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AUGMENTATION OF CAVITY OPTICAL INSPECTION BY REPLICAS WITHOUT PERFORMANCE DEGRADATION

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Abstract

Although cavity optical inspection systems provide a huge amount of qualitative information about surface features, the amount of quantitative topographic information is limited. Here, we report the use of silicone-based RTV for replicas and moldings that provide increased details of topographic data associated with the optical cavity images. Profilometry scans of the molds yield micrometer-scale details associated with equator weld structures and weld pits. This confirms at least two different types of pits, one which is bowl-shaped, and one which has a small peak at the bottom. The contour information extracted from profilometry can be used to evaluate mechanisms by which pits and other features limit RF performance. We present calculations based on a conformal transformation of the profiles above. We also show that application of the replica followed by rinsing does not adversely affect the cavity performance.

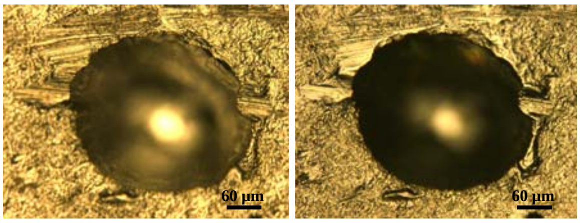
INTRODUCTION

Optical inspection systems have transformed the ability to obtain useful information about the internal surface features of superconducting radio-frequency (SRF) cavities [a]. Many features, such as weld structure, pits, grain boundaries, oxidation, scratches and cracks, and so on are revealed with vivid clarity compared to previous approaches. Pits located at the edge of the heat affected zone of equator welds have received particular attention, due to the somewhat high rate of correlation between their location and the location of hot spots in temperature maps [b,c]. Adjustments of the illumination of the optical inspection systems provided some clues to the contour of pits [d], but the amount of detail is not sufficient to provide detailed understanding why a particular pit quenches a cavity at a given field.

In this work, we combine optical inspection with a replica technique to extract the detailed topography of pits. The replica allows us to duplicate the cavity surface with micrometer accuracy. Scanning profilometry applied to a mold of the replica then reproduces the 3-D profile of cavity surface. This contour information can be used to evaluate mechanisms by which pits and other features limit RF performance. Also, the greater detail provided by replicas and profilometry allows more quantitative comparisons to be made between different surface etching techniques. Importantly, we measured cavity performance before and after application of the silicone replica and found no degradation. Replica techniques, therefore, appear to be a viable means to greatly improve the amount of detail of cavity surface analyses.

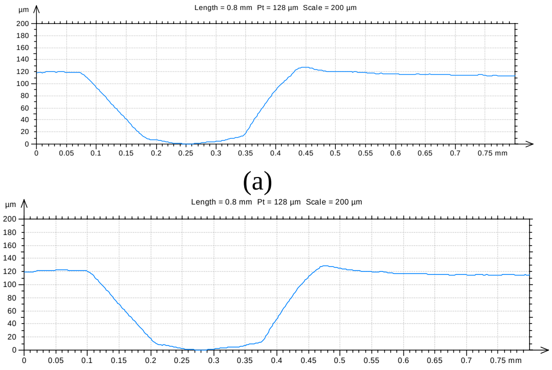
REPLICA TECHNIQUE

Replica techniques are not new; the original idea of applying replica technique to SRF cavities is from S. Berry, C. Antoine, *et al*. [3]. The main concerns are the accuracy of preserving the surface details and a lack of any effect on cavity RF performance. New compounds permit replicas while accommodating these concerns. A two-component translucent silicone RTV compound (Freeman Mfg., Inc. V3040) was used to make the replicas. This material was chosen because no release agent is necessary. The silicon rubber must be outgassed in vacuum before pouring into the cavity. It cures at room temperature over about 18 hours after mixing without the need for baking. Moldings of the replica were then made using a second RTV compound (Momentive RTV630) that is specially formulated to maintain dimensions at 1 µm accuracy. Alternately, a low-temperature 5-minute epoxy was also used to make moldings of small areas of replicas with good accuracy (see Fig. 1).



(a) (b)

Fig. 1. (a) Image of a pit in a Nb coupon, (b) image of the replica using an epoxy mold.



(a)

(b)

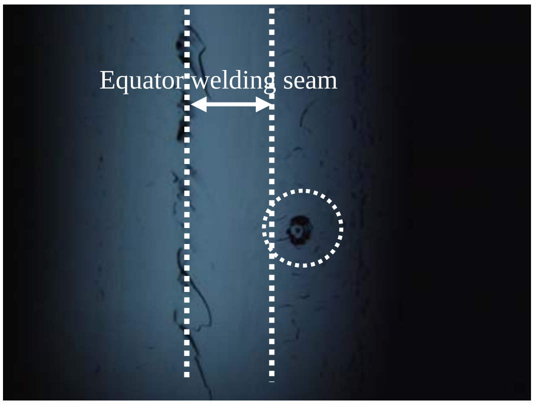
Fig 2 (a) Profile of a pit on the Nb coupon, (b) Profile of the pit's replica.

Fig 1 shows the image comparison of a deliberate pit made on Nb coupon and its positive replica. Fig 2 shows the profile comparison of that pit and replica.

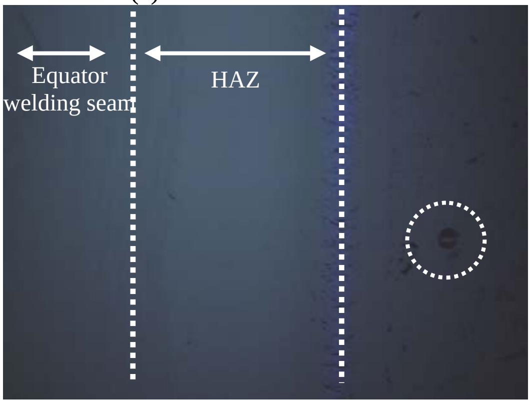
This pit was made by a simple punch tool, about 125 μm deep and 300 μm in diameter. The replica preserves the most details of the pits, including the contour information and the surface morphology around the pit. The accuracy of the replica with epoxy mold is about 2 μm, which is good enough for analyzing pits inside SRF cavities, since many are typically 250 μm in diameter and at least 15 μm in depth.

CAVITY PITS

We then extended the replica technique to real pits observed in the heat affected zone of equator welds for 1.3 GHz single-cell SRF cavities. Two candidates were identified by Fermilab's cavity optical inspection system, as depicted in Fig. 3. Pit A was observed in cavity TE1AES004 and Pit B was observed in TE1ACC003.



(a) Pit A in TE1AES004

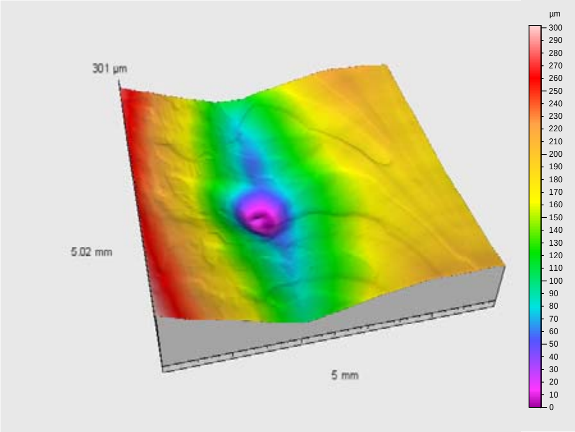


(b) Pit B in TE1ACC003

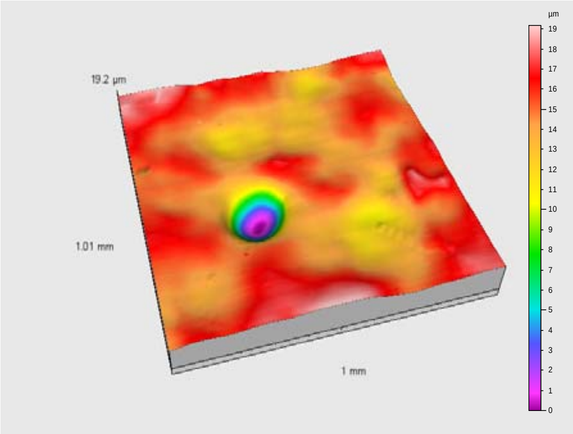
Fig. 3 (a) image of Pit A t in 1.3GHz single-cell cavity TE1AES004, (b) image of Pit B in 1.3GHz single-cell cavity TE1ACC003.

Replicas were obtained for these cavities and castings made from the replicas. Profilometry scans, shown in Fig. 4, reveal rich detail of surface information, including grain-boundary contours and other surface variations in addition to the pits. Fig. 5 shows the profile from left to right across the center of either pit, which is a direction perpendicular to the weld path and parallel to that of the applied magnetic field when the cavity is operating.

The diameter of Pit A is about 1300 μm and its depth is 60 μm with a 15 μm tiny bump in the center. Pit B, on the other hand, is ~260 μm in diameter with depth of about 15 μm. Its shape is hemispherical. Also, a curvature ratio *r*/*R* for field enhancement was estimated using the edge radius *r* and the hemispherical radius *R*. The *r*/*R* of Pit A is 0.88, and that of Pit B is 0.69.



(a) Pit A
The scan covers 5 x 5 mm^2 with total height of 300 μm.

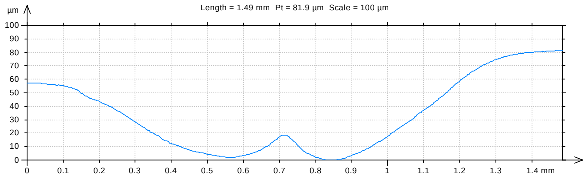


(b) Pit B.
The scan covers 1 x 1 mm^2 with total height of 20 μm

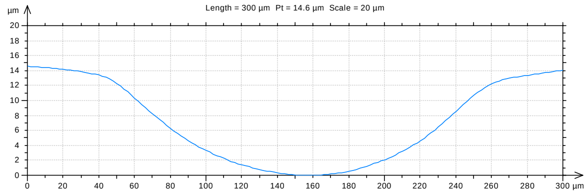
Fig 4. Profilometry scans of castings made from the replica moldings of Pit A and Pit B.

CAVITY RF PERFORMANCE

The application of the replica followed by high-pressure rinsing does not adversely affect the cavity performance. Vertical tests of the two cavities are compared in Figs 6 and 7, with test data shown for before and after molding in each plot. The RF performance before and after molding remains within the test-to-test variation of similar single-cell cavities. It is interesting to see that, in the case of cavity TE1AES004, there is actually somewhat higher *Q* after molding than before.



(a) Profile of Pit A. Vertical full scale is 100 µm, horizontal full scale is 1.5 mm.



(b) Profile of Pit B. Vertical full scale is 20 µm, and horizontal full scale is 300 µm.

Fig 5 profiles of Pit A and Pit B. These profiles were used to estimate the field enhancement using the radius of curvature at the rim, as described in the text.

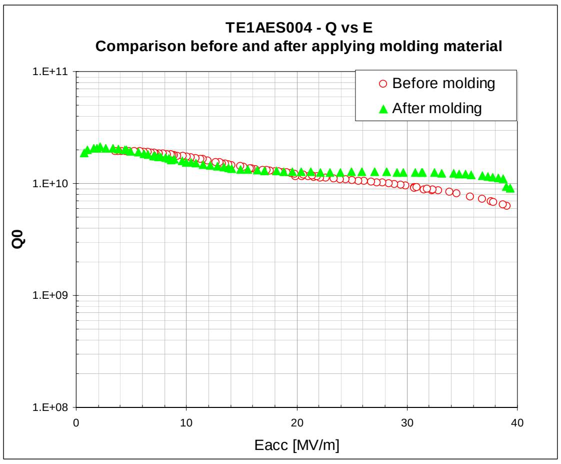


Fig 6 Cavity TE1AES004 RF performance comparison before (red, lower curve) and after (green, upper curve) applying moulding material.

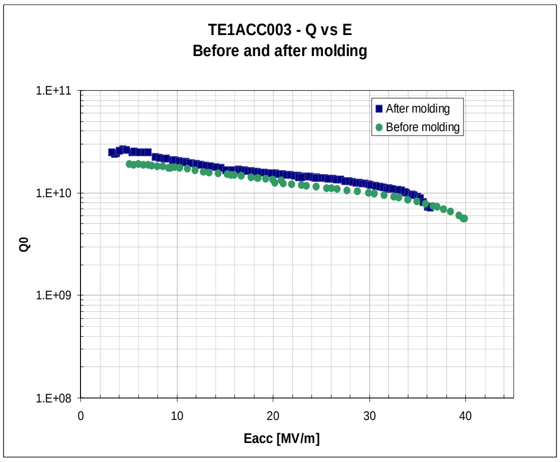


Fig 7. Cavity TE1ACC003 RF performance before (green diamond) and after (blue square) applying replica material.

FIELD ENHANCEMENT ANALYSIS

Large pits near the equator of the cavities are known to reduce performance. Here, although we cannot yet directly correlate the limitation of performance with the location of pit A, pit B indeed was correlated with a location of temperature rise. We suppose that either pit reduced the performance from ~50 MV/m to 39 (for pit A) and 36 (for pit B) MV/m. These values correspond to surface magnetic fields of 170 and 157 mT respectively. If we assume the critical magnetic RF field of Nb is 180 mT, then the field enhancement factor *h* can be calculated following the method in [1], where $h = (r/R)^{-0.28}$. In our case, enhancement factors of 1.06 (pit A) and 1.15 (pit B) are therefore needed. This corresponds to *r*/*R* values higher than 0.5 and approaching 1.0. This is summarized in Table 1.

The replicas provide direct profiles to test field enhancement models, an ability that is not conferred by cavity optical inspection alone. Indeed, we find that both pits have high values of *r*/*R* and therefore minimal field enhancement because the rim is rather blunt. Moreover, Pit A is approximately 5 times the size of Pit B, yet the similarity in performance is retained. This supports the edge enhancement model.

Table1.

Pit	*r*/*R*	*h* meas.	*h* simulation
A	0.69	1.06	~ 1.11
B	0.88	1.15	~ 1.04

CONCLUSION

We have applied replica techniques in concert with cavity optical inspection to increase the amount of detailed information about the cavity surface. The replicas were shown to not degrade performance within error bars when rinsing was applied before testing. The replica technique has high accuracy, revealing micrometer features of the surface. We used profiles taken from moldings of the replicas to calculate magnetic field enhancement factors, which were consistent with performance seen in cavity tests.

REFERENCES

[1] V. Shemelin, H. Padamsee, “Magnetic field enhancement at pits and bumps on the surface of superconducting cavities”, TTC-Report 2008-07, (2008).

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