Surface preparation processing for superconducting cavities postprint

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Abstract

Surface preparation is a critical step in the manufacturing process of superconducting niobium cavities, determining whether their performance meets specifications. A series of surface preparation methods and associated equipment have been developed at the Shanghai Institute of Applied Physics (SINAP), and standardized cavity processing procedures have been established and successfully applied to various types of cavities. Using standard surface preparation procedures on a 500 MHz 5-cell niobium cavity, the accelerating voltage reached 7.5 MV at T=4.2 K while its quality factor remained higher than $1\$\times10^{9}.The accelerating gradient of the IMP-HWR010 cavity reached 4.9 MV/m with a quality factor exceeding 3\times\$10\^8$ at 4.2 K.

Full Text

Preamble

Surface Preparation Processing for Superconducting Cavities

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Surface preparation is a critical step in the fabrication of superconducting niobium cavities, directly determining whether their performance meets specifications. A series of surface preparation methods and relevant apparatuses have been constructed at the Shanghai Institute of Applied Physics (SINAP), and standard cavity processing procedures have been established and successfully applied to different types of cavities. Following standard surface preparation procedures on a 500 MHz 5-cell niobium cavity, the cavity accelerating voltage reached 7.5 MV at T = 4.2 K while its quality factor remained higher than 1×10^9. The accelerating gradient of the IMP-HWR010 cavity reached 4.9 MV/m with a quality factor better than 3×10^8 at 4.2 K.

Keywords: Surface preparation, Barrel polishing, Buffered chemical polishing, High temperature baking, High pressure rinsing
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Introduction

Superconducting (SC) niobium cavities are key components for accelerating charged particles to compensate for beam loss or strike target materials. Their accelerating field gradient can reach 50 MV/m with minimal power dissipation [1]. With high Q-values, the high-gradient performance of SC niobium cavities is highly sensitive to surface imperfections such as damaged layers, scratches, inclusions, electron beam welding defects, and contamination. Each of these may trigger cavity loss mechanisms including field emission or thermal breakdown [2]. Cleanliness of the inner surface is an indispensable condition for successful performance of superconducting accelerating structures, making surface preparation essential for eliminating these problems. Methods for surface preparation of niobium cavities include barrel polishing [3], buffered chemical polishing (BCP) [4, 5], electropolishing (EP) [6], high pressure rinsing (HPR) [7, 8], and low or high temperature baking [9], among others.

A 500 MHz 5-cell niobium cavity was fabricated at the Shanghai Key Lab of Cryogenics & Superconducting RF Technology of the Shanghai Institute of Applied Physics (SINAP) [10, 11]. Barrel polishing treatment was employed as the primary procedure due to its effective processing technique and lower cost. Bulk chemical polishing, high temperature baking, and slight chemical polishing treatments were then implemented sequentially. HPR was used as the final step of cavity preparation to reduce field emission [7]. Additionally, surface preparation for a 162.5 MHz $\beta = 0.10$ niobium half-wave resonator cavity at the Institute of Modern Physics, Chinese Academy of Sciences (IMP-HWR010) was undertaken at SINAP. This cavity underwent a series of surface treatments including degreasing, bulk chemical polishing, high temperature baking, slight chemical polishing, and ultrasonic rinsing with ultra-pure water. The enormous internal volume and surface area of the 500 MHz 5-cell niobium cavity, along

with the complicated structure of the HWR cavity, were the most important considerations for surface preparation processing. This paper reports the standard procedures of surface preparation processing and results of radio frequency (RF) vertical tests for these two types of niobium cavities.

II. Cavity Surface Preparation Sequence

A. Degreasing and Barrel Polishing

It is well known that a rather thick niobium layer of approximately 150 µm (commonly called the damaged layer) must be removed from the inner surface during cavity preparation to achieve high accelerating gradients. Barrel polishing, often called tumbling for cavities, is a mechanical grinding process that rotates the cavity with chips, water, and compounds. Barrel polishing can partially replace chemical or electrochemical polishing, which is costly and environmentally critical. Additionally, the fairly smooth surface achieved after barrel polishing provides excellent starting conditions for chemical polishing. Buffing was applied to each half-cell of the 500 MHz 5-cell cavity before electron beam welding, and barrel polishing was adopted for the completed structure. This method is quite convenient for multi-cell structures, as it can grind the entire inner surface including the welding seams.

The barrel polishing apparatus was installed at SINAP for the 500 MHz 5-cell prototype cavity (Fig. 1 [Figure 1: see original paper]). It features two pedestals connected by four stands, with the frame rotated by a main motor at controllable speeds between 0–200 rpm. The 5-cell cavity was filled with 200 kg of grinding chips with plastic binding, 150 kg of water, and 1.5 kg of compound. The cavity, covered tightly and fixed in the lodgment, was rotated around its axis at speeds of 40–50 rpm. After 163 hours of barrel polishing, a layer of 90–100 µm was removed, which is sufficient for complete elimination of all protrusions, scratches, and other surface defects. Additionally, the barrel polishing provided preparatory smoothing of the welding areas. Barrel polishing was not performed on the IMP-HWR010 cavity; it was simply degreased and cleaned using acetone and alcohol separately.

B. Bulk Chemical Polishing and Rinsing

Since mechanical grinding itself results in a damaged layer or contaminated surface from the abrasives, the surface must be refinished using stress-free and contamination-free preparation techniques such as chemical polishing and high pressure rinsing. Buffered chemical polishing, a convenient surface preparation method, has been used as the main preparation technique for SC niobium cavities at SINAP. For the 500 MHz 5-cell niobium cavity, dunk chemistry was impractical due to the large volume of acid required. Therefore, a cavity surface closed-loop chemical preparation system was developed. The BCP system (Fig. 2 [Figure 2: see original paper]) mainly consists of an acid circulating loop, cooling-water circulating loop, low-pressure water rinsing pipeline, and waste

acid recovery pipeline. Operators are carefully protected against exposure to acids and noxious fumes.

The two cavities were assembled into the closed-loop BCP apparatus. A total of 400 L of acid solution containing 1 part HF (40%), 1 part HNO_3 (65%), and 2 parts H_3PO_4 (85%) by volume was pre-mixed in the acid tank and cooled by iced flowing water pipes inside the tank to control the acid temperature at 10–15 °C. Next, the acid solution was pumped through a filter, sent to the IMP-HWR010 cavity, and flowed back to the acid tank while the valve before the 5-cell niobium cavity remained closed. The acid filling time to the cavity corresponding to the acid pumping speed was optimized to avoid noticeable shape distortion of the lower part of the cavity from excessive acid exposure. Iced water showers on the outer surface of the cavity were used for cooling. Temperatures of the acid solution and cavity itself were well controlled to achieve ideal and stable etching speed. The acid pump was then switched off, and the acid solution was dumped from the cavity when the damaged surface layer (sufficiently deep) was removed. Finally, low-pressure water rinsing was immediately carried out to remove residual acid from the inner surface, lasting for 30 minutes. A 100–110 µm layer of niobium was removed from the inner surface of the IMP-HWR010 cavity during the 80-minute BCP treatment. The cavity was dismounted and placed into a moveable class-100 clean-room for 2-hour ultrasonic rinsing using ultra-pure water.

The 5-cell cavity underwent a similar chemical polishing process: 80-minute BCP treatment and 60-minute low-pressure water rinsing, removing a 90–100 µm layer of niobium from the inner surface. The difference in etched thickness between the two cavities was due to different pipe diameters connected to them, leading to different acid flow velocities within the cavities.

To thoroughly remove chemical residues or particles that could cause field emission, the automated HPR system—consisting of a high-pressure pump, spray wand, and custom spray nozzles—was applied as the immediate next step in surface preparation for the 5-cell niobium cavity. Ultra-pure water with resistivity of 18 $M\Omega \cdot cm$ and pressure of 80 kg/cm^2 was sprayed from 6 nozzles on top of the feeding cane, which moved up and down inside the rotating cavity. Finally, the cavity was dismounted and moved into a class-100 clean-room for 2-hour HPR, followed by drying in a class-10 clean room for 24 hours.

The distribution of removed thickness from the 500 MHz 5-cell cavity, shown in Fig. 3 [Figure 3: see original paper], was obtained with an ultrasonic thickness meter measuring cavity wall thickness along the axis. The etching thickness was significantly larger at cavity iris sections, while the etching speed was lower at cavity equator sections in vertical BCP. A barrier of etched niobium and bubbles could buffer further reaction of the acid with the niobium surface. Achieving uniform etched thickness in multi-cell cavities will be an issue for further study.

C. High Temperature Baking

It is well known that high-purity niobium cavities pick up hydrogen during bulk chemical polishing or electropolishing, resulting in hydrogen Q-disease. The hydrogen precipitates as niobium hydride during slow cooling between 150 K and 90 K [9] in cold tests. Niobium hydride is a weak superconductor that remarkably increases the surface residual resistance of cavities. Since fast cool-down is difficult in accelerator complexes, the problem must be eliminated before final cavity assembly. Hydrogen in niobium bulk is easily degassed at temperatures above 600 °C. The two cavities were placed in a titanium box and heated to approximately 680 °C in a vacuum furnace at better than 1×10^{-3} Pa. Degassing lasted for three hours. Fig. 4 [Figure 4: see original paper] shows the baking temperature and vacuum pressure. Although the baking temperature was too low for titanium solid gettering [12], using a titanium box with niobium cavities is safer to prevent material degradation from residual gas in the furnace.

D. Slight Chemical Polishing and Rinsing

To eliminate titanium or other contamination caused by high temperature baking, slight chemical polishing was necessary. Another 400 L of fresh acid solution was remixed. The IMP-HWR010 cavity underwent 20-minute BCP and 50-minute low-pressure water rinsing, while the 5-cell cavity received 40-minute BCP and 90-minute low-pressure water rinsing. The cavities were moved into a class-100 clean-room for 2-hour ultrasonic and HPR rinsing, respectively, followed by drying in a class-10 clean room for 24 hours. It should be emphasized that the vertical positions of the two cavities in the BCP apparatus were reversed this time to minimize inequality of etching thickness caused by cavity geometry as much as possible.

E. Assembling and "In-Situ" Baking

With proper chemical etching and high pressure rinsing, proper assembly in a clean room was necessary to avoid defects and field emission sites in the cavity. Sealing flanges, low-power input couplers, and pickup antennas were mounted on both the 5-cell and IMP-HWR010 cavities. The assembled cavities were gradually evacuated with a dedicated pumping system and leak-checked outside the clean room immediately to confirm leak-tightness at room temperature. After evacuation and successful leak checking, the niobium cavities were mounted onto the vertical test stand and subjected to "in-situ" baking under ultrahigh vacuum at 120 °C for 48 hours as the final preparation step. The cavity vacuum was maintained better than 1×10^{-6} Pa.

III. Results of RF Vertical Tests

The main purpose of RF vertical tests [13, 14] was to obtain cavity accelerating performance and verify whether the procedures and treatments adopted during

fabrication, electron beam welding, and surface preparation could meet requirements. Vertical tests were carried out in a vertical cryostat filled with liquid helium at 4.2 K. The measured quality factor Q_0 (unloaded Q value) of the IMP-HWR010 cavity as a function of accelerating field gradient (E cc) is shown in Fig. 5 [Figure 5: see original paper]. The IMP-HWR010 cavity achieved accelerating field gradients of approximately 4.9 MV/m without quench, with quality factor Q_0 above 3×10^8. Figure 6 [Figure 6: see original paper] shows the vertical test result for the 500 MHz 5-cell cavity, in which the cavity accelerating voltage reached as high as 8 MV while the quality factor Q_0 remained better than 1×10^9.

IV. Conclusion

Surface preparation is a critical step in SC niobium cavity fabrication. Barrel polishing machines, closed-loop BCP apparatus systems, high temperature vacuum furnaces, and ultra-pure water HPR systems were constructed at SINAP and successfully applied to the 500 MHz 5-cell SC cavity and IMP-HWR010 cavity. The standard procedures for cavity processing and handling can be summarized as follows:

- Degreasing and cleaning using acetone and alcohol separately
- Barrel polishing to remove approximately 100 µm
- Bulk chemical polishing to remove 90–110 µm in 80 minutes, followed by 1-hour low-pressure water rinsing
- Rinsing with ultra-pure water (18 MΩ · cm and 8 MPa) for 2 hours or ultrasonic rinsing using ultra-pure water
- Annealing at 680 °C for 3 hours to remove hydrogen absorbed during bulk chemical polishing
- Slight chemical polishing to remove 15–30 µm in 20–40 minutes, followed by 1.5-hour low-pressure water rinsing
- HPR for 2 hours or ultrasonic rinsing using ultra-pure water
- Drying in a class-10 clean room for 24 hours
- Assembly in a class-100 clean room and leak checking
- "In-situ" baking under ultrahigh vacuum at 120 °C for 48 hours

After undergoing this sequence of standard surface preparation processing, the IMP-HWR010 cavity exceeded an accelerating gradient of 4.9 MV/m with quality factor $Q_0 \geq 3 \times 10^8$ at 4.2 K, while the 500 MHz 5-cell cavity exceeded an accelerating voltage of 7.5 MV with quality factor $Q_0 \geq 1 \times 10^9$.

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Note: Figure translations are in progress. See original paper for figures.