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Nb_3Sn THIN FILM FOR THE PRODUCTION OF HIGHER GRADIENT SRF CAVITIES AT REDUCED COSTS*

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Abstract

High gradient superconducting cavities (SRF) will be needed for future accelerators. The higher gradient can achieve the high energy with fewer cavities. However, the accelerating field of niobium cavities is limited by the peak magnetic field on the cavity surface. Cavities coated with Nb_3Sn have a significantly larger H_{c2}, allowing the cavity to achieve a larger gradient. Measurements of Nb_3Sn coated cavities have achieved about half the theoretical predicted gradient. It is possible to improve Nb_3Sn plated cavity performance.

INTRODUCTION

Niobium has been used as a fabrication material for superconducting cavities. Much R&D on niobium SRF cavities has been done over the years [1], but there are fundamental limitations to the performance of these cavities. The accelerating gradient in SRF cavities is proportional to the peak magnetic field on the cavity wall. At RF frequencies the peak magnetic field is limited by the metastable superheating field, H_{sh} [2]. Based on the limiting value of the peak magnetic field for niobium cavities the maximum accelerating gradient is ~40 MV/m. Nb_3Sn is an attractive alternative because it has a high T_{c0} = 18 K and $H_{c20} \approx 30$ T. SRF cavities with a layer of Nb_3Sn coated on the cavity surface have been demonstrated to improve the cavity quality factor, but have not significantly improved the gradient. Most experiments to fabricate SRF cavities with a Nb_3Sn coating have used a vapor diffusion process followed by a thermal reaction at high temperature to form the Nb_3Sn compound to coat the cavity [3, 4]. A review of the SRF cavities coated with Nb_3Sn using the vapor diffusion process is given in Ref. [5]. In this paper we will examine an alternate process, where an electrodeposition of copper and tin layers onto niobium, followed by reaction in inert atmosphere, forms a Nb_3Sn film on the niobium substrate. Electrodeposition is likely to be less expensive than the vapor deposition technique previously mentioned.

Nb_3Sn SRF CAVITIES

SRF cavities with a thin layer of Nb_3Sn coated onto the inner surface of the cavity should produce larger accelerating gradients as well as larger cavity quality factor, Q_0, than niobium cavities. Figure 1 shows a theoretical comparison of Q_0 for 1.3 GHz Nb_3Sn and Nb cavities which illustrates the effect of larger T_c of Nb_3Sn on Q_0. Also the larger T_c of Nb_3Sn has the advantage of allowing the cavities to operate at 4.5 K rather than ~2 K that is used for niobium cavities to obtain a higher gradient. This means less expensive refrigeration and more cryogenic reliability.

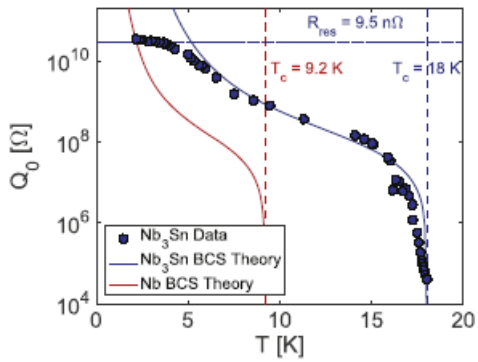

Figure 1: Calculation of Q_0 for 1.3 GHz SRF cavities with Nb_3Sn and Nb inner surfaces. From Ref. [5].

VAPOR DIFFUSION TECHNIQUE

The vapor diffusion technique has been largely successful for coating Nb_3Sn onto the niobium surface of a cavity [5] and has been the preferred technique for Nb_3Sn SRF cavities. The method does require a higher temperature for the heat treatment reaction. For best performance pure Nb_3Sn is formed at temperatures greater than 950° C in a Nb-Sn mixture with tin atomic fraction between 23% to 26%. At temperatures below 950° C there are contaminations from $NbSn_2$ and Nb_6Sn_5 which are not superconducting at 4.5 K The vapor diffusion process goes through five stages, although there are some variations in the process at different laboratories. These stages are summarized in Fig. 2 and include:

1. A degassing stage at 100° to 200°C where pumping on the chamber removes moisture.
2. A nucleation stage where sites are created on the chamber surface. This stage is performed at an intermediate temperature. A nucleation agent such as SnF_2 or $SnCl_2$ is used to provide uniformity of the nucleation sites.
3. A ramp up to the coating temperature.
4. The coating stage where the cavity is held at a constant temperature above 950° C where Nb_6Sn_5 and $NbSn_2$ formation is disfavored. The temperature of the tin source must be high enough to provide a uniform coating, which can be several hundred degrees higher than the cavity surface.
5. The annealing stage to allow the excess tin at the

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surface to diffuse into the niobium layer and form Nb_3Sn. This stage must be above 950°C.

The high temperature used in the vapor diffusion process can make the Nb_3Sn coated layer brittle, which can limit the strain that can be tolerated. This can locally reduce its superconductivity.

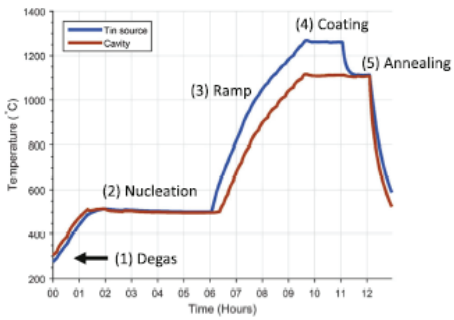

Figure 2: Temperature profile during the coating process used at Cornell. From Ref. [5].

ELECTROCHEMICAL DEPOSITION

Electrochemical deposition techniques can provide an alternate approach to Nb_3Sn coatings on SRF cavities. Electrochemical deposition techniques using a $SnCl_2$ molten salt eutectics to produce Nb_3Sn coatings for cavities has previously been explored [6]. That approach required temperatures higher than 370° C during the plating process at very low pressures. We are proposing to use a novel electro-chemical technique that had been jointly developed by Politecnico di Milano and FNAL [7, 8], and further improved at FNAL to deposit tin and copper layers from aqueous solutions onto a niobium substrate. The most recent improved technique increased the T_{c0} of the Nb_3Sn films from 17.1 T to 17.7 K. Figures 3 and 4 show the T_{c0} results obtained for one of the film samples using a resistance and a SQUID measurement respectively. The H_{c1}(4.2K) for this samples was measured to be 550 Öe.

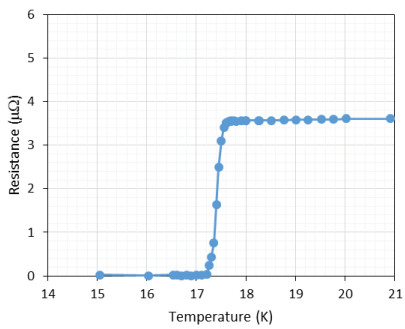

Figure 3: DC test at FNAL of T_{c0} = 17.6 K of a Nb_3Sn film sample obtained with the latest improved technique.

This approach allows the electroplating to be performed at near room temperature and at atmospheric pressure. The advantage of electrochemical deposition is its simplicity, accurate control, and low costs. Electrodeposition should be among the least expensive ways to produce SRF cavities. Furthermore, electrochemical techniques can eliminate the problem of a low tin concentration at the niobium interface, which is a fundamental limit of the current vapor deposition techniques. Electrodeposition can be performed on any 3D surface such as the inner surface of SRF cavities.

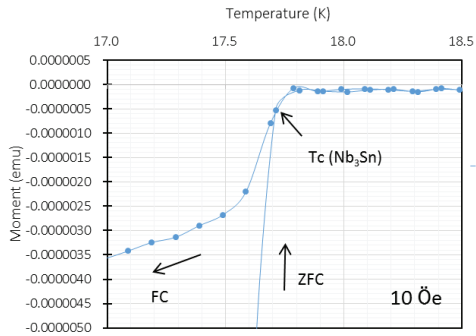

Figure 4: M-T curve obtained with SQUID magnetometer at NIMS. The T_{c0} = 17.7 K.

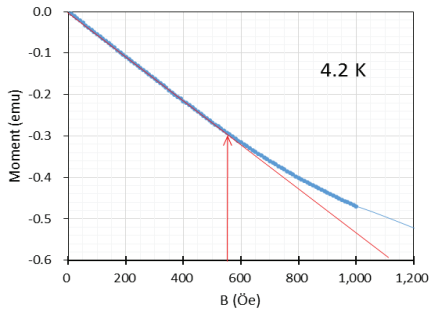

Figure 5: M-H curve obtained with SQUID magnetometer at NIMS. The H_{c1}(4.2 K) = 550 Öe.

We are proposing to use the electrochemical technique that has been developed for niobium substrates, along with thermal solid diffusion, to put a Nb_3Sn coating onto a niobium surface. The electroplating procedure plates a layer of copper onto the niobium substrate followed by a tin layer onto the copper. Tin does adhere well to the copper layer. A second copper layer is applied as a barrier layer during formation of the liquid phases. The electrodeposition procedure is carried out at near room temperature and at atmospheric pressure. The procedure is described in detail in Ref. [8]. The most efficient method of forming Nb_3Sn is through solid diffusion. The temperature profile during solid diffusion which is shown in Fig. 6 is used to control the reaction process. Initially the temperature is set just below the tin melting point to relax stresses in the metal layers and start diffusion between copper and tin. The second step raises the temperature to 450° C to allow the formation of a liquid tin phase and start the inter-diffusion with niobium and copper. This avoids the movement of the material boundaries. The final temperature step to 700° C for 24 hours forms the Nb_3Sn superconducting phase. With the ternary Nb-Cu-Sn system only Nb_3Sn remains after the heat treatment [8]. The diffusion from the Cu-Sn solid solution to the

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Nb-Sn solution passes through compounds with the A15 stoichiometric ratio such as the Nb_3Sn compound [9]. The copper lowers the formation temperature for the A15 compound and suppresses the unwanted $NbSn_2$ and Nb_6Sn_5 contaminants. This temperature reduction is one of the advantages of the electrochemical deposition/solid diffusion method.

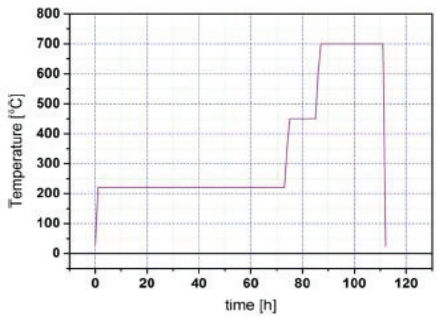

Figure 6: Temperature profile during Nb/Cu/Sn/Cu solid diffusion.

THEORETICAL PREDICTION

The two most important aspects of SRF performance are the accelerating field E_{acc} and the cavity quality factor, Q_0. E_{acc} is limited by the peak magnetic field reaching or exceeding the superheated critical magnetic field, H_{sh}. The superheated metastable critical limit is possible because the RF period is much shorter than the relaxation time of the Meissner stage. A theoretical estimate of H_{sh} can be made using the one-dimensional Ginzburg-Landau equation [10]. This estimate is however most valid for the range where the temperature is near the superconducting critical temperature. Figure 7 shows a comparison of niobium and Nb_3Sn measurements with the G-L model predictions. The figure shows reasonable agreement for the niobium measurements with the theory for $T > 0.5\ T_c$. However, the Nb_3Sn measurements are much lower than the predictions. The difference between niobium and Nb_3Sn is not well understood. The coherence lengths of niobium and Nb_3Sn are quite different (which is also reflected in H_{c2}). Nb_3Sn is a more granular material than the defect free niobium that is used for SRF cavities. The electrochemical deposition should provide a more uniform Nb_3Sn coating. Improving the quality of the Nb_3Sn could reduce the large gap between the theoretical and measured H_{sh}.

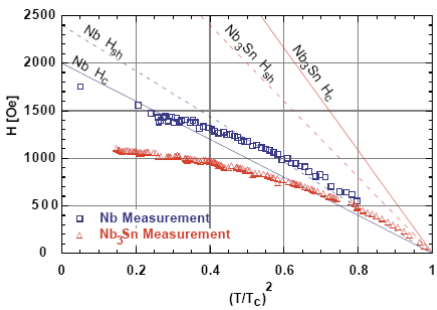

Figure 7: Comparing Nb and Nb_3Sn measurements with H_{sh} predictions [10].

RESEARCH PROPOSAL

As an R&D effort we would like to use thin film Nb_3Sn samples to study processing properties. These samples can be fabricated, processed and tested with rapid turnaround as a cost-effective approach to optimizing the electrodeposition process to uniform plated layers with a minimum number of defects. The microstructure of the plated layers can be examined. Glow-discharge optical emission spectroscopy (GDOES) can be used to study tin, copper and niobium composition of the layers. X ray diffraction (XRD) can reveal the cubic crystalline structure of the Nb_3Sn phase that is expected for an A15 compound. XRD is sensitive to the $NbSn_2$ contamination phase. A scanning electron microscope (SEM) can be used to produce cross section images of the plated layers with micron accuracy for layer thickness. Figure 8 shows an SEM image of a Nb_3Sn sample from Ref. [8]. The Nb_3Sn layer has a thickness of 5.7±0.5 μm on the niobium substrate. Outside the Nb_3Sn layer is a bronze layer formed from the excess tin alloyed with the copper protective layer which should be removed through etching and electropolishing. The measurement of the Nb_3Sn layer thickness and grain size are important data for the sample characterization.

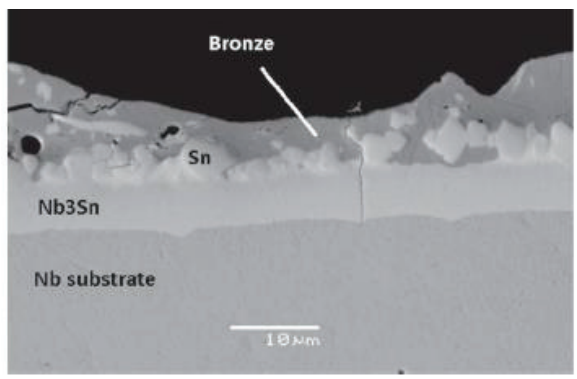

Figure 8: SEM cross-section of a sample analysed in[8].

It is important to know how well these thin film samples would perform in a cavity. A test facility that can include the Nb_3Sn thin film sample in the cavity resonant circuit would be needed. This would allow the measurement of the surface impedance which can be obtained from the measurement of Q_0. A TE011 cavity with a demountable endplate where the sample can be placed can be used for the measurement of the surface impedance. A cavity test facility of this type exists at Jlab [11].

CONCLUSIONS

We have presented a prescription for a more cost-effective approach to coating niobium RF cavities with a Nb_3Sn layer. In this process, electrodeposition of copper and tin layers onto a niobium substrate is followed by a solid diffusion heat treatment at 700° C. This procedure should be less expensive than the vapor diffusion process that is typically used.

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