

- SS in between
- 60 sec ebonol
- 30 sec ebonol
- 10 sec ebonol
- Ni plated SS in between
- SS coated SuNam
- SS coated SuNAM 4.2 K
- Cu plated SS in between
- As received 4.2 K
- Ni-P/Ni plated
- Cu tape in between
- As received
Summary

• Rc has considerable variations.
• Load cycling can significantly reduce Rc.
• Rc is lower at 4.2 K than at 77 K.
• Rc can be controlled in a wide range by either
  1. oxidation of copper, or
  2. electroplating of stainless co-winding tape.

Acknowledgement

We thank Prof. Seungyong Hahn and his team for helpful discussions and for providing SS coated conductor samples. Dr. Chris Rey for providing Ebonol® C.
THANK YOU!