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RECENT PROGRESS IN Nb_3Sn SRF CAVITY DEVELOPMENT AT CORNELL*

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Abstract

Nb_3Sn coatings on niobium SRF cavities have the potential to significantly reduce cryogenic costs due to their extremely small surface resistance (R_s). In this paper, we present new results showing the repeatability of Cornell's fabrication process, which produces high Q_0 cavities that reach medium fields with minimal Q-slope. We also show the results of attempts to smooth RF surfaces and reduce defects via material removal. However, both HF rinsing and centrifugal barrel polishing resulted in strong performance degradation.

INTRODUCTION

Nb_3Sn is a material that has the potential to have a transformative impact on superconducting RF. Due to its large critical temperature (T_c) of approximately 18 K, Nb_3Sn cavities can have far smaller R_s values at a given temperature than standard $T_c \sim 9$ K Nb cavities. Pioneering work into developing Nb_3Sn for SRF applications was performed by Siemens AG [1], Kernforschungzentrum Karlsruhe [2], University of Wuppertal [3], Cornell University [4], Jefferson Lab [5], CERN [6], and SLAC [7], and we are building on their work at Cornell [8] [9].

Until recently, 4.2 K Nb_3Sn R_s values on the order of 10 nΩ were obtained only at very small accelerating gradients $E_{acc} \sim 5$ MV/m, above which a strong increase in R_s with field occurred (called Q-slope for the decrease in quality factor with E_{acc}). However, in 2013, a Cornell Nb_3Sn cavity maintained $R_s \sim 10$ nΩ up to fields ~ 13 MV/m. With the strong Q-slope removed, the limit for high-field high-Q operation was quench at medium fields. The maximum field obtained is promising and already useful for some applications, but it is still well below the ultimate potential of the material. It would be desirable to understand the limitation so that the maximum field can be increased.

For an ideal surface, the magnetic field should be limited only by the superheating field of the material. A real surface will have some amount of disorder, and if the size of this disorder is similar to the coherence length ξ, it can lead to a reduction in the energy barrier to vortex penetration. With $\xi \sim 4$ nm [9], our Nb_3Sn cavities are much more vulnerable to small-scale disorder than niobium cavities that have received electropolish/120 C bake, which have $\xi \sim 20$ nm [10]. It is therefore possible that the maximum field would be increased by removing defects from and smoothing the Nb_3Sn surface. Material removal could accomplish this, though it would have to be very light, as the layer is only a few microns thick.

Previous researchers attempted to use oxipolishing on low-R_s Nb_3Sn cavities [5], a removal method that had been used previously to improve performance in Nb_3Sn cavities with excess Sn [11]. However, they observed a decrease in Q_0 and the onset field for strong Q-slope.

RF RESULTS

The performance of the Cornell Nb_3Sn cavity that maintained $R_s \sim 10$ nΩ up to fields ~ 13 MV/m is shown in Fig. 1. After coating, it was treated only with a high pressure water rinse (HPR) before RF test. After testing, it was given five cycles of HF rinsing, each of which consisted of filling the cavity with HF and leaving it for 2 minutes, emptying it, filling it with water and leaving for 5 minutes to regrow the oxide layer, and then emptying it again. This procedure should cause a very uniform, light removal, similar to oxipolishing. The total removal is expected to be on about 30-50 nm. Afterwards, the cavity was high pressure rinsed and tested again. A strong degradation was observed (Fig. 1), similar to that reported from oxipolishing. R_s increased strongly with B_{pk}, even though the material removal was very light. The maximum field was limited by RF power.

After the performance degradation from HF rinsing, the Nb_3Sn layer was fully removed with a 10-micron buffered chemical polish (BCP). It was then given HPR and recoated with the same parameters as the previous coating and tested again. The performance was very similar (Fig. 1), showing the repeatability of the coating procedure to obtain small R_s values up to medium fields, where quench occurred. Similar to the first test, an array of temperature sensors around the cavity during testing (T-map) revealed that the quench location was a small region where magnetic fields are very near the peak value. This is shown in Fig. 2.

Material removal was again used to attempt to smooth the surface and remove any quench-inducing defects. For the first time, centrifugal barrel polishing (CBP) was used on a Nb_3Sn cavity. Only the finest polishing step of the standard niobium recipe [12] [13] was used. Shown in Fig. 3, 40 nm colloidal silica with wood blocks were put into the cavity, and it was barrel polished for 4.5 hours (to be cautious not to remove too much material, this is much shorter than 40-300 hour duration given in the recipe). Afterwards, it was given an HPR and tested, yielding an even stronger performance degradation than after the HF rinses (Fig. 1). The maximum field was again limited by RF power. If this were a niobium cavity, there would be a concern that CBP would cause significant uptake of hydrogen that could cause

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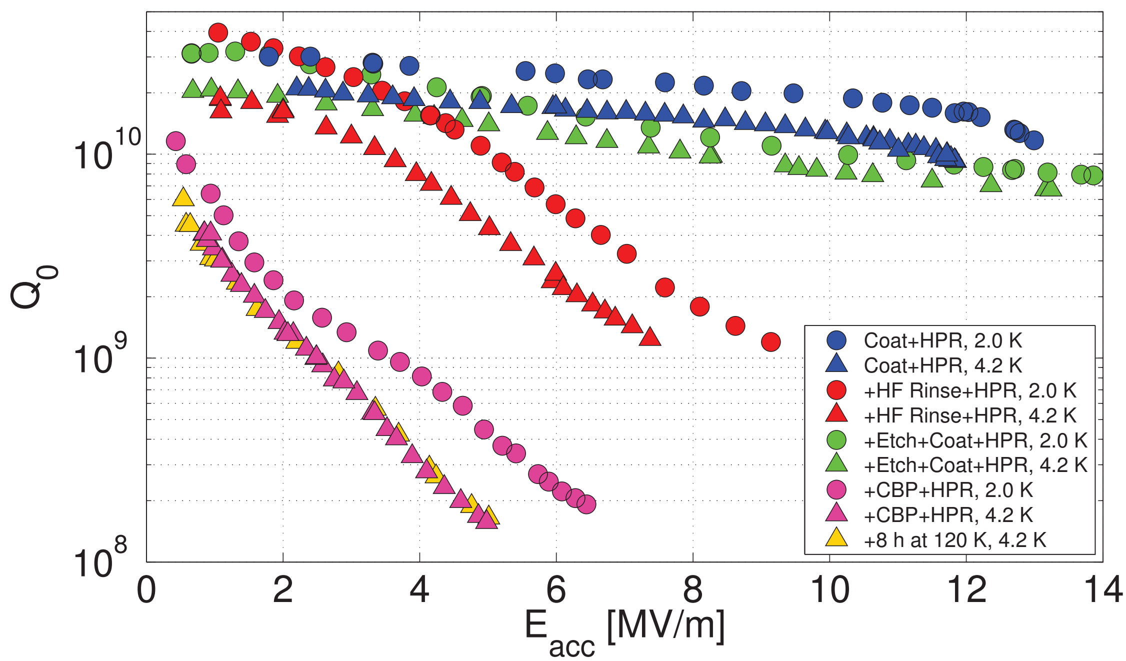

Figure 1: Q vs E curves of the Cornell Nb_3Sn cavity at 2 K and 4.2 K after each treatment. Both HF rinse and barrel polishing result in a strong increase in Q-slope. The small-Q-slope performance was recovered after an acid etch to reset the niobium surface and re-coating.

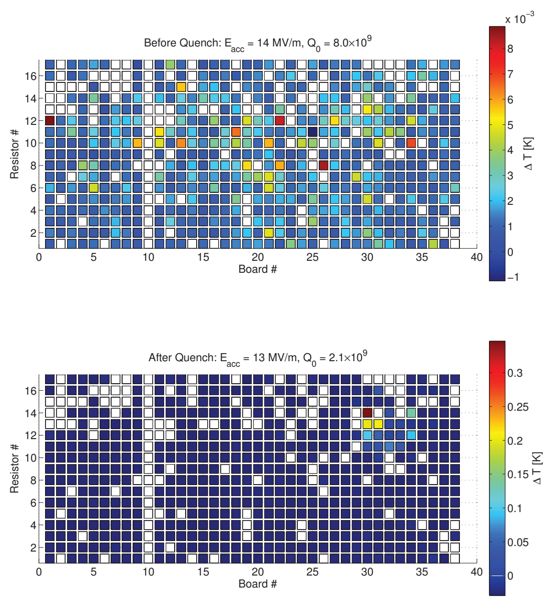

Figure 2: Maps of surface heating after the second coating and HPR. After quench, a region shows very strong heating, indicating large amounts of trapped flux. There was a small amount of pre-heating in that region before quench occurred.

Q-disease. This was ruled out by parking the Nb_3Sn cavity at ~120 K overnight, and RF testing again the next day, with unchanged performance (Fig. 1).

Figure 3: Centrifugal barrel polish machine loaded with Nb_3Sn cavity (left); and polishing media after 4.5 hours (right).

Q vs E_{acc} curves were taken at many temperatures post-HF rinse and post-CBP. The CBP data are shown in Fig. 4. The R_s values at E_{acc}=5 MV/m were extracted, and plotted as a function of temperature. A fit to this data was performed, including an iterative correction for thermal effects, as outlined in [14].

Fig. 5 shows the Q vs T data taken at low fields before and after HF rinsing. After HF rinsing, for temperatures above ~ 6 K, lower Q values are measured.

DISCUSSION

Though the lack of performance improvement after material removal is disappointing, it does provide interesting clues for the limitation mechanisms that affect Nb_3Sn cavi-

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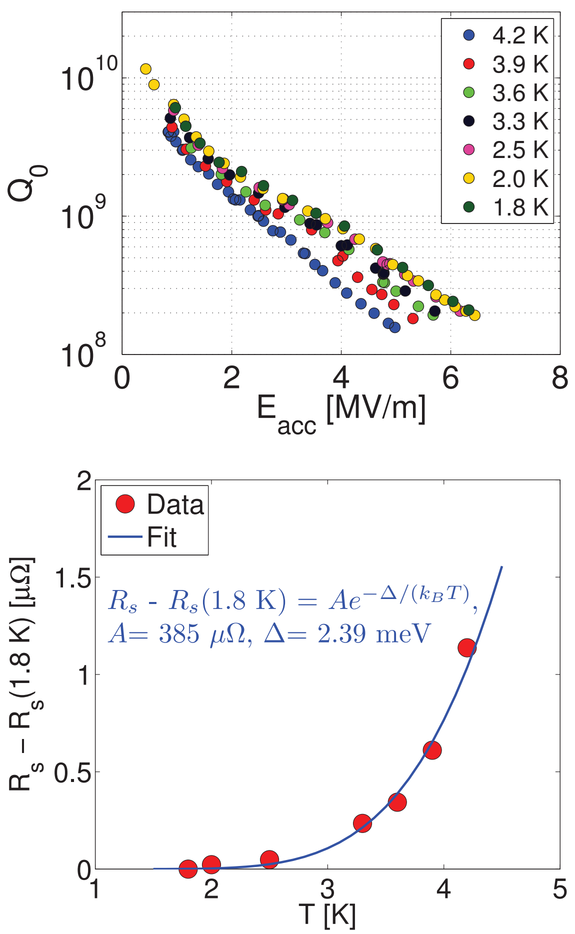

Figure 4: Q vs E curves after barrel polishing (top) and extracted R_s vs T values at 5 MV/m with BCS fit (bottom). The strong temperature dependence in the Q-slope region shows that the extra losses are not caused by residual resistance.

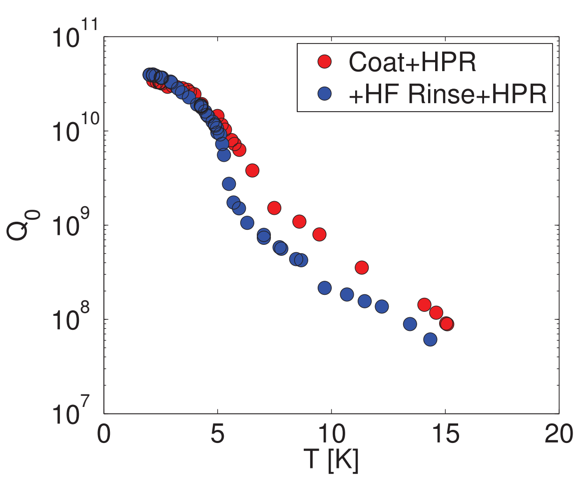

Figure 5: Q vs T before and after HF rinsing.

ties. Both HF rinsing and CBP should remove only a small amount of material, so the strong degradation is unexpected. One possible explanation is that the high quality Nb_3Sn layer is relatively thin, and when even a small amount is removed, it does not shield the lower quality regions below as fully. Another possible explanation is that grain boundaries act as weak links, for example by having off-stoichiometry material inside them. Material removal could cause them to get worse, possibly by increasing the amount of imperfect material between grains.

The post-CBP Q vs E curves show a strong temperature dependence, even in the higher field regions where Q-slope is strong, as seen in Figure 4. This shows that temperature independent residual resistance R_{res} cannot be the sole cause of the excess losses. BCS resistance of a lower quality superconductor fits the temperature-dependent part of the measurements well, as shown in the figure, but losses from small normal conducting regions (for example in the intergranular regions) may also explain the behavior.

The Q vs T data suggest that after removal, there is a significant amount of material in the RF layer that does not become superconducting until it is below approximately 6 K. A low-tin content Nb-Sn alloy could have this behavior [15].

It should be noted that we do not know if reduction of quench-inducing defects was achieved after removal–the maximum field was limited by available RF power to well below the field where quench occurred before removal.

CONCLUSIONS

A cavity was coated with Nb_3Sn, HF rinsed, re-coated, and given CBP. The Nb_3Sn coating process was shown to, with repeatability, give low R_s performance up to medium fields. Both methods of material removal led to strong performance degradation. Two possible explanations are proposed that fit the observations: low quality material below the surface and low quality material in the grain boundaries. Future work will focus on studying the cause of the post-removal Q-slope and finding ways to push the quench field without inducing Q-slope.

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