Effect of Heat Treatment Temperature on the Thermal Conductivity of Large Grain Superconducting Niobium

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The heat needs to be dissipated into surrounding liquid helium to maintain the bulk temperature below $T_c$

- Imperfections in the Nb surface result in local heating
Conduction in Nb at 2 – 4.2 K is a function of

- purity
- imperfection density
- grain size
- grain orientation?
Motivation for this study

- Need to relate thermal conductivity $k$ with
  - metallurgy
    - e.g., grain size, grain orientation, purity
  - processing history
    - e.g., deformation, heat treatments

- Doing so
  - Allows prediction of thermal response of final device
  - $k$ can be used as a diagnostic tool
    - e.g., imperfection density, purity
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Model for $k$

$$k(T) = R(y) \left[ \frac{\rho_{295}}{LRRR T} + aT^2 \right]^{-1} + \left[ \frac{1}{D e^{-y} T^2} + \frac{1}{B \lambda T^3} \right]^{-1}$$

- $\rho_{295}$ – electrical resistivity at 295 K
- $L$ – Lorentz constant
- RRR – ratio of electrical resistivity at 295 K to that at 4 K
- $a$ – coefficient of momentum exchange with lattice
- $D$ – quantifies phonon scattering by electrons
- $B$ – value from Casimir for scattering at crystal boundaries
- $\lambda$ – phonon mean free length
- $y \approx \alpha T_c / T$

Parameters to be estimated

\[ k(T) = R(y) \left[ \frac{\rho_{295}}{LRRR} T + aT^2 \right]^{-1} + \left[ \frac{1}{De^{-y} T^2} + \frac{1}{B\lambda T^3} \right]^{-1} \]

\[ \Downarrow \]

\[ k(T) = R(y) \left[ \frac{\beta_1}{T} + \beta_2 T^2 \right]^{-1} + \left[ \frac{\beta_3}{e^{-y} T^2} + \frac{\beta_4}{T^3} \right]^{-1} \]

and

\[ y \approx \alpha \frac{T_c}{T} \]

\[ \Downarrow \]

\[ y \approx \beta_5 \frac{T_c}{T} \]
Specimen History: Set 1 – Different ingots

- Large grain specimens
- Unstrained specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Est. RRR</th>
<th>Ta content (ppm)</th>
<th>First heating</th>
<th>Second heating</th>
</tr>
</thead>
<tbody>
<tr>
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<td></td>
<td></td>
<td>$T_h$ ($^\circ$C)</td>
<td>$t$ (hrs.)</td>
</tr>
<tr>
<td>1</td>
<td>191</td>
<td>1275</td>
<td>600</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>131</td>
<td>668</td>
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<td>3</td>
<td>190</td>
<td>756</td>
<td>750</td>
<td>2</td>
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<tr>
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<td>756</td>
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<td>2</td>
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<tr>
<td>5</td>
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<td>1322</td>
<td>800</td>
<td>2</td>
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<tr>
<td>6</td>
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<td>140</td>
<td>48</td>
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<tr>
<td>8</td>
<td>200</td>
<td>704</td>
<td>140</td>
<td>48</td>
</tr>
</tbody>
</table>
Thermal conductivity: \( T_h = 140 \, ^\circ\text{C} - 800 \, ^\circ\text{C} \)

- \( k_{pp} \) dependent on heat treatment temperature
- 140 \(^\circ\text{C}, 48\) hrs.: no change in bulk
Thermal conductivity: $T_h = 1100 \, ^\circ C$

- $k_{pp}$ shows dependence on RRR
- $k$ for all specimens: too many variables
Specimen History: Set 2 – Same ingot disc

- Reduce extraneous factors affecting $k$
- Specimens cut from one grain, same orientation w.r.t. heat flow
- Unstrained specimens

<table>
<thead>
<tr>
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<tr>
<td></td>
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<td>$t$ (hrs.)</td>
<td>$t$ (hrs.)</td>
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<td>9</td>
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<tr>
<td>12</td>
<td>141</td>
<td>1357</td>
<td>1200</td>
<td>-</td>
</tr>
</tbody>
</table>
No change in $k$ after 600 °C, 2 hrs.

Similar $k_{pp}$ for 1000 °C & 1200 °C
Sigmoidal dependence on temperature
Plateau above 1000 °C?
1100 °C, 4 hrs. data supports plateau

All data from unstrained LG Nb
Lower $\beta_4$ with increasing heat treatment temperature

Asymptotic convergence
Local average misorientation

- Dislocation recovery at the surface
- 0.005° bins used
Conclusions

- 140 °C, 48 hrs.; 600 °C, 2 hrs.: no change in $k$
- $k_{pp}$ shows dependence on RRR
- $k_{pp}/k_3$ shows sigmoidal dependence on $T_h$
- Possible plateau in $k_{pp}/k_3$ for $T > 1000$ °C
  - For unstrained LG Nb
- Rate constants may be estimated from Set 2
- $T < 1000$ °C, longer $t$ could reproduce max. $k_{pp}/k_3$
  - Economically beneficial
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