R&D PROGRESS IN SRF SURFACE PREPARATION WITH CENTRIFUGAL BARREL POLISHING (CBP) FOR BOTH Nb AND Cu*

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Abstract

Centrifugal barrel polishing (CBP) is becoming a common R&D tool for SRF cavity preparation around the world. During the CBP process a cylindrically symmetric SRF cavity is filled with relatively cheap and environmentally friendly abrasive and sealed. The cavity is then spun around a cylindrically symmetric axis at high speeds uniformly conditioning the inner surface. This uniformity is especially relevant for SRF application because many times a single manufacturing defect limits a cavity's performance well below it's theoretical limit. In addition CBP has created surfaces with roughness's on the order of 10's of nm, which create a unique surface for wet chemistry or thin film deposition. CBP is now being utilized at Jefferson Lab, Fermi Lab and Cornell University in the US, Deutsches Elektronen-Synchrotron in Germany, Laboratori Nazionali di Legnaro in Italy, and Raja Ramanna Centre for Advanced Technology in India. In this report we present the current CBP research from each lab including equipment, baseline recipes, cavity remov al rates and subsequent cryogenic cavity tests on niobium as well as copper cavities where available.

INTRODUCTION

Centrifugal barrel polishing (cbp) for SRF application is becoming more wide spread as the technique for cavity surface preparation [1–5]. CBP is now being utilized at Jefferson Lab (JLab), Fermi Laboratory (FNAL) and Cornell University in the US, Deutsches Elektronen-Synchrotron (DESY) in Germany , Laboratori Nazionali di Legnaro (INFN/LNL) in Italy , and Raja Ramanna Centre for Advanced Technology (RRCAT) in India. During the CBP process a cylindrically symmetric hollow vessel is filled with an abrasive media, sealed, and rotated around the vessel's symmetry axis in one direction while also begin rotated in the opposite direction around an additional axis parallel to the vessel axis [6]. The rotation about the cavity symmetry axis moves the abrasive along the surface, while the parallel machine axis rotation creates an outward force on the inner surface. This combination creates uniform surface finish and relatively fast removal rate. This report is designed to be an update from the 2011 presentation of world wide CBP at SRF2011 by Cooper *et al.* [4]. In this report we present current status of CBP experiment for SRF application at different laboratories around the world, including cavities processed the last report and proceedings within SRF2013 (these proceedings) where one can find more detailed information about the current studies.

CBP EQUIPMENT AND LAB UPDATE

In the United States, JLab, FNAL, and Cornell as well as DESY in Germany are all using a version of the Mass Finishing HZ280 two barrel CBP machine, designed for CBP of 9 cell 1.3 GHz and smaller cavities. FNAL has also just taken delivery of a 650 MHz and smaller 4 cavity machine also manufactured in collaboration with Mass Finishing. RRCAT is using as custom designed machine for single cell 1.3 GHz and smaller cavities, and finally INFN/LNL has designed and built a custom 1.3 GHz single cell CBP machine. Pictures of the various machines are shown in Figure 1.

Since Fall 2011, the number of cavities which have undergone CBP processing has expanded quite rapidly, with many new laboratories setting up their own systems. Prior to SRF2011 only hand full of cavities had been processed using modern CBP machine. In the last two years the number of cavities process has gone up over 6-fold. The full known list (as complete as possible at the time of publication) of cavities process by CBP is shown in Figure 2. From the list, one can see that FNAL and JLab (the ones with fully operational CBP machines in Fall 2011) have process the most cavities, but the other laboratories are ramping up their operations as their machines come on-line.

CBP BASELINE RECIPES

All current baseline recipes follow the same general recipe pattern. Three to five step CBP, light chemistry

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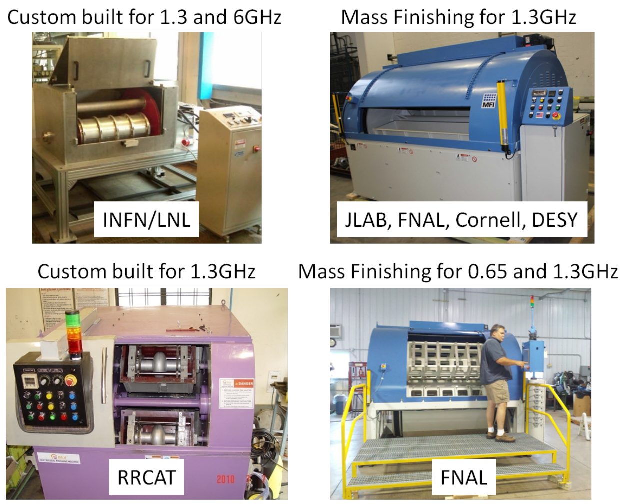

Figure 1: CBP machines from around the world. Designed elliptical cavity frequency, manufacturer if built outside the host laboratory (custom if built inside the lab), and lab location is shown in the text for each machine.

FNAL
•Nine Cell (TB9XXXX)
-ACC015, NR002, AES006, AES012, AES016
-AC114 – Large Grain
-IHEP02 – Large Grain – Low Loss Shape
•Single Cell (TE1XXXX)
-JL001, JL002, ACC001, ACC004, ACC006, CAT001-CAT004, CATLZW001, PAV001, PAV005, PAV007, PIPPS03, AES008-AES011,
-1DE20, IHEPLG01 – Large Grain
-RICU001 (several others as well) – copper
-CAT05 – Aluminum (contact Cooper first)
•Coupon Cavity
–TACAES001 & 002 (~40 runs)

DESY
•Machine setup and beginning to process multi-cell cavities

JLAB
•Multi-cell
-TB9NR001
-DESY 3.5 cell gun cavity – large grain
•Single cell
-RDT4-7, TE1G002-003, PS-1307 (1.5GHz)
-F1F2 (1.5GHz), G1G2, PJ1-1 – Large grain
-LSF-1,2,3 - copper
-6 sets of beam pipes (Cu and Nb)

RRCAT
•Multiple single cell

INFN/LNL
•Over 10 6 GHz (resonate vibration)

Cornell
•Beginning to process multi-cell cavities

Figure 2: List of CBP processed cavities since SRF2011, categorized by laboratory and type. All cavities are 1.3GHz unless noted.

(totaling about 5 to 30 μm total removal), high temperature heat treatment to remove hydrogen, HPR, and assembly. Depending on the laboratory there are two sets of light chemistry, one before the high temperature heat treatment and another afterward. The best practices (cleaning procedure) and optimized parameters (run time/media choice) are still under investigation depend on the purpose of the CBP, i.e. defect repair, final surface roughness, and Qo optimization. For a reference most laboratories are using a recipe very similar to the one published in 2011 by FNAL, although the run time for each step is different between labs depending on the application. The baseline media and run time for each step is shown in Figure 3. In general for the first three step, one can use almost any type of media as long as the grit is reduced between steps to 3-10 μm; for the final step a jump below 100 nm with an oxidizing slurry is needed to create a mirror-like surface [7]. Alternative final step media such as diamond

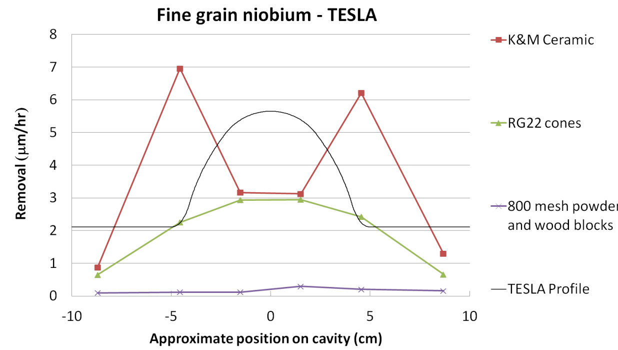

Figure 4: CBP removal rate vs. position for different media types for TE1G003 - fine grain TESLA shaped 1.3 GHz for the first three CBP steps. The markers are the approximate measurement location on the cavity with the connecting lines as a guide to the eye as is the TESLA profile in thin black [8].

suspension and acidic slurries as well as final step media carriers are also under investigation by JLab and FNAL.

CAVITY REMOVAL RATES

As CBP becomes a common step in the cavity surface preparation on elliptical cavities, knowing the amount and profile of material removed during CBP process is becoming more vital. For instance, if CBP is to become part of the base line recipe for accelerator components or for targeted removal of defects of a know depth, the variability of removal along the cavity profile needs to be known. Currently JLab has begun measuring to profiled removal rate (μm/hr) vs cell location and frequency shift for multiple SRF cavities including large and fine grain niobium 1.3 GHz TESLA shaped cavity, large grain niobium 1.5 GHz CEBAF shaped cavity, and fine grain copper low surface field 1.3 GHz cavities. An example of the CBP removal rate vs cavity position is shown in Figure 4. There are two important items to note from the removal; one, the coarse media removes more from the side walls than the equator, and two, the profile of the removal changes between different types of media. The detailed analysis and profiles for all 4 cavity types are presented in the these proceedings by Palczewski *et al.* (TUP064) [8] .

DEFECT REMOVAL AND VOID EXPOSURE

One of the aspects of CBP which makes it very promising for SRF application is that CBP has the ability to remove defects that chemistry (EP or BCP) cannot, but it can also uncover voids/bubbles in the weld. For example, in ILC 9-cell cavity TB9NR001 CBP completely removed a dual cat eye defect in cell 5 which limited the cavity below 20 MV/m, but uncovered another detect in cell 6 at the edge of the fusion zone of the weld (Figure 5). No other

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Figure 3: Standard CBP recipe used by various labs. The run time varies between labs depending on the application. Course (6 hours or longer), medium (12 to 30 hours), polish 1 (20 to 40 hours), and polish 2 (40 to 300 hours).

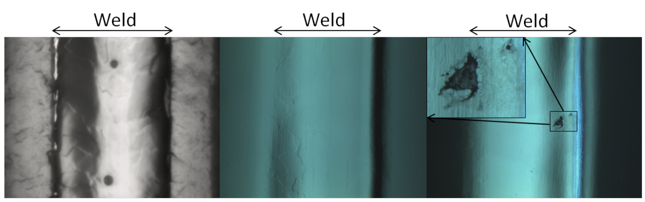

Figure 5: Internal inspection of NR1 before and after mirror like finish CBP. Moving from left to right dual cat eye defect in cell 5, the same location after 20 μm EP (no effect) and 4 step CBP, and new defect at the edge of the equator in cell 6 not see before CBP.

locations inside the cavity after CBP showed any sign of a defect. It is interesting to note, NR1 went through at least 300 μm total chemistry/CBP at the equator before the weld pore was uncovered. Although the defect in cell 6 is rather large, $\approx$250 μm by 350 μm it is rather shallow, only 10-20 μm deep (measured using the CYCLOPS interferometer) [9]. It is also unclear how large the full defect might be as there is another small hole next to the larger defect which could be part of the same defect if more material is removed. During RF tests, cell 5 went above 36 MV/m and cell 6 went to 35 MV/m with only a standard ILC final EP of 30 μm.

CBP COPPER

One of the alternative materials for SRF application which may benefit from CBP is copper. The primary goal of the this endeavor is to create a uniformly smooth and defect free surface for thin film deposition. Initial results from JLab suggest the standard baseline CBP recipe for Nb on copper does create a surface that although rougher than typical thin film sample substrates, but does create good film adhesion using energetic condensation. The detailed CBP recipe and removal rates can be found in these proceedings by Palczewski *et al.* (TUP064) and the surface analysis post thin film deposition can be found in these preceding by Zhao *et al.* (TUP083) [10]. The best recipe at JLab which creates a surface as close to polished flat coupons uses 3μm colloidal diamond. Similarly to niobium, within a particle size region the surface actually becomes more rough and possibly even smears the surface rather than polishing to a mirror finish [7]. This can be seen in Figure 6 where the best finish on the beam tube is with 3 μm diamond suspension, while using 1 μm diamond paste with neutral cutting fluid and 40 nm colloidal silica (ph of 10.4) actually roughen the surface. This is similar to what has been seen with copper coupons where any particle size below 3 μm causes the surface to scratch and not polish [11]. It is unclear at this time whether the particle size matters on copper, or the interaction with the wood block/liquid and the copper which actually roughens the surface independent of the particle size.

In addition to JLab, FNAL is also looking into CBP of copper cavities for thin film development. Using extended mechanical polishing (XMP) with a non standard media (different from the copper and niobium recipe described above) they were able to produce a copper surface free of viable scratches by standard optical inspection techniques [12]. An example image of the weld area from a XMP copper cavity with zero post CBP chemistry is shown in Figure 7. The dark color is surface oxidation from cleaning and is not inherent in the CBP process.

ZERO POST CHEMISTRY CBP

CBP was originally identified a possible way to reduce the amount of chemistry need for final surface preparation of elliptical SRF cavities. Current CBP recipes from JLab and FNAL have shown that the surface roughness can be on the order of 10's of nm with a damage layer possibly on the same order [1, 2, 13]. Since the roughness and damage layer is on the order of the RF penetration depth for niobium (approximately 40 nm), a purely CBP surface might be be able to support at RF field. This hypothesis was originally tested at JLab in 2012 on cavity D-II. The zero post chemistry CBP surface produced a reasonable good Q of 2e10 at 2 Kelvin on a 1.5 GHz cavity at 1 MV/m, but quickly degraded to 1e9 at 10 MV/m which was repaired by light EP (Figure 8 Top) [2]. The results were

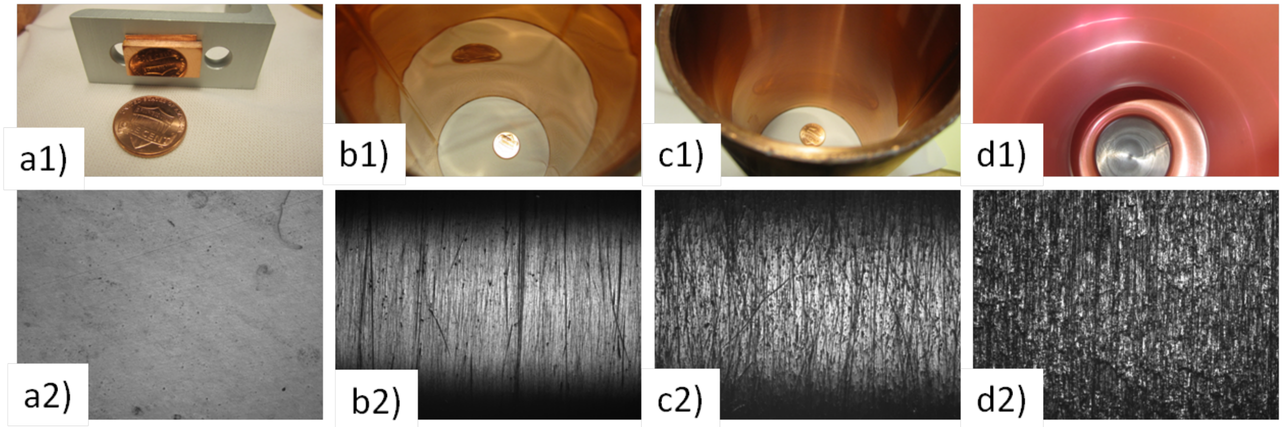

Figure 6: Images of 4 different mechanically polished copper items, the top is the digital camera image and the bottom is a mono-chromatic image taken by the CYCLOPS (images are 1.2mm×1.6mm), moving from left to right, flat copper coupon finished with 3 μm diamond suspension on buffing wheel [11], 3 inch beam tube finished with 3 μm diamond suspension and wood blocks, 3 inch beam tube finished with 1 μm diamond paste with cutting fluid and wood blocks, and LSF1-1CU copper cavity side wall finished with 50 nm colloidal silica and wood blocks (oxidized during cleaning).

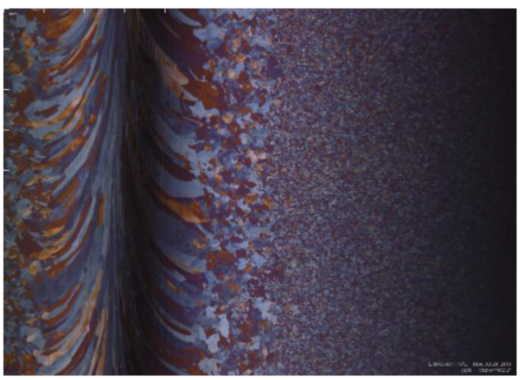

Figure 7: Internal optical inspection of the weld are on a 1.3 GHz XMP copper cavity after cleaning but without chemistry. Image size approximately 1.5 cm×1.5 cm.

interpreted as a damaged surface from CBP. The cavity was later re-heat treated again which returned the cavity again to a degraded state with a strong Q slope process, the data is shown in Figure 8 top black. The current understanding is that the original strong Q slope may have been from furnace contamination and not inherent in the CBP process.

During approximately the same time, FNAL was able to eliminate the furnace contamination by covering their cavities's opening with caps during heat treatment, the results of capping cavities to avoid contamination during heat treatment are published in theses proceedings by Grassellino *et al.* (TUP030) [14]. After the furnace contamination was mitigated at FNAL, they began testing zero post chemistry CBP cavities after furnace treatment. An example result is shown in Figure 8 bottom. During this experiment the cavity was baseline with CBP, heat treatment and then light chemistry. After the reasonable baseline result the cavity was then re-cbp'ed with just the final media and the heat treated with caps. Following this procedure the cavity showed no sign of degradation, the detailed analyses of this and other zero post chemistry CBP cavities can be found in these proceedings by Cooper *et al.* (TUP060) [15]. Within the two contributions, TUP030 and TUP060, there is also data from full recipe CBP with no chemistry reaching 33 MV/m, although with a stronger than normal Q slope.

RESONATE VIBRATION MECHANICAL POLISHING

One of the problems inherent in the CBP process is the machines produce a large amount of force and angular momentum that, without the proper safety systems, can be quite dangerous. This is particularly a concern as the machines become larger to accommodate lower frequency cavities and larger torque arms. In addition, on higher frequency cavities, such as the 6 GHz cavities, the rotation speeds need to be much higher to produce the same removal rates as lower frequency machines. Because of these concerns, INFN/LNL have designed a resonant vibration system for 6 GHz cavities. A picture of the machine is shown in Figure 9. This new machine can produce removal rates very similar to CBP with a composite course media producing a removal of 14 μm per hour. Detailed analysis of the system, removal rates, and current studies can be found in two master theses by Guolong and Thakurt [16, 17]. Plans are in the works to build a 1.3GHz system which uses resonant vibration technology which may produce similar results. One other advantage to such a system is it might enable better surface finishes than CBP alone, similar to metallurgically flat sample polishing, where the initial steps are done on a lapping machine while the final finishing step are performed on a vibratory polisher.

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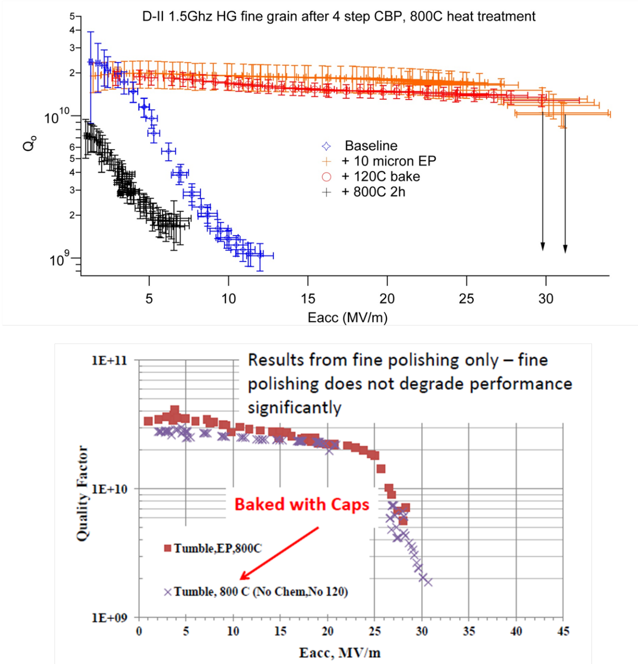

Figure 8: Top: Test results from D-II at JLab, the baseline results are from CBP and heat treatment with no chemistry. Additional light chemistry and low temperature bake improved the cavity. Final heat treatment with no chemistry showed a strong Q slope attributed to furnace contamination. Bottom: Test results from Large grain 1.3 GHz cavity showing the final CBP step does not degrade cavity performance.

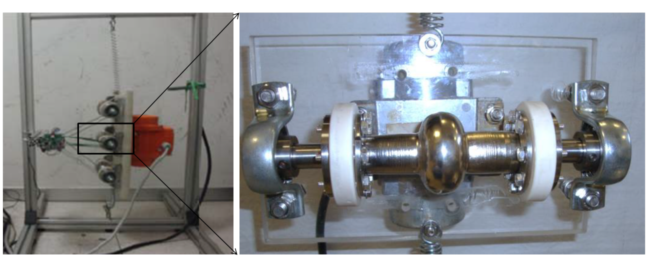

Figure 9: Image of resonant vibration system at INFN/LNL designed for 6gHz cavities.

CONCLUSION

CBP for SRF application continue to grow in the last two year. Many laboratories around the world are ramping up their processing using CBP as new machines come on-line. Larger machines for 650MHz cavities will help the community to understand the scaling factors on larger cavities and the scaling force on 1.3GHz cavities with larger torque arms. New results on zero post chemistry CBP of niobium as well as mirror finish CBP on copper for thin film development continue to add new possibilities for CBP in SRF applications. New alternatives to CBP from resonant vibration many also produce similar results with less complicated, and possibly safer machines.

ACKNOWLEDGMENT

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