Surface Studies on Niobium
for Superconductivity Radio Frequency (SRF) Accelerator

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Abstract

Niobium rf superconductivity is a nanoscale, near-surface phenomenon because of the shallow rf penetration depth. Accordingly, the performance of Nb SRF accelerator cavities is strongly impacted by the topmost few nanometers interior surface, especially as impacted by the final surface conditioning treatments. Removal of residual fabrication damages by etching with the buffered chemical polish (BCP) approach is being displaced by electropolishing (EP) to obtain smoother surfaces. Improved performance desired for new accelerator projects is believed to result, but detailed process understanding is needed.

Surface topography impacts performance through local loss of superconductivity (quenches) caused by intrusion of the rf magnetic field, which is enhanced at sharp protrusions. "Sharpness" comprises both vertical and lateral aspects, requiring development a new characterization approach beyond the familiar roughness measurements (R_a, R_z), which view only the vertical component. Stylus profilometry and atomic force microscopy (AFM) traces view surface topography from mm size to near atomic dimensions. Power spectral distribution (PSD) analysis combines data across this whole dimensional scale, so that the effect of preparation variables on topography has been studied systematically for the first time.

Surface chemistry impacts performance through the presence of a complex surface oxide structure and the response of the surface to post-treatments, notably low temperature baking (e.g., 125°C, 24 hrs). Previous XPS studies consistently found that the surface chiefly comprises a few nm of Nb_2O_5 on top of Nb metal, with small amount of Nb suboxides near the interface. Efforts to unambiguously discern the variation of composition with depth in the surface region by angle-resolved (variable take-off angle) XPS have been confounded by the effect of surface roughness. The problem was avoided here by, for the first time, using a synchrotron source to vary x-ray photon energy at fixed take-off angle, obtaining a range of sample depths in a fixed column of material spanning the oxide layer thickness. One result is that variation of etching practice chiefly affects the thickness of the top Nb_2O_5 layer, but the sub-oxide accommodation zone at the interface remains substantially constant. A second is that low temperature baking in vacuum results in significant thinning and reduction of the oxide layer, which is completely recovered on subsequent air exposure without loss of the SRF performance improvement.

The effect of the most commonly employed treatment-BCP on polycrystalline niobium sheet over a range of realistic solution flow rates has been examined through multiple surface characterization techniques. The surface exhibits micron-scale roughness, whose extent does not change with treatment conditions. The outermost surface consists of a few-nm thick layer of Nb_2O_5, whose thickness increases with solution flow rate to a maximum of 1.3~1.4 times that resulting from static solution.

Electropolishing is believed to be an effective technique to treat niobium cavity surfaces for achieving reproducibly high performance SRF cavities. However the operation condition is basically optimized through practical processing. The microscopic understanding is lacking. By using improved electrochemical techniques, the temperature, flow rate and HF concentration dependence of each potential were indentified. The first use of electrochemical impedance spectroscopy (EIS) on this system was reported. EIS results are consistent with the compact salt film mechanism for niobium electropolishing in hydrofluoric sulfuric acid electrolyte and do not supports either the porous salt film or the absorbate-acceptor mechanism. Microscopic understanding of the basic Nb EP mechanism is expected to provide an appropriate foundation with which to optimize the preparation of high-field niobium cavity surfaces.