VERTICAL ELECTROPOLISHING OF SRF CAVITIES AND ITS PARAMETERS INVESTIGATION

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Abstract

An advanced set-up for vertical electropolishing (VEP) of SRF niobium elliptical cavities has been installed at CEA Saclay. Cavities are VEP'ed with circulating standard HF-H_2SO_4 electrolyte. Parameters such as voltage, cathode shape, acid flow and temperature have been investigated. Low-voltage (6V), high acid flow (25L/min) and low acid temperature (20°C) are considered as promising parameters. Such recipe has been tested on single-cell and 9-cell ILC cavities with nice surface finishing. After 70µm VEP on single-cell, the cavity shows similar performance at 1.6K compared to previous Horizontal EP (HEP): Eacc > 41MV/m limited by quench. Another single-cell cavity reaches 36MV/m after heavy removal by VEP in spite of a pitted surface due to initial VEP treatment at higher temperature (> 30°C). The baking effect after HEP&VEP is similar. An asymmetric removal is observed with faster removal in the upper half cells. Nice surface finishing as well as standard Q0 value are obtained at low/medium field on 9-cell but achieved performance is limited by Field Emission.

INTRODUCTION

Electropolishing in hydrofluoric-sulfuric acid mixtures has become the reference process to achieve high performance on niobium cavities [1]. The achieved performance makes it possible to match the performance required for latest projects such as CEBAF upgrade [2], X-Free Electron Laser linac [3], and future International Linear Collider (ILC). According to the standard process, the cavity is electropolished in horizontal position, while rotating and half filled with circulating acid. Vertical electropolishing (VEP) is studied in some laboratories as an alternative [4-7]. The aim is to develop an easier process compared to horizontal electropolishing (HEP) and providing similar performance.

High gradients have already been achieved by VEP with stirred static acid [8, 9] but low final removal: a Q slope is observed for deeper removal [9]. We anticipate that circulating acid and better acid renewal should provide better electropolishing conditions. An automated VEP device with circulating acid system has been developed at CEA Saclay (see Fig. 1). The cavity is filled from the bottom and the acid runs back to the tank by gravity from the top of the set-up. The technical characteristics of this set-up are detailed elsewhere [5]. It has been designed for the treatment of large cavities such as SPL 5-Cell cavity (96L) [10]. Single-cell Tesla-shape cavities have been used to commission the set-up and optimize the parameters and multi-cell (SPL 5-cell and ILC 9-cell) cavities have also been electropolished. Results will be presented for Tesla-shape single-cell cavities and an ILC nine-cell cavity.

Figure 1: 5-cell SPL cavity during VEP treatment.

PARAMETERS STUDY

Vertical electropolishing at a voltage of 20V has already been investigated [5] on single-cell cavity, and a gradient of 30MV/m achieved. In a second step, single-cell cavities have been electropolished with parameters derived from standard horizontal EP:

- Moderate acid flow (8L/min).
- Voltage above 12 V.
- Temperature around 30°C.

The electrolyte is HF(40w%)-HF(96w%) in volume proportions 1-9. The cathode chosen for these experiments consists in a rod shape with a small protuberance (20mm length and 50mm diameter). This cathode is used in [5].

Inspection of inner surface of 1AC3 after VEP reveals that these parameters are not compatible with proper electropolishing. In fact, the surface is deteriorated after 70µm removal: a ring of pits is observed between the equator and the iris in the upper half cell (see Fig. 2). The local removal rate is above 1µm/min. It is too high (for comparison, the rate should be 0.6µm/min for HEP) for desirable electropolishing conditions.

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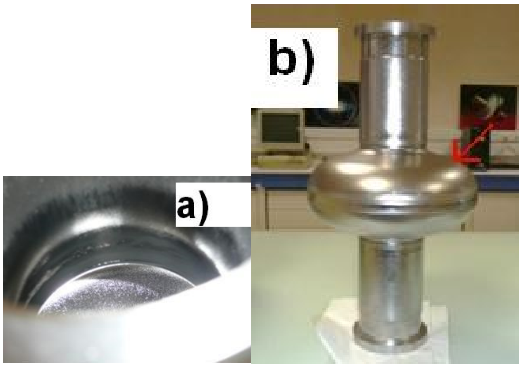

Figure 2: a) 1AC3 inner surface after VEP at 12V-30°C. A ring of pits is observed which location is marked on b)

The pits location coincides with a singularity of the fluid distribution modeled at low fluid velocity (see later). Furthermore, the presence of hydrogen bubbles insufficiently evacuated by the acid flow might also amplify this phenomenon.

As a consequence, we decided to increase the acid flow up to 25L/min for coming VEP sequences so as to improve fluid distribution (symmetry in the cell), hydrogen removal out of the cavity and achieve both efficient acid renewal and temperature control inside the cavity. Nitrogen is also blown in the acid tank and in the top of the cavity in order to favor the removing of the gas generated during the process. Previous EP investigations proved that a reduced electropolishing voltage (down to 5V) has no influence on cavity performance (process called "Low-Voltage electropolishing") [11]. We decided to apply Low-Voltage VEP with the following expectations:

- A decreased joule heating and decreased temperature gradient in the cavity.
- Reduced parasitic electrochemical reactions as sulfur forming [11-14].

A higher acid flow rate is thus expected to provide improved electropolishing conditions. The highlighted set of parameters was applied on 1DE1 cavity, previously HEP'ed. After 70µm additional VEP, the achieved surface is very shiny. The average removal rate is 0.2µm/min. No pitting is observed and shallow stripes are observed at the equator area in the upper half cell. The new set of parameters seems promising and the performance of the cavity at 1.7K will be evaluated.

CAVITY RESULTS WITH OPTIMIZED PARAMETERS

Results on Single Cell Cavities

The performance of 1DE1 as received (after HEP) was very high (Eacc > 42MV/m, high Q0). It was tested at 1.6-1.7K after the additional 70µm low Voltage VEP sequence (tests before & after baking). Q0=f(Eacc) curves are shown in Fig. 3. Following results have been observed:

- The baking effect is similar compared to HEP: the high field Q-sloped is removed in order to reach a quench at Eacc > 40MV/m.
- The Q0=f(Eacc) curve after HEP/VEP are superimposable. Low voltage VEP offers similar performance compared to HEP.

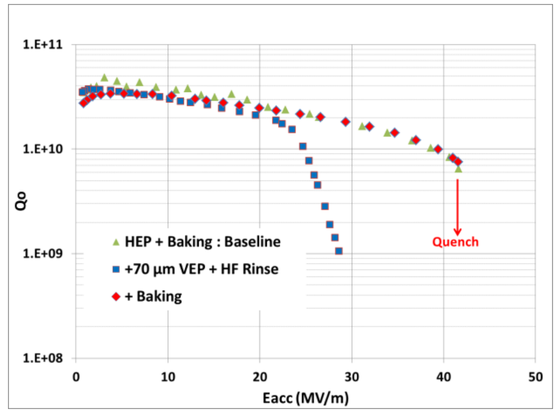

Figure 3: RF results for 1DE1 cavity at 1.6-1.7K before/after VEP at 6V.

Additional tests were carried out with 1AC3, VEP'ed with optimized parameters to prove that an exclusively VEP'ed cavity should also reach high gradients. 1AC3, as described in Fig. 2, was electropolished according to two VEP sequences with 'optimized' parameters and baked under vacuum (110°Cx60h). After each sequence, it was tested at 1.6K (see results in Fig. 4). Performance is satisfactory since a gradient of 35MV/m is achieved, in spite of the pitted surface (limited by quench at the pitted area). Moreover the gradient is improved after additional VEP sequence at low voltage.

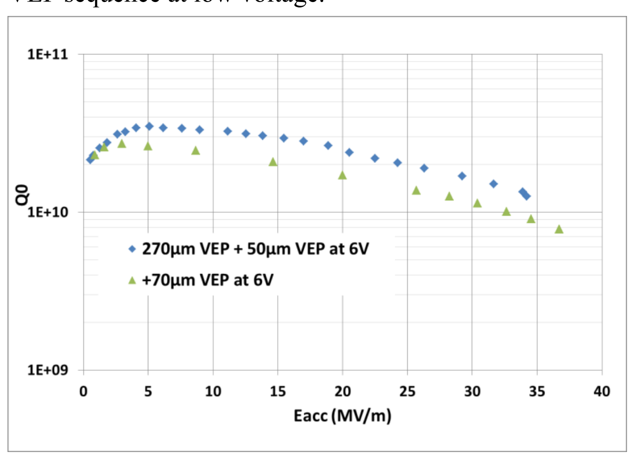

Figure 4: RF results for 1AC3 cavity at 1.6-1.7K after VEP sequences at 6V.

Results on ILC 9-cell Cavity

The same set of parameters (6V – 20 L/min – T<20°C) was applied on nine-cell cavity: 50µm were removed from TB9R1025 ILC cavity from FERMILAB, previously HEP'ed. A 40mm diameter rod cathode was used for the VEP of the cavity. The diameter was reduced compared to previous experiments [5] to avoid contact with HOM antennas. Unfortunately, the performance was

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limited by Field Emission, with onset at 15MV/m. The Q0 value at low and average fields are satisfactory (see Fig. 5 below).

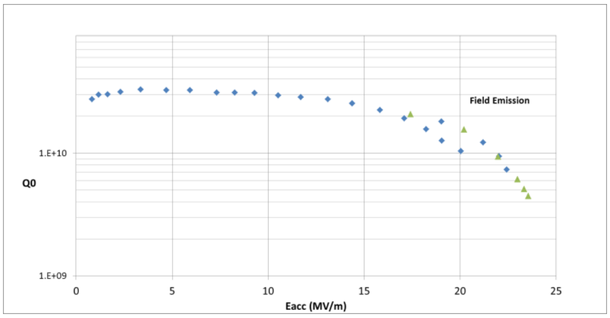

Figure 5: RF results for ILC TB9R1025 cavity at 1.6-1.9K after HEP + 50µm VEP at 6V.

Additional VEP sequences and cleanroom assembly are planned for improvement.

ASYMMETRY OF THE PROCESS AND CATHODE DESIGN

Alternative Cathode Shapes

The possible benefits of alternative cathode shapes have been widely investigated [7, 15-17]. The effectiveness of an optimized electrical field in the case of the Buffered Electrochemical Polishing [18] has been demonstrated [7]. Alternative shapes have been investigated in order to improve the homogeneity of the process. We have decided to focus on cathode shapes compatible with an easy insertion in the cavity (narrower than the beam pipe diameter). The work done in [5] was pursued with a more exhaustive study: Design of Experiment (DOE) method was carried out using COMSOL software so as to obtain both uniform electric field and fluid distribution inside the cell. Dominant parameters which have been put forward are:

- The shape of the cathode (ellipsoid or cylindrical).
- The length and diameter of the protuberance.

Optimized cathode is shown in Fig. 6 (shape#2).

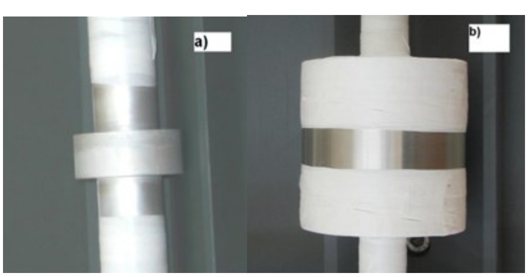

Figure 6: a) Cathode used in previous VEP experiments (shape#1) and b) optimized shape (shape#2)

It is a 70mm diameter and 70mm length cylinder. Fig. 7 shows the improvement of the modeled fluid distribution inside the cell at low flow rate (< 0.2m/s): the vortex noticed with previous cathode (shape#1) should be suppressed.

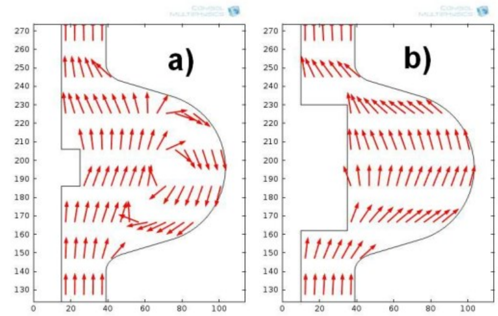

Figure 7: Direction of the flow modeled with COMSOL for VEP with shape #1 and #2. Flow of the acid in the beam pipe: 0.2m /s.

The electropolishing process is limited by the diffusion of the fluorine ions [11, 19]. The signature of this diffusion is the plateau observed on I(V) curves. Such curves were plotted during VEP of single-cell cavity using both cathode shapes. Shape#2 associated with higher flow rate is efficient to obtain a wider diffusion plateau, clearly visible in Fig. 8.

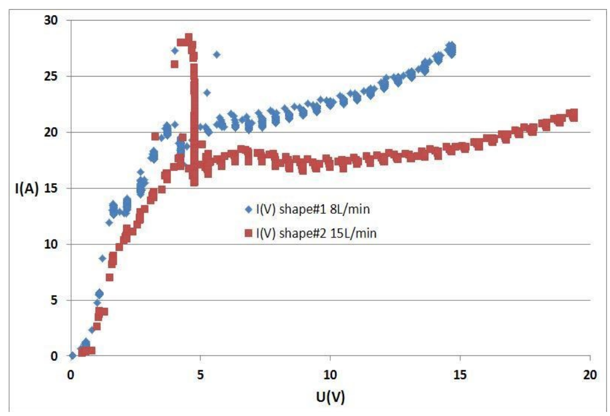

Figure 8: I(V) curves plotted on single-cell cavity with cathode shape #1 & #2.

Asymmetry of the Process

During this investigation following variations for key parameters have been investigated:

- Flow rate between 8 and 25L/min.
- Voltage between 6 and 20V.
- Temperature between 18 and 30°C.
- Cathode shape #1 or #2.

Thickness measurements have been carried after each VEP sequence, so as to evaluate the uniformity of the removal. As previously discussed, the parameters are of paramount importance with respect to surface finishing. However, in each case, a strong asymmetry between the upper and the lower half cells in the removal and in the brightness are noticed. The removal rate in the upper half cell is at least three times as high as in the lower cell. The brighter surface should be attributed to this higher removal.

Similarly to [7], we have to consider in this study the viscous layer which forms at the niobium surface during VEP. We infer that the benefits of improved electric field and fluid distribution are dominated by its macroscopic movement. This phenomenon has already been observed during the EP of flat samples [20, 21]. We might distinguish the two half cells during VEP:

- In the upper half cell, the layer runs or slides down the cavity due to gravity and becomes thicker in the lower part of the cell. In some areas, the surface might be "viscous layer free".
- In the lower half cell, the surface is smooth due to this thicker layer but the removal is low due to its high electric resistance.

According to this statement, the lower polishing rate achieved at the equator of cavities during HEP should mainly be attributed to the thicker viscous layer, and not to the decreased electric field.

OUTLOOK AND CONCLUSION

Low-voltage (6V), high acid flow (25L/min) and low acid temperature (20°C) are considered as promising parameters. Such recipe was tested on single-cell and 9-cell ILC cavities with nice surface finishing. After 70 µm VEP on single-cell, the cavity show similar performance at 1.6K compared to previous Horizontal EP (Eacc > 41MV/m) limited by quench. VEP with circulating acid is promising for at least for final treatment after bulk EP/tumbling, etc. Another cavity reaches 36MV/m after heavy removal by VEP in spite of a pitted initial surface. The baking effect after VEP is similar Vs. HEP. Nice surface finishing as well as standard Q0 value are obtained at low/medium field on 9-cell. Unfortunately, the performance of the tested cavity was limited by Field Emission.

An asymmetric removal is observed with faster removal in the upper half cells. For large material removal, a 2-step VEP (with cavity reversal in-between) is considered.

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