CENTRIFUGAL BARREL POLISHING OF CAVITIES WORLDWIDE

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Abstract

Much interest was generated in the mid to late 1990s in an alternative cavity surface processing technique called centrifugal barrel polishing, that mechanically polishes the inside of superconducting RF (SRF) cavities by rotating them at high speeds while filled with abrasive media. This work, which was originally done at the KEK High Energy Accelerator Research Organization (KEK) by Kenji Saito & Tamawo Higuchi, has received renewed interest recently because of work done at the Fermi National Accelerator Lab (Fermilab) which has produced mirror like finishes on the 1.3 GHz Tesla-type cavity SRF surface. In addition to Fermilab & KEK, the Cornell University SRF Group (Cornell), the Thomas Jefferson National Accelerator Facility (JLab) and the Raja Ramanna Centre for Advanced Technology (RRCAT) are all exploring CBP as a cavity processing technique. CBP is interesting as a cavity processing technique because it removes defects associated with the manufacturing process, it can yield surface finishes (Ra) on the order of 10s of nanometers, it is a simple technology that could transfer easily to industry, it could help increase cavity yields and it requires less acid than other techniques. Recent progress and the current status of CBP as a baseline and repair technique will be discussed.

INTRODUCTION

After niobium superconducting radio frequency (SRF) cavities are made there is a 80-120 micron damage layer on the inside of the cavities which must be removed [1]. This material has typically been removed in the past by buffered chemical polishing (BCP) or electropolishing (EP), if higher accelerating gradients are required [2,3]. Much interest was generated in the mid to late 1990s in an alternative cavity surface processing technique called centrifugal barrel polishing (CBP), that mechanically polishes the inside of SRF cavities by rotating them at high speeds while filled with abrasive media[4-6]. Part of the original motivating factor of this work was to remove the hazards associated with the toxic hydrofluoric acid used in electropolishing (EP) and buffered chemical polishing [2,3].

In addition to the early work in CBP, some work was done at Cornell on the tumbling of re-entrant cavities to repair them [7,8].

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There has been renewed interest in CBP recently because of new results coming out of Fermilab [9,10]. New media types and a new basic approach were used in the CBP process that allowed for mirror like finishes with average surface roughness (RA) values in the order of 10 nm [10]. This is better than any other processing technique for polycrystalline cavities, including EP which can yield RA values in the order of 100 nm [11].

The current state of and possible future work on CBP programs at Fermilab, KEK, Cornell JLab and RRCAT will be discussed.

CENTRIFUGAL BARREL POLISHING PROCESS

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. A schematic is shown in Figure 1 below.

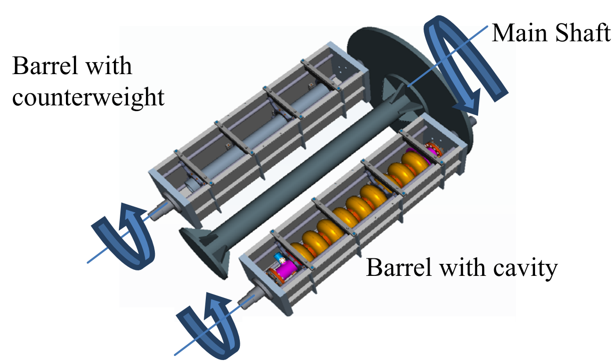

Figure 1: Schematic of main shaft and 2 barrels of a centrifugal barrel polishing machine denoting the directions of rotation. This is a model of the Fermilab machine with a 9-cell Tesla – type cavity and counterweight shown in the barrels.

In the CBP process the cavity is filled approximately 50% by volume with a mixture of different media. The media is typically used with water and a surfactant to cool the cavity and remove material from the surface to allow for further polishing.

In the CBP process two or 4 barrels spin around a central shaft. Each barrel spins around its own axis at the same speed and in the opposite direction as the main shaft. This secondary rotation of the barrel around its own axis greatly reduces processing time.

The tumbling process by comparison, which will not be discussed extensively in this paper, only involves rotation about one axis. Cornell achieved tumbling of cavities on a simple custom built machine [8]. Tumbling takes considerably longer than CBP, but similar results should be ultimately obtained from tumbling as seen by CBP.

CBP Media

There are many different types of media that can be used in the CBP process. These media have a vast number of different shapes, sizes and compositions. However, commercially available media are typically designed for tumbling parts in a slurry of media, water and soap. This is quite different than CBP applied to SRF cavities as the media is held within the part being polished. This difference coupled with the unique properties of niobium (soft and work hardens easily) means that industry has no experience with this process and can offer little help in media selection.

Media choice is the most difficult part to achieving the final desired properties of the niobium surface. A media The fact that the exact condition needed or desired for the niobium surface is not known presents additional challenges. In general a smoother surface is considered to be better as seen by improvement in cavity performance in going from BCP (RA of 1 micron) to EP (RA of 0.1 micron) [11].

Using CBP a surface roughness (RA) of on the order of 10 nanometers can be achieved. The worth of this new mirror like finish must be proven though. In general the smoother the surface the more processing time is required. For instance, the time required to go from roughly 0.1 micron to 0.015 micron RA requires 4 days of CBP[10].

Figure 2 shows the media that have been used for CBP to produce a mirror like finish at Fermilab. Figure 2A. shows the first step used primarily for cutting the weld bead away. This is a very aggressive ceramic media that removes niobium at the rate of approximately 10 microns / hour [10]. The material removal is nearly uniform through the entire cell. Other cutting media have been tried that removed material as much as 4 times faster but had much more material removal at the equator as compared to the iris of the cavity.

Figure 2: Picture of some of the media used for CBP of cavities at Fermilab to achieve a mirror like finish on the inside of cavities.

Advantages to CBP

CBP can produce smoother surfaces than electropolishing, the current standard processing technique for producing cavities with high accelerating gradient. Cavities that have had CBP need on the order of 20 microns of chemistry as compared to the 120 microns typically removed by EP. This means that less toxic hydrofluoric acid must be used. CBP is a much simpler technology than EP that has a cheaper installed cost and would be easily transferred to industry.

CBP produces a uniform surface. The CBP process can be used to remove defects (pitting, scratches) created in standard cavity manufacturing processes and processing techniques which cannot be repaired by chemistry alone.

Disadvantages to CBP

CBP, like EP, drives a substantial amount of hydrogen into the niobium which necessitates an additional hydrogen degassing step after CBP. Some work was done replacing water with a fluorocarbon in the CBP process [5]. This work showed only a small amount of hydrogen uptake which may be able to eliminate the hydrogen bake out step.

The CBP process is considerably longer(1 week for mirror finish) than the EP process (one day). However, 2 to 4 cavities can be processed per CBP machine. In addition, the installed cost of CBP is so much smaller than an EP tool that multiple machines can easily be purchased.

CURRENT STATUS OF CBP AT VARIOUS FACILITIES

Fermilab, JLab, and Cornell all have the same custom built CBP machine manufactured by Mass Finishing Inc. This machine can fit cavities up to the size of 9-cell Tesla type cavities in the provided barrels. As mentioned earlier Cornell also has a custom built machine for tumbling that can be modified to fit various size cavities. The Cornell CBP machine is currently in the process of being relocated.

JLab has processed some cavities by CBP but is currently building new 4-bar frames, based off the Fermilab design, before they proceed with processing single cell cavities further. JLab is currently processing niobium samples in a stainless steel coupon cavity and validating results obtained using Fermilab's media.

RRCAT has a CBP machine that can CBP single cell Tesla type cavities. Their machine is unique in that the main shaft and individual barrels can spin at different speeds. RRCAT is currently processing aluminum and copper cavities and coupons. They will be processing niobium cavities soon and are designing a CBP machine for 650 MHz 5-cell and 1.3 GHz 9-cell cavities.

KEK, who did much of the pioneering work with CBP, currently uses CBP as one of standard procedures prior to EP. KEK views the combination of CBP and EP as the best way to get high yields from SRF cavity production, especially for the International Linear Collider. KEK does not pay much attention toward mirror surface by CBP because they believe the current CBP process is sufficient for current cavity processing needs. Fermilab is currently processing single cell and nine cell polycrystalline 1.3 GHz Tesla type cavities. Fermilab plans to CBP single cell large grain and reentrant type cavities soon. Fermilab is also awaiting several coupon cavities (single cell niobium cavity with detachable niobium samples). Fermilab is in the process of designing the barrels of a CBP machine for 650 MHz and 1.3 GHz cavities.

RESULTS FROM CAVITIES PROCESSED BY CBP

9-Cell Repairs

Because of the cost associated with 9-cell niobium Tesla-type cavities, most of the cold test data available for cavities going through the CBP process is from cavities that have had severe performance limiting defects. Figure 3 below shows the cold test data of 3 such niobium 9-cell Tesla type cavities.

TB9ACC015 had a 200 micron defect in cell 3 that was confirmed to be the quench spot at Jlab [12]. The cavity only reached 19 MV/m with the defect. After CBP to an intermediate finish, followed by 40 microns of EP, the pit was completely removed and the cavity reached 34.5 MV/m with a good quality factor [10]. This cavity has since received an additional CBP to a mirror finish, followed by 20 microns of EP, and is now awaiting cold testing.

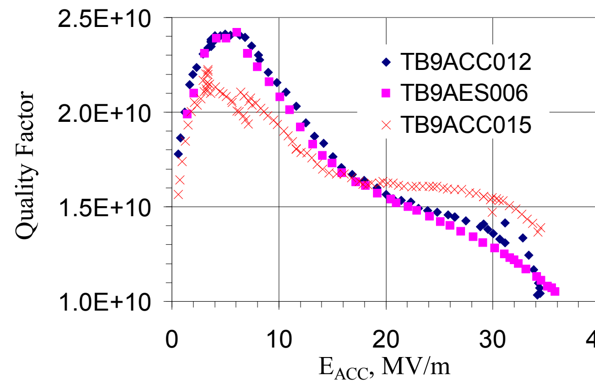

Figure 3: Cold test data from 3 damaged 9-cell Telsa-type cavities that have been processed with CBP.

TB9AES006 also had some surface defects that limited performance to 20 MV/m after a light EP was tried as a repair technique. CBP was done to a mirror finish at Fermilab and the cavity received 35 microns of EP and heat treatment at JLab. The cavity improved to 36 MV/m with a good quality factor. The results are detailed further in this conference [13].

TB9ACC012 had the entire end group and last 1 and 1/2 cells cut off and replaced. Because the cavity was already processed when this repair occurred, there is a thickness difference between the 2 half cells in cell 2. After CBP followed by light EP the cavity reached over 34 MV/m with a good quality factor [10]. The individual cells all reached 39 MV/m or above with the exception of the 2 and 8 cells (The 2 cell was the repair cell).

Single Cell Results

In addition to the 9-cell cavity results some single cell results show that CBP is a very promising technique. Figure 4 below shows the results of single cell cavity TE1ACC002 that was first electropolished and tested and then processed by CBP, followed by 20 microns of EP, and tested [10]. The gradient improved from below 35 MV/m to 43 MV/m . What is perhaps more impressive is the substantial improvement in quality factor at 2° K after CBP at low and high gradient. The 1.8° K cold test shows even further improvement in the quality factor. The cavity was shown to have a residual surface resistance of 1.34 ± 1.19 nano-Ohms.

This cold test also showed that as little as 20 microns of chemistry is needed after CBP to a mirror finish.

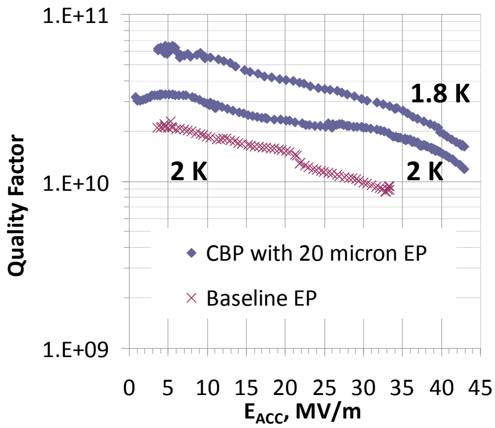

Figure 4: Cold test data at 2 and 1.8 °K for single cell cavity TE1ACC002. The data is for the cavity after EP and after CBP with 20 microns of EP.

FUTURE WORK

CBP has showed some promising results, but there are many questions which still need to be answered. All cavities processed by CBP at Fermilab have had improved quality factor and accelerating gradient except for one which had imbedded media due to insufficient processing time at the second step. Improvement of quality factor after CBP needs to be further examined to better understand the mechanism.

CBP to a mirror finish is not needed to reach the 35 MV/m mark. A better understanding of what type of mechanical finish is needed to reach a specific accelerating gradient is needed. The more rough an acceptable surface is the less time is needed to achieve it. KEK concluded the roughness of 2mm (Rz) is enough for Eacc~30MV/m from a magnetic field enhancement point of view [14].

Conversely, to understand the full potential of CBP to a mirror finish, other cavity geometries (Reentrant, low loss) that allow for higher accelerating gradients must be used. It would be worthwhile to know at what accelerating gradient the mechanical finish produced by CBP would be the performance limiting factor. The effects of CBP to a mirror finish on large grain cavities as compared to polycrystalline material may also prove very interesting to see the effects on quality factor.

It is nearly impossible to understand the effect of each processing step on a cavity from just the cold test done at the end of processing. The use of coupon cavities is critical in understanding the effect of each CBP step on the surface of the cavity. Each media will have different effects on material removal rate, average surface roughness, Rp (maximum peak height), and Rv (maximum valley depth). Fermilab and JLab are both currently pursuing coupon cavity work. Some of the most useful information gained on CBP to this point was obtained on coupon cavities at KEK [4].

More work needs to be done on media selection. As little as 20 microns of chemistry has been shown to be needed after CBP to a mirror finish [10] while 40 microns of chemistry is needed after CBP to an intermediate finish. Getting CBP to the point where little or no post-CBP chemistry is needed would be very useful. It would be useful because of the elimination of the toxic chemicals used for niobium processing and in understanding cavity performance.

The quality factor of a particular cavity geometry is dominated by surface chemistry and surface geometry. With a perfect surface geometry, which CBP to a mirror finish is getting closer to, the effects of surface chemistry can be better studied. Being able to cold test a cavity processed by CBP with no post-CBP chemistry would give another data point on the effect of surface chemistry on cavity performance. This would likely enhance the understanding of the decrease in quality factor with increasing accelerating gradient.

Also of interest is the fact that the surface created by CBP to a mirror finish may prove to be a gateway technology to allow for the deposition of thin superconducting films. Previous work on the CVD of thin films onto electropolished niobium has not meet with full success. This could be due to the fact that the roughness of the substrate was too high [15]. CBP may be able to solve this problem by creating a surface smooth enough to do CVD or other deposition techniques on.

CONCLUSIONS

CBP has proven to be a very useful technique for repairing defects in 9-cell Tesla-type cavities that could not be repaired by further chemistry. Single cell results are very promising and demonstrate increased accelerating gradient and quality factor when compared to processing by electropolishing alone. CBP offers many advantages over EP including a more homogeneous surface, no toxic chemicals, the possibility for extremely smooth surface finishes, and it is a simple technology which should transfer easily to industry. The renewed interest in CBP created from the ability to produce mirror like finishes is from preliminary work that could be improved through further process development aided by the use of coupon cavities.

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