Introduction talk on SRF issues about materials and surfaces

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Outline

Materials and surfaces
• Surface roughness
• Impurities
• Oxide
• Grain boundaries
• Thermal properties

RF Superconducting properties
• Breakdown field
• Surface resistance
Surface roughness

- Cause magnetic field enhancement → lower breakdown field
- More difficult to clean → lower field emission onset

- The equator weld is typically the roughest area of the cavity
- Large steps at grain boundaries
Surface roughness (2)

- It has been shown that the field enhancement at a grain edge causes a quench\(^1\)
- In some cases, cavities with rough-looking surface achieve very high magnetic field\(^2\)

\[\text{Quenched at 170 mT}\]

- Smoother surfaces obtained with EP on polycrystalline Nb or BCP on single-crystal

\(^1\)S. Berry, C. Antoine, M. Desmons, *Proc. of the 2004 EPAC*, p. 1000

\(^2\)B. Visentin et al., Proc. of the 2003 SRF Workshop, MoP19
Surface roughness (3)

- Reduce roughness of the equator weld by barrel polishing

\[ S_q = 251 \text{ nm on 200x200 } \mu\text{m}^2 \text{ area} \]

- Use EP on polycrystalline Nb, BCP on single-crystal

\[ S_q = 27 \text{ nm on 200x200 } \mu\text{m}^2 \text{ area} \]

Courtesy T. Saeki

Courtesy A. Wu
Surface roughness: issues

- What is the most meaningful way to describe it?
- Surfaces with similar roughness but different field enhancement
- What scale is important? How to maintain it on m² areas?

C. Antoine, Proc. of the Single Crystal Nb Workshop, to be published
Impurities

- Most common in Nb are Ta, H, O, N and C
  - Clusters of nitride, carbide or tantalum caused quenches in cavities made of reactor-grade Nb
  - Interstitial oxygen depresses superconductivity in Nb (reduction of $T_c$, $\Delta$, $H_c$
  - Metallic suboxides are suspected to reduce $\Delta$, $H_c$ and contribute to the $R_{\text{res}}$
  - Metallic hydrides contribute to high values of $R_{\text{res}}$
Impurities - Tantalum

- Current specification requires < 500 wt. ppm
- In a recent study of BCP treated single-cells made from Nb sheets with 150 < Ta conc. < 1300 wt. ppm showed no significant difference in performance (quench at 120 – 160 mT, no correlation with Ta content)

- If Ta is uniformly distributed, it does not seem to affect the performance of Nb cavities: can the specification be relaxed and reduce the cost of Nb?

3P. Kneisel et al., Proc. of the 2005 PAC, p. 3955
Impurities - Hydrogen

• It is difficult to have consistent results on hydrogen distribution in Nb by surface analytical methods due to:
  – High affinity with Nb
  – High mobility in Nb
  – Main residual gas in a vacuum system
• The bulk concentration should be < 5 wt. ppm to avoid hydride precipitation (increase RF losses by orders of magnitude)
• Tends to segregate at the surface in the presence of other impurities and crystallographic defects
Impurities – Hydrogen (2)

1) ERDA (C. Antoine et al., Proc. of the 1991 SRF Workshop, p. 616)
2) SIMS (F. Stevie et al. Proc. of the Single Crystal Nb Workshop, to be published)
3) NRA (W. Lanford et al. Proc. of the 2003 SRF Workshop, WeO14)

~ 40 at. %

~ 60 at. %

1) ERDA (C. Antoine et al., Proc. of the 1991 SRF Workshop, p. 616)
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Impurities – H – issues

- Very high hydrogen concentrations were found at the Nb/oxide interface, some reduction was observed after low-temperature baking:
  - are there issues with the detection methods?
  - does H play any role in high-field losses (Q-drop)?
  - what is the contribution of hydrogen to $R_{\text{res}}$ (small amount of hydrides)?
**Impurities - Oxygen**

- Interstitial oxygen has been the prime suspect to cause the Q-drop
  - High concentrations ($\sim 10$ at. %) were found at the Nb/oxide interface
  - The theoretical diffusion length is $\sim 40$ nm at $120$ °C/48 h, compatible with mean free path variation measured on baked cavities
**Impurities – Oxygen – Issues**

- There is no clear evidence of oxygen diffusion during 120 °C bake, as measured by SIMS.
- A large-grain cavity which was baked in air at 120 °C showed reduced Q-drop up to 140 mT.

![Graph](image)

**SIMS results on sample**

**Single-cell results**
Niobium oxide

- Studied since 1975, always been suspected of degrading niobium SRF properties (Quench field, Q-drop, $R_{\text{res}}$)
- Recent work by XPS, TEM, APT show that:
  - There are no extended “layers” of sub-oxide between $\text{Nb}_2\text{O}_5$ and Nb

Niobium oxide (2)

- $\text{Nb}_2\text{O}_5$ is like an oxygen “sponge”: thinned by UHV baking, back to initial thickness when exposed to air

X-Ray Photoelectron Spectroscopy

H. Tian, this workshop
Niobium oxide (3)

– well defined metal/oxide interface

TEM on polycrystalline Nb


F. Stevie et al., private communication
Niobium oxide - issues

- There are no indications that Nb$_2$O$_5$ degrades SRF properties of Nb

- The oxide/metal transition is thin (1-2 nm) and non-uniform
  - what kind of structure? Is it changed by baking?
  - is the increase of $R_{\text{res}}$ after UHV baking due to this interface modification?
Grain boundaries

- Regions of degraded superconducting properties (depairing current density, $R_{\text{res}}$) due to preferential segregation of impurities such as O, H, C.

- Abrikosov-Josephson vortices can diffuse into grain boundaries at fields $<< H_{c1}$, causing field-dependent RF losses

- The type of vortices and the depairing current density depend on the grain boundary angle\(^4\)

Grain boundaries (2)

- No major difference was found in the performance of single-cell cavities with the same shape made from polycrystalline, large-grain and single-crystal Nb.\(^5\)

\[
\begin{array}{c}
\begin{array}{c}
\text{Eacc (MV/m)} \\
0 & 5 & 10 & 15 & 20 & 25 & 30 & 35 & 40 \\
\hline
\end{array}

\begin{array}{c}
\text{单晶} & \text{大晶粒} & \text{细晶粒} \\
\hline
1E+11 & 1E+10 & 1E+9 \\
\end{array}

\end{array}
\]

BCP, post-purified and baked

\(^5\)G. Ciovati et al. Proc. of the 2006 LINAC, paper TUP033

- The results from ~ 30 RF tests on a large-grain SC show that only ~ 40% of all hot-spots occurred near or on a GB.\(^6\)

\(^6\)G. Ciovati et al., submitted to Phys. Rev. STAB.
Grain boundaries – Issues

- A systematic study of the flux-flow characteristic of Nb grain boundaries for different misorientation angles and surface treatments may help clarifying the mechanism and strength of anomalous RF losses
Thermal properties

• For the same surface resistance, thermal properties determine the quench field due to thermal feedback

\[ T_m - T_s \] must be kept as small as possible: high thermal conductivity and Kapitza conductance

Thermal properties (2)

- The Kapitza resistance is reduced for rougher surfaces, it accounts for \( \sim 40\% \) of the total thermal resistance at 2 K for RRR\( \sim 200 \) Nb and \( \sim 70\% \) for RRR\( \sim 600 \) Nb\(^7\)

Thermal properties - issues

• There is no “standard” preparation of the outer surface of Nb cavities

• Post-purification with Ti (RRR~500) improves the quench field in BCP treated cavities, even large-grain ones. However, cavities treated by EP achieved $B_p \sim 180\text{mT}$ without post-purification.
  – is the quench of “magnetic” or “thermal” origin?
Conclusions

• Several issues concerning bulk and surface properties of Nb need to be addressed to reliably achieve $B_p$-values $>\sim 140\text{mT}$ in SRF cavities:
  – what roughness "scale" is important and how to maintain it on very large areas?
  – what is the optimum point in the curve cost-purity-performance for Nb?
  – what is the role of hydrogen and of the metal/oxide interface in high field losses and residual resistance?
  – how small is the contribution of grain-boundaries to the cavity performance?
  – How to minimize the Kapitza resistance?