Investigation on the fabrication of the 3rd harmonic superconducting cavity for the SSRF storage ring*

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Abstract A third harmonic superconducting niobium cavity has been proposed for installation in the Shanghai Synchrotron Radiation Facility (SSRF) storage ring to improve the Touschek lifetime. In order to investigate the feasibility of the superconducting cavity fabrication indigenously and the possibility to master the fabrication techniques, cavities were fabricated from copper and niobium sheets by deep drawing and electron-beam welding, and a series of measurements, such as resonant frequency, shape dimensions and wall thickness, were carried out during this process. After analysis of various problems existing in the fabrication process, technique improvements were proposed, and finally the precise shape as designed and resonant frequency within 1.2 MHz were achieved for the new completed cavities. In addition, full annealing was finally proved to be a good cure for niobium sheets' tearing up during deep drawing. By fabricating niobium cavities successfully, some problems to the next step were cleared. This paper introduces the process of cavity fabrication and its technique improvements towards forming, and the initial vertical test result of niobium cavity is also presented.

Key words SSRF, higher harmonic cavity, superconducting radio frequency, fabrication technology

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1 Introduction

The third generation light sources, pushing for high brilliance with very low emittance storage ring, entail short beam lifetime due to the Touschek scattering. The focusing magnetic structure and Radio Frequency (RF) system of the storage ring need to be elaborately optimized to obtain ample momentum acceptance, and thus reach a reasonable beam lifetime[1]. An achievable beam lifetime of 10—20 h at 200—300 mA beam current and 1% transverse coupling, however, seems to be inadequate to reach high average photon brilliance or weaken thermal effects. One method for further increasing the Touschek lifetime without compromising the beam cross section or increasing the beam energy spread is to reduce the peak longitudinal charge density of an electron bunch by stretching the bunch using a higher harmonic cavity[2]. A third harmonic cavity is a common choice to implement this stratagem, and has been successfully operated in several light sources, such as ALS[3], ELETTRA[4], PLS[5], BESSY-II[6], etc. In the modern light source, the TOP-UP injection mode is a standard method to overcome the short beam lifetime[7], though it can not give any essential help to increase the beam lifetime of the storage ring, whereas a longer beam lifetime achieved by higher harmonic cavity can sufficiently weaken the impact of the safety problem and stored beam oscillation in frequent TOP-UP injection.

The Shanghai Synchrotron Radiation Facility (SSRF) is a third generation light source now under construction and commissioning, and the TOP-UP injection has been designed from the beginning and is being tested now[8]. A passive third harmonic cavity with 1.5 GHz resonant frequency was also proposed

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for the storage ring to increase the beam lifetime. Because superconducting cavity well damps High Order Modes (HOM) and can provide the required voltage at a reasonable field gradient (5.0 MV/m) with negligible beam energy loss, it seems to be the most attractive solution. The Shanghai Superconducting Cavity Key Laboratory has undertaken the design and fabrication of this passive third harmonic superconducting cavity. The design of this cavity is finished[9]. However, the issues of the superconducting technology are new challenges for our laboratory, so a feasibility study has been carried out in the preliminary stage of the cavity fabrication and is discussed here.

From the test results on the existing cavities, the solid-niobium is proved to be most common and suitable for the superconducting cavities production and promises a higher accelerating gradient. Presently superconducting cavities can be constructed by three different methods: depositing a niobium film on a preformed copper cavity substrate[10], electron-beam welding half-cells from solid niobium[11], and forming seamless cavities by hydroforming or spinning[12]. By the second method cavities are used successfully in many larger-scale accelerator projects and great improvements in accelerating gradients have been achieved in the last decade. Even though there are still some problems with making defect-free electron beam welds[13] and fabrication cost reduction for future applications like TESLA, FEL, and ERL projects, this method absolutely satisfies our requirements with manipulation simpleness and reproducibility. The niobium cavity fabrication work has been taken up in a gradual manner. In this paper, we give a brief description of the cavity forming process first, and then, some effective technique improvements applied in the fabrication process aiming at various problems are put forward. A new fabrication result as well as a vertical test result for the last completed niobium cavities are given.

2 Cavity fabrication sequence

2.1 Material choice

The high purity niobium sheets used for the fabrication of cavity cells and beam pipes, were purchased from two different companies in Japan and China, in order to compare different cavity performances resulting from different niobium properties. The residual resistance ratio (RRR) of the niobium sheets from Japan and China is 310 and 250, respectively. RRR is the ratio of niobium's resistivity at room temperature and at 4.2 K, when the niobium stays in the normal conducting state by applying a high magnetic field. The flanges for the beam pipes were machined from reactor grade niobium instead of the high purity material needed for the cavity cells, because of their location at the low magnetic field. The Japanese niobium specification for the cavity cells is listed in Table 1. Besides that, the high purity copper sheet could be used for test production, as its mechanical properties are similar to those of niobium.

Table 1. Technical specification for the Japanese niobium sheet used in SSRF 3rd harmonic cavities.

Mechanical properties	
RRR	~ 310
surface roughness (Ra)	~ 0.24 μm
grain size	ASTM#6
tensile strength	>165 MPa
yield strength	>47 MPa
elongation at break	55%
vickers hardness HV	53.7

2.2 Half-cell deep drawing

The set of deep drawing dies for this half-cell shape made from a 3 mm thick niobium sheet were made out of a high yield strength aluminum alloy and designed by the current KEK design method, where the inner surface of the female die is the same as the designed half-cell shape. Both sides of the niobium sheets were inspected for defects and the side with better surface was chosen as the RF side of material prior to forming. It was critical to hold down the niobium sheet to the female die with a right torque. A center hole (30 mm in diameter) on the blank sheet was designed for two purposes: one was for keeping the niobium sheet fixed during the deep drawing; and the other one was for suppressing the wall thickness reduction. Clean motor oil was painted onto the niobium sheet and the male die surface for lubrication. The copper sheet was first formed prior to niobium and the relevant hydraulic pressure was 8 MPa which was applied to the later niobium sheet for deep drawing.

2.3 Trimming

After deep drawing, the half-cells were trimmed at the iris and the equator section on a lathe to the final size for electron-beam welding. In the lathe-trimming operation, the half-cell was fixed over a trimming die similar to the deep drawing dies. At the iris section the half-cell was first cut and the incision location was decided by measuring the specified length from the straight line at the half-cell waist section, while the incision location at the equator was decided by measuring the total cavity length from the iris.

2.4 Electron-beam welding

Before welding, the parts must be properly cleaned, since inadequate surface cleaning of the weld metal can cause weld flaws resulting in a deterioration of superconducting performance. The half-cells and beam pipes were chemically treated by buffered chemical polishing using BCP 1:1:2 (a mixture of the following acids: 40% HF, 65% HNO_3, 85% H_3PO_4 in the volume relation 1:1:2), followed by ultra-pure water rinsing. Then they were covered by clean bags and sent to the welding factory immediately. The pressure in the welding chamber must be lower than 666.61×10^{-5} Pa, since the RRR value depends on the chamber residual pressure. The weldings of all parts were done from outside and at full penetration with a niobium rod running across the cell, which served to intercept the remnant electron-beam and niobium spatter, and prevent contamination to the internal surface. The beam pipes were rolled and electron-beam welded longitudinally. The typical width of the underbead was about 4 mm, and the internal weld seam was a little protuberant which could be barrel polished smoothly later. Finally every electron-beam weld was visually inspected and leak checked.

3 Analysis of fabrication results and improvements

3.1 Failure of deep drawing

When applying pressure on the niobium sheet purchased from the Chinese company, it was successfully formed, while the niobium sheet from the Japanese company was torn at the bottom during deep drawing. Such issues also happened to two other Japanese niobium sheets. Deep drawing was sensitive to niobium's mechanical properties. The technical specifications of the niobium sheets of the two companies were compared and no difference could be found. From experience in labs abroad[14], it was concluded that the accidents were caused by incomplete recrystallization of the material. The problem could be resolved by re-annealing for 24 h at (740±20) ℃ in a vacuum oven at a pressure of 133.32×10^{-5} Pa to achieve full recrystallization.

Another problem with the symmetry of circularity at the top edge of the half-cell could be resolved by releasing the torque to 5 Newton.

3.2 Cavity shape distortion

A batch of cavities including 2 copper cavities and 1 niobium (Chinese material) cavity were fabricated for the first time. In our type of cavity the resonant mode used for acceleration is TM_{010}. The cavity resonant frequency measurement and the precise 3D geometrical measurement are the two most convincing techniques used to control the cavity fabrication quality. Table 2 shows the cavities resonant frequency measured by a network analyzer. It is found that the measured resonant frequencies have a great deviation value from the designed frequency (1499.693 MHz), especially for a niobium cavity whose frequency shift is as high as 84.7 MHz.

Table 2. Frequency and frequency shift for the first batch of cavities.

cavity No.	frequency/MHz	frequency shift/MHz
1# (Cu)	1528.95	29.257
2# (Cu)	1529.14	29.447
1# (Nb China)	1584.3	84.677

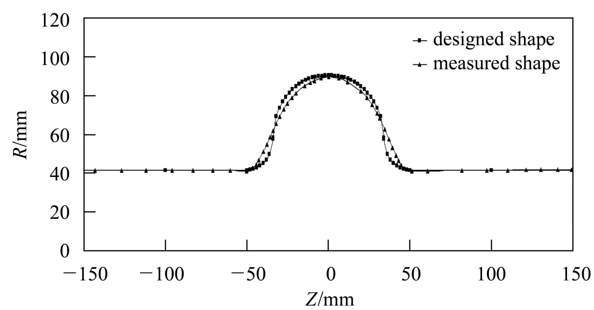

Fig. 1. Comparison between the measured shape and the designed shape for the niobium cavity.

The precise cavity shape was measured by the 3D laser scanning FARO arm. Fig. 1 shows the comparison between the measured cavity shape and the designed cavity shape for the niobium cavity. It is clear that the cavity has a serious shape distortion at both the iris and the equator. In addition, by measuring the cavity dimensions with a vernier caliper, it was found that the designed straight segment at the equator section of the half-cell was cut carelessly during trimming, while the same length segment was extended at the iris section compensating for the total cavity length unchanged. Fig. 2 shows the segment location of the half-cell and the sensitivity of the frequency shift by errors in the R and Z directions, which was calculated using the SUPERFISH code. The dependence of the cavity resonant frequency on the cell geometry can be found in this picture. It is obvious that the straight segment at the equator section makes the greatest contribution to frequency shift, as much as 7.9 MHz, and that the influence of segments at the equator circular section on frequency shift is greater than that at the iris circular section. The numerical analysis mentioned above appropriately accounts for the reasons why the distorted cavities have such great frequency shift and the frequency shift for the niobium cavity is larger than that for the copper cavities.

The cavity shape distortion problem reveals the fact that the half-cells are not completely deep drawn. It can be resolved in two ways: one is to increase the hydraulic pressure to 10 MPa, and the other one is to repeat the process of deep drawing for the half-cell with an increase of the rotation angle from 0° to 90°. Besides that, a technique which involves periodic frequency checks during fabrication together with a corresponding precise length trimming has been developed to reliably produce cavities with the correct resonant frequency and the right cavity length. First, the half-cell is cut at the iris to the specified length (allowing for weld shrinkage) while at the equator an extra length of 2 mm is left to retain the possibility of a precise length trimming after the frequency measurement. The half-cell is held sandwiched between two aluminum plates and measured by a network analyzer. The precise trimming length is decided by the difference between the measured frequency and the calculated value. Here the weld shrinkage we test is around 0.3 mm.

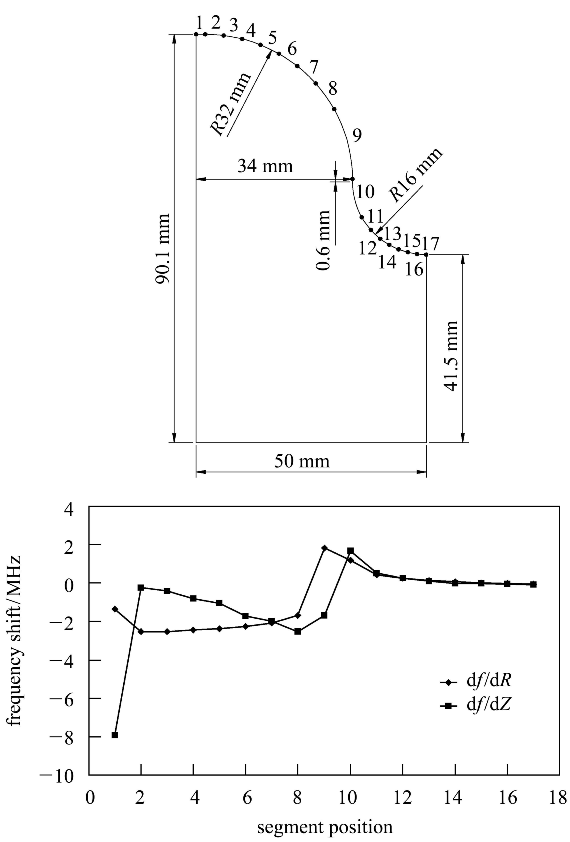

Fig. 2. Segment location and sensitivity of the frequency shift by errors in R and Z.

3.3 Cavity wall thickness distribution

Figure 3 shows the wall thickness distributions of the niobium sheet after deep drawing. It is clearly seen that the wall grows thicker towards its top edge after deep drawing and its thickness is larger than the original of 3.0 mm by over 9%, while the thicknesses at the iris circular section does not deviate much from the original. This situation can be improved by repressing the half-cells but it can not be completely resolved, as it is limited by the fabrication technique.

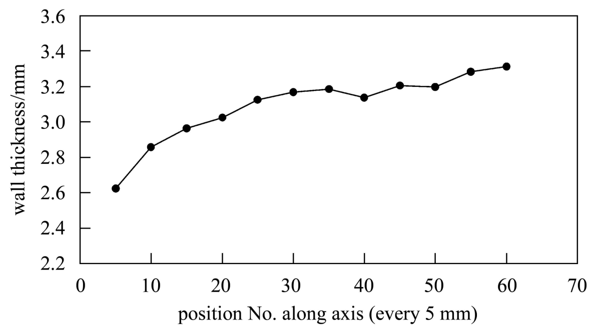

Fig. 3. The wall thickness distribution of the niobium half-cell along the axis direction after deep drawing.

Figure 4 shows the distributions of outer diameters and wall thickness at different locations of the niobium beam pipe after rolling. The peripheral angle starts from the rolling direction of the niobium

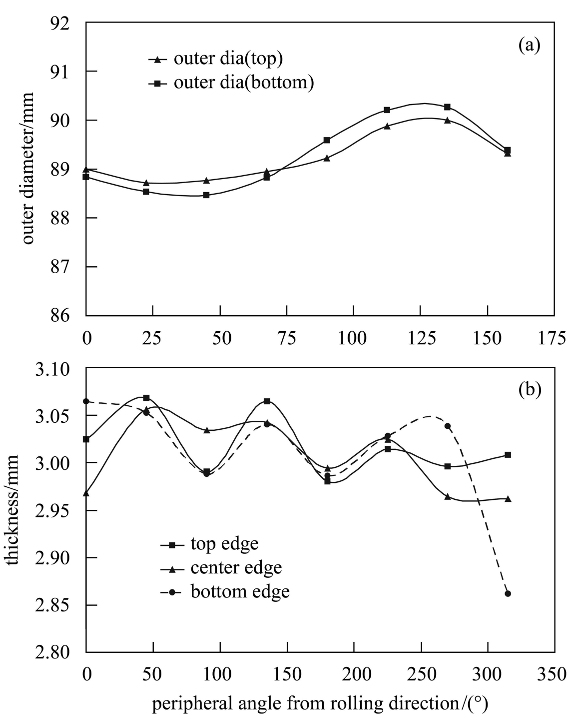

Fig. 4. Peripheral distributions of the outer diameter (a) and wall thickness (b) at the top and bottom edges of the niobium beam pipe after rolling.

sheet. The outer diameter at the bottom has slightly larger fluctuations of about −0.6 to 1.4 mm around the theoretical value 89 mm than that at the top of about −0.4 to 1.1 mm. The angle difference from the rolling direction between the maximum and the minimum diameters at both the bottom and the top is about 90°.

It can be obviously seen from the results mentioned above that the beam pipe has the shape of an oval. In addition, from the viewpoint of the peripheral distributions of wall thickness, three maxima periodically appear in every direction of 90 degrees from the rolling direction. Such an uneven thickness may be caused by the manual rolling technique. The maximum thickness change at the top is not larger than 0.07 mm, and that at the bottom is not larger than 0.05 mm. Therefore, it can be simply concluded that the rolling technique for the beam pipe has little influence on the wall thickness distribution, but it is not good for achieving uniform roundness.

3.4 New results after improvements

After the technique improvements towards the various problems which happened in the cavities fabrication process, a total of 3 niobium cavities have been produced successfully. Table 3 shows the resonant frequency and vacuum leak rate measurement results for the niobium cavities. It is shown that the resonant frequency shift of niobium cavities is greatly decreased and limited within 1.2 MHz. Besides that, the measured cavity shape is in excellent agreement with the designed shape, and the half-cell wall thickness variation at the top edge after repressing becomes 8%. Every electron-beam weld seam has been leak checked and shows good gas impermeability.

Table 3. Frequency and frequency shift for the second batch of Nb cavities.

cavity No.	frequency /MHz	frequency shift/MHz	leak rate/(Pa·m^3/s)
2# (China)	1498.64	−1.053	2.2×10^{-10}
3#(Japan)	1498.5	−1.193	3.2×10^{-11}
4#(China)	1498.7	−0.993	5.0×10^{-11}

4 Result of RF test

The unpolished niobium cavity made from the Chinese company was vertically tested at KEK to investigate its performance at low temperature. After ultrasonic rinsing the cavity was evacuated to 8×10^{-7} Pa and sealed in vacuum. The standard cool-down procedure took a few hours for the cavity to fall from room temperature to 4.2 K. During cooling down, the resonant frequency of the cavity was increased 2.21 MHz. The measured Q_0 (unloaded Q value) of the cavity as a function of accelerating field gradient ($E_{\rm acc}$) is shown in Fig. 5. The cavity achieved accelerating field gradients $E_{\rm acc}$ of ∼1.07 MV/m without quench and Q-values up to 5.609×10^7. Since no surface treatments were applied, the power supply was limited to protect the cavity.

The vertical test result shown in Fig. 5, as well as the achieved high vacuum at 4.2 K, proves that the fabricated cavity has good mechanical and vacuum performance at a low electric field. Higher accelerating field gradients and an unloaded quality factor can be expected after surface treatments.

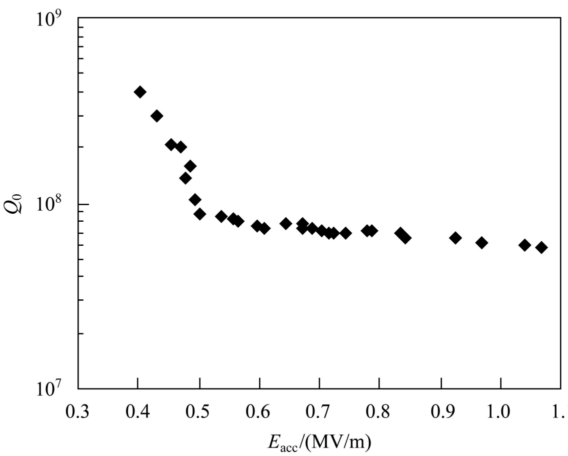

Fig. 5. Q_0 versus accelerating field curve at 4.2 K for the niobium cavity just after ultrasonic rinsing.

5 Conclusions

Among several kinds of techniques to fabricate superconducting cavities, the deep drawing technique used in this paper is one of the simplest ones with high reproducibility. Full annealing is a good method for improving the Japanese niobium material mechanical property, and the problem with niobium sheets torn during deep drawing never happens. An iterative process of half-cells deep drawing and frequency measuring followed by precise trimming eventually yields completed cavities with frequencies within 1.2 MHz. Moreover, the wall thickness variation of half-cells after repressing becomes less but not obvious, because it is limited by the fabrication technique. The initial vertical test result of the unpolished niobium cavity has sufficiently proved the success in the cavities fabrication techniques.

However, there are still issues with the forming die and the beam pipe fabrication technique. Generally the half-cell formed by deep drawing deforms after the trimming due to spring-back[15], but this effect was neglected in the design of forming dies. The work of designing a new forming die is now under way and will be completed in the next work schedule. From the fabrication results of the beam pipes, it is found that the outer diameter of the beam pipe varies largely and its symmetry is not good. Purchasing the seamless niobium tube directly or changing to another fabrication technique will be considered.

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