Growth and Properties of Vapor Diffused Nb_3Sn Coating for Superconducting Radiofrequency Accelerator Cavity Applications

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Abstract

The desire to reduce construction and operating costs of future SRF accelerators motivates the search for higher-performing alternative materials. Nb_3Sn (T_c ~ 18.3 K and H_{sh} ~ 425 mT) is the front runner. The tin vapor diffusion process is currently the technique of choice to produce promising Nb_3Sn-coated cavities. Understanding Nb_3Sn nucleation and growth in this process is essential to progress. Samples representing different stages of Nb_3Sn formation have been produced and studied to elucidate the effects of nucleation, growth, process conditions, and impurities. Nb_3Sn films with thickness from a few hundred nm up to ~15 µm were grown and characterized. The microscopic examination of samples suggests the mechanisms of thin film nucleation and growth. Broadly, nucleation deposits tin as a thin surface phase and, under some conditions, a few hundred nanometersized particles as well. Conditions that impair nucleation promote the formation of defects, such as "patches", in subsequent coating growth. Analysis of coated samples is consistent with the model of Nb_3Sn grown in which tin diffuses via grain boundaries to Nb_3Sn-Nb interface, where the growth pf Nb_3Sn into the niobium bulk takes place. Similar scaling laws are found for grain growth and layer thickness. Non-parabolic layer growth is consistent with significant grain growth, which reduces the number of Sn-transport channels. Examination of patchy regions in Nb_3Sn coating revealed it to be large single crystalline grains, pointing to impeded Nb_3Sn layer growth due to low grain boundary density, resulting in a significantly thin coating in those areas. Examination of RF loss regions from a coated cavity, identified with a thermometry mapping system showed patchy regions and carbonus defects were associated with strong local field-dependent surface resistance. RF measurements of coated cavities were combined with material characterization of witness samples and coated-cavity cutouts to improve the coating process. Understanding obtained and applied to cavity coatings, resulted in single-cell Nb_3Sn cavities with a quality factor of ~3 $\times 10^{10}$ up to 15 MV/m accelerating gradient at 4 K, without "Wuppertal" Q-slope. We have also produced Nb_3Sn-coated CEBAF 5-cell cavities with accelerating gradients useful for accelerator cryomodules. We will discuss the genesis of the Nb_3Sn coating in a typical tin vapor diffusion process, effects of different process parameters, and its consequences to the coating of single-cell and multi-cell SRF accelerator cavities.