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OPTIMIZATION OF THE BCP PROCESSING OF ELLIPTICAL NB SRF CAVITIES*

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Abstract

At present, the electropolishing (EP) process is considered the key technology unleashing the capability to produce Niobium SRF cavities performing at or above 35 MV/m. Nevertheless buffered chemical polishing (BCP) remains a cheap, simple and effective processing technique for single grain high gradient and polycrystalline lower gradient cavities. BCP will be adopted to chemically process the third harmonic 3.9 GHz cavities being fabricated at Fermilab [1]. The dimensions and the shape of these cavities yield a strong non-uniformity in the material removal between iris and equator of the cells. This paper describes the thermal-fluid finite element model adopted to simulate the process, the experimental flow visualization tests performed to verify the simulation and a novel device fabricated to solve the problem.

INTRODUCTION

Surface polishing is a necessary step during SRF cavity production, which consists of removing the superficial layer of material though a chemical reaction or mechanical friction. This process is applied during several steps of the cavity fabrication procedure such as Niobium rolling, weld preparation, pre heat treatment conditioning and post heat treatment conditioning. The total amount of Niobium removed from the cavity inner surface is typically 200 μm. There are three techniques used for material removal: buffered chemical polishing (BCP) [2], electropolishing (EP) [3] and centrifugal barrel polishing (CBP) [4]. The first two involve a chemical reaction, while the third one is based on mechanical friction. BCP, in use for over 20 years, is recognized to be the most reliable and stable process. However its preferential action at the grain boundaries increases the surface roughness thus typically limiting the cavity performance below 30 MV/m. EP generates a smoother surface compared to BCP and allows pushing the cavity gradient above 40 MV/m. This technique is still in the R&D phase resulting in a large spread in the cavity performances. CBP is considered a valuable method that limits the use of harsh chemicals, which would decrease the environmental impact of the surface treatment process while increasing the smoothness of the surface. Fermilab has established BCP capabilities in collaboration with ANL, while EP and CBP R&D are ongoing programs. In terms of cavity production, Fermilab is fabricating and commissioning a 3.9 GHz SRF four cavity cryomodule to be delivered to DESY in 2007. The cavities for this unit are considerably smaller then the 1.3 GHz ILC/TESLA standard posing a number of critical issues both in fabrication and in conditioning. In particular the shape and the dimensions of these cavities increase the effect of differential etching between iris and equator of the cells. This paper describes the design, the fabrication and testing of a novel device, which should significantly reduce this phenomenon.

BUFFERED CHEMICAL POLISHING OF SRF CAVITIES

Buffered chemical polishing of Niobium, performed using the standard mixture of acids, is an exothermic reaction. The composition of the mixture is 1:1:2 in volume of hydrofluoric (49%wt), nitric (69.5%wt) and ortho-phosphoric (85%wt) acids, with a viscosity, at room temperature, of 0.022 Pa-s and a density of 1545 Kg/m^3 [5]. The reaction rate is controlled by keeping the acid temperature below 15°C corresponding to an average removal rate of 1 μm/min. The inside and outside surfaces of the Fermilab 3.9 GHz cavities are etched at ANL in the G150 facility as shown in Figure 1. The most critical step in terms of RF performance is the inside etching, while the outside process is performed to avoid contamination of the inner surface during the heat treatments. At the beginning of the procedure, the cavity, assembled in a cooling jacket, is held in vertical position and filled with acid by means of a gravity-feed system; later the acid is slowly circulated to provide cooling and mixing while on the outside the Nb is cooled with water circulating in the jacket at 10 gpm. Typically the cooling water temperature is maintained at 6°C. The velocity of the acid in the cavity is a fundamental parameter to assure uniform removal rate and has been optimized for this particular type of cavity at 1.5 gpm yielding a removal rate ratio of 1.9 between iris and equator.

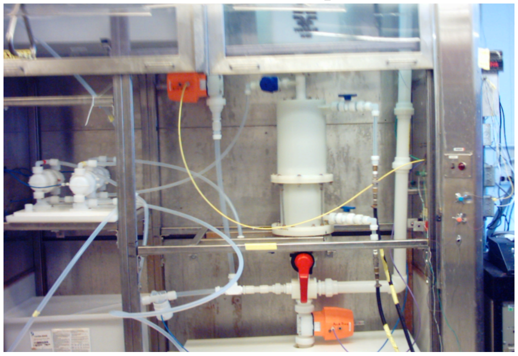

Figure 1. ANL BCP setup, G150 facility.

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BCP PROCESS MODELING

A full-featured model of the BCP process is very difficult to solve numerically. Such simulation involves the solution of the Navier-Stokes equations for a complex geometry, the solution of the conductive and convective thermal systems and finally the solution of the chemical reaction equilibrium, which itself is strongly coupled to the thermal-fluid variables.

The solution of the fluid simulation for a similar type of cavities is reported in [6]. The same technique was adapted and extended to the Fermilab 3.9 GHz cavities including the cooling jacket. In addition the thermal simulation was coupled to the fluid model in order to evaluate the temperature distribution in the cavity during the process. The heat generated during the exothermic chemical reaction between niobium and acid is dissipated through both the acid and the cooling water. The removal rate depends on the fluid temperature and on the acid velocity, but, in order to simplify the modeling, it was assumed constant for the whole surface of the cavity with a value of 1 um/min. The corresponding heat generated per unit of surface in the case of full reaction is 1.2 KW/m^2. The simulation was computed for 3-cell and 9-cell 3.9 GHz cavity by means of a standard finite element solver adopting the parameters summarized in Table 1.

Property	Unit	Value
Acid inlet temperature	C	15
Water inlet temperature	C	6
Reaction heat generation	kW/m^2	1.2
Acid flow rate	GPM	1.5
Water flow rate	GPM	10

Table 1. Simulation input parameters.

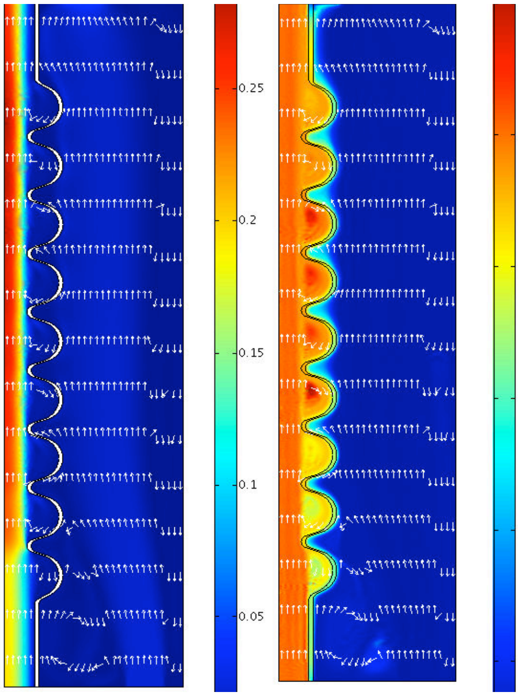

Figure 2. 9-cell simulation: flow pattern (left) and temperature map (right).

Figure 2 demonstrates that the cold acid flows only in the center of the cavity while the temperature within the cells grows due to lack of circulation. Further studies show that the absence of strong water-cooling with the acid inlet at the bottom cell of the cavity causes the cell temperature to raise along the length of the cavity.

This simulation, which does not take into consideration the acid speed and temperature dependence of the etching rate, is nevertheless consistent with experimental observations of the BCP process. In particular it confirms the limited cell circulation as the main factor influencing the differential etching between iris and equator. In addition it demonstrates that increasing the water-cooling capacity helps in optimizing the cell-to-cell temperature distribution.

These results are also consistent with bench-top experiments performed at Fermilab [7] demonstrating that for this type of cavities, given their acid volume to Niobium surface ratio, the reaction rate slows down and eventually stops after 30 minutes if the acid is not properly circulated.

In order to improve the process, several simulations were performed introducing a flow diverter in the cavity to determine its impact on flow pattern and temperature distribution. As shown in Figure 3 left, installing a simple baffle with dimensions smaller than the iris is not very effective due to the high acid viscosity.

Better results are obtained, as shown in Figure 3 right, when the device is extended inside the cell volume. Adopting a flow diverter with optimized shape and dimensions can therefore help in reducing temperature and flow gradients in the cavity during the process thus allow equalize the material removal between iris and equator.

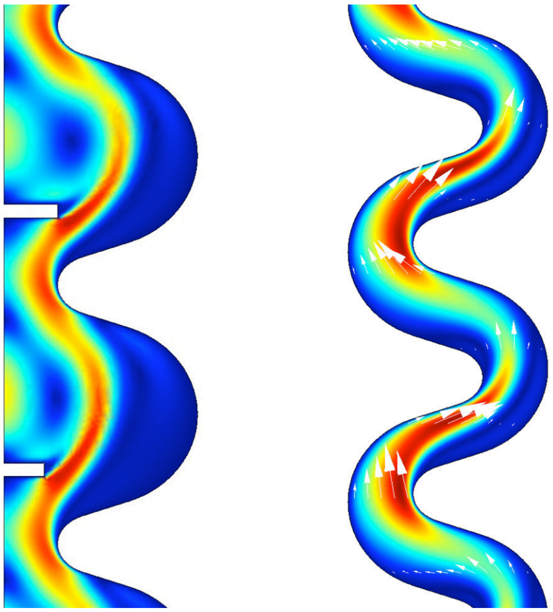

Figure 3. 9-cell flow pattern simulations with baffles (left) and with balloons (right).

EXPERIMENTAL VERIFICATION

A flow visualization experiment was performed in order to verify the numerical simulation and later the effectiveness of the flow diverter. A transparent polyurethane 9-cell cavity was produced and a basic device to introduce small amounts of colored dye in the main stream of water was designed. The tests were performed using water and, in order to maintain the same Reynolds number, the velocity was proportionally reduced to mimic the acid flow of the BCP process.

The test demonstrated that even if the flow at the center of the cavity is fully developed, the acid remains trapped in the cell volume with leading to differential etching between iris and equator.

FLOW DIVERTER

Inserting a device in the cavity during the BCP process leads to the possibility of scratching the surface during the extraction procedure. A demountable plastic device was already proposed in [6] for large low-beta cavities, but the small dimensions of the Fermilab 3.9 GHz cavities would require very precise manufacturing of the components which is a challenging objective when working with acid resistant soft plastic such as PTFA. For this reason we designed a completely new device consisting of an inflatable balloon as shown in Figure 4.

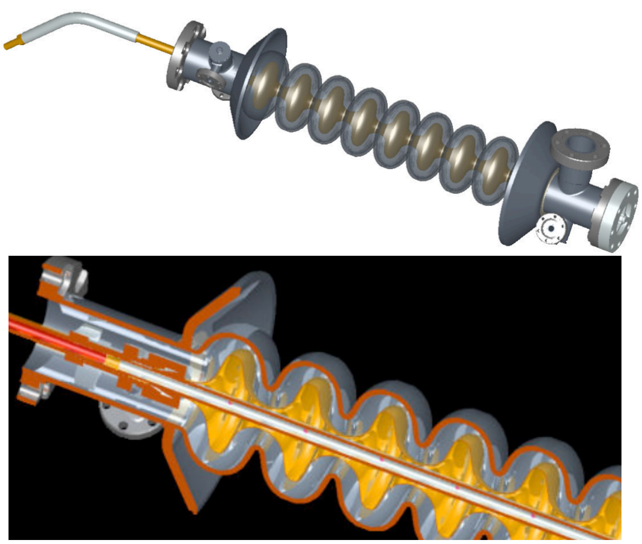

Figure 4. Flow diverter in the cavity.

The device, after insertion, would be inflated in the cavity and expand within the cell volume. Once the process is finished it would be deflated by releasing the air pressure and covered by a Teflon sleeve for easy extraction.

Several materials were tested for acid compatibility but most of the rubbers, even fluorine doped, do not withstand the acid contact while maintaining the proper mechanical stability properties. In order to meet the acid resistance requirements and at the same time the inflating/deflating capability, we opted for a pre-shaped PET (Polyethylene Terephthalate) thin balloon, which would collapse at pressure release. PET samples were tested in acid environment comparable to the BCP process showing good acid resistance after four hours exposure, which is more than twice the duration of a typical cavity etching.

Due to its dimensions, the balloon is molded in three separate segments, which are later glued together with the proper bounding technique. For this purpose cyanate and UV cured glues were tested. Several samples of glued PET tubes were immersed for 4 hours in acid environment similar to the standard BCP process. As a result the UV cured glue was chosen being the most reliable. After assembly the balloon is mechanically fixed to a PVDF tube that serves also as centering device and inflating system.

CONCLUSIONS

The thermal-fluid aspects of the BCP process of elliptical SRF cavities were simulated. As a result of the simulations a novel device was designed and is being fabricated. The flow visualization tests showed that such device is needed to force the exchange of acid in the cell volume to equalize the material removal rate between iris and equator. The device will soon be tested with water using the transparent cavity and later its effectiveness will be determined during an etching process.

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