SURFACE TOPOGRAPHY TECHNIQUES AT CORNELL UNIVERSITY: OPTICAL INSPECTION AND SURFACE REPLICA*

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Abstract

Surface imperfections significantly limit the performance of superconducting radio frequency (SRF) cavities. The development of surface topography techniques aims to locate the surface flaws in an SRF cavity and profile their geometry details. This effort plays an important role of quality control in cavity productions as well as provides contour information of the defects for understanding quench mechanisms. The surface topography techniques at Cornell University include an optical inspection system and surface replica technique. In this paper, we present the details of the techniques and show features found in the SRF cavities at Cornell.

INTRODUCTION

Surface defects such as pits, bumps, cracks, scratches, etc. can limit the performance of SRF cavities; because the defects can cause cavity quench at a low accelerating-gradient (E_{acc}) or can become sources of hot-spots degrading the intrinsic quality factors (Q_0) of cavities. Typically, the surface flaws are formed during cavity fabrications and/or surface preparations, especially in the processes of electron beam welding (EB Welding) and electropolishing [1, 2]. Therefore, to inspect cavity-surfaces becomes a very necessary step after each fabrication and preparation step. The optical inspection systems, for this purpose, have been developed in many SRF labs around world [3], and have become an important measure for quality control in cavity productions. Even though the optical system can provide the defect's location as well as 2-D information, it lacks 3-D profiles which are significant for understanding the mechanisms of quenches. Therefore the surface replica technique [3-6] has been developed as an effective method for providing shape information of the defects. The 3-D profiles, for example, can be used to calculate magnetic-field enhancements at the rim of a pit [7, 8]. Both techniques are non-destructive for the cavities, with focus on the topography of the defects but not surface characterizations [9, 10].

DESCRIPTIONS OF THE TECHNIQUES

The Optical Inspection System

The Cornell optical inspection system, shown in Figure 1, is a Questar long-distance microscope based system. It is equipped with a 21MPixels Canon camera (Figure 1 a)); a motor-driven carrier displayed in Figure 1 b), which can provide rotations and movements of a single-cell or multi-cell SRF cavity; and a light with 40 LED bulbs lays on two sides of a 45°-tilted mirror providing soft and diffused lighting, which is shown in Figure 1 c). The mirror is hold by a 2m-long Teflon rod.

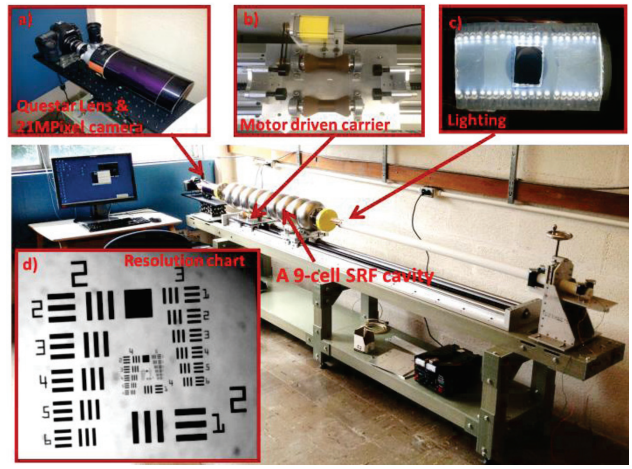

Figure 1: The Cornell optical inspection system. The subplots a)-d) show the details of the system and the resolution of the system (2.77 $\mu m/pixel$).

The system was tested with a 1951 USAF resolution chart. A scaled-and-cropped result is shown in Figure 1 d). The resolution can be calculated by Eq. (1),

$$Resolution\left(\frac{lp}{mm}\right) = 2^{Group+\frac{element-1}{6}}. \quad (1)$$

In the chart, the patterns can be divided into eight groups, from large to small, numbering 0 to 7. Each group has six elements. Our system can observe the group 7 and the element 1 in the group. Thus the resolution of the system is 128 lp/mm, or 2.77 $\mu m/pixel$.

The software of the system is interfaced via Matlab GUI which can communicate to an Arduino microcontroller to drive the motors. The programmable GUI allows us to inspect full cavities or just specific regions.

The Surface Replica Technique

At Cornell, all the features we found were located in single-cell cavities or in the end-cells of 9-cell cavities, where they were reachable by hand. Hence we used a syringe to deliver the replica material to the target region by hand wearing clean gloves; the schematic of the process is displayed in Figure 2 a). After ~16 hour's solidification at room temperature, the surface replica can be peeled out of the cavity by hand, which is shown in Figure 2 b). The material we selected is a two-component translucent silicone-based compound, RTV-3040 (Freeman Mfg., Inc.), exhibited in Figure 2 c). The material can preserve surface details with $\sim 1 \mu m$ accuracy. The surface replica produces negative surfaces of a cavity; in

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other words, if a pit is located on a cavity, it will produce bump on the surface replica. The 3-D profile of the features on the replica can be measured by a laser confocal microscope with a non-contact scan. Examples of the features found will be presented in the next sections.

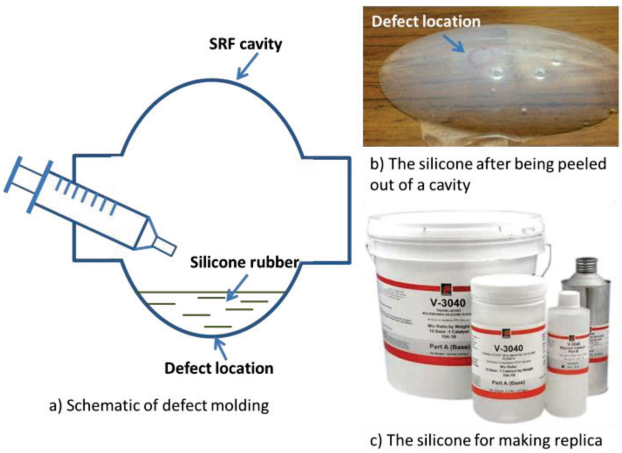


Figure 2: Surface replica technique developed at Cornell University.

FEATURES FOUND IN CAVITIES

Many features have been found by the Cornell system in the past 5 year, we select three interesting cases to present in this paper.

A Bump in a LCLS-II 9-cell Cavity

A feature was found in the cavity TB9AES022 which was prepared and tested for the LCLS-II project [11]. The cavity quenched at E_{acc} 14MV/m [12]. The quench location has been detected by Cornell's multi-cell temperature-mapping system [13, 14] and Oscillating Superleak Transducers (OST) system [15, 16] during vertical tests. Corrdinated with the information from the T-map and OST, the quench location was indicated by the red laser point on the exterier wall of the cavity, shown in Figure 3 a). From inside of the cavity on that spot, the optical inspection system observed a feature located near the welding seam, within the heat-affected-zone, which is shown in Figure 3 b). The radius of the feature is approximately 500μm.

From the inspection image, it's impossible to judge if the feature is pit or bump. Surface replica therefore has been made on that spot. 3-D scans of the feature were done by Fermilab with their laser confocal microscope. A top-view 2-D image of the feature from the microscope is shown in Figure 3 c) in which the red line indicates the direction of the equator; the slicing direction of the feature from the 3-D topography is depicted by the blue line which is parallel to the equator. The contour of the feature is shown in Figure 3 d). Instead of a pit, this feature is a bump, ~141μm high. A possible reason for this feature is a welding bead that was accidentally attached on the surface during the EB Welding. The bump has been removed by tumbling, increasing the maximum gradient to 26MV/m [17].

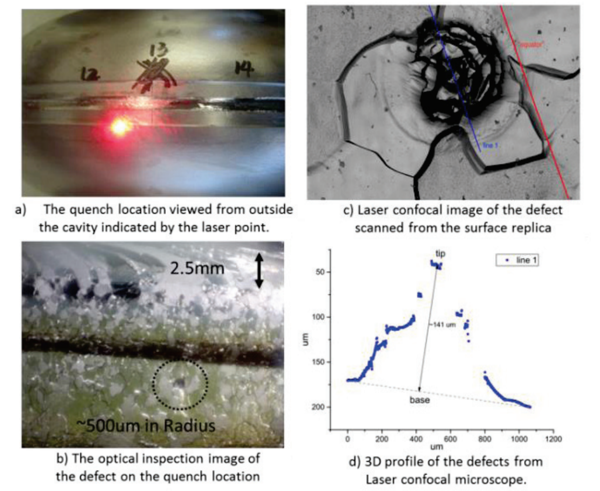


Figure 3: The defect observed on the quench location of TB9AES022 by inspection system and its surface replica.

A Sharp Grain Boundary in a Single-cell Cavity

The large-grain single-cell cavity LR-5 quenched at 24MV/m. After an inspection of the quench location in the cavity [18], the results indicate the grain boundary might have sharp edge causing the quench. The grain boundary is shown in Figure 4 a). A surface replica on that region was made; it showed that the total height of the grain boundary is about 500μm (Figure 4 b) and c)). The step depicted along the horizontal axis at position 200-250μm, is very steep: its angle is close to 90° and its height is about 250 μm.

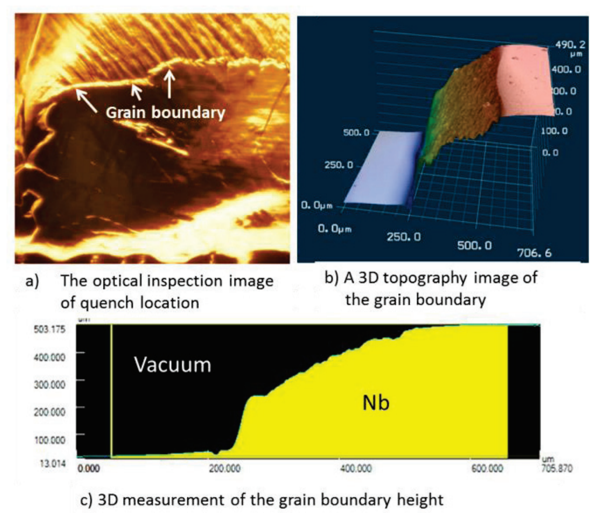


Figure 4: Sharp grain boundaries observed in the single-cell cavity LR-5 with the height of the step ~500μm in totals.

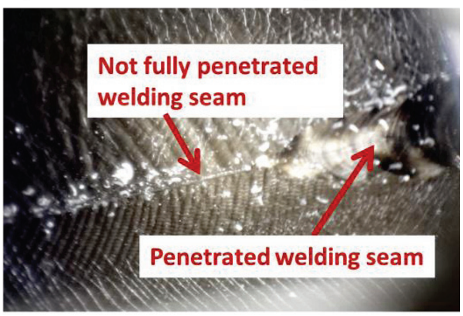
Incomplete Welding in SPX Crab Cavities

Argonne's Short-pulse X-ray (SPX) project explored crab cavities to generate a continuous train of deflected bunches [19]. Since the mechanical structure of the crab cavity is very complicated as shown in Figure 5 a), it has significant technical challenges in fabrication, especially

ISBN 978-3-95450-147-2

in EB Welding. This is because the heat capacity along the equator welding seam is un-uniform due to the three waveguide ports connected to the cavity equator. Hence the welding power has to be adjusted on the joint of the waveguide and equator. Otherwise, incomplete penetration welding could happen on some spots. Thereby optical inspection is a very necessary step to verify good welding quality.

a) Two crab cavities for the SPX project.



b) An inspection image of equator region indicates the unpenetrated welding seam.

Figure 5 Argonne's Crab cavities and the not fully penetrated welding seams observed by Cornell optical inspection system.

Cornell University inspected two crab cavities of the SPX project after the EB Welding. Because of the structure of the cavity, it is very difficult to rotate the cavity body by the carrier of our inspection system. Hence we kept the cavity fixed and rotated the mirror during the inspection. Several not fully penetrated spots on the joint of the waveguide and equator were observed in the cavities. Figures 5 b) shows an example image of the not fully penetrated seam which is a very narrow line, not covered by melted material. On the right-side of the seam, by contrast, it is the full penetrated seam which becomes much wider than on the left side, because the melted material covered the seam sufficiently. All the not fully penetrated welding has been repaired by re-welding since then.

CONCLUSION

Cornell University had developed a surface topography technique that includes optical inspection and surface replica. This technique has been heavily used in several SRF projects for quality control or for investigating the sources of quenches. Three interesting features found in the cavities have been presented here.

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