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SURFACE ROUGHNESS REDUCTION OF Nb_3Sn THIN FILMS VIA LASER ANNEALING FOR SUPERCONDUCTING RADIO-FREQUENCY CAVITIES*

Z. Sun†, M. Ge, M. U. Liepe, T. Oseroff, and R. D. Porter
Cornell Laboratory for Accelerator-Based Sciences and Education (CLASSE), Ithaca, NY 14853, USA
A. Connolly, M. O. Thompson
Materials Science & Engineering, Cornell University, Ithaca 14853, USA

Abstract

Superconducting radio frequency (SRF) cavities, a key component of particle accelerators, await new SRF materials beyond the state-of-the-art niobium. Nb_3Sn is one of the most competitive candidates, since it increases the superheating field, allows the operation temperature up to 4K, and improves cavity efficiency. Surface roughness and grain boundaries, however, significantly affect the RF performance of current Nb_3Sn cavities. Here, we explore a post laser annealing technique to reduce the surface roughness. In doing so, we deposited a TiN laser-absorber on Nb_3Sn and Nb surfaces, and then annealed the samples by laser scanning via different laser systems. The Nb_3Sn surface roughness was minimized to 101 nm (Ra) by laser annealing via 308 nm, 35 ns pulses. Surface imaging and Fourier analysis revealed laser annealing is able to remove sharp edges and <1 μm wavelength features.

INTRODUCTION

Of great interest to the SRF community is Nb3Sn thin film that pushes the theoretical superheating field to nearly doubled as compared to conventional niobium-based cavities and enables use of the cryocooler, a cost-effective option, for accelerator operation owing to the relatively high critical temperature of 18 K [1, 2]. However, Nb3Sn cavities of different frequencies that are made from Sn vapour diffusion currently observe a consistent gradient limit at 17-23 MV/m [1, 3] that is much lower than the predicted ~100 MV/m limit. Among several possible quench defects, such as Sn deficiency [4, 5] and surface oxides [6, 7], surface roughness is most likely a major cause for the quench, which is evidenced by the insignificant dependence of quench limits on their cavity frequency [1]. Surface peak regions result in the unwanted field enhancement, while the valley regions that consist of grain boundaries in the Nb3Sn case are identified to be nucleation sites for vortex entry [8]. We explore two paths to reduce the surface roughness: through improving the alloy nucleation uniformity such as pre-deposition of a smooth Sn layer for thermal conversion [9]; and through post treatments such as chemical/electrochemical polishing and laser annealing, the latter of which is the focus of this work.

Laser annealing is widely used to modify the surface morphology of materials including but not limited to thin films [10]. The laser-material interaction, depending on control of laser parameters, leads to either laser melting or ablation of materials on the surface. Both laser melting with a continuous wave or limited pulses, and laser ablation with multiple pulses are able to generate a smooth surface while minimizing a laser-texturing behaviour that could significantly increase the surface roughness. Here, we focus on a laser melting process aiming to smooth and anneal the film [11-13]. The annealing effect could likely enable the epitaxial growth of Nb_3Sn grains on the large-grain Nb substrate and also remove the disorders induced by vapor diffusion.

(a)
(b)

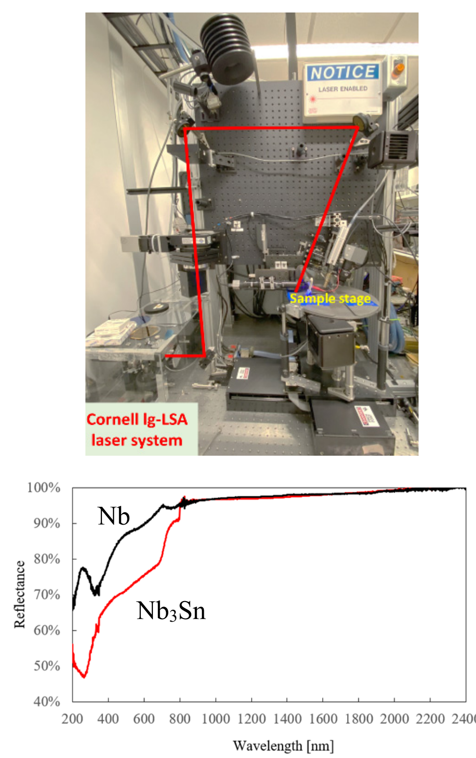

Figure 1: (a) Cornell lg-LSA laser annealing system. (b) Reflection spectra for Nb and Nb3Sn surfaces.

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† zs253@cornell.edu

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EXPERIMENTAL PROCEDURES

Nb_3Sn films of ~ 2 µm thickness were coated on the Nb substrate through Sn vapor diffusion as detailed in Reference [1]. As reference, Nb bulk samples were prepared using a typical buffered chemical polishing (BCP) process to remove surface contaminations while reducing the initial surface roughness to ~1 µm.

Sample surfaces were then scanned using a 35 ns pulsed XeCl (308 nm) excimer laser together with a Cornell lateral-gradient laser spike annealing (lg-LSA) system of 125 W, 1064 nm CO_2 and 250 W, 980 nm diode lasers. The lg-LSA system (Fig. 1a) provided a 320 µm wide, 5 mm long guassian-shaped beam that allowed a decreased temperature gradient across the laser strip during annealing. However, the extremely high reflection of ~95% at 1000 nm wavelength (Fig. 1b) resulted in small energy deposition on the sample surface, and negligible change of surface morphology was observed. As such, a 308 nm wavelength ultraviolet laser with a beam size of 3*3 mm and a uniform beam profile over the scanned area was exploited to improve the laser absorption up to ~50% (Fig. 1b). Moreover, an antireflection layer of 75 nm thin TiN films was coated on both Nb_3Sn and Nb samples using an Arradiance Gemstar-6 atomic layer deposition system. The refractive index of the ALD-deposited TiN is 1.88 at 380 nm wavelength (measurement limit) as confirmed by ellipsometry.

After laser annealing at a fluence of 650 mJ/cm2 for 20 shots, samples were cleaned in HF for 30 min to remove the TiN layer.

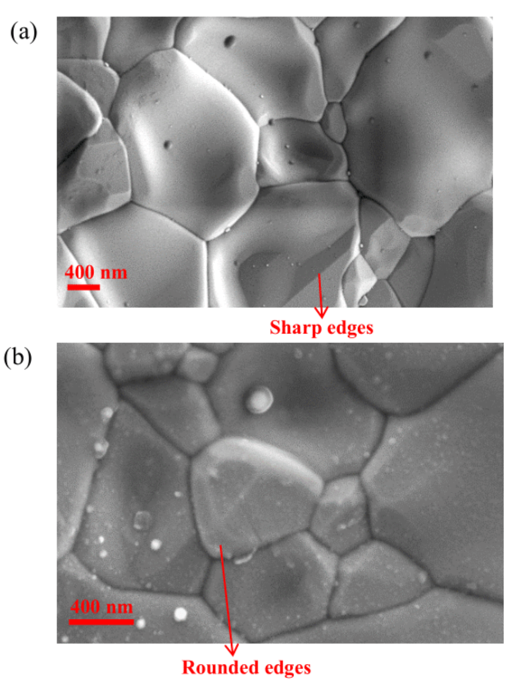
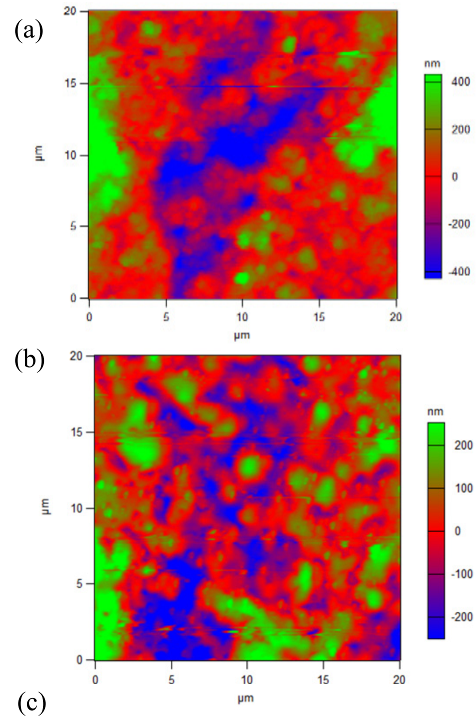


Figure 2: Surface SEM images of Nb_3Sn (a) before and (b) after laser annealing, showing the removal of sharp edges and generation of rounded edges.



(c)

	Ra	Rq	Rz
Before laser annealing	157.8 nm	211.9 nm	1.94 µm
After laser annealing	101.0 nm	125.9 nm	1.39 µm

Figure 3: Atomic force microscopy images of Nb_3Sn (a) before and (b) after laser annealing. (c) Comparison of average roughness (Ra), root mean square (Rq), and absolute height difference (Rz) before and after laser annealing.

Surface morphology was then evaluated by scanning electron microscope (SEM, Zeiss Gemini 500). Surface roughness was measured and quantified using atomic force microscopy (AFM). Moreover, fast Fourier transformation (FFT) was performed to evaluate the surface profile at a range of characteristic wavelengths. Lastly, X-ray diffraction (Rigaku SmartLab) was measured to confirm any phase change during laser annealing, especially any contamination from the TiN layer.

RESULTS AND DISCUSSION

Figure 2 shows a comparison of Nb_3Sn surface morphology before and after laser annealing (and HF cleaning). Sharp edges were removed by a shallow surface melt (Fig. 2a), while rounded edges were observed after annealing (Fig. 2b). Note that these sharp features, although small, play an important role in enhancing the local field and causing the quench.

However, we noticed some residue particles that were likely from TiN, although samples were soaked in HF for 30 min. X-ray diffraction showed little change in diffrac-

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tion pattern after annealing. These nanoparticles are difficult to be detected due to the large penetration depth of X-ray in the sample.

Moreover, Nb samples exhibited negligible change after annealing, while Nb_3Sn samples did not observe a noticeable increase of grain size. Both behaviors suggest increase of laser energy deposition is expected to improve the annealing effect.

Figure 3 shows the quantification of Nb_3Sn surface roughness probed by atomic force microscopy. The comparison of results obtained before and after annealing supports our understanding of the annealing mechanism in this work. The sharp regions (green color) were mitigated to multiple small islands with reduced height.

The average roughness and root mean square of surface profile were reduced by around 40% via laser annealing (Fig. 3c). More importantly, the absolute height difference on the surface decreased from 1.94 μm to 1.39 μm, which demonstrates the effectiveness of laser smoothing.

In order to further obtain statistical information on the topography, fast Fourier transformation was given to decompose the surface profile into amplitude spectral density at different characteristic wavelength (reciprocal to spatial frequency), and results are shown in Fig. 4. Indeed, the amplitude spectral density for laser annealed samples is significantly lower than the value before annealing at wavelength below 1 μm. This observation strongly proves the theory of laser removal of the sharp edges on the Nb_3Sn surface.

Additionally, the amplitude spectral density between 4 – 10 μm is also minimized after laser annealing.

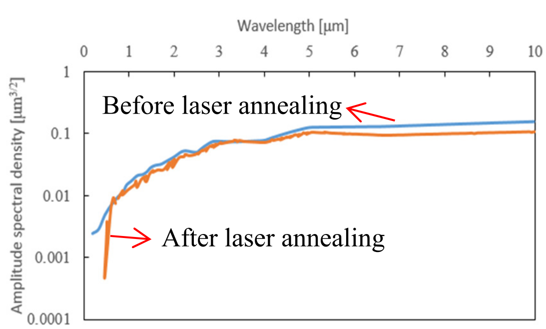

Figure 4: Fast Fourier transformation (FFT) spectra for Nb_3Sn samples before and after laser annealing.

CONCLUSIONS

In conclusion, a post laser annealing process was demonstrated to reduce the surface roughness of Nb_3Sn surface. Average roughness is minimized by 36% together with the drop of absolute height difference. Surface morphology shows removal of sharp edges after laser annealing. Fourier analysis of atomic force microscopy images confirms the reduction of <1 μm wavelength features by laser annealing. Current results demonstrate the feasibility and effectiveness of laser smoothing, while high laser fluence is expected to enhance the annealing effect in the future work.

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