

RECENT DEVELOPMENTS IN ELECTROPOLISHING AND TUMBLING R&D AT FERMILAB

C. Cooper[#], J. Brandt, L. Cooley, M. Ge, E. Harms, T. Khabiboulline, J. Ozelis, Fermilab, Batavia, IL., U.S.A.

C. Boffo, Babcock Noell GmbH, Würzburg, Germany

Abstract

Fermi National Accelerator Lab (Fermilab) is continuing to improve SRF cavity processing infrastructure. A single-cell 3.9 GHz electropolishing (EP) tool was designed and built at Fermilab and then installed and commissioned at an industrial partner. This tool was used to process a single-cell 3.9 GHz cavity that reached an impressive accelerating gradient of 30 MV/m with a quality factor of 5×10^9 . 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 with a single-cell 1.3 GHz cavity 30 MV/m was attained with a quality factor of 1×10^{10} . First tumbling results show interior finish quality visibly better than was obtained by standard EP procedures at the ANL/FNAL processing facility. Details of these results are also discussed.

INTRODUCTION

The manufacture of niobium superconducting radio frequency (SRF) cavities incorporates forming steps that cause damage approximately 120 μm into the interior surface [1]. The cavities are also electron beam welded, which produces weld beads on the interior surface of the cavity. Both are detrimental to cavity performance. Electropolishing and tumbling are two processing techniques that remove the damage layer and reduce the

contour of the weld bead.

Neither tumbling nor electropolishing have been applied to SRF cavities on a scale required for construction of a large facility. Recent developments therefore address two additional issues: To better understand the science beneath these processes and remove processing pitfalls, Fermilab is currently building a single-cell cavity processing facility, and we report on its status here. To improve the capabilities of industry, cooperative research with one vendor near to Fermilab is also described.

EQUIPMENT & FACILITIES

Fermilab currently has single-cell and 9-cell cavity processing capabilities at Argonne National Lab, including electropolishing (EP), high pressure rinse (HPR), and ultrasonic washing / degreasing. The scope of the Argonne facility is more in line with cavity production, in that established processing parameters remain fixed for most work.

Single-cell Cavity Processing Facility

The single-cell Cavity Processing Facility at Fermilab, shown in Figure 1, is designed to allow flexibility to vary processes and obtain understanding while also carrying out work safely. The emphases of this facility will be

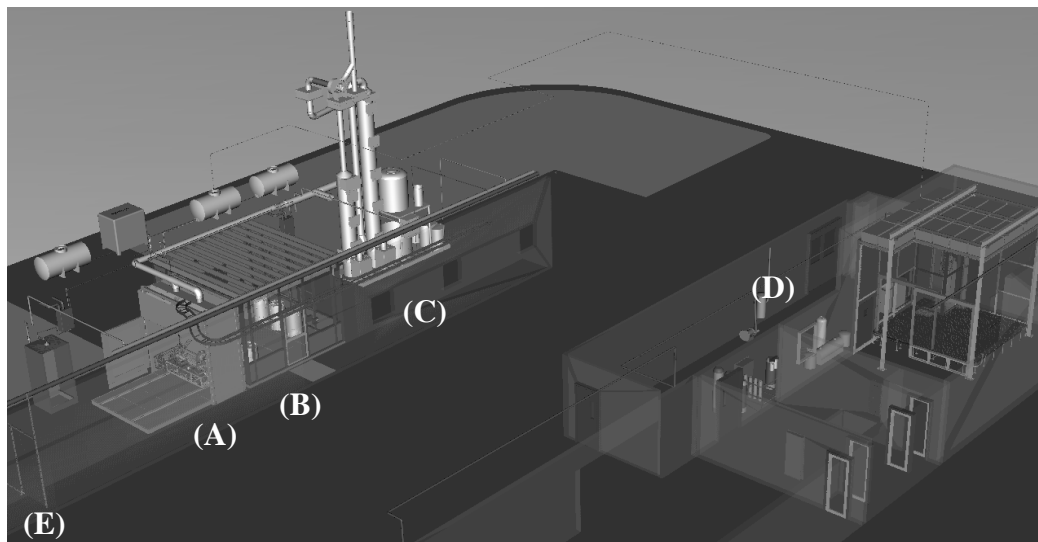


Figure 1: Cartoon of single-cell Cavity Processing Facility at Fermilab. (A) Electropolishing tool and cabinet (B) Chemical storage area (C) Scrubber and acid neutralizer (D) Clean room with high pressure rinse (E) Tumbling and ultrasonic degreasing areas not shown.

[#]ccooper@fnal.gov

material R&D and process R&D, both on single-cell 1.3 GHz niobium SRF cavities [2]. The facility will include tumbling, EP, ultrasonic degreasing, and HPR. Tumbling is currently in place and has started operations 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 with modifications to isolate the cavity during drying from particle generation in other areas of the clean room. This should permit evaluation of simultaneous rinse and assembly activities. The EP tool design is based largely on the 3.9 GHz tool to be described shortly in this paper. Presently, parts are being built, with assembly of the EP tool expected to complete in the first quarter of 2010.

Tumbling at Fermilab

The tumbler is shown in Figure 2. The tumbler is capable of tumbling two single-cell or two 9-cell cavities at a time. The tumbler rotates at 115 RPM with a 42 cm 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 [4] is shown in Figure 3. 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 be 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.

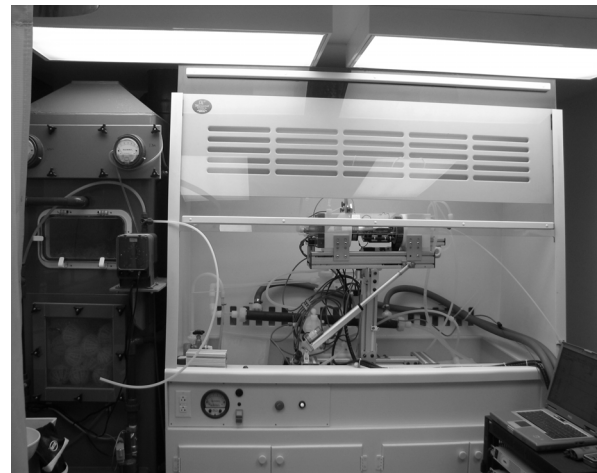


Figure 3: Picture of single-cell 3.9 GHz tool at Able Electropolishing.

CAVITY PROCESSING

The progress made on two single-cell 3.9 GHz cavities and two 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 fine-grained cavity-grade 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 °C) Micro 90 cleaning solution (Cole-Palmer EW-18100) and then rinsed with ultrapure water. Bulk EP was done to remove approximately 150 μm of material. After bulk EP the cavities were thoroughly rinsed to remove acid and then heat treated under vacuum at 800 °C. 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 μm 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 3 L min^{-1} . 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°C 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°C or below. Cavity 1 received a second 800°C bake and subsequent “light” EP to help recover the quality factor of the cavity.

The current 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 so current densities were in the range of 800 to 1080 A m^{-2} . To reduce the current draw and concomitant temperature rise at the beam tubes, the cathode was partially masked with Teflon tape. This was done before the 2nd “light” EP of Cavity 1. The current 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

Cavity 3 was processed in the Fermilab tumbler at 115 RPM with these general conditions: 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.

A 5 step sequence was used. 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 was then performed to remove between 80 and $120 \mu\text{m}$ of niobium from the inside of the cavity. After tumbling the cavity was ultrasonically degreased at 60°C for one hour. The cavity was then EPed at Argonne to remove approximately $40 \mu\text{m}$ of material. The temperature of the EP solution remained at 30°C or below. The cavity was then high pressured rinsed at Argonne and shipped to Fermilab for cold testing.

Vertical EP of a Single-cell 1.3 GHz Cavity

Cavity 4 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 part of 50% concentrated hydrofluoric acid. Other processing information was 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; in particular, the typical high temperature vacuum bake to de-gas hydrogen and a “light” EP were not applied.

CAVITY RESULTS

Record Gradient in 3.9 GHz Single-cell Cavities

The accelerating gradients E_{Acc} and quality factors Q_0 of cavities 1 and 2 are shown in Figure 4. During the first cold test of cavity 1, Q_0 versus E_{Acc} was severely limited, partly due to an unintended rise in the EP temperature to 40°C . This most likely caused a rougher surface than desired and a large amount of hydrogen to be driven into the bulk niobium. There was possibly a slight helium leak in the first test which could have caused the unusual trend seen. Subsequently, cavity 1 was given an 800°C high-vacuum heat treatment and a $20 \mu\text{m}$ “light” EP. 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 . The expectation of large in the cavity interior makes tumbling attractive for future work.

Cavity 2 was tested 4 times. Figure 4 shows the 2nd

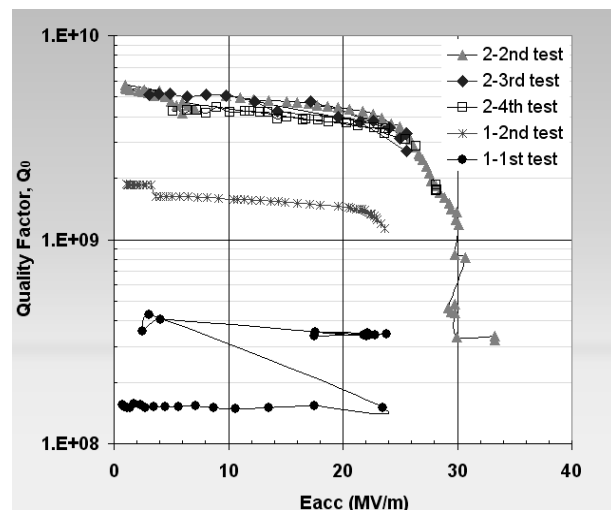


Figure 4: Accelerating gradient vs. quality factor results for Cavities 1 and 2.

through 4th tests only since equipment issues limited the 1st test. The second test yielded an E_{Acc} of 30 MV/m (terminated due to power limit) while the 3rd and 4th tests reached 28 MV/m (terminated due to quench). These values are higher than have been achieved before and higher than previously thought possible [7,8]. Importantly, the cavity shape factor yields a ratio of equatorial field B_E to E_{Acc} of 5.86 mT per (MV/m), implying that B_E reached 175 mT in test 2. Further, this result was *not* improved by final baking, since the 48 hour, 120 °C bake between the 2nd and 3rd test actually appeared to have decreased the performance.

Previous 3.9 GHz cavities were processed using buffered chemical polishing (BCP) which yields a rougher surface than EP. It is believed that this is the reason that record accelerating gradients were seen in Cavity 2. Analyses of cavity 2's surface have not been attempted yet.

Vertical EP 1.3 GHz Single-cell Cavity

Results from the 1.3 GHz cavity that was electropolished 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 good candidate for a low temperature baking treatment in future work.

Although the maximum accelerating gradient reached 30 MV/m, radiation began to increase at only 24 MV/m. It is believed that this is due to field emitters caused by a lack of adequate temperature control during the first half of the electropolishing. Later analyses revealed a rough surface and a white haze on the portion of the cavity that would have been facing up (upon which bubbles would nucleate). Better temperature control was established during the second half of the EP, and later analyses showed that the corresponding finish of the opposite half of the cavity looked smooth with no blemishes.

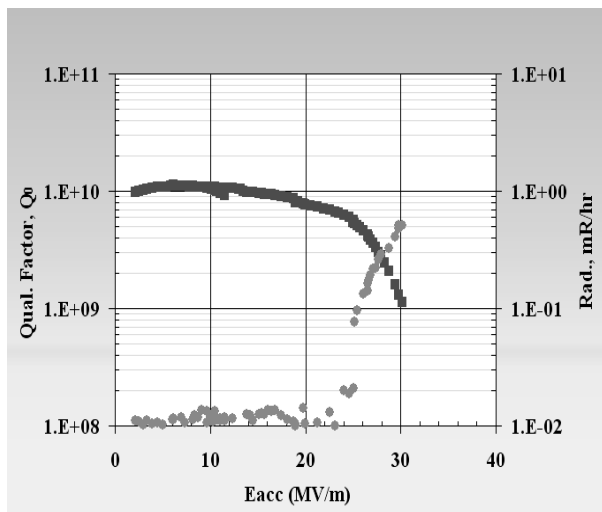


Figure 5: Accelerating gradient vs. quality factor results for cavities 3 and 2.

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A witness coupon was electropolished at the same time as the cavity. Figure 6 shows a 1 mm by 1 mm surface that was analyzed with a KLA-Tencor P-16 Surface

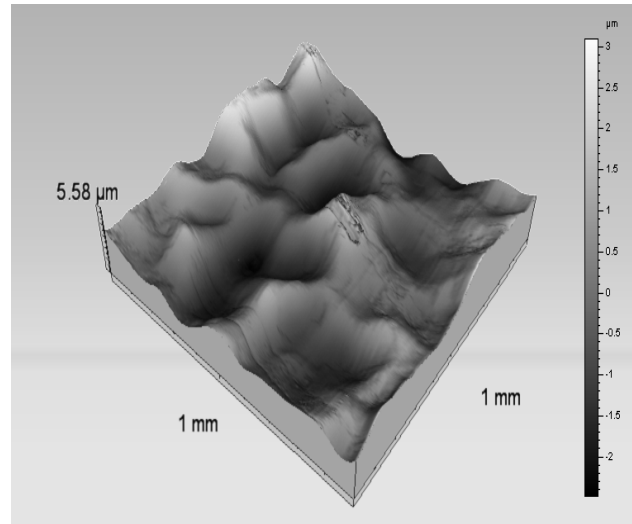


Figure 6: 3-D image of witness coupon showing bubble track.

Profilometer. The average surface roughness (R_a) is 0.32 +/- 0.11 µm. Average roughness values of 0.1 µm are representative of high-quality EP. The R_z (maximum peak to valley height) was on the order of 2.5 µm. 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.

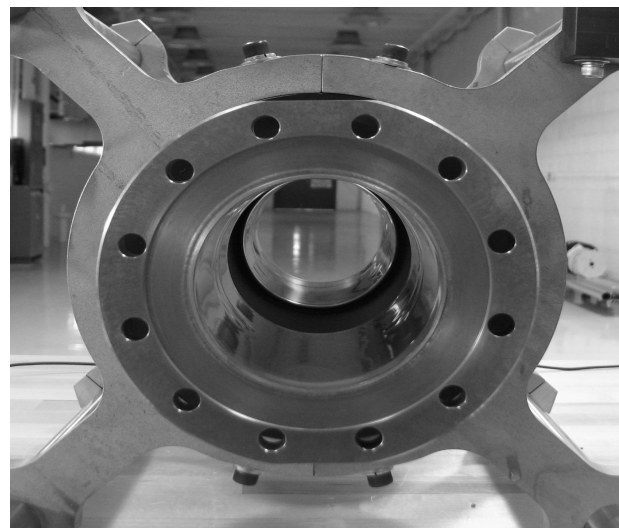


Figure 7: Image of single-cell 1.3 GHz cavity and its mirror-smooth inner surface after tumbling.

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. In fact, electropolishing at the ANL/FNAL facility degraded the surface by visual inspection. 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]. On the other hand, very little heat was evolved during tumbling—the cavity got slightly warm to the touch, whereas other tumbling processes have yielded cavities to hot to handle without gloves [3]. This could help in preventing hydrogen from being driven into the cavity. Work has been done in the past on using hydrogen free solutions to try to prevent hydrogen absorption during tumbling [3] to combat this effect. Here, tap water was simply used.

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 defects such as sputter and pits. 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 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.

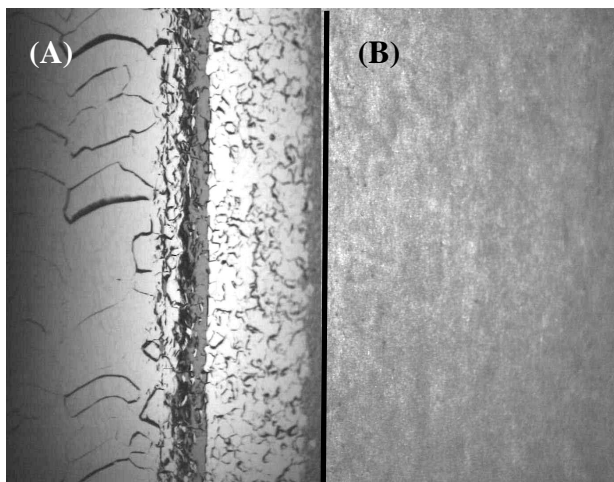


Figure 8: Image of single-cell 1.3 GHz cavity equator weld (A) before and (B) after tumbling.

SUMMARY

Fermilab is currently increasing its infrastructure for processing and materials R&D. Fermilab has recently added the ability to tumble cavities and soon will be

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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. Two 3.9 GHz cavities were electropolished in a Fermilab tool and one of them reached 30 MV/m, significantly higher than the 25 MV/m previous highest accelerating gradient seen in 3.9 GHz cavities given buffered chemical polishing. This demonstrates that the effectiveness of electropolishing carries over to 3.9 GHz cavities. Able Electropolishing used a vertical full immersion technique of their own to electropolish a single-cell 1.3 GHz cavity. That cavity reached an accelerating gradient of 30 MV/m and had a Q_0 of 1.0×10^{10} .

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