SRF CAVITY SURFACE TOPOGRAPHY CHARACTERIZATION USING REPLICA TECHNIQUES*

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Abstract

To better understand the roll of topography on SRF cavity performance, we seek to obtain detailed topographic information from the curved practical cavity surfaces. Replicas taken from a cavity interior surface provide internal surface moulds for fine atomic force microscopy and stylus profilometer. In this study, we confirm the replica resolution both on surface local defects such as grain boundary and etching pits and compare the surface uniform roughness with the aid of Power Spectral Density characterization in which we statistically obtain roughness parameters at different scales. A series of sampling locations at the same magnetic field are chosen at the same latitude on a single cell cavity to access the uniformity. Another series of sampling locations at different magnetic field amplitudes are chosen for this replica on the same cavity for later power loss calculation.

INTRODUCTION

Superconducting Radio Frequency (SRF) cavity resonators see increasing application in particle accelerators. Their quality factor Q is understood to be impacted by surface roughness. [1] Rough topographic features having sharp edges as well as large amplitude are understood to be more harmful. For superconducting resonators, materials will surrender superconductivity if temperature, magnetic field or current exceed the critical values. This confines SRF cavities operating within a limited electromagnetic field configurations. In addition, a perfectly smooth surface is presumed when a cavity is designed and optimized in order to get the desired performance parameters. Thus, surface defects aggravate enhancing local temperature, magnetic field or current exceeding thresholds before designed parameters. In this sense, to obtain optimum performance, surface topography should be carefully polished and monitored during each step of cavities production. To investigate the internal surface morphology, it is necessary to cut the cavities' walls to extent accessible samples for characterization. The cutting prevents further RF testing and unaffordable for production. Alternatively, surfaces can be replicated in-situ and characterized in a timely fashion. Such replica technique is designed to transfer the structure of a solid surface to a flexible, highly accurate and stable polymer material. [2] [3] The result is a good 3D copy of surface, allowing further microscopic examination and precise surface measurements.

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White light interferometer (WLI) is non-contact thus favourable for this first stage replica technique. [4] It also has an extensive application in aerospace, semiconductor, medical, solar panel, MEMS, etc. The spatial resolution is related to field of view (FOV) limited by pixel number on the camera. In order to obtain high resolution, one has to compromise with the scanning FOV. The total magnification is the product of two magnifications from objective lens and camera, while the systematic spatial resolution of this replica measurement is overwhelmed by the largest among three spatial resolutions from objective, camera and replica materials. In a commercial tabletop system, the instrumental spatial resolution ranges from 0.02μm up to 7.2μm. Correspondingly, FOV are $4.6\times3.5mm^2$~$0.02\times0.02mm^2$, while combined magnification covers 2.5×0.55x and 115×2.0x respectively. In general, WLI is capable to measure very rough surface, and its z range is 10nm to 10mm. Some also tried to combine Atomic Force Microscopy (AFM) and WLI to extend resolution and FOV in frequency domain. Combining these thoughts, new characterization techniques based on one stage replication and AFM/optical interferometry are introduced to the cavities internal surface characterization of cavities. Power Spectral Density (PSD) analysis is utilized to access accuracy at different roughness scales. [5]

In this paper, topography is replicated and characterized from cm-square coupons as tentative demonstration for Nb cavity practice. These coupons are subjected to different surface treatments. Initial results for replicas and WLI are encouraging, and detailed studies are discussed in later sections.

EXPERIMENT DESIGN

Samples preparation

Four fine grain specimens previously subjected to 100 μm BCP removal continue their EP treatments at 20°C. Such an incremental EP removed 5 μm, 10 μm, and 15 μm surface Nb material. Polished surface conditions were considered to explore the final stage EP in current polycrystalline Nb cavity production.

Replica Material and WLI

In this study, we use a 'Repliset system' from Struers Denmark. This Repliset is a gel ingredient. The mixture is opaque and has fair mobility but a curing time of 4 minutes at room temperature. This one stage replica system claims lateral resolution 0.1μm with negligible shrinkage over time. The package includes a dispenser gun with mixing nozzles. Within the nozzles, two helical channels are delicately designed to ensure the plastic

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agent and curer fully mixed with 1:1 ratio. 12 cm long nozzles are easily implemented inside a narrow pipe; and their lengths can still be extended.

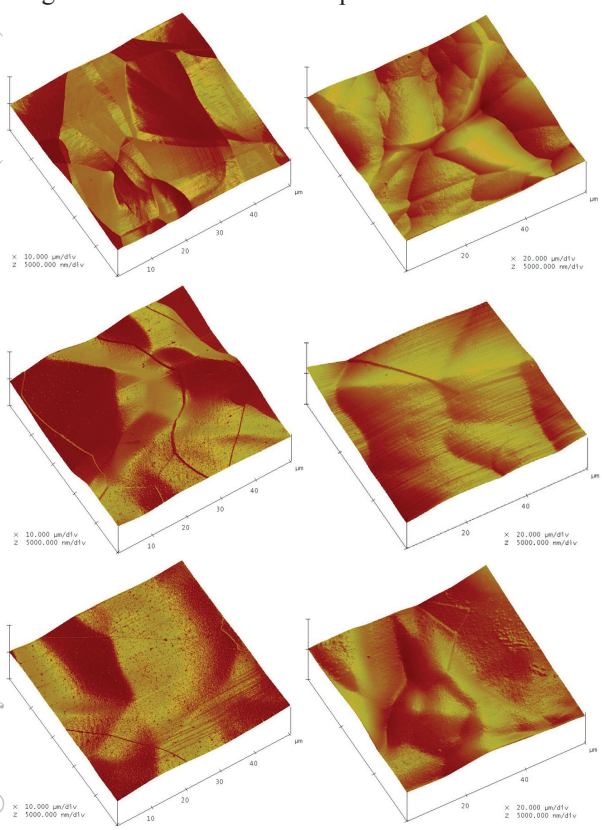
A contourGT-K1/X8 3D white light interferometer from Bruker Inc. is operated in Phase shifting interferometry (PSI) modes because our surface is quite smooth compared with its Z range capability. This PSI mode is also capable of characterizing high slope samples such as BCP polycrystalline Nb surfaces. In PSI mode, a lateral resolution is determined by the objective lens magnification, camera zoom and pixel resolution. In this report, 5X objective lens magnifications and 1.0X camera magnification is combined 5X as low magnification WLI image; and 50 X objectives lens magnification with 0.55X camera magnification is providing 27.5X in high magnification. Respectively, the spatial resolution is 1.94 µm and 0.36 µm, and with a field of view of up to 1.24 mm x 0.933 mm and 0.231 mm x 0.173 mm. 30 The vertical resolution is less than 0.1 nm.

PSD from WLI and AFM are calculated using an algorithm is described in previous references.[4]

To gain better reproducibility, five measurements at random locations of each sample are collected by both AFM and WLI and averaged to compare the uniformity and reproducibility

RESULTS AND DISCUSSION

Grain boundary evolution during early stage electro polishing is compared with its replica counterpart in AFM and WLI. In addition, range of PSD on analysis isotropic roughness is extended and compared.



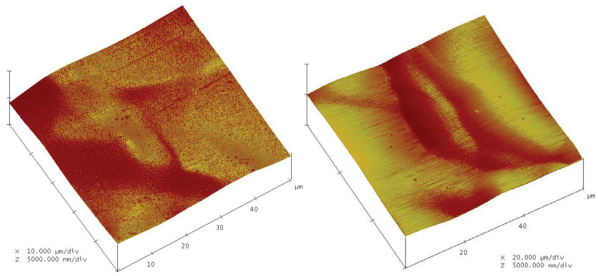


Figure 2: AFM images from a direct and replica FG niobium sample (a) after 100µm BCP surface, then electro-polished at 20 °C to remove (b) 5 µm, (c) 10 µm, (d) 15 µm EP process.

Table 1: Roughness Parameters

Rq Value (nm)	Direct	Replica
100µm BCP	169.2	164.7
+5 µm EP	163.2	159.2
+10 µm EP	162.3	156.6
+15 µm EP	138.3	156.1

PSD are calculated and averaged from above AFM image set. Frequency range covers from 1/195nm^{-1}~1/50000nm^{-1}.

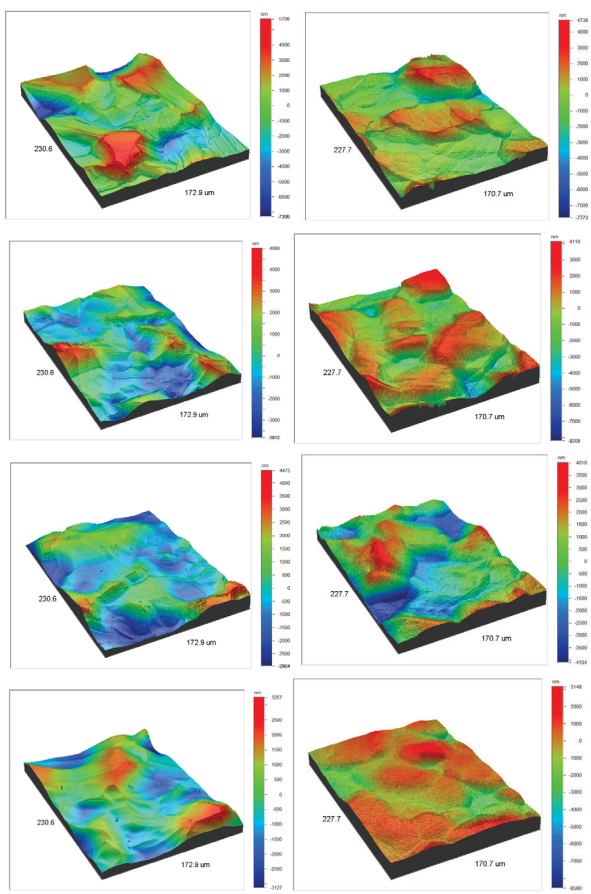


Figure 3: AFM images from a direct and replica FG niobium sample (a) after 100µm BCP surface, then

electro-polished at 20 °C to remove (b) 5 μm, (c) 10 μm, (d) 15 μm.

PSD are calculated and averaged from above WLI images. Frequency range covers from 8.1×10^{-7} nm^{-1} to 5.1×10^{-4} nm^{-1}.

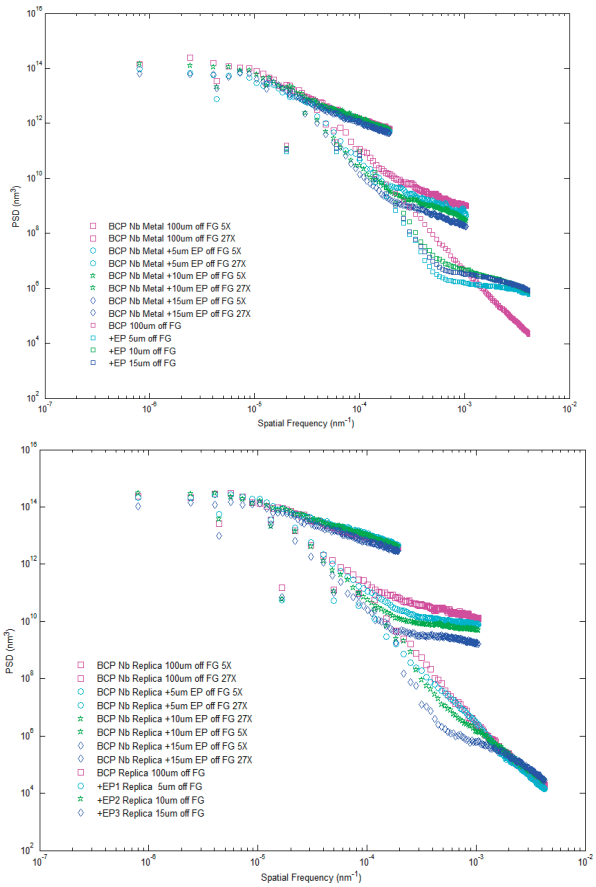


Figure 4: AFM images from a direct and replica FG niobium sample (a) after 100 μm BCP surface, then electro-polished at 20°C to remove (b) 5 μm, (c) 10 μm, (d) 15 μm.

PSD as shown are combined from AFM and WLI low/high magnification measurement. The total covered frequency is from 8.1×10^{-7} nm^{-1} to 5.1×10^{-3} nm^{-1}. One shall see the PSD agrees very well on overlapped frequency ranges, though PSD at high frequency of each WLI characterization show flatten. Note that the cut-off frequency for each measurement is Nyquest frequency which is $1/2\Delta$, where Δ is the resolution.

Note in Fig 4, PSD can be combined within the overlap frequency range as in equation list below.

$$PSD_{\text{combined}} = \left(\prod_{i=1}^{n} PSD_i^{w_i(f)}\right)^{1/\sum_{i=1}^{n} w_i(f)} \quad (1)$$

PSD as shown are combined from AFM and WLI low/high magnification on replica in Fig 4. The covered frequency is the same as in direct measurement. As PSD agrees on overlapped frequency ranges between different characterization measurements: AFM covers from 1/60000 nm^{-1}~1/234 nm^{-1}, and WLI low magnification 1/227000 nm^{-1} ~ 1/490nm^{-1}; and WLI high magnification covers 1/1420000nm^{-1}~1/1940nm^{-1}.

In previous table 1 and 2, RMS height value drops in Replica AFM scans. PSD amplitude from direct and replica measurements confirms Rq decreasing trend. Emprically, Rq values are more accurate and closer to real direct measurements on fresh replica surface.

PSD with frequency range 1×10^{-7} ~ 1×10^{-4} nm^{-1} are from non-contact WLI measurements. PSD from replica and direct measurements agree well on their amplitudes. PSD amplitudes decrease from BCP->+5μm EP->+10μm EP->+15μm, and this sequence agrees with the Rq drop in Table1. Moreover, PSD with frequency range 1×10^{-5} ~ 3×10^{-3} nm^{-1} come from AFM characterization. Though it shows a similar PSD amplitude drop as in WLI's PSD, PSD from replica have lower amplitude than PSD from direct measurement. This phenomenon suggests that the AFM is not the ideal characterization methods for replica measurement.

CONCLUSION

PSD from AFM and WLI are combined and extend from 7×10^{-7} ~4×10^{-3} nm^{-1}. Real and replica PSD are agreeable within this frequency range. This characterization and analysis procedure can be utilized on samples and actual cavities or other interior surface to imprint internal surface with micron resolution and without damaging them. The extended PSD acquired from in-situ cavities are expected to help characterize niobium cavity surfaces and to model of RF losses in near future.

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