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EFFECT OF CATHODE ROTATION AND ACID FLOW IN VERTICAL ELECTROPOLISHING OF 1.3 GHz NIOBIUM NINE-CELL CAVITY

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Abstract

We have been carrying out R&D on vertical electropolishing (VEP) technique to establish it as an alternate of the horizontal EP (HEP) technique used for the surface treatment of niobium (Nb) superconducting RF (SRF) cavities. We have earlier reported on a VEP parameter study for 1.3 GHz single and nine-cell Nb cavities. The optimized VEP parameters and a unique rotating cathode yielded uniform removal and a smooth surface in the single cell cavity. The unique cathode and a dual flow mechanism for acid circulation were applied to improve the removal uniformity in the nine-cell cavity. The vertically electropolished single and nine cell cavities achieved the same RF performance as achieved after the HEP processes. We are making efforts to further improve the removal uniformity in the nine-cell cavity. Here, we report on a VEP of the 1.3 GHz Nb nine-cell cavity at a higher cathode rotation speed of 50 rpm. The VEP results reveal that the speed could be considered for improving the uniformity in removal while maintaining the surface smoothness. Required improvements in the VEP facility and acid flow condition for achieving uniform EP and a smooth surface are also described.

INTRODUCTION

Niobium superconducting RF (SRF) cavities are electropolished to remove the top 100-200 μm damaged surface layer and to make the surface smooth and contaminant free. An electropolishing (EP) process is performed with the horizontal EP (HEP) process (in the horizontal position of the cavity) or vertical EP (VEP) process (in the vertical position of the cavity). The HEP is a standard and promising process for attaining the desired surface and good SRF performance at a cryogenic temperature. The VEP process, which is performed with a simple setup, yielded strong asymmetry in removal and traces of hydrogen (H_2) gas bubbles on the Nb surface. Our previous studies have shown that the major cause of the asymmetric removal is an accumulation of H_2 gas bubbles on the Nb surface [1–4]. Bubbles staying on the Nb surface might impair the diffusion layer present on the interface of Nb surface and electrolyte (H_2SO_4 and HF in a volumetric ratio of 9:1). The thin diffusion layer enhances the EP rate or removal. The local attack of the bubbles enhances the removal locally to make the surface rougher by leaving the surface with bubble footprints or traces.

In order to resolve the issues, we have made different approaches. Different models of a unique rotating cathode (Ninja cathode) were designed tested [4]. A cathode with insulating blades, cathode housing covered with PTFE meshed sheet, and with a larger surface area of the Al cathode was designed [5]. Parameter studies were extensively carried out for the single cell cavity with the cathode and a unique coupon cavity [5, 6]. The VEP parameters including a cathode rotation speed, cavity and acid temperatures, flow rate of circulating acid in the cavity, and applied voltage have been optimized by carrying out the study of polarization curves for the coupons and the cavity. The parameters were employed to 1.3 GHz TESLA shape/type Nb single cell cavities which resulted as good SRF performance as after the HEP treatment [7, 8].

The VEP of a nine-cell cavity is more challenging because the surface area of the cavity is around six times larger compared to that of the single cell cavity. The larger surface area enhances the generation rate of gas bubbles proportionally. Removal of around six times larger quantity of bubbles efficiently from the nine-cavity is extremely difficult. A huge amount of bubbles finally accumulates in the upper cells of the cavity. The bubble accumulation deteriorates surface state and led to a strong asymmetric removal along the cavity length [9]. The study on the nine-cell cavity was also performed using a unique nine-cell coupon cavity [9] and the same design of the Ninja cathode [10, 11]. A novel approach, in which the acid was flown separately in the cathode housing and the cavity, has been applied to move the bubbles along the cathode and discharge them quickly from the cavity. The method is named as dual flow method. The flow rates were optimized for quick discharging of bubble from the cavity [10]. The accumulation of the bubbles significantly reduced in the top cell. It was confirmed with the viewports available on the iris positions and the coupon currents in the cell. As a result of these approaches and optimized VEP parameters, the asymmetry in removal for the nine-cell cavity was significantly reduced. VEP of 1.3 GHz Nb nine-cell cavity for bulk removal of totally 130 μm was performed and the cavity was tested in a vertical cryostat. The cavity showed the same SRF performance as measured after the HEP process [11].

In this paper, we show results of a VEP experiment performed with a higher cathode rotation speed. The goal of the study is to understand the effect of cathode rotation and acid flow rates on removal uniformity and surface morphology.

EXPERIMENT

A VEP setup, which has facilities for carrying out VEP under different parameters for R&D, was made in the last six year and used for the VEP experiment. The detail of the

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setup has been reported elsewhere [11]. The nine-cell coupon cavity [9] and the Ninja cathode [10] with an optimized design were utilized. In the nine-cell coupon cavity, the first (top), fifth (center), and ninth (bottom) cells contain coupons at the top iris, equator, and bottom iris positions. The coupon currents are measurable. These cells also have viewports, which allow seeing inside the cavity during the VEP process, near the iris positions. The VEP parameters applied to the coupon cavity are summarized in Table 1.

A removal thickness on different positions of the cavity was measured with an ultrasonic thickness gauge. The coupon surfaces after the VEP were observed with an optical microscope. Surface roughness of the coupons was measured by line-scanning in a length of 2.4 mm with a surface profilometer.

Table 1: VEP Parameters Applied on the Nine-Cell Cavity

Condition/ Parameter	**Value**
Cathode Type	Ninja Cathode
Cathode Rotation	50 rpm
Cavity Temperature	< 15 °C
Acid Flow Type	Dual Flow
Acid Flow Rate in Cathode housing	5 L/min (Target: 10 L/min)
Acid Flow Rate in Cavity	4 L/min (Target: 5 L/min)
Applied Voltage	18 V (On-Off Cycles)

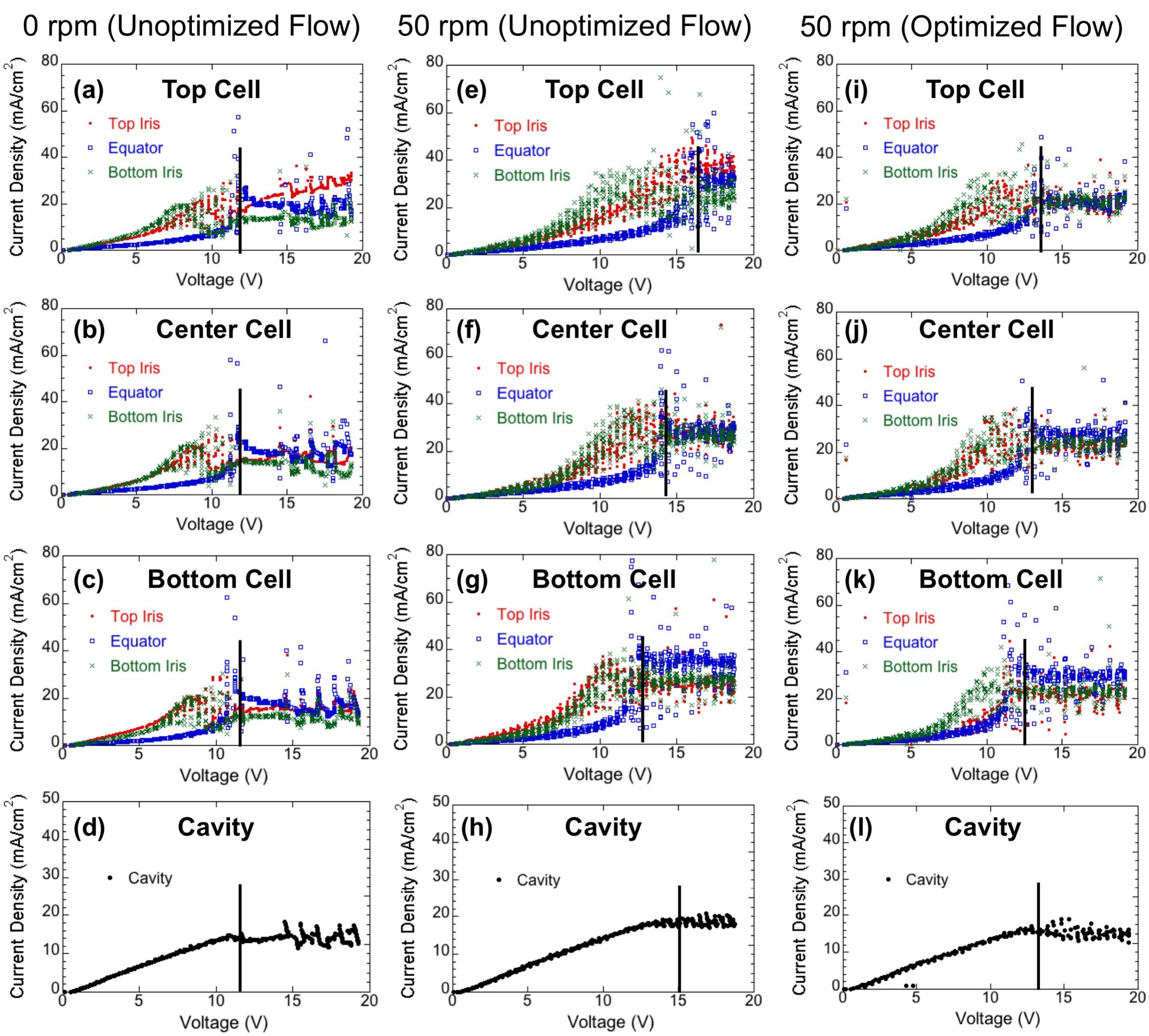

Figure 1: Polarization curves for the cavity and coupons located in the top, center, and bottom cells. (a-d) Curves with cathode rotation at 0 rpm and unoptimized acid flow rates. (e-h) Curves with cathode rotation at 50 rpm and unoptimized acid flow rates. (i-l) Curves with cathode rotation at 50 rpm and optimized acid flow rates in the cathode housing and the cavity. The cavity temperature during all the tests was kept to be ~15°C. The vertical lines on the plots indicate the starting of the EP plateaus.

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RESULTS

Polarization Curves for Coupons and Cavity

Polarization curves (current density *J* versus voltage *V* curves) were measured for the coupons and the cavity with cathode rotation at 0 and 50 rpm. The dual flow method was applied. However, the target optimized flow rates were not maintained due to an issue with the acid inlet pump. The applied flow rates are shown in Table 1. The cavity temperature was kept to be around 15 °C during the tests. The curves are shown in Fig. 1 (a–d & e–h). An explanation on a polarization curve is given in ref. [4]. In a previous experiment, *J-V* curves were measured at 50 rpm and under the optimized flow rates of 10 L/min in the cathode housing and 5 L/min in the cavity. These curves are shown for the comparison in Fig. 1 (i–l). The curves obtained at 0 rpm show clear EP plateaus for all the coupons in the top, center, and bottom cells. At 50 rpm, scattering in the current was seen and the EP plateaus except for the equator coupon in the top cell shifted slightly in the higher voltage side. The EP plateau for the equator coupon in the top cell significantly shifted to the higher voltage side whereas the shift was not large when the optimized flow was used.

A higher cathode rotation might affect the diffusion layer due to a higher acid flow rate on the Nb surface. This might be the reason for the scattering in the EP current data and a slight shift in the EP plateaus for all the coupons at 50 rpm compared to that at 0 rpm. The large shift in the EP plateau in the top cell at 50 rpm should be due to a low electric field caused by the cathode screening with a huge amount of accumulated bubbles. It is because the only difference from the bottom to the top side of the cavity is the different gas bubble densities. The cathode rotation might collect the bubbles on the cathode axis and slow down the bubble discharge from the cavity. The shift is not due to the cavity temperature because the same temperature was maintained on the whole cavity by spraying cold water the on exterior surface of the cavity. The large shift disappears when the optimized acid flow that discharges bubbles quickly from the cavity was applied. This also indicates the shift is due to a large amount of bubbles.

VEP of Nine-Cell Coupon Cavity

Although the desired flow rates were not maintained, a VEP was performed for an average removal of 30 µm. On-Off voltage cycles were applied where the on and off times were set to be 3 min. The purpose of the On-Off voltage cycle is to reduce the circulation of the bubbles from the acid tank to the cavity. The acid tank has a small size with a capacity of ~70 L only. Bubbles return back to the cavity when the flow rate is ~10 L/min and higher. The cavity current density and temperature of acid at the cavity outlet during the VEP are shown in Fig. 2. The temperature of the cavity and acid at the outlet of the cavity were well maintained at around 15 °C to keep the EP conditions as in the *J-V* curves. The removal rate (average removal thickness divided by the total on-time) was calculated to be 0.28 µm/min.

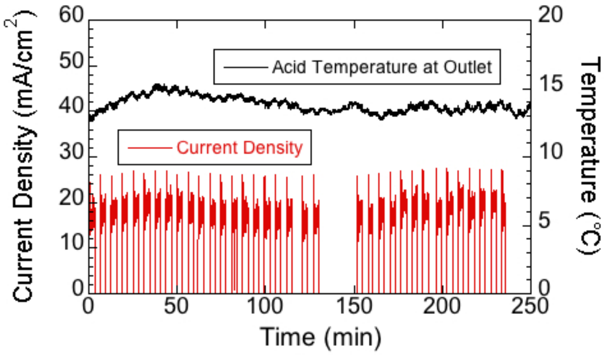

Figure 2: Cavity current density and acid temperature profiles during the VEP performed with cathode rotation at 50 rpm and unoptimized acid flow. The temperature was measured at the outlet of the cavity.

Removal Thickness

A removal thickness trend in the VEP performed at 50 rpm under unoptimized flow rates is shown in Fig. 3. The top three cells show asymmetric removal with higher removal on the top irises whereas other cells show uniform removal. In the previous experiments performed at 20 rpm under optimized flow rates [11], the asymmetry along the cavity length was significantly reduced. However, the asymmetry was found in each cell.

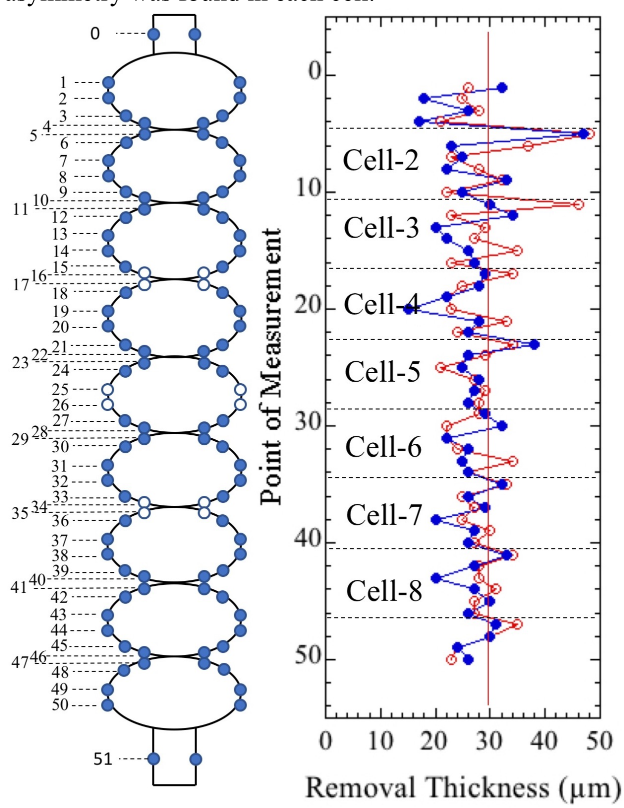

Figure 3: Removal thickness along the cavity length in VEP performed with cathode rotation at 50 rpm and unoptimized acid flow. The vertical line on the plots shows average removal thickness. The schematic in the left shows the positions where the removal thicknesses were measured.

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In the case of single cell cavity, a cathode rotation of 20 rpm yields a uniform removal in the cavity cell [6, 7]. In the nine-cell cavity, although the dual flow method significantly reduces the bubble accumulation in the cavity cells, some bubbles return back to the cavity from the tank and might diffuse from the cathode housing to the cells. These bubbles remain on the surface and move slowly with the acid flow on the surface. The cathode rotation of 20 rpm seems to be less effective to displace all the bubbles from the surface. In the current experiment, the uniform removal in the six bottom cells is attributed to two phenomena. (1) The total flow rate in the unoptimized condition was around 9 L/min which was less than the total flow rate of 15 L/min in the optimized case. The slow flow rate reduced the returning bubbles from the tank to the cavity. (2) The high rotation of 50 rpm displaced the bubbles more efficiently from the surface in the lower cells and yielded the uniform removal. The cathode rotation at 50 rpm in the top cells was not effective since the quantity of bubbles was large in these cells.

Coupon Surface and Roughness

Optical microscope images of the coupon surfaces after 30 µm average removal in VEP are shown in Fig. 4. The measured roughness Ra and Rz are shown in Fig. 5. Ra is an arithmetic average roughness and Rz is defined as an average height difference between five tallest peaks and five deepest valleys. The surface morphology and roughness reveal that the coupon surfaces were smooth. The equator in the top cell was slightly rougher than the other coupons. The higher roughness is explained with the shift in the EP plateau for the equator in the top cell. The removal of the equator in the top cell occurred in semi-polishing condition in which the material is partially removed by the etching phenomenon. The surface roughness in the top cell could be reduced even at 50 rpm when the optimized flow rates are applied.

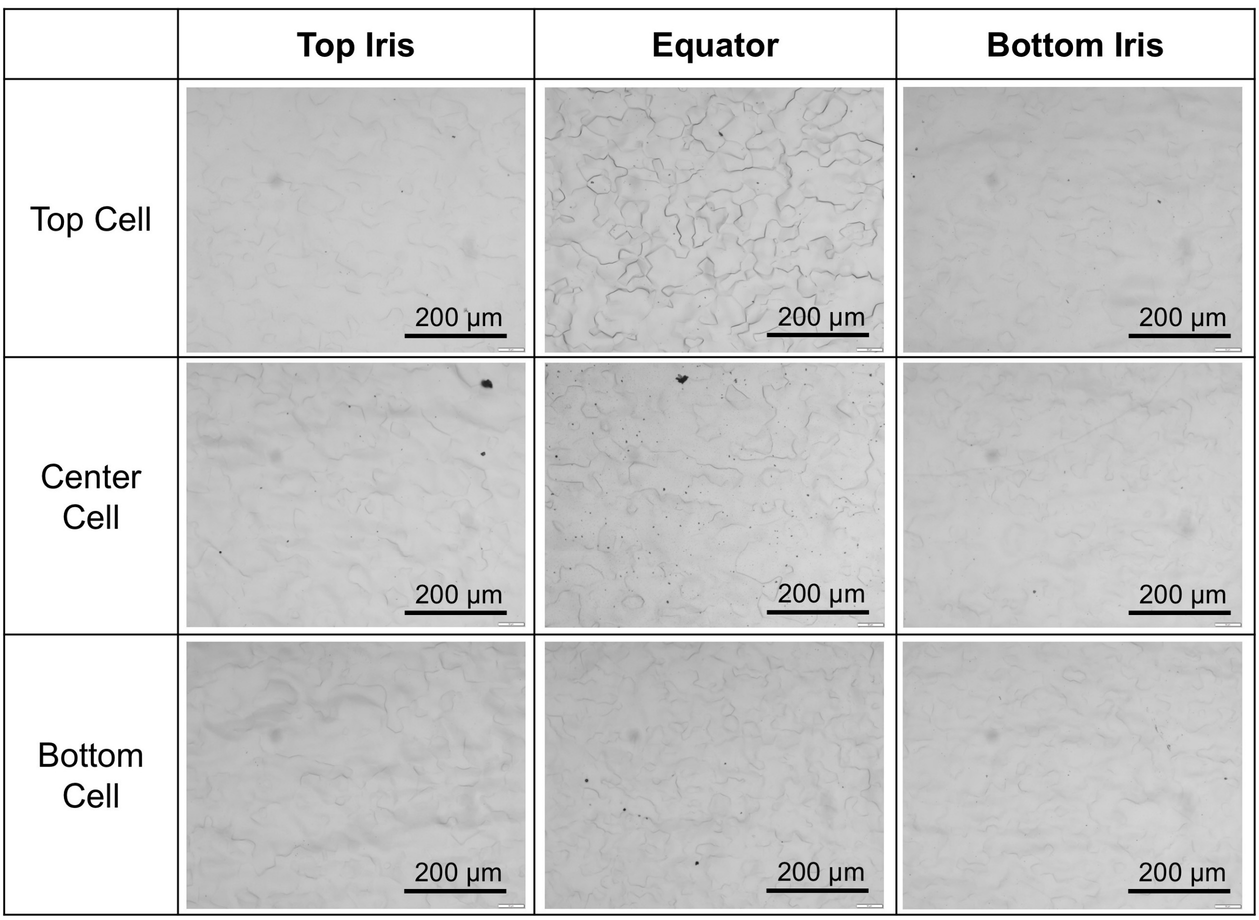

Figure 4: Optical microscope images of the nine coupons after VEP with cathode rotation at 50 rpm and unoptimized acid flow rates.

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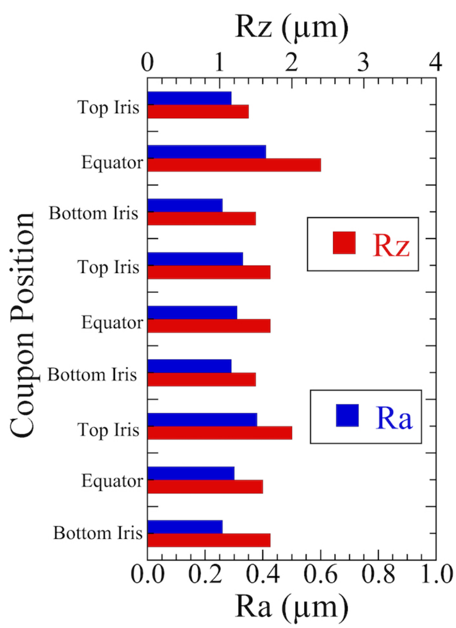

Figure 5: Coupon surface roughness Ra and Rz after VEP performed for an average removal of 30 μm at cathode rotation of 50 rpm and unoptimized flow rates.

CONCLUSION

The VEP experiment for the nine-cell coupon cavity was performed with the Ninja cathode rotating at 50 rpm. The dual flow was applied for acid circulation inside the cathode housing and the cavity. In this experiment, the acid flow rates could not be maintained to the desired flow rates in the cathode housing and cavity. The VEP results reveal the following: (1) Higher cathode rotation of 50 rpm shifts the EP plateau in a polarization curve significantly only in the presence of a huge amount of gas bubbles. (2) The uniformity in removal could be improved at cathode rotation of 50 rpm and using a larger acid tank. (3) Coupon surfaces remain smooth even at the cathode rotation of 50 rpm. The equator surface in the top cell was slightly rougher than other coupons. The rough surface is attributed to the accumulation of a large amount of bubbles in the top cell. (4) Cathode rotation of 50 rpm could be opted for VEP of a nine-cell cavity when the optimized flow rates in the cathode housing and cavity are applied.

FUTURE WORK

The results obtained with the cathode rotation speed of 50 rpm is promising in terms of removal uniformity and surface smoothness. The issue in this VEP experiment was that the unoptimized acid flow rates were applied. Further VEP tests are necessary to be performed. The next VEP experiments will be conducted with cathode rotation at 50 rpm and the optimized flow rates in the cathode housing and the cavity. Moreover, the acid tank with a larger capacity will be prepared to stop the returning of gas bubbles from the tank to the cavity.

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