LASER MELT SMOOTHING OF NIOBIUM SUPERCONDUCTING RADIO FREQUENCY CAVITY SURFACES*

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Abstract
Superconducting Radio Frequency (SRF) niobium cavities are at the heart of an increasing number of particle accelerators. Their performance is dominated by a several nm thick layer at the interior surface. Maximizing the smoothness of this surface is critical and aggressive chemical treatments are now employed to this end. We describe laser-induced surface melting as an alternative "greener" approach. Modelling predicts the surface temperature as a function of per-pulse energy density. Guided selection of laser parameters achieves melting that reduces the surface roughness and may also mitigate surface damage from the fabrication process. The resulting topography was examined by SEM, and AFM. PSD spectra computed from AFM data were used for studying the topography of the treated niobium.

INTRODUCTION

Accelerators based on superconducting niobium RF cavities will play a growing role in the future. The science and technology has been recently reviewed [1]. A key feature is that in the superconducting state the RF field penetration is limited to the surface adjacent 40 nm, lending great importance to the composition and topography of the cavity interior surface. Accordingly, the final steps of cavity fabrication seek to remove damaged or contaminated material by etching off approximately 100 microns. A disadvantage is that the etching processes uses aggressive acids (hydrofluoric, nitric, sulfuric) creating cost, safety and environmental impact issues.

Laser Surface Melting (LSM) offers a greener alternative approach. Briefly, a laser pulse melts an area on the surface and surface tension causes some leveling before solidification intervenes. Advantages of LSM over conventional heat treatment are: localized treatment of a selected part of a surface, leaving the other parts unaffected [2], superior bonding as deposited layers, reduced distortion and improved physical properties (smoothing, hardness levels, and wear and corrosion resistance due to rapid quenching [3]. Characterizing the surface topography is a challenging task as it is unknown at what scale roughness is important to SRF performance; a recent review is available [4]. The present work gives results obtained by laser melting to smooth the surface of niobium. The resulting topography was examined by Scanning Electron Microscopy (SEM) and Atomic Force Microscopy (AFM). PSD's were computed from AFM data.

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LASER-MATERIAL INTERACTION

The optical absorption of metals depends upon the angle of incidence, plane of polarization and wavelength of the laser beam. Optical constants for niobium at 1064 nm wavelength were used [5] for calculating the absorption. If the pulse duration (τ_p = 15ns) is much longer than the electron-phonon collision frequency of the niobium ($\tau_{ep} \cong$ 60 ps) [6] then, thermal Fermi distribution can be assumed for the electrons. Thus, the temperature rise can be described by Fourier heat conduction equations [7]. In the present work, the laser spot (≅80 μm) is much larger than the thermal diffusion length (≈nm), justifying use of a 1-D diffusion equation. The heat flow in niobium can be represented by [7, 8]

$$\frac{\partial T(z,t)}{\partial t} - \frac{\partial}{\partial z}\left(k(T)\frac{\partial T(z,t)}{\partial z}\right) = \frac{A(z,t)}{\rho(T)c_p(T)} \quad (1)$$

where T(z,t) is temperature at depth z at time t, ρ is mass density, k is thermal diffusivity, c_p is specific heat capacity and A(z,t) is the heat generation. As there is no analytical solution for the Eq.(1), we use the finite differences method (forward difference approximation) to solve. Time (t) and space (z) are divided equally such that, t^i = i.Δt and z_n=n.Δz (where n= 0…..N). Evaluation of the first order derivative with respect to time and the second order with respect to direction (here z direction), Eq.(1) can be rewritten in forward time centered space scheme.

The simulation for the surface temperature and other parameters are done using C++. We were interested in the fluence required to bring the surface temperature just above the melting point to facilitate the niobium particles do not ablate and it just melts the rough surface. Thermal calculations given by F.Spaepen [9] on metals were used to find the melt duration in niobium (4-5 ns) at different melt thickness produced by different fluences, which ensured the experiments performed for this experiment had long melt duration.

EXPERIMENTAL SETUP

A PVD Products Inc. PLD 5000 system was used to carry out the experiments, as shown in Fig. 1. The system consists of a vacuum chamber evacuated to 10^{-7} Torr by a rotary backed turbo pump. A reflecting mirror placed in

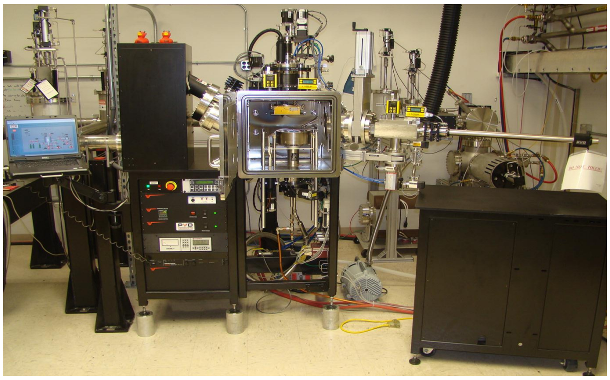

Figure 1: Vacuum chamber (PLD 5000) at the Jefferson Lab Facility Free Electron Laser, used for surface treatment on SRF Niobium disc.

the optical train is used to raster the laser beam over a radial range on the target up to ~1.8 inch. The target pedestals can hold the targets of 2 inches in diameter, 2-3 mm in thickness and can rotate individually with the maximum speed of 12 rpm. In each run, three bare niobium discs were mounted and the rotation speed was varied according the experiment to obtain the intended amount of overlap from pulse to pulse. The laser beam is incident at an angle of 60^o from normal of the rotating niobium target. The laser fluence and pulse overlap are the experimental parameters explored in this study.

To produce thermal energy for surface melting on niobium, a Spectra Physics, "High Intensity Peak Power Oscillator" (HIPPO) nanosecond laser (λ = 1064 nm, E_{max}= 0.430 mJ, τ_p =15ns, beam spot≅80 µm) was used. Laser beam fluences of 0.665 to 2.36J/cm^2 were focused on the niobium target, intending that the niobium surface reaches around the melting temperature. Niobium discs (2" in diameter, 2-3 mm thickness) were cut from multigrain sheet stock used for SRF cavities. To make melting evident, the disc surfaces were roughened using 600 number grit sandpaper, then were placed in the target holder and the chamber was pumped down to 10^{-7}torr. The laser fluence was varied from 0.665 to 2.36 J/cm^2, with the number of pulses per unit area constant to perform the first set of experiments. The target rotation was adjusted to make sure the number of pulse (same energy per pulse) overlap on an area remains between 75 – 80 for this set of test. To understand the effect of pulse accumulation per area, a second set of experiments was performed by keeping the laser fluence constant and varying the number of pulses accumulated.

SURFACE ROUGHNESS MEASUREMENT

The surface topography was investigated by FE-SEM (Hitachi 4700 SEM/EDX) and with a Digital Instruments Nanoscope IV Atomic Force Microscope in tapping mode using silicon tips with diameter 10 nm. A series of 50 µm X 50 µm areas was scanned on each sample. PSD's were calculated and averaged from at least three scans from different areas. Since the surface after polishing will reveal some level of non uniformity, averaging can effectively and accurately smooth out noise and give more statistically representative PSD.

RESULTS AND DISCUSSION

Figure 2a and 2b shows the SEM and AFM images of the roughened/untreated niobium surface. The AFM image captured at 50 µm X 50 µm scan area had roughness RMS (Rq) of 745 nm.

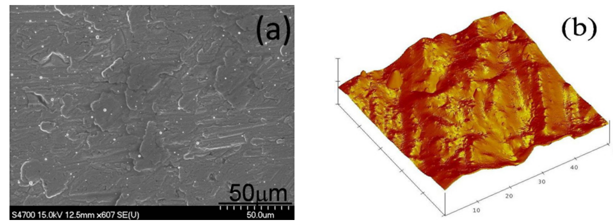

Figure 2: Untreated surface (before laser processing). (a) SEM image (b) 3D AFM image.

Figure 3 shows the series of images of the first set of experiment data. Based on the single pulse simulation model, an uniform laser fluence less than 1 J/cm^2 could not melt the surface of niobium still, the roughness was reduced from 745 nm (Fig. 2b) to 556 nm (Fig. 3a) and 493 nm (Fig. 3b). The fluence per pulse which could reach just above the melting point of niobium (Fig. 3c), shows a distinguished feature of the melting of sharp edges and smoothening the niobium surface to the roughness to 202 nm. Once the fluence per pulse was increased farther above the melting point of niobium, the surface roughness starts to increase (Figs. 3d and 3e).

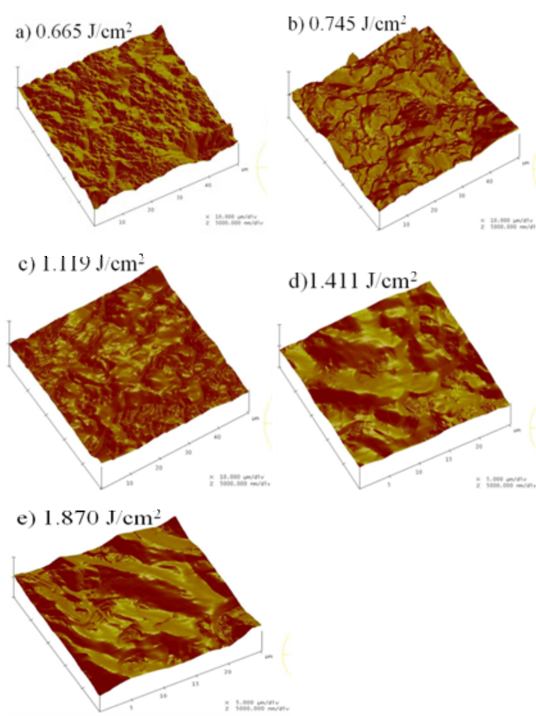

Figure 3: 3D image from AFM on the treated niobium surface at different laser fluences. (In each image x = 5.000 µm/div: z = 5000.00 nm/div).

The laser source used in these experiments produces a Gaussian beam so that the fluence at the center exceeds the average. Accordingly, melting at the center is expected to occur at lower fluence than the threshold calculated for a uniform beam. At still higher fluence, the laser pulse that melts launches mechanical waves in the centre of the material and expels melt, which starts to vaporize/ablate the surface causing melt splashing from the center of the laser beam spot hitting the surface and promotes increased roughness rather than smoothening. For the higher fluences (>2.36 J/cm2) the surface roughness was so high, that AFM reaches its limitation to measure the surface roughness. These images were observed through SEM (Fig 5). The plot of the image surface roughness (taken from Figs. 3a-e and 2b) of the niobium vs the fluence is shown in Fig 4. It can be observed that, when the fluence is just above the melting temperature of niobium, the rough surface melts and the roughness also reduces from 745 nm to 202 nm. The SEM image from Fig. 6, clearly differentiates treated (1.119J/cm2, 16 kHz, ~ 75 pulses total per area) and untreated niobium surface.

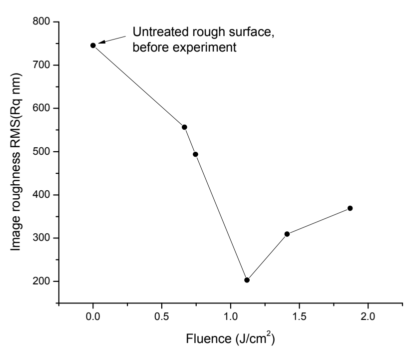

Figure 4: Surface roughness Vs fluence.

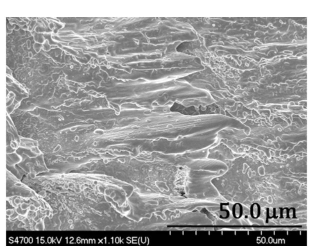

Figure 5: Niobium surface treated with higher fluence.

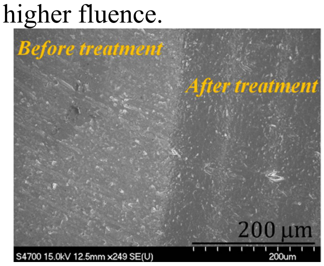

Figure 6: Interface between the treated and untreated niobium surface.

PSD data shows that the effect of laser processing on surface topography over a range of spatial frequencies (length scales). For the fixed number, variable energy case, essentially all the variation occurs at length scales longer than 10 microns, a length scale on the order of the abrasive scratches and the laser spot. The fluence below the melting temperature (0.665 J/cm^2 and 0.745 J/cm^2), the surface appearance did not change much. For surface temperature just above the melting point at the fluence of 1.119 J/cm^2, surface melting begins. The PSD of 1.119 J/cm^2 had a clear differentiation at both higher and lower frequency region compared with untreated niobium. This also shows that characterization of the surface topography in terms of Ra is not enough to give the complete information; we also need to analyze through PSD. The PSD data tells that, more total pulses does not improve the surface roughness, though the laser fluence is just above the melting temperature of the niobium.

CONCLUSION

The present results provide evidence that laser surface melting on the niobium surface can reduce roughness. The simulated surface temperature results were consistent with the AFM results. PSD allows for a more detailed analysis of the topography information inaccessible to simpler methods of quantifying roughness.

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