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RECENT DEVELOPMENTS OF Nb_3Sn AT JEFFERSON LAB FOR SRF ACCELERATOR APPLICATION*

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Abstract

The desire to reduce the construction and operating costs of future SRF accelerators motivates the search for alternative, higher-performing materials. Nb_3Sn (T_c ~ 18.3 K and H_{sh} ~ 425 mT) is the front runner. However, tests of early Nb_3Sn-coated cavities encountered strong Q-slopes limiting the performance. Learnings from studies of coated materials related to cavity performance prompted significant changes to the coating process. It is now possible to routinely produce slope-free single-cell cavities having $Q_0 \geq 2\times10^{10}$ at 4 K and $> 4\times10^{10}$ at 2 K up to the accelerating gradient in excess of 15 MV/m at its best. Obtaining similar results in five-cell cavities is a current goal to test them under an accelerator environment. This contribution discusses recent developments at Jefferson Lab.

INTRODUCTION

Nb_3Sn (T_c ~ 18.3 K and H_{sh} ~ 425 mT) is a prospective alternative material to replace Nb (T_c ~ 9.2 K and H_{sh} ~ 220 mT) in SRF cavities [1]. It promises more powerful, economical, and simplified SRF accelerators. Its potential for SRF accelerators was recognized early, and it has been researched since the 1970s. Because of extreme brittleness and low thermal conductivity, Nb_3Sn can be used only as a thin-film or coating. So far, the most successful technique that can deposit Nb_3Sn coating on the interior surface of a cavity is vapor diffusion. The basic premise is to create tin vapor and transport it to the interior surface of a Nb-cavity at about 1200 °C, where Nb_3Sn exclusively forms. The process was adopted at JLab in 2012 with the Nb_3Sn deposition system, which was designed to coat 1.3-1.5 GHz single-cell cavities [2]. Several single-cell cavities were coated and tested. They consistently attained quality factors (Q_0) as high as $> 1\times10^{10}$ at 4 K at low field, but the maximum gradient was limited by a precipitous Q-slope. The slope was very similar to the "Wuppertal-slope," seen in early cavities coated there. Although [3] several laboratories reported the Wuppertal-slope, its origin is still not known completely. Researchers here pointed to Ti contamination of the Nb_3Sn layer from Ti-parts residing inside the deposition chamber during the coating process. Almost all cavities at that point had Nb-Ti flanges, known to contaminate the Nb_3Sn layer [4, 5]. The issue was addressed during the recent upgrade of the coating system to allow a multi-cell (CEBAF 5-cell) cavity coating. We were now able to produce almost a Q-slope free Nb_3Sn cavity for the first time, but Q was below 1×10^{10} at 2 K [6]. Since then, several single-cell and 5-cell cavities were systematically coated and tested. This paper presents results from recent cavities coated here and gives an overview of Nb_3Sn development.

SINGLE-CELL CAVITY COATINGS

Following the coating system upgrade, several new (all niobium) cavities were added to the Nb_3Sn program in hope of avoiding the strong Q-slope by adopting a Ti-free coating protocol. Though the first cavity coated after the coating system upgrade was a success, several cavities coated afterward exhibited typical Q-slopes (Fig. 3). The witness samples coated with each of those cavities were analyzed with SEM/EDS revealing several issues. Although the coating was excellently uniform, the coated surface appeared to have nano-residues of Sn at the surface, Fig. 1, possibly contributed to the Q-slope which we observed in several cavity coatings. Those residues were believed to be the result of Sn-vapor condensation at the end of the coating process.

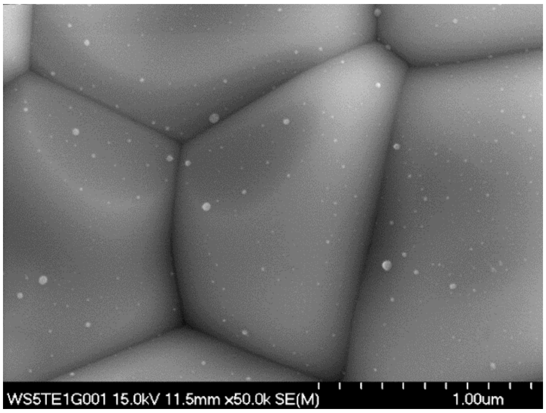

Figure 1: SEM image showing Sn nano-residues observed in a witness sample coated with a single-cell cavity. The bright circular features are Sn residues. EDS examination of larger residue showed that these features are Sn-rich.

Some cavities that have visible non-uniformity, as shown in Fig. 2 [right], usually had Q-slopes. Analysis of corresponding witness samples often showed patchy regions, e.g., Fig. 2 [left], which are thin film regions in the Nb_3Sn coating. They are often attributed to low tin flux during the coating. It indicates that an undersupply (or oversupply) of Sn during the process can lead to patchy

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regions (or Sn-residues) on the surface, both could lead to Q-slopes.

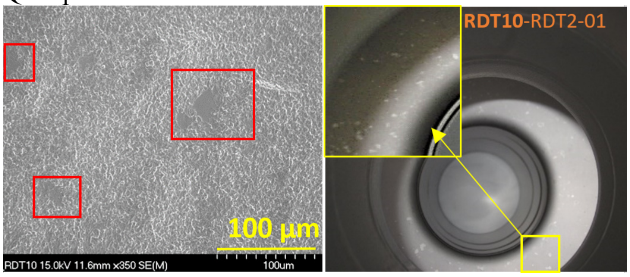

Figure 2: SEM image of a witness sample [left] coated with a cavity having the visibly non-uniform coating.

To avoid non-uniformity and Sn-residues, the coating process was modified. In the new setup, cavities to be coated were coupled to another dummy single-cell cavity on top. We added a secondary tin source, which was attached to the top cover with a Nb rod, and hung around the middle of the two-cavity setup. The heat profile was the usual one except there was a temperature gradient (~85 °C) between the top and bottom of the setup. The details of the coating are available in [7]. The idea was to condense the residual tin vapor into the dummy cavity at the end of the coating process. Such modifications in the latest coating made it possible to produce almost Q-slope free cavities. The RF results of two cavities RDT10 and RDT7 from the latest coatings are compared with their first coatings in Fig. 3. The best coated cavity RDT 7 had a Q_0 of $\sim\geq 2\times10^{10}$ at 4 K and $> 4\times10^{10}$ at 2 K before quench at $\geq$15 MV/m. The measured value of low field Q_0 was 3×10^{10} at 4 K and 1×10^{11} at 2 K without any significant Q-slope.

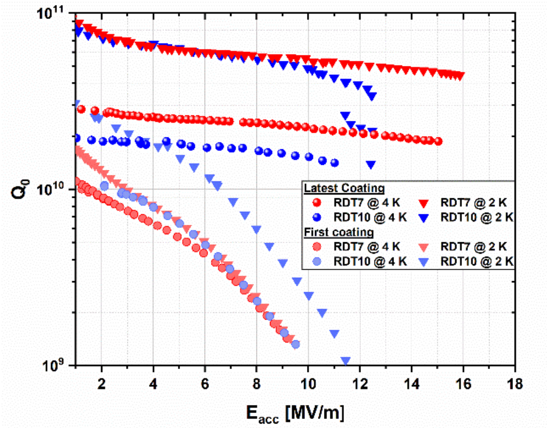

Figure 3: RF performances of RDT7 and RDT10 from the latest coating compared with those from their first coating. RDT10 is expected to have higher Q_0 at 4 K than presented here as we expect losses on the flanges because of shorter beam pipes [7].

FIVE-CELL CAVITY COATINGS

Besides the progress made in single-cell cavity coating, an important goal is translating single-cell results into five-cell CEBAF cavities. Testing Nb_3Sn cavities under an accelerator environment has not been done yet. Several five-cell cavities were coated following the system upgrade in 2017. The intent was to advance toward the Nb_3Sn cryomodule to explore "aging," irradiation, magnetic field, and other practical effects related to accelerator operation. Initially, we attempted to coat five-cell cavities using a protocol similar to that used to coat single-cell cavities. Post-coating inspections revealed an up-down asymmetry in the cavity coating. Cells at the top of the cavity, which were away from the Sn and $SnCl_2$ source during the process had developed a non-uniform coating. Non-uniformity was mainly seen in the out-of-sight regions from the tin source at the bottom. Cells at the bottom were uniformly coated. It clearly indicated that a single source of $Sn/SnCl_2$ was not sufficient to maintain uniform flux of tin inside the cavity. The examination of witness samples often revealed that the non-uniformity is often correlated with patchy regions, similar to 2. The details of the coating process and witness sample studies are available elsewhere [8]Formatting... please wait.

The problem of non-uniformity was mitigated by the addition of a secondary Sn source, which hung at about the middle of the cavity by a Nb rod attached to the top cover. It was found that the cavity with up-down asymmetry had a lower Q_0 compared to that of a uniformly coated cavity, see Fig. 4. Quality factors above 3×10^{10} at 4 K and in excess of 10^{11} at 2 K were measured in a uniformly coated cavity. Accelerating gradients were limited to 2-5 MV/m. Although the addition of secondary tin source helped to overcome non-uniformity, further analysis of witness samples coated with two tin sources revealed nano-residues of tin on the surface, similar to Fig. 2. Defects in the Nb cavity substrates were suspected of limiting the attainable maximum accelerating gradient. Note that the cavities IA110, IA114, and IA 320 in Fig. 4 were fabricated in the 1990s, and had several defects inside the cavity [8].

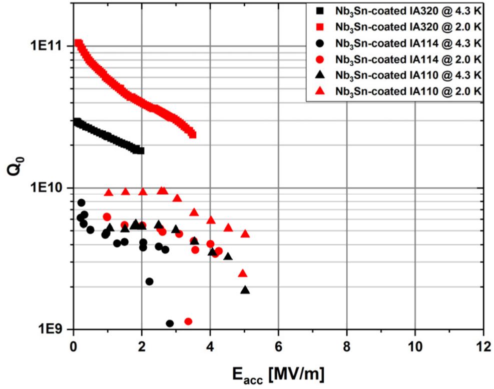

Figure 4: Results from the first few five-cell cavities coated at JLab. IA320 was coated uniformly, whereas IA110 and IA114 had up-down asymmetry.

Two (C-75 CEBAF) five-cell cavities, C75-RI-NbSn1 and C75-RI-NbSn1, were recently purchased from RI Research Instruments GmbH with a purpose to have a good quality, defect-free Nb substrate. As-received cavities were first subjected to optical inspection and followed by 120 μm EP and 800 °C baking for 2 h. They further received 25 μm EP before the final HPR. Cavities attained maximum gradients of about 23 MV/m (C75-RI-NbSn1) and 28 MV/m (C75-RI-NbSn2), both maintaining $Q_0 >$

10^{10} up to 23 MV/m. Previously coated 5-cell cavities coated before had reached ~10 MV/m with $Q_0 < 10^{10}$ during the baseline test.

C75-RI-NbSn1 was coated first. A few modifications were introduced in the coating process. The supplied amount of tin for the coating was adjusted based on our previous experiments so that no excess tin would be left at the end of the coating process, which we believe to condense on the surface depositing Sn nano-residues. The coating was 6 h instead of 24 h. A temperature gradient of about ~85 °C was maintained by adjusting the different heating zone of the furnace. The pictures from the interior surface of the cavity are shown in Fig. 5. Note that the fundamental power coupler side of the cavity resides at the bottom during the coating. The cavity appeared to have a visible non-uniformity in the view from the top. SEM images from a witness sample that was close to the top cell showed patchy regions, as expected for such appearances. Tin residues were still found on the surface.

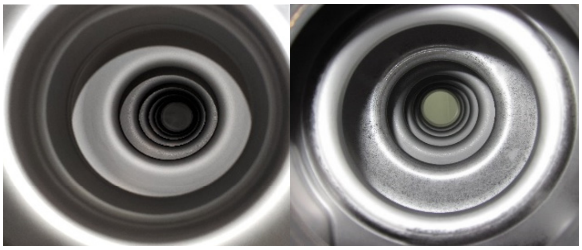

Figure 5: Pictures C75-RI-NbSn1 taken from the bottom [left] and the top [right]. The coating looks non-uniform from the top.

A new tin source was added to avoid non-uniformity in the next coating of C75-RI-NbSn2. There were three tin sources inside the cavity: first at the bottom, second around the center and the third close to the the top. The amount of supplied tin was further adjusted. The coating process otherwise was similar to the previous coating of C75-RI-NbSn1 cavity. The cavity was coated uniformly this time as seen in Fig. 6. SEM examination of witness samples showed complete absence of Sn-residues at the surface, Fig. 7 [right]. A witness sample that was close to the top cell showed only a few patchy regions occasionally. Else, the coating was mostly uniform as shown in Fig. 7 [left].

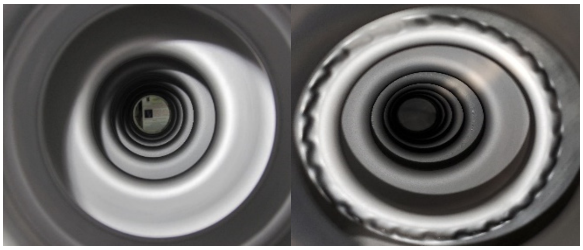

Figure 6: Pictures from C75-RI-NbSn2 taken from the bottom [left] and the top [right]. The coating looks mostly uniform from each side.

Both cavities were tested at about 4 K and 2 K following a typical, described in [8]. Test results from both cavities are presented in Fig. 8. The low field Q_0 is about 7×10^9 at 4 K and 2×10^{10} at 2 K for C75-RI-NbSn1. C75-RI-NbSn2 has a low field Q_0 of about 2×10^{10} at 4 K, and 2.5×10^{10} at 2 K. C75-RI-NbSn1 and C75-RI-NbSn2 were limited to 9 MV/m and 13 MV/m respectively, both exhibiting a mild Q-slope. The lower quality factor of C75-RI-NbSn1 seems to come from the presence of patchy regions and Sn-residues. The performance of these cavities shows significant improvements compared to previous results obtained with coated legacy cavities, Fig. 4. Since the achieved accelerating gradients are useful for an accelerator application, one of these cavities is will move on to be installed in a quarter cryomodule.

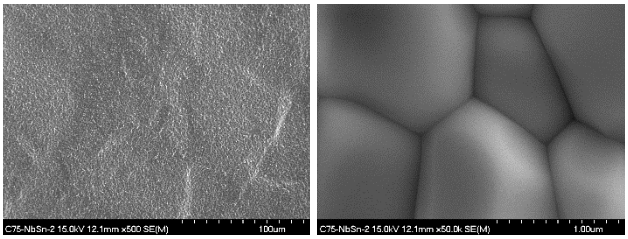

Figure 7: SEM images from the witness sample coated with C75-RI-NbSn2. Note the absence of patchy regions [left] and tin Sn-residues [right].

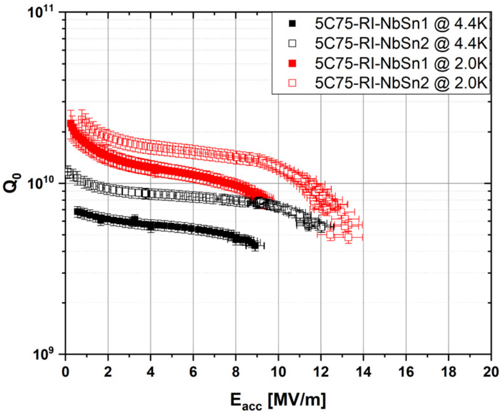

Figure 8: Test results from C75-RI-NbSn1 and C75-RI-NbSn2 at 4 K and 2 K.

SUMMARY

Nb_3Sn deposition system has been used to coat several single-cell and CEBAF 5-cell cavities. A recent development of the coating process has resulted in Q-slope-free Nb_3Sn cavities. The best coated single-cell cavity has attained a Q_0 of $\sim\geq 2\times10^{10}$ at 4 K and $\geq 4\times10^{10}$ at 2 K before quenching at ≥15 MV/m. At the same time, we have produced Nb_3Sn-coated CEBAF 5-cell cavities with accelerating gradients useful for cryomodules. We plan to to build a Nb_3Sn cryomodule in the near future. We have recently started to coat cavities with resonant frequencies (e.g., 950 MHz) other than typical 1.3-1.5 GHz cavities.

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