Thermal Conductivity of Ingot Niobium – Estimating with Processing History

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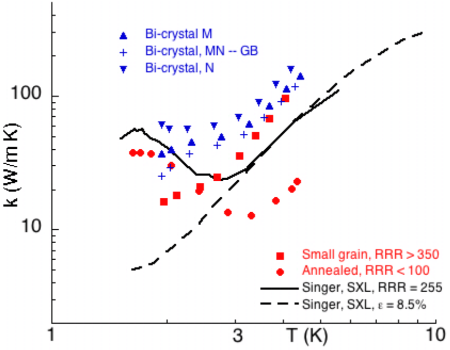
Thermal Conductivity of Superconducting Nb

Conduction in Nb at
2 – 4.2 K is a function of

- purity
- imperfection density
- grain size
- grain orientation?

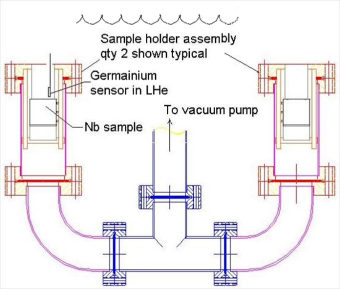


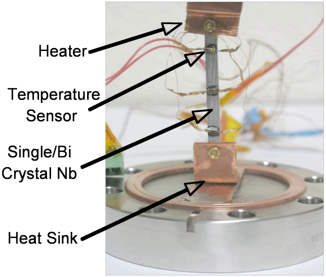
Motivation for this study

- Need to relate thermal conductivity k with
  - metallurgy
  - processing history
- Doing so,
  - Allows prediction of k in final cavity
  - k can be used as a diagnostic tool

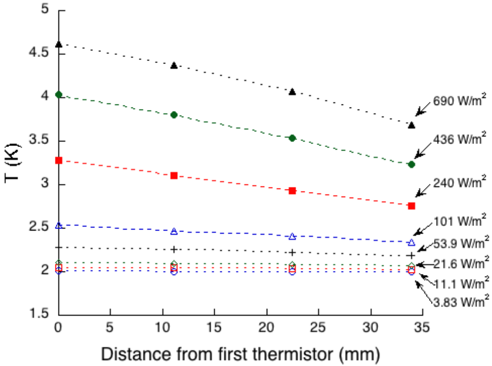
Measurement Apparatus

- Steady state temperature profile measured
- Apparatus can accommodate 4 samples
- Ge and C resistors used to measure temperature
- 3 – 4 sensors on each sample
- Apparatus tested in LHe Dewar at 1.5 – 1.9 K





Temperature data



- Points represent thermistor temperature measurements
- Dotted lines assume uniform conductivity between the sensors
- Thermal conductivity estimated by $k = -\frac{q''}{dT/dx}$

Model for k

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

- ρ_{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 within lattice
- D – quantifies phonon scattering by electrons
- B – value from Casimir for scattering at crystal boundaries
- λ – phonon wavelength
- $y \approx \alpha T_c / T$

Ref.: F. Koechlin and B. Bonin, Supercond. Sci. Technol. **9** (1996)

- Method often used

$$T \text{ and } q'' \text{ measurements}$$
$$\downarrow$$
$$\text{Estimate } k \text{ using } k = -\frac{q''}{dT/dx}$$
$$\downarrow$$
$$\text{Estimate parameters using model}$$

- Current method

$$T \text{ and } q'' \text{ measurements}$$
$$\downarrow$$
$$\text{Estimate parameter groups directly using model}$$

Ref.: S.K. Chandrasekaran *et al.*, Therm. Cond. **30** (2009)

Parameters to be estimated

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

$$\Downarrow$$

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

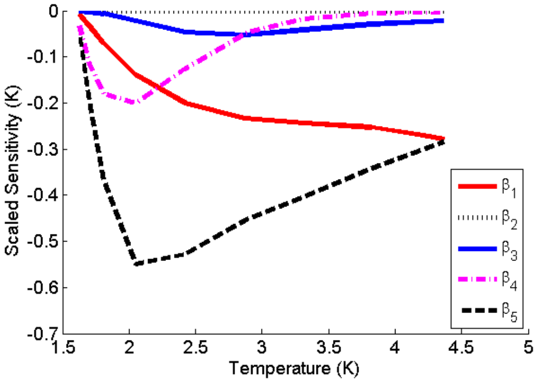
and

$$y \approx \alpha\frac{T_c}{T}$$

$$\Downarrow$$

$$y \approx \beta_5\frac{T_c}{T}$$

Scaled Sensitivity Coefficients



- Sensitivity coef.:

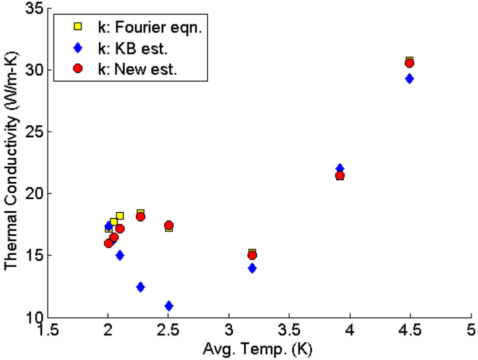
$$\gamma_i = \beta_i \frac{\partial T}{\partial \beta_i}$$

- $\beta_1 = \frac{\rho_{295}}{LRRR}$
- $\beta_2 = a$
- $\beta_3 = \frac{1}{D}$
- $\beta_4 = \frac{1}{B\lambda}$
- $\beta_5 = \alpha$

Specimens Analyzed

- Parameters estimated from
  - 15 ingot specimens with $70 \leq \text{RRR} \leq 450$
  - As rec'd condition
  - 2 specimens heat treated at 600 °C, 6 hrs
  - 4 specimens heat treated at 750 °C, 2 hrs
  - 2 specimens heat treated at 800 °C, 2 hrs
- Not presented here
  - 2 specimens heat treated at 140 °C, 48 hrs
  - 2 specimens from zone melted tube

Example: Sample A



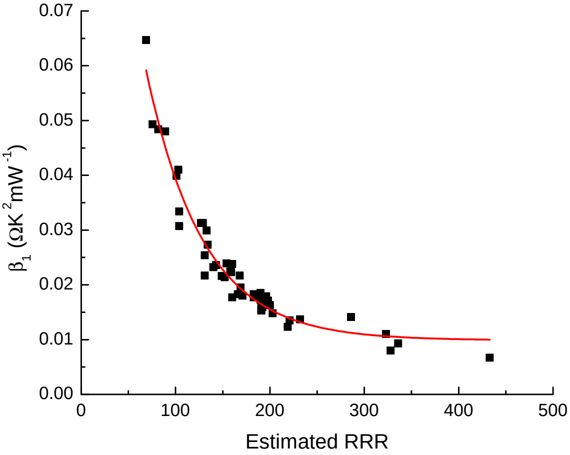
K & B method

- $\beta_1 = 0.058\ \Omega K^2 mW^{-1}$
- $\beta_3 = 234.0\ mK^3 W^{-1}$
- $\beta_4 = 0.076\ mK^4 W^{-1}$
- $\beta_5 = 1.530$

New estimates

- $\beta_1 = 0.033\ \Omega K^2 mW^{-1}$
- $\beta_3 = 404.083\ mK^3 W^{-1}$
- $\beta_4 = 0.447\ mK^4 W^{-1}$
- $\beta_5 = 2.045$

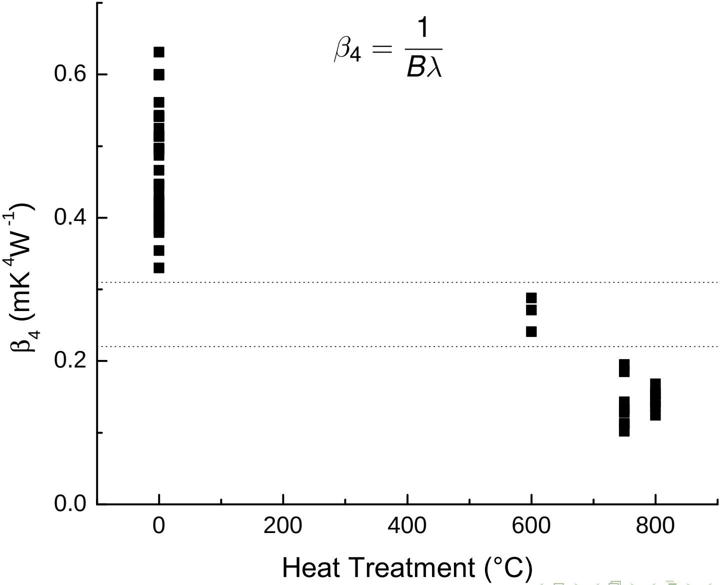
β_1 and RRR



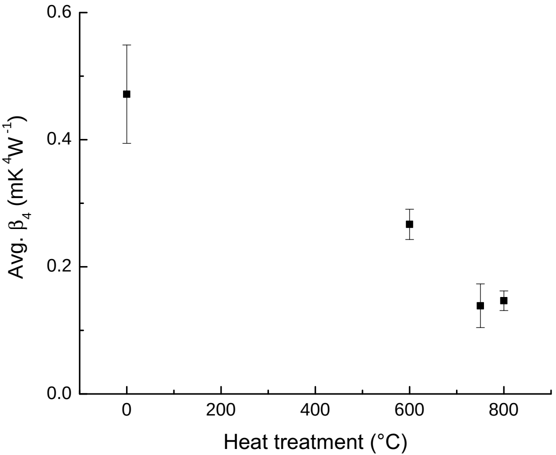
$$\beta_1 = \frac{\rho_{295}}{L\mathrm{RRR}}$$

- β_1 floats from initial guess
- Estimated relationship gives confidence in reduction

β_4 and Heat Treatments



β_4 and Heat Treatments



$$\beta_4 = \frac{1}{B\lambda}$$

0 °C→ As rec'd
600 °C→ 6 hrs.
750 °C→ 2 hrs.
800 °C→ 2 hrs.

- Lower β_4 with increasing heat treatment temperature
- As rec'd specimens exhibit greater thermal resistance

Conclusions

- k of superconducting Nb is a function of material processing
- Koechlin and Bonin good starting point – but more needed
- New parameter estimation technique skips intermediate step
- β_1 - RRR relation gives confidence
- Data shows strong relationship between β_4 and heat treatments
- Greater β_4 values for as rec'd – Residual stresses from ingot production?

Conclusions

- Refine specimen characterizations
  - grain orientations
  - mis-orientation map and angle
- Other heat treatment protocols are being characterized
  - 140 $^\circ$C, 48 hrs
  - 600 $^\circ$C, 10 hrs
- More data at high temperature
  - Capture the kinetics of heat treatment
- Correlation with mechanical properties sought

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