UPDATE ON Nb₃Sn PROGRESS AT CORNELL UNIVERSITY

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Abstract

Niobium-3 Tin (Nb₃Sn) is the most promising alternative material for SRF accelerator cavities. The material can achieve higher quality factors, higher temperature operation and potentially higher accelerating gradients compared to conventional niobium. Cornell University has a leading program to produce 2 - 3 micrometer thick coatings of Nb₃Sn on Nb for SRF applications using vapor diffusion. This program has been the first to produce quality factors higher than achievable with conventional Nb at usable accelerating gradients. Here we present an update on progress at Cornell University, including studies of the formation of the Nb₃Sn layer, density functional theory calculations of Nb₃Sn growth, and designs for a sample host cavity for measuring the quench field of Nb₃Sn.

INTRODUCTION

Nb₃Sn is a promising alternative material for SRF accelerator cavities due to a $T_c$ of 18 K and a superheating field of $\approx$ 400 mT [1]. This allows for higher quality factors, higher temperature operation, and for accelerating gradients twice that of conventional niobium. Cornell University has a program for creating Nb₃Sn cavities using vapor deposition of tin onto a niobium cavity to form a 2 - 3 μm Nb₃Sn layer [1–5]. Current Nb₃Sn cavities produced at Cornell achieve $Q \approx 10^{10}$ at 4.2 K and $\approx 16$ MV/m in continuous wave operation [6].

The superheating field of niobium suggests that the maximum achievable accelerating gradient for a 1.3 GHz TESLA style cavity should be $\approx 90$ MV/m, far higher than what is currently achieved. Klystron pulsed test measurements and T-mapping show that the maximum gradient is being limited by thermal quench at a defect [7]. Two main candidates have been suggested: flux vortex entry at particularly vulnerable grain boundaries [8]; and areas of tin depleted Nb₃Sn where the atomic percentage of tin is lower, causing the superheating field to be suppressed [7].

The tin depleted sites can appear both on the surface of the Nb₃Sn and within the layer (see Fig. 1). The surface depletions sites are likely formed late in the coating process after all free tin has been used and tin starts being pulled from the surface to form Nb₃Sn at the Nb-Nb₃Sn interface. The tin depletion defects within the Nb₃Sn are often deep enough to be shielded from the RF, but any chemical polishing to reduce surface roughness or remove surface defects could expose the tin depleted sites. For this reason, it is critical to deal with the tin depleted defects both on the surface and in the bulk.

Figure 1: An EDS cross-section of a Nb₃Sn layer showing a tin depleted region within the Nb₃Sn layer.

Here we present an update on progress at Cornell University towards increasing the maximum accelerating gradient. This paper primarily concerns itself with studying how the Nb₃Sn layer forms through both experimental and theoretical methods, so that coating methods can be changed to suppress the formation of defects. A brief update is included on the development of a high field sample host cavity to measure the quench field of Nb₃Sn and other materials.

Nb₃Sn GROWTH PROCESS

The most successful method to create SRF suitable Nb₃Sn is vapor deposition of tin onto niobium, in which a niobium cavity is placed in a high temperature vacuum furnace and then tin is vaporized at a high temperature and allowed to absorb into the niobium [4]. This is done at a temperature $> 1000$ °C where, in a tin rich environment, only Nb₃Sn and liquid tin may form. SnCl₂ is used to nucleate tin onto the surface of the cavity. Cornell uses a secondary heater to heat the tin source to increase the vapor pressure of tin separate from the Nb₃Sn growth rate, allowing the availability of tin to be controlled and increase the availability of tin while the temperature is ramping up. A typical coating temperature profile is shown in Fig. 2.

LAYER GROWTH STUDIES

In order to understand how defects on the surface form, and in order to find ways of altering the coating process to remove defects we are examining how the Nb₃Sn layer forms. This is done by placing niobium samples in our coating furnace and stopping the coating at various temperatures while the temperature is increasing from the nucleation temperature to the coating temperature; a process we believe is critical to the formation of a good Nb₃Sn layer.
Figure 2: Temperature during Nb$_3$Sn coating showing both the cavity and the tin source temperatures. Not shown is a 24 hr degas period at 180°C prior to nucleation.

Figure 3 growth shows false colored SEM images of the surface of these samples for two different surface preparations before coating: a normal BCP niobium surface, and a BCP niobium surface that has been anodized to form a $\approx 70$ nm oxide, which has been previous shown remove certain surface defect and decrease the surface resistance [6]. These samples were coated in pairs, ensuring that the cutoff temperatures were identical.

As the layer grows, for both sets of samples, we can first see tin on the surface, then see structures start to form on the surface. At certain temperature these structures break down into multiple grains: likely an indication that another Nb-Sn compound has formed, and then underwent a phase transition at a critical temperature. Eventually a thin Nb$_3$Sn layer has formed.

Interestingly, anodization significantly changes the surface morphology of the samples. The anodized samples appear to have more tin (red and purple in nucleation images) on the surface after nucleation. The crystal structures on the surface are much larger on the anodized samples. This could be indicative of more tin gathering on the surface before the Nb$_3$Sn starts to form by the oxide either: acting as a barrier that must be destroyed before Nb$_3$Sn can form, or by somehow encouraging the depositing on tin early in the process. In the end the unanodized surface forms a large, thin crystal grain (highlighted in green), which is too thin to fully shield the RF, resulting in increased losses.

GROWTH DYNAMICS

Density Functional Theory calculations have improved our understanding of how tin-depleted regions form in Nb$_3$Sn. We model the phase as an A15 crystal in which niobium substitutional defects can occupy tin lattice sites, thus allowing for tin depletion. Using the cluster expansion method with Monte Carlo sampling, we can calculate the equilibrium concentration of these defects, and therefore the equilibrium stoichiometry of the phase, as a function of temperature and tin chemical potential.

This calculation accurately reproduces the experimentally observed stoichiometry range and indicates that the tin depletion defects should tend to spread evenly throughout the crystal due to repulsive pairwise interactions, not cluster at any preferred density as observed. This suggests that the tin depleted regions we observe in our layers are likely a result of kinetic processes, in particular varying tin chemical potential during layer growth, rather than phase separation.

Based on this result, we plan to alter our coating procedure to ensure a steady supply of liquid tin to the growing layer, thereby maintaining the tin chemical potential at a level conducive to tin-rich Nb$_3$Sn growth (see Fig. 4). We hope to verify that doing so indeed prevents the formation of tin-depleted regions in Nb$_3$Sn.

HIGH FIELD SAMPLE HOST CAVITY

Advancing the accelerating gradient will require testing multiple coating processes to find the correct recipe and give feedback to growth models. For this reason, we are creating a sample host cavity to measure the quench fields of our
added bonus that it will allow us to probe further into the thermal runaway, allowing for us to better experimentally determine the superheating field in quench field vs temperature tests [7]. A transmitted power coupler has also been added and has negligible impact on the field distribution.

Due to the host cavity being made from copper, the sample must be thermally isolated from the host. This is accomplished by creating a gap between the sample and the host. This requires the addition of a second chamber and supporting the sample on a rod. Previous work showed that the use of a sapphire support rod is needed to reduce the field in the bottom cavity [10]. Thermal simulations show that the thermal transport through the sapphire rod is sufficient to prevent thermal runaway on the time scale of the pulse lengths, and the pulse repetition rate is slow enough to allow for the sample to return to the bath temperature between pulses.

**CONCLUSION**

The layer growth studies demonstrate the complexities of the forming Nb$_3$Sn layer and show a promising first step to understanding how the layer forms and is changed by different coating recipes. These layer growth studies will be used to inform the development of growth models. Surface analysis is currently underway to determine the compounds that are present on the surface during the layer formation. Density functional theory calculations are providing great insight into the formation of the Nb$_3$Sn layer. Current results suggest we could eliminate tin depleted defects within the Nb$_3$Sn layer.

The development of a sample host cavity for testing quench fields will lead to a useful tool in advancing the accelerating gradient. The electromagnetic, structural and thermal simulations of this cavity are complete, but a few final design considerations must be completed. Soon design schematics will be made and construction will commence.

**REFERENCES**

[1] S. Posen and D. L. Hall, "Nb3Sn Superconduction Radiofrequency Cavities: Fabrication, Results, Properties, and


