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RECENT DEVELOPMENTS IN ELECTROPOLISHING AND TUMBLING R&D AT FERMILAB

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Abstract

Fermi National Accelerator Lab (Fermilab) is continuing to improve its infrastructure for research and development on the processing of superconducting radio frequency cavities. A single cell 3.9 GHz electropolishing tool built at Fermilab and operated at an industrial partner was recently commissioned. The EP tool was used to produce a single cell 3.9 GHz cavity that reached an accelerating gradient of 30 MV/m with a quality factor of $5x10^9$. A single cell 1.3 GHz cavity was also electropolished at the same industrial vendor using the vendor's vertical full-immersion technique. On their first and only attempt the vendor produced a single cell 1.3 GHz cavity that reached 30 MV/m with a quality factor of $1x10^{10}$. These results will be detailed along with preliminary tumbling results.

INTRODUCTION

In the process of manufacturing niobium superconducting radio frequency (SRF) cavities a damage layer that is approximately 120 microns thick is created on the interior surface of the cavities [1]. The cavities are also electron beam welded which produces weld beads on the interior surface of the cavity. Electropolishing and tumbling are two processing techniques that are used to remove the damage layer and weld bead that are created on the inside surfaces of the cavities during manufacturing.

Neither tumbling nor electropolishing are proven technologies on a scale that would allow for the mass production of niobium SRF cavities. To better understand these processes Fermilab is currently building a single cell cavity processing facility. There is also work being done in industry to simultaneously increase the capabilities of vendors and to better understand cavity processing pitfalls.

EQUIPMENT & FACILITIES

Fermilab currently has single cell and 9 cell cavity processing capabilities at Argonne National Lab. There is electropolishing (EP), high pressure rinse (HPR), and ultrasonic degreasing capability at Argonne. The scope of the Argonne facility is more in line with cavity production with some process development.

Single Cell Cavity Processing Facility

The single cell Cavity Processing Facility at Fermilab, shown in Figure 1, is designed with safety as a first consideration. The emphasis of this facility will be material and process research and development on single cell 1.3 GHz niobium SRF cavities [2]. The facility will include tumbling, EP, ultrasonic degreasing, and HPR.

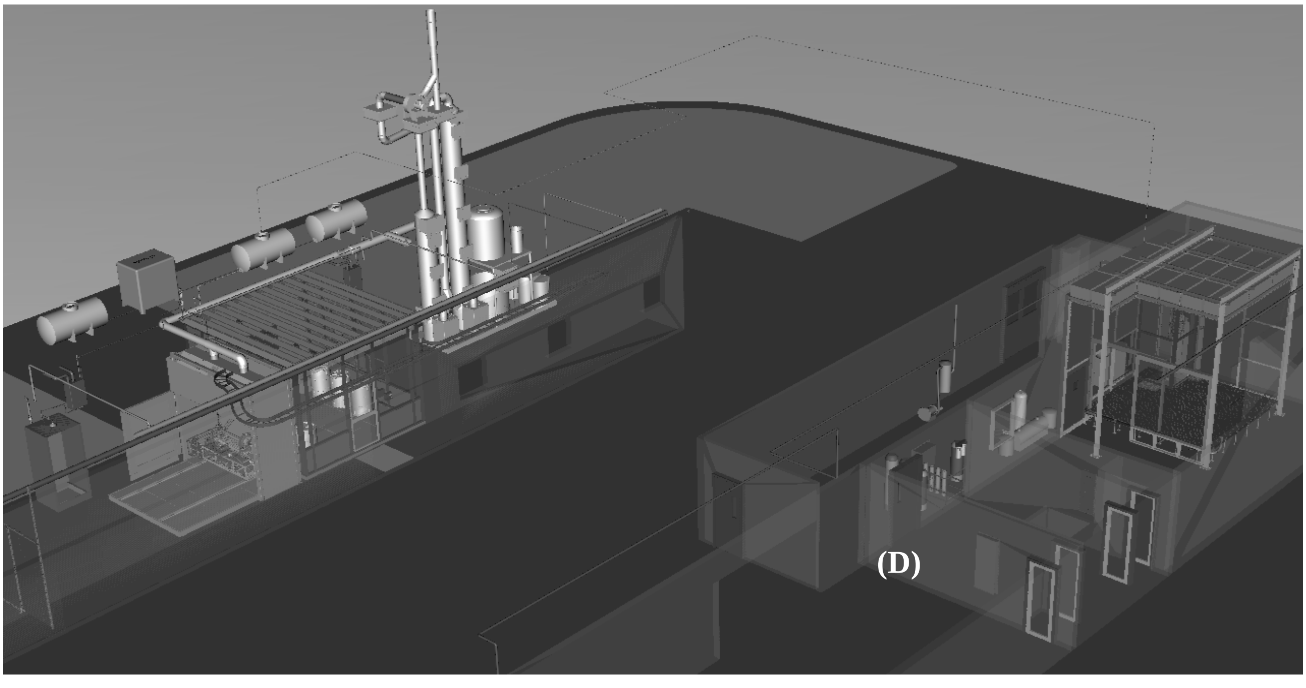

Figure 1: Cartoon of single cell Cavity Processing Facility at Fermilab. (A) Electropolishing tool and cabinet (B) Chemical storage area (C) Scrubber and acid neutralizer (D) Clean room with high pressure rinse (E) Tumbling and ultrasonic degreasing areas not shown

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Tumbling is currently in place and has started for single cell 1.3 GHz cavities. Improvements to tumble 9 cell 1.3 GHz cavities will be completed in 2009. The clean room is in place and it is expected that the HPR tool will be operational in 2009. The HPR tool design is based on the Cornell and Argonne designs. The EP tool design is done and parts are built. Assembly of the EP tool should be complete in the first quarter of 2010.

Tumbling at Fermilab

The tumbler is show in Figure 2. The tumbler is capable of tumbling 2 single cell or 2 9 cell cavities at a time. The tumbler rotates at 115 RPM with a 16.5 inch moment arm. The gear ratio between the main drive and the barrel rotation point is currently 1:1. The 1:1 gear ratio dictates that the cavity does not spin around its own axis of rotation (similar to a Ferris wheel). The ability to change the gear ratio to 2:1 is currently being added to the tumbler. With the 2:1 gear ratio the cavity will rotate 2 times around its own axis per revolution of the tumbler. The design of this tumbler is based off of work done at KEK [3].

Figure 2: Picture of tumbling machine at Fermilab.

3.9 GHz Single Cell EP Tool

The single cell 3.9 GHz electropolishing tool is shown in Figure 3 below [4]. This tool was designed and built at Fermilab. It is currently operated in a hood at Able Electropolishing. The basic design is similar to other horizontal EP tools seen at Jefferson Lab, Argonne Lab, or KEK with some modifications made in the end-groups to minimize trapped fluid[5,6]. This EP tool also has the capability for thermocouples to me mounted on the cavity in up to 6 locations. The tool is fully automated with pneumatic valves and pumps to allow for remote operation by way of a touch screen human machine interface. All wetted flow paths are made of appropriate fluoropolymers, with the exception of the aluminium cathode and the high density polyethylene acid and water bathes. A counter current plastic shell and tube heat exchanger was originally used to remove heat from the acid. This heat exchanger did not remove enough heat so it was removed and replaced by an aluminium tube in the acid bath which successfully maintains the acid temperature. The cathode is 1000 series aluminium and runs through the center of the cavity.

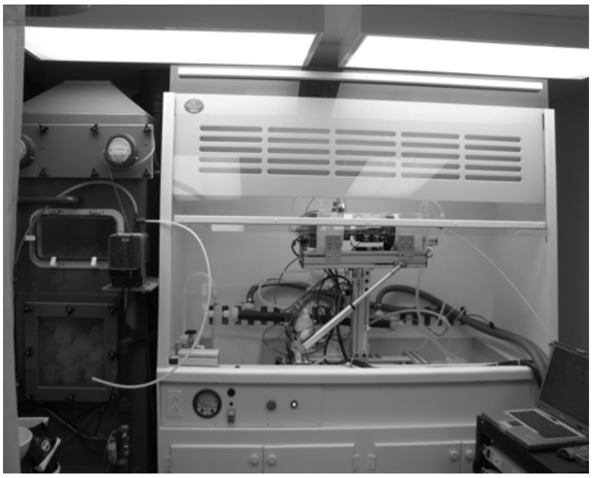

Figure 3: Picture of single cell 3.9 GHz tool at Able Electropolishing.

CAVITY PROCESSING HISTORY

The progress made on 2 single cell 3.9 GHz cavities and 2 single cell 1.3 GHz cavities will be discussed here. The two 3.9 Ghz cavities will be called Cavity 1 and 2. The two 1.3 GHz cavities will be called Cavity 3 (tumbled) and 4 (vertical EP).

Single Cell 3.9 GHz Cavities

Cavities 1 and 2 were made from 300 RRR polycrystalline 3.0 mm thick sheet. The cavities were formed at Fermilab and electron beam welded at Sciaky Inc. Prior to electropolishing the cavities were ultrasonically degreased for one hour with warm (60 ºC) Micro 90 cleaning solution (Cole-Palmer EW-18100) and then rinsed with ultrapure water. Bulk EP was done to remove approximately 150 microns of material. After bulk EP the cavities were thoroughly rinsed to remove acid and then heat treated under vacuum at 800 ºC. Both cavities showed strong hydrogen peaks by residual gas analysis (SPECTRA VacScan model LM6-I). This demonstrates that the EP process is driving hydrogen into the bulk niobium. After heat treatment the cavities underwent a “light” EP removing 20 microns of material. After the “light” EP the cavities were stored in ultrapure water until they were rinsed, high pressure rinsed, and prepared for cryogenic performance testing.

The EP of cavities 1 and 2 was done in the EP tool shown in Figure 3. The EP mixture was a 9:1 mixture of 98% concentrated Sulphuric acid and 50% concentrated hydrofluoric acid. The flow rate of the acid was as slow as possible without the pump stalling out. The flow rate was roughly 0.75 GPM. The acid flows through the cathode and exits into the cavity through a hole in the cathode. The hole in the cathode is aligned with the cavity equator and is pointing directly up. The cathode is wrapped in a perforated Teflon sheet to prevent hydrogen bubbles from hitting the cavity.

The bulk and first "light" EP of Cavity 1 was done at 40 ºC due to an error in the data acquisition system that was subsequently fixed. The bulk and "light" EP of Cavity 2 and the second "light" EP of Cavity 1 were run at 30 ºC or below. Cavity 1 received a second 800 ºC bake and subsequent "light" EP to help recover the quality factor of the cavity.

The amp draw for the processing of cavities 1 and 2 was unexpectedly high at typically 30 amps but as high as 40 amps. The surface area of these cavities is 372 cm^2 yielding amp draws in the range of 80 to 108 ma/cm^2. To reduce the amp draw and temperature at the beam tubes the cathode was partially masked with Teflon tape. This was done before the 2nd "light" EP of Cavity 1. The amp draw after masking the cathode was only 20 amps. The current flow at the cavity cell is most likely still the same since no masking was done near the cell.

Tumbled Single Cell 1.3 GHz Cavity

The single cell 1.3 GHz cavity, called Cavity 3 herein, was tumbled in the previously mentioned tumbler following a 5 step sequence. This cavity was made by Niowave Inc. and the Roark Welding & Engineering Company. The cavity was tumbled at 115 RPMs. The media was filled to 50% volume of the cavity and enough water was used to just cover the media. The exact ratio differed for each media, but typically there was on the order of 2.0 Kg of media to 1.0 Kg of water. Domestic water was used. In addition approximately 0.2 Kg of soap (TS Compound made by Mass Finishing Inc.) was used to help prevent the media from sticking to the cavity wall.

The cavity was first filled with water and soap, followed by the media. This sequence was used to help prevent the iris from getting nicked by media falling into an empty cavity. Between tumbling runs the media was rinsed out with domestic water. Tumbling removed between 80 and 120 microns of niobium from the inside of the cavity. After the tumbling process was done the cavity was ultrasonically degreased at 60 ºC for one hour. The cavity was then EPed at Argonne to remove approximately 40 microns of material. The temperature of the EP solution remained at 30 ºC or below. The cavity was then high pressured rinsed at Argonne and shipped to Fermilab for cold testing.

Vertical EPed Single Cell 1.3 GHz Cavity

The single cell 1.3 GHz cavity, called Cavity 4 herein, was made by Accel Instruments GmbH in Germany. It was EPed at the industrial vendor Able Electropolishing. The cavity was EPed in the vertical position while being fully immersed in the acid bath. The sealing surfaces on the end flanges were masked. The acid bath was the typical mixture of 9 parts concentrated sulphuric acid to 1 parts of 50% concentrated hydrofluoric acid. Other processing information is withheld by the vendor.

After Cavity 4 was EPed, it was ultrasonically degreased and high pressure rinsed at Argonne. No further processing was done before it was cold tested at Fermilab. It was not high temperature treated or processed with a "light" EP.

CAVITY RESULTS

EPed 3.9 GHz Single Cell Cavities 1&2

The accelerating gradients and quality factors of cavities 1 and 2 are shown in Figure 4. Cavity 1 was tested once and processed again by 800 ºC heat treatment and 20 micron "light" EP. The Q_0 versus E_{ACC} for this cavity was very unusual in the first test possibly because of a helium leak. It was also believed that the quality factor and maximum accelerating gradient (E_{ACC}) were both low because the cavity was unknowingly electropolished at 40 ºC. This most likely caused a rougher surface than desired and a large amount of hydrogen to be driven into the bulk niobium. The second cold test gave a much better quality factor. This was expected as the high temperature bake out removed a large amount of hydrogen as seen by residual gas analysis. Unfortunately the maximum accelerating gradient did not improve above 23 MV/m. It is possible that additional chemistry could improve the E_{ACC}, but it is more likely that tumbling would have a better chance to improve the E_{ACC} since tumbling is better at removing pits.

Cavity 2 was tested 4 times. Figure 4 shows the 2nd through 4th tests only as there were system issues in the 1st test. The second test yielded an E_{ACC} of 30 MV/m while the 3rd and 4th tests reached 28 MV/m. These values are higher than have been achieved before and higher than previously thought possible [7,8]. There was a 48 hour 120 ºC bake between the 2nd and 3rd test which may have attributed to the decreased performance. Test 2 had no quench while tests 3 and 4 both quenched.

Previous 3.9 GHz cavities were processed using buffered chemical polishing (BCP) which yields a rougher surface that EP. It is believed that this is the reason that record accelerating gradients were seen in Cavity 2.

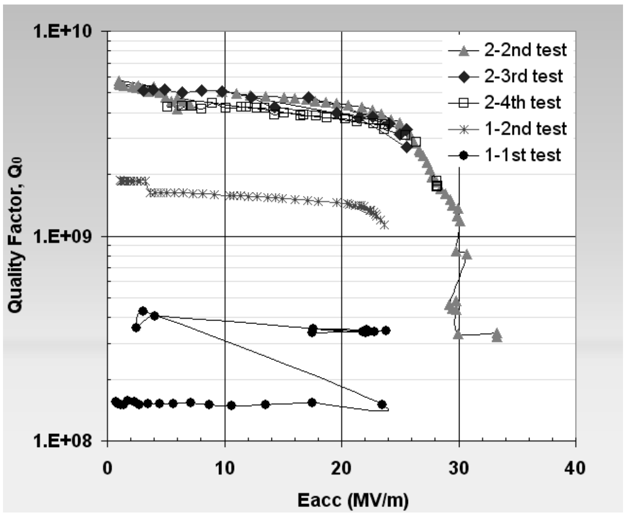

Figure 4: Accelerating gradient vs. quality factor results for Cavities 1 and 2.

Vertical EPed 1.3 GHz Single Cell Cavity

Results from the 1.3 GHz cavity (Cavity 3) that was EPed at Able Electropolishing by a full immersion vertical technique are shown in Figure 5. The Quality Factor was good, especially when the fact that the cavity did not receive any baking is considered [9]. There is high field and mid field Q slope which makes the cavity a candidate for a low temperature treatment. Results of this will be presented when available.

The maximum accelerating gradient reached was 30 MV/m and radiation was seen at only 24 MV/m. It is believed that this is because the temperature was not controlled properly during the first half of the electropolishing. Able Electropolishing processed the cavity too hot for the first half of the EP cycle and the half of the cavity that was pointing up appeared rough and to have a light white haze on the surface. For the second half of the EP, where the temperature was under control, the half of the cavity that was facing up was now pointing down. For this EP cycle the finish on the top half of the cavity looked smooth with no blemishes.

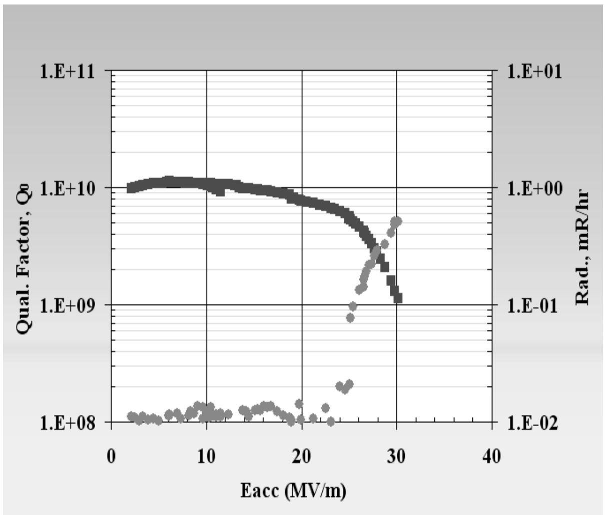

Figure 5: Accelerating gradient vs. quality factor results for Cavity 3.

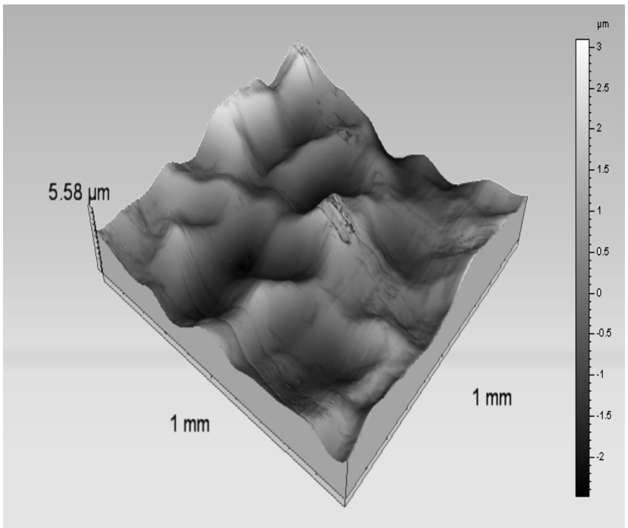

Figure 6: 3-D image of witness coupon showing bubble track.

A witness coupon was EPed at the same time as the cavity. Figure 6 shows a 1mm by 1mm surface that was analyzed with a KLA-Tencor P-16 Surface Profilometer. The average surface roughness (Ra) is 0.32 +/- 0.11 microns. Average roughness values of 0.1 microns are possible through EP. The Rz (maximum peak to valley height) was on the order of 2.5 microns. This is very bad for EP. One very interesting part of this image is the apparent hydrogen bubble track on the peak in the middle of the sample. If there are in fact hydrogen bubble tracks inside of the cavity it would also help explain the relatively poor accelerating gradient achieved.

Tumbled 1.3 GHz Single Cell Cavities

Figure 7 shows an image of Cavity 4 after the final tumbling process. The surface was mirror like and had a superior looking finish when compared to chemical polishing techniques. After the cavity was EPed the surface still looked very good but looked slightly worse. As mentioned earlier the cavity did not rotate around its own axis during tumbling. One side effect of this is that the total tumbling time was approximately 50 hours, which is 4 times longer than has been seen elsewhere [3]. One advantage to this long tumbling time is almost no heat was evolved during tumbling. This could help in preventing hydrogen from being driven into the cavity. The cavity got slightly warm to the touch. Other tumbling processes have yielded cavities to hot to handle without gloves [3]. Work has been done in the past on using hydrogen free solutions to try to prevent hydrogen absorption during tumbling [3].

As discussed earlier, tumbling can be used to produce smoother surfaces that wet chemistry can. However, perhaps the main reason that tumbling is used for SRF cavities is that it removes defects associated with the equator weld bead. The weld bead is a very irregular area and the welding process in general can create bad surface defects like sputter. Figure 8 shows pictures taken with an optical inspection system at Fermilab. Figure 8(A) is the weld bead in the as received cavity. Figure 8(B) is the

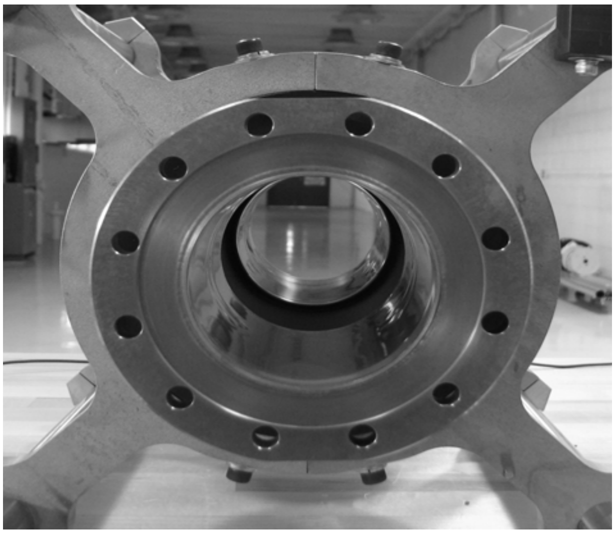

Figure 7: Image of single cell 1.3 GHz cavity after tumbling.

weld bead after the first tumbling process only. After the first tumbling step there is no visible sign of the weld bead remaining. The first tumbling step is a cutting media that is designed to remove material quickly. The first tumbling media actually makes the average surface roughness worse. The subsequent 4 tumbling steps recover and greatly improve the average surface roughness. This cavity is currently waiting for cold testing and results will be published when available.

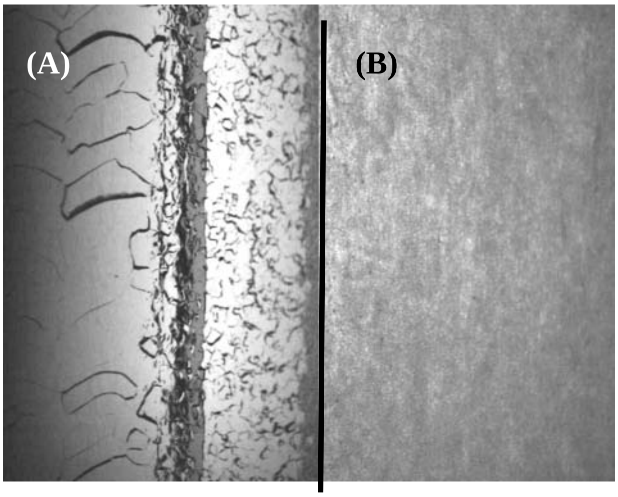

Figure 8: Image of single cell 1.3 GHz cavity equator weld (A) before and (B) after tumbling.

SUMMARY

Fermilab is currently increasing its infrastructure to process single cell cavities for process and materials R&D. Fermilab has recently added the ability to tumble cavities and soon will be adding additional on-site capability for 1.3 GHz single cell electropolishing and high pressure rinsing. Tumbling was done on a single cell 1.3 GHz cavity completely removing the weld bead and producing a mirror like finish. Cold test results are still pending. Two 3.9 GHz cavities were electropolished in a Fermilab tool and one of them reached 30 MV/m. 25 MV/m is the highest accelerating gradient seen in 3.9 GHz cavities (which were all treated with buffered chemical polishing) previously. Able Electropolishing electropolished a single cell 1.3 GHz cavity using a vertical full immersion technique of their own. The cavity they made reached an accelerating gradient of 30 MV/m and had a Q_0 of 1.0 x 10^{10}.

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