THERMAL DESIGN STUDIES OF NIOBIUM SRF CAVITIES

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Heat Generation In SRF Cavities

\[ q'' = \frac{R_s}{2\mu_0^2} B^2 \]

\[ R_s = A \frac{f^2}{T_s} \exp\left(-\frac{\Delta(0)}{K_B T_s}\right) + R_o \]

\[ B_c(T_s) \approx 180 \left[ 1 - \left( \frac{T_s}{9.2} \right)^2 \right] \]
Heat Transfer Problem

Assumptions:
• Steady state
• No internal heat generation (surface penetration of B is in the order of nanometers)

\[ q'' = \frac{\Delta T}{R_T} \]
\[ \Delta T = (T_s - T_b) \]
\[ R_T = \left( \frac{e}{k} + \frac{1}{h_k} \right) \]
Thermal-magnetic interactions in defect free cavities

Motivation

- Improved k & h leads to
  - Higher B and thus greater accelerating gradients, and
  - Smaller $T_s$ and thus low $R_s$ providing reduced cryogenic load

Cavity Parameters

- $R_o = 5 \ \text{n}\Omega$
- $e = 3 \ \text{mm}$
- $T_b = 2 \ \text{K}$
- $f = 1.3 \ \text{GHz}$
- $RRR = \frac{\rho_{300\text{K}}}{\rho_{4.2\text{K}}} = 230$

Units:
- $k$: (W/cm/K)
- $h$: (W/cm²/K)
Outline of Experiments

Samples:
- Two cylindrical (RRR 232) – Tokyo Denkai
- Two rectangular flat plates (RRR 390) – FermiLab/Wah Chang
- One single crystal and one bi crystal sample (RRR 280) – JLab/CBMM

Treatments:
- Cylindrical sample 1
  - 3% strain
  - Titanification
- Cylindrical sample 2
  - Surface deformation (SI >3)
  - 750 °C heat treatment
  - Titanification
- Flat plate samples
  - 750 °C heat treatment
  - Titanification
  - RRR measurement
- Single/bi crystal samples (EDM cut)
  - Baseline measurements

For all samples,
- 750 °C heat treatment for 2 hrs – Fermi Lab
- Titanification at 1300 °C for 2 hrs and then at 1200 °C for 4 hrs – Cornell University
Experimental Apparatus

Sample holder assembly qty 2 shown typical
Germainium sensor in LHe
To vacuum pump

C1, C2, C3 Heater

Conflat flange

Flat plate Nb sample

Temperature Sensor

Single Crystal Niobium

Heater

Heat Sink

2006/10/27
Results

Cylindrical sample 1

<table>
<thead>
<tr>
<th></th>
<th>As received (M. polish + light BCP etch)</th>
<th>After 3% strain</th>
<th>Post-titanification</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_k$</td>
<td>–</td>
<td>No change</td>
<td>Increased (~125% at 2.1 K)</td>
</tr>
<tr>
<td>$k$</td>
<td>Phonon peak</td>
<td>No phonon peak</td>
<td>Phonon peak recovered; No improvement above 3 K</td>
</tr>
</tbody>
</table>

Post-titanification:
1300 °C (2 hrs), 1200 °C (4 hrs)
## Results (cont.)

Cylindrical sample 2

<table>
<thead>
<tr>
<th></th>
<th>As received (Machine cut)</th>
<th>After surface deformation</th>
<th>Post-heat treatment 750 °C (2 hrs)</th>
<th>Post-titanification 1300 °C (2 hrs), 1200 °C (4 hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( h_k )</td>
<td>–</td>
<td>Increased (~75%)</td>
<td>Increased (~100%)</td>
<td>Increased (~30%)</td>
</tr>
<tr>
<td>( k )</td>
<td>Phonon peak</td>
<td>No phonon peak</td>
<td>No significant recovery of phonon peak</td>
<td>Phonon peak recovered; No improvement above 3 K</td>
</tr>
</tbody>
</table>
**Results (cont.)**

Flat plate samples

<table>
<thead>
<tr>
<th></th>
<th>As received</th>
<th>Post-heat treatment</th>
<th>Post-titanification</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>750 °C (2 hrs)</td>
<td>1300 °C (2 hrs), 1200 °C (4 hrs)</td>
</tr>
<tr>
<td>$k$</td>
<td>No phonon peak</td>
<td>Slight increase @ &lt; 2.5 K</td>
<td>Phonon peak recovered; significant decrease &gt; 2.5 K</td>
</tr>
</tbody>
</table>

- Post-titanification thermal conductivity measurements suggest $RRR \sim 80$
- Post-titanification expectation of $RRR \sim 600$
- Twice repeated $RRR$ measurements in samples cut from same plate indicate $RRR \ 67 \pm 20\%$ confirming above measurements
Results (cont.)

Single/Bi crystal samples (RRR 280)

- Reduced phonon contribution observed in either sample
- Both samples to be annealed and re-tested
Plastic deformation caused the phonon peak to disappear
   - Thermal conductivity of Nb decreased by ~80% at 2 K

Annealing at ~750 °C for 2 hrs insufficient to recover the phonon peak

Annealing at ~1200 – 1300 °C for 6 hrs during titanification recovers the phonon peak

Kapitza conductance persistently increased after each heat treatment
   - Total increase is ~300% at 2.1 K due to annealing and titanification

Post titanification RRR of flat plate sample 67 ± 20 %
Recommendations / Future Steps

- Numerical simulations demonstrate the importance of $k$ and $h$ in the performance improvement of defect free SRF cavities.

- Titanification found to be the single most important step to improve both $k$ and $h$ of the SRF cavities.

- Re-purification of flat plate samples.

- Low and moderate temperature annealing of single and bi-crystal samples.
Questions ?