Centrifugal Barrel Polishing of Superconducting RF Cavities at Fermilab

Accelerator Seminar
At
Thomas Jefferson National Accelerator Facility

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Layout of Presentation

1. Intro – What is CBP & Why do it?
2. Current Baseline Cavity Manufacturing & Processing
3. Problems with Baseline Process
5. How CBP is done on 1.3 GHz geometry.
6. 1.3 GHz Centrifugal Barrel Polishing Results
7. 1.3 GHz Centrifugal Barrel Polishing Results
8. Summary of Current Results
9. Future Work
1. Introduction to Centrifugal Barrel Polishing
1. What is Centrifugal Barrel Polishing?

Centrifugal Barrel Polishing (CBP) is an alternative processing technique that polishes the inside of superconducting rf cavities by rotating the cavities at high speeds while filled with an abrasive media.

Individual Barrels 115 RPM in opposite direction to main shaft
1. Why do Centrifugal Barrel Polishing?

- Creates a more uniform surface
  - Increase accelerating gradient by removing surface defects
  - Remove artifacts of the Electron–beam welding process.
  - Remove pits, bumps, scratches
    - Make QC of sheets prior to forming easier.
- Can yield surface finishes (Ra) on the order of 10s of nanometers. Best by EP alone is around 100 nanometers.
  - Both accelerating gradient and quality factor may be increased
  - Smoothest surfaces in general produced by mechanical polishing.
    - Chemical purity recovered by chemistry. (Optics, Microchips)
- Environmentally friendly.
  - Most likely will still require a small amount of chemistry (on the order of 5–10 microns compared to 120 microns for EP)
- Possibly Remove Electropolishing Process.
- Cheaper installed cost.
- More easily transferable to industry.
- Should be a repeatable process.
1. Goals of Centrifugal Barrel Polishing

- To produce Tesla type cavities with high $Q_0$ and $E_{ACC}$ with a 90% or better yield (Current Process at 56%).
  - Needed to make next generation particle accelerators feasible from an installed and operating cost standpoint.
  - Examine if $Q$ and $E_{ACC}$ are better with CBP
- Eliminate electropolishing from current baseline process.
  - Expensive, Complicated, Large amount of concentrated acid
- Investigate use of Re–entrant shape cavity which operates at a higher field and may require a smoother finish that EP can provide.
  - World Record 57 MV/m Re–entrant cavity was mechanically polished.
- Investigate the deposition of thin films on SC rf cavities (requires mirror smooth finish)
- Eliminate 800 C hydrogen bake out step (and subsequent chemistry step)
2. Current Baseline Cavity Process

Baseline Cavity Processing Tools at Fermilab
(1) Horizontal Electropolishing
(2) High Pressure Rinse
(3) Hydrogen Degassing Furnace
2. Goal of Cavity Processing

To with high repeatability (ILC 90% Yield) make cavities with good $Q_0$ and accelerating gradient.

Quality coefficient

$$Q_0 \propto \frac{G}{R_s}$$

$G = \text{geometry factor which depends on the cavity shape}$

$R_s = \text{surface resistance which depends on cavity surface geometry and chemical purity}$

CBPed Mirror finish cavity has residual surface resistance of $1.34 \pm 1.19 \text{ nano-Ohms}$
2. What must be done during cavity processing to get high quality factors and accelerating gradients?

- Start with High Purity Niobium Sheet
- End with High Purity Niobium Cavity
- End with a “Smooth” Homogeneous Surface
- End with a Clean Surface

### Fermilab Niobium Specification

<table>
<thead>
<tr>
<th>Element</th>
<th>PPM (Weight)</th>
<th>Element</th>
<th>PPM (Weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>70</td>
<td>Ni</td>
<td>30</td>
</tr>
<tr>
<td>Ti</td>
<td>40</td>
<td>O</td>
<td>10</td>
</tr>
<tr>
<td>Fe</td>
<td>30</td>
<td>N</td>
<td>10</td>
</tr>
<tr>
<td>Si</td>
<td>30</td>
<td>C</td>
<td>10</td>
</tr>
<tr>
<td>Mo</td>
<td>50</td>
<td>H</td>
<td>2</td>
</tr>
</tbody>
</table>
2. How Niobium Sheets are Made

Fabrication process of Nb sheets for Superconducting Cavities
Tokyo Denkai Co., Ltd.

1. Mother Material
2. Pressing
3. Outgassing and Sintering
4. EB Melting (1st)
5. EB Melting (2nd, 3rd)
6. Cutting
7. Forging
8. Mechanical grinding
9. Rolling
10. Polishing
11. Rolling
12. Cutting
13. Annealing
14. Testing
15. Polishing
16. Packing

Graphic from Tokyo Denkai
Before forming half cells, sheets are annealed and should have little mechanical stress.
2. How Cavities Are Made.

Niobium is cleaned, etched and electron beam welded.

Graphic from Hitoshi Hyano
2. Electron Beam Welding – W. Singer

Data from Waldemar Singer, ISOHIM 2005
2. After Manufacturing, How Cavities Are Currently Processed

Baseline Cavity Process Path

- 120–150 Micron Electropolishing
- Water Rinse
- High Temperature Bake
- Light Material Removal
- (Alcohol Rinse)
- High Pressure Rinse
- Assembly
- (Low Temperature Bake)
- RF Test

Reprocess for low $E_{\text{ACC}}$

- 800 C for 2 hours – Hydrogen Contamination
- 20 Micron EP
- For Sulfur Precipitate Removal
- 1200 psi, Ultrapure Water
- Class 10 Clean–room
- 48 Hour, 120 C

Reprocess for Field Emission

5/10/2011
2. How Cavities Would be Processed with CBP

Baseline Cavity Process Path

- 120–150 Micron Electropolishing
- Water Rinse
- High Temperature Bake
- Light Material Removal
- (Alcohol Rinse)
- High Pressure Rinse
- Assembly
- (Low Temperature Bake)
- RF Test

Proposed CBP Process Path

- 120–150 CBP
- Chemical Rinse
- High Temperature Bake
- Light Material Removal
- High Pressure Rinse
- Assembly
- (Low Temperature Bake)
- RF Test

Proposed “Hydrogen Free” CBP Process Path

- 120–150 CBP
- Chemical Rinse
- High Pressure Rinse
- Assembly
- (Low Temperature Bake)
- RF Test

800 C for 2 hours – Hydrogen Contamination
20 Micron EP
For Sulfur Precipitate Removal
1200 psi, Ultrapure Water
Class 10 Clean-room
48 Hour, 120 C
2. Hydrogen-free processing by CBP

- T. Higuchi and K. Saito did work on CBP replacing water with a hydrogen-free fluorocarbon (CF-77).
- When doing CBP with water they found approximately 80 ppm of hydrogen in the niobium.
- When doing CBP with CF-77 they found approximately 5 ppm of hydrogen. Compared to 1 ppm hydrogen in annealed niobium.
- They were doing 50 micron chemistry after CBP which meant that standard EP put hydrogen back into the niobium.
- Our current CBP process requires 20 microns chemistry which is similar to the “light” EP which is not thought to cause substantial hydrogen uptake.
- Goal is to reduce (eliminate) amount of material that must be removed after CBP and use a chemical rinse instead of EP.
2. Electropolishing Chemistry Area
2. Electropolishing Tool

- Operated in a cabinet to mediate any potential gas or vapor risks
- Process as “hands-free” as practical
- All wetted parts should be made out of PVDF, PFA, or PTFE
- Sled comes in and out of cabinet for ease of assembly/dissassembly
- Heavy integration of safety components in operation
2. Chemical Storage Room
2. Chemistry Area – Safety

- 1000 CFM Scrubber to clean process air.
- Neutralization system to pH adjust process effluent.
- All areas with concentrated chemicals have 2 to 3 layers of containment. Potential spills automatically trigger a pump which contains the spill in a drum.
- Several Monitoring Systems
- Safety Showers/Eye Wash Stations
3. Problems with baseline process?
3. Problems with Baseline Process

1.) Yield – Need a higher yield than currently obtainable to make accelerator economically feasible
2.) Pit formation – Unknown mechanisms, sometimes made worse by electropolishing
3.) Sputtering & Voids (porosity) from E-Beam Weld
4.) Sulfur precipitation from electropolishing process
5.) Hydrogen contamination from electropolishing process

Field emission – Improper cavity handling during general assembly or testing
3. Current Yield

1st-pass cavity yield at >35 MV/m is (29 +/- 8) %

2nd-pass cavity yield at >35 MV/m is (56 +/- 10) %

90% Yield desired for economic feasibility

From Camille Ginsburg – ALCPG Meeting – Eugene, Oregon Mar. 2011
3. Pit formation during baseline processing
Pictures of 8–9 iris weld of TB9RI026 – grains shaded to help show area of defect

As received – no pit visible

After additional EP pit grows

After bulk EP characteristic pit appears

Cavity made as high as 29 MV/m but currently at 19 MV/m

5/10/2011
4. Preliminary work on 3\textsuperscript{rd} Harmonic Geometry Tumbling Apparatus Shown
4. Experimental 3rd Harmonic Tumbling

Purpose of work:
1.) Find how smooth surface could be after tumbling
2.) Minimize material removal rate difference between equator and iris

• Many medias tried
• Tumbling time weeks per media

Can get Ra’s on the order of 10s of nm for smaller samples of niobium using different types of media

Ra = 0.00226 µm +/- 0.000171 µm
Min: 0.00175 µm / Max: 0.00332 µm

By Rotating 20° off horizon able to minimize difference in material removal rate between iris and equator
5. CBP Process for 1.3 GHz Cavities
5. Single Cell Cavity Preparation
5. Single Cell Cavity Preparation
5. 9-Cell Cavity Preparation
5. 9–Cell Cavity Preparation – Plugs

- HOM Can Must Be Protected or the Antenna Would be Destroyed.
- Caps are Made From Niobium to Avoid Contamination.
5. 9-Cell Cavity Preparation
6. 1.3 GHz Results intermediate Polishing
### 6. Media Used for Following Results

<table>
<thead>
<tr>
<th>Step</th>
<th>Description</th>
<th>Time</th>
<th>Media</th>
<th>Alumina</th>
</tr>
</thead>
<tbody>
<tr>
<td>Step 1</td>
<td>Cutting, Time as needed</td>
<td></td>
<td>+ Soap &amp; Ultrapure Water</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Removal: 11 µm/hr</td>
<td></td>
</tr>
<tr>
<td>Step 2</td>
<td>Intermediate Polishing, 12 hours</td>
<td></td>
<td>+ Soap &amp; Ultrapure Water</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>3 µm/hr</td>
<td></td>
</tr>
<tr>
<td>Step 3</td>
<td>Intermediate Polishing, 15 hours</td>
<td></td>
<td>Water + 400 Mesh Alumina</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Polishing time is being</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>optimized. Present values</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>based on optical inspection.</td>
<td></td>
</tr>
<tr>
<td>Step 4</td>
<td>Intermediate Polishing, 20 hours</td>
<td></td>
<td>Water + 800 Mesh Alumina</td>
<td></td>
</tr>
</tbody>
</table>
6. Results – Pit Repair – Nine Cell

Had a large (~200micron) pit in cell 3 – previously processed and tested at JLab to 19 MV/m

Before CBP

After CBP and 40 microns EP – Pit completely removed
6. 1st Cavity 40 MV/m!

- ACCELL manufactured single cell 1.3 GHz Cavity
- 100/120 micron tumbling
- 40 micron EP at Argonne
- 3 hour 800 C bake at JLab
- 20 micron EP at Argonne
- HPR at Argonne
6. Results of ACC004 – Single Cell 40 MV/m!

CBPed Single Cell 1.3 GHz ACC004

ILC Specification

$Q_0 > 1 \times 10^{10}$ at 31.5 MV/m

$8 \times 10^9$ at 35 MV/m

Tested by J. Ozelis - 1/7/2010
6. 40 MV/m?
6. 40 MV/m?
6. **ACC004 CBP with Different Set of Media**

- Picture after first CPB with typical media & 60 micron EP
- Picture after 2nd CPB with porcelain balls & 40 micron EP
NR-6 was tested after tumbling and reached as high as any of the other 6 single cell cavities from Niowave/Roark from that lot. Weld bead was successfully removed but surface shows general pitting after processing. Apparent porosity in material.
6. RRCAT2 Single Cell Performance

Tested 12/17/10: Tumbling, HT, Light EP, HPR/Assy, then 120°C Bake @ IB1

- Blue – Tumbling
- Red – EP

Irregular weld
Voids in weld by x-ray

After Processing Still Large Areas of Weld Bead Not Removed

Figure 2. Comparison of $Q_0$ vs $E$ @ 2K with previous result.
7. 1.3 GHz Results for Mirror Finish
## 7. Current Media – Mirror Finish

<table>
<thead>
<tr>
<th>Step 1</th>
<th>Step 2</th>
<th>Step 3</th>
<th>Step 4</th>
<th>Step 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cutting, Time as needed</td>
<td>Intermediate Polishing, 12 hours</td>
<td>Intermediate Polishing, 15 hours</td>
<td>Intermediate Polishing, 20 hours</td>
<td>Final Polishing, 40 hours</td>
</tr>
</tbody>
</table>

**+ Soap & Ultrapure Water**

- Removal: 11 µm/hr

**+ Soap & Ultrapure Water**

- 3 µm/hr

**Water + 400 Mesh Alumina**

**Water + 800 Mesh Alumina**

**Colloidal Silica**

Polishing time is being optimized. Present values based on optical inspection.
Ra = 0.0139 µm +/- 0.00216 µm
Rz = 0.139 µm +/- 0.0242 µm

Typical finish achieved by fine polishing.
7. How much chemistry needed to remove artifacts of CBP with Mirror Finish?

![Graph showing the comparison of ACC002 - HF Rinse & 20 Micron EP, AES005 - 10 Micron EP, and ACC002 - HF Rinse Only. The graph plots data against a logarithmic scale on the y-axis and a linear scale on the x-axis. The x-axis is labeled with numbers from 0 to 45. The y-axis ranges from 1.00E+09 to 1.00E+11.]}
Cavity tested many times after baseline EP processing and reprocessing techniques. Best baseline results shown. Cavity improved greatly after CBP.

Gigi's program (using the approximate BCS theory) gives a residual surface resistance of $1.34 \pm 1.19$ nano-Ohms after CBP/20micron EP. Testing by J. Ozelis
First polishing step was 5 hours instead of 12, leaving **embedded media** in the cavity. May explain drop in accelerating gradient. Quality factor did increase substantially.
8. Summary of Current Work

- **Determined**
  - Remove damage associated with welding process.
  - Less acid usage (20 micron EP).
  - Repair cavities damaged with pits that EP could not fix.
  - Shown improved accelerating gradient compared to EP (35 MV/m to 43 MV/m).
  - All CBPed cavities show improved quality factors, but not decoupled from heat treatment process yet.
  - Simple technology, easily transferable to industry.
  - Cheaper installed cost.

- **Experimental**
  - May solve yield problems.
  - May improve quality factor.
  - May match or improve (Re-entrant) accelerating gradient.
  - May eliminate EP.
  - May be spring board for other manufacturing technologies like thin film deposition.
9. Future Work

- To see if CBP gives better yield:
  - Set baseline CBP process
  - Process 10, 9-cell cavities from a qualified vendor
- To prove the quality factor is improved by CBP
  - On a virgin single cell cavity
    - Process with baseline technique, test
    - CBP, test
    - Reset surface with 60 micron BCP
    - EP for 60 micron, test
9. Transition from intermediate to fine polishing is key.

Step 4
(15 µm)
Intermediate Polishing, 20 hours

Samuels’ textbook: Intermediate stage is polishing by micro-machining. Fine stage is polishing by delamination.

Step 5
(.04 µm)
Final Polishing, 40 hours

Metallography polishing in this range is not successful for flat niobium samples because regions smear or are pulled out (large-scale delamination).

15 µm → 6 µm → 3 µm → 1 µm → 0.5 µm → 0.1 µm

Water + 800 Mesh Alumina

Tumbling niobium with the hardwood blocks and 1200 grit (10 µm) media pulled grains out.

Colloidal Silica
9. Methods to Reduce Amount of Post-CBP Chemistry Needed

- Problem: Avoid smear and pull–out.
- Pull–out tendency is a function of particle size, shape, and force against cavity surface.

Ideas for solution:
- Increase the amount of tumbling time for step 5.
- Try particle shapes that favor machining over laminating at particle sizes below 15 µm.
- Try other carriers with different density & aspect ratio to change force on the cavity surface.
- Adjust rotation speed to change force.
- Modify pH to favor micro–machining below 15 µm.
Present focus is on improving the transition between steps 4 and 5

- Increasing the length of the final tumbling step will be examined (easiest from R&D standpoint).

- With the use of coupon cavities perfect process.
  - New media, different applied force, different pH
  - Use Surface Profilometry and SEM/EDS to determine the average surface roughness and chemical contamination present after each step.
9. Future Plans

- Process re-entrant cavity to mirror finish.
  - Correlate Ra to cavity performance.
  - Examine effects of surface chemistry on cavity performance.
- Evaluate “Hydrogen Free” processing that would eliminate the heat treatment step.
  - Already demonstrated at KEK
- Prepare single cell cavities for thin film studies.
- Examine processing 650MHz cavities
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