COMPARISON OF CAVITY FABRICATION AND PERFORMANCES BETWEEN FINE GRAINS, LARGE GRAINS AND SEAMLESS CAVITIES*

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Abstract

At KEK, L-band superconducting cavity fabrication studies have been carried out. One target of the R&D is investigation of cavity fabrication methods using different Nb materials and applying different cavity fabrication techniques. Different Nb materials are compared, between fine grain Nb and large grain Nb from different vendors including low RRR large grain Nb, from which cavities were fabricated by electron beam welding method. The difficulty with the large grain cavity fabrication comes from the deformation due to stressed grain boundaries. In addition to nominal electron beam welded cavities, hydro-formed seamless cavities have been fabricated. The large amount of expansion required for Nb tubes makes successful full deformation difficult. Good qualified Nb pipes are essential and the control of hydro-forming steps including annealing of materials is also important. In order to evaluate these cavity performances, vertical tests were carried out and they showed good performances. In this paper, fabrication processes, technical difficulties, mitigation strategies and vertical test results are presented.

INTRODUCTION

Techniques of superconducting RF (SRF) cavity fabrication have been developed for several decades. At present, the most popular material and fabrication method used for SRF cavity fabrication are fine grain Niobium (Nb) and electron beam welding (EBW) of deep-drawn half-cells. High gradients of more than 30 MV/m can be achieved with good yield rates, for example for TESLA 9-cell cavities [1]. By applying nitrogen doping technique and / or optimized cooling procedure, high-Q of $3x10^{10}$ is also possible at 2.0 K [2, 3].

KEK also have conducted cavity fabrication R&D studies at CFF (Cavity Fabrication Facility) [4]. KEK-CFF is a facility for SRF cavity fabrication and every machine and equipment, such as a pressing machine, a vertical lathe, and an EBW machine and a chemical polishing (CP) area are located in clean environment. They are shown in Fig. 1. In-house cavity production under clean condition is possible at KEK-CFF.

One aim of our R&D programs is development of cavity fabrication techniques, which include studies on different Nb materials and different cavity fabrication methods. For the material study two kinds of large grain Nb, high-RRR and low-RRR, were used in addition to nominal fine grain Nb disk. For the study on cavity fabrication methods we have been trying seamless cavity fabrication with hydro-forming [5].

Figure 1: (a) Press machine, (b) CP area, (c) vertical lathe, (d) EBW machine, which are located in KEK-CFF.

MOTIVATION OF STUDY

To investigate cavity fabrication and their performances, a total of six single-cell cavities were produced. Table 1 is a list of cavities. Two fine grain, two large-grain and two seamless 1.3 GHz single-cell cavities were fabricated.

The R-1, R-2 and R-5 cavities are TESLA-like end-cell structure with 80mm diameter beampipes and the R-4, W-1 and U-4 cavities are TESLA-like center-cell structure with 70mm diameter beampipes.

Table 1: List of fabricated single-cell cavities

Cavity type	Nb Material	Vendors	Cavity name
Fine grain single cell	Fine grain Nb sheet	Tokyo Denkai	R-2
		ULVAC	R-4
Large grain single cell	Sliced Nb ingot (large grain)	Tokyo Denkai (RRR = 390)	R-1
		CBMM (RRR = 100)	R-5
Seamless single cell	Fine grain Nb tube	Wah Chang	W-1
		ULVAC	U-4

For the fine grain cavities, two vendors, Tokyo-Denkai and ULVAC, delivered fine grain Nb sheets. Cavities made by fine grain Nb sheets are current standard.

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For the large grain cavities, also two different materials were used. One was high-RRR sliced large grain Nb disk provided by Tokyo-Denkai, and the other was low-RRR large grain Nb ingot prepared by CBMM [6]. To prepare large grain Nb ingot, a process of forging can be omitted, compared with fine grain case. Furthermore, smaller number of melting process is needed for low-RRR ingot case. In that sense, large grain cavities might be more cost-effective. From the view-point of cavity performance, relatively high-Q may be anticipated.

Two hydro-formed seamless single-cell cavities were fabricated from fine grain Nb tubes, which were provided by two vendors, Wah Chang and ULVAC. Sometimes performances of electron beam welded cavities are limited by defects, which are produced during welding procedures. Thus, seamless cavities could lead to higher reliability.

FINE GRAIN SINGLE-CELL CAVITIES

Fabrication Procedure

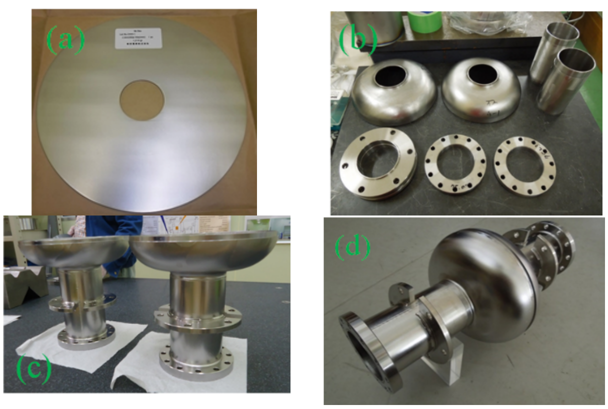

Figure 2: (a) Fine grain Nb disk, (b) cavity components before welding, (c) end groups and (d) completed cavity.

Figure 2 shows a typical fabrication procedure for EBW cavities. Figure 2 (a) shows a fine grain Nb disk, which was delivered by a vendor. Nb disks were deep-drawn and male and female type of half-cells were prepared. Beampipes, flanges and support components were also made, as shown in Fig. 2 (b). These components were electron beam welded and two end parts were fabricated. Finally the equator parts were electron beam welded and a cavity was completed.

Surface Treatments

Typical surface treatment procudures at KEK are the following.

1. EP-I (Eletropolishing) 100 μm
2. Anneal at 750 C, 3 hours
3. EP-II 20 μm
4. High pressure rinse (HPR)
5. Flange assembly
6. Baking at 140 C, 48 hours

These procedures were applied to the fine grain single-cell cavities. After above procedure, vertical tests were carried out.

Vertical Test Performances

Vertical test results of fine grain single-cell cavities are shown in Fig. 3. Left and right figures are results for the R-2 cavity which is made from Tokyo-Denkai Nb disks and the R-4 cavity which is made from ULVAC disks, respectively. Generally Q-E curves are taken for different temperatures. Silicon diode sensors, which were calibrated down to 1.5 K, were located on both side of beampipes and used for temperature measurements. During measurement of the R-4 cavity, vacuum trouble was suspected and measurement was stopped after taking 2.0 K data, although the vacuum turned out to be no problem later. Both performances were excellent with E_{acc} > 35 MV/m, as shown in Fig. 3.

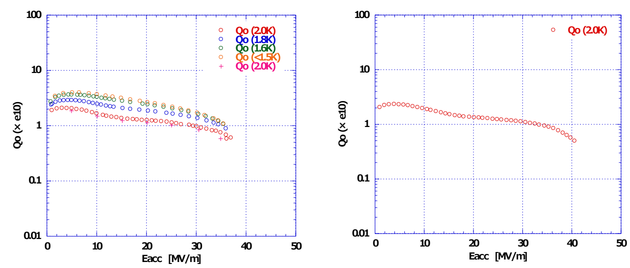

Figure 3: Vertical test results for the R-2 cavity (left) and the R-4 cavity (right).

LARGE GRAIN SINGLE-CELL CAVITIES

Two types of large grain Nb of high-RRR and low-RRR were used and cavity fabrication was investigated [7, 8].

Large Grain Disks

Figure 4: Large grain Nb disk from Tokyo-Denkai (left) and sliced large grain Nb disk from CBMM Nb ingot.

Figure 4 shows sliced large grain Nb disks, which clearly show large grains. Tokyo-Denkai supplies large grain disks after slicing by themselves. On the other hand, CBMM delivered a large grain Nb ingot. Diameter of the disks from Tokyo-Denkai and CBMM are 270 mm and 260 mm, respectively.

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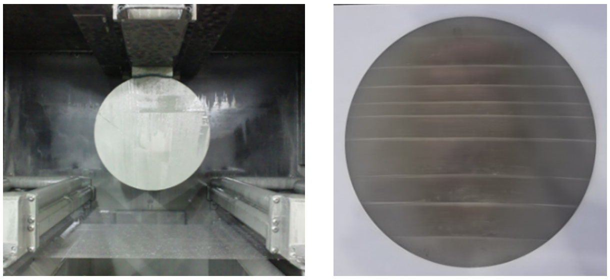

Figure 5: (Left) Slicing large grain Nb ingot by a multi-wire saw and (right) one sliced large grain disk.

The delivered Nb ingot was sliced at a Japanese company. Figure 5 left shows the large grain ingot which was sliced using by a multi-wire saw. Since this was the first trial for them to slice Nb, slicing conditions were not optimized and saw-marks remained on Nb surface as shown in Fig. 5 right. Therefore, additional mechanical polishing was applied for the Nb disks to prepare smooth surface and disks were delivered. At KEK, chemical polishing was applied and surface conditions were checked.

Typical differences between Tokyo-Denkai large grain disks and CBMM large grain disks were RRR and the amount of Ta content. RRR values were measured at KEK and they were 390 and 100 for Tokyo-Denkai and CBMM materials, respectively. The amount of Ta content from mill-sheets were 80 and 1000 ppm for Tokyo-Denkai and CBMM, respectively. The effect of Ta content on the cavity performance was our primary interest.

The mechanical strength of materials is also important since SRF cavities are parts of pressure vessels. The tensile strength at room temperature was measured at KEK. Figure 6 shows a tensile testing machine and obtained results, in which typical two results for both materials are shown. For both materials, measured tensile strength were around 80 MPa. This value is around half, compared with the case for fine grain Nb sheets.

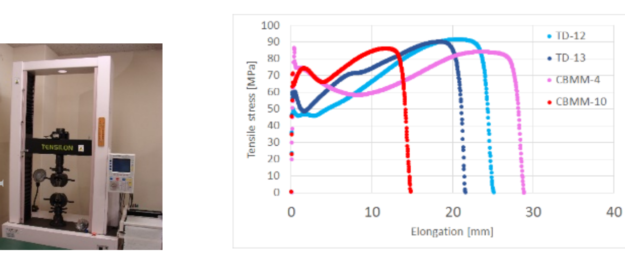

Figure 6: (Left) Tensile testing machine and (right) measured results of tensile tests.

Deformation and Welding

As with the fine grain case, large grain cavity fabrication was started with deep-drawing of Nb disks to half-cells. A deep-drawn half-cell is shown in Fig. 7.

Figure 7: Views of deep-drawn large grain half-cell cavity from side (left) and top (right).

One big issue for the large grain cavity fabrication is nonuniform deformation. It occurs because elongation is different on each grain and also on boundaries. The grain boundaries sometimes get wavy and the thickness of each grain varies. Deformations are observed at both equator and iris regions, but the effect is severer at the equator region because of larger diameter.

Deformations lead to a difficulty in electron beam welding. In the case of the R-1 cavity, only one side of groove surface was machined. This is a nominal procedure, which we apply for fine grain cavity fabrications. As a result, Nb thickness of welding part varied as much as 400 μm and this led to an unstable EBW bead, since the penetration condition of electron beam depends on the Nb thickness. Figure 8 shows an example of stable and unstable EBW beads. The narrow unstable EBW bead appeared on thicker part.

In the case of the R-5 cavity, both side of groove surface were machined, in order to control Nb thickness. Welding bead became more stable. It is important to control Nb thickness of groove surface to realize stable EBW beads.

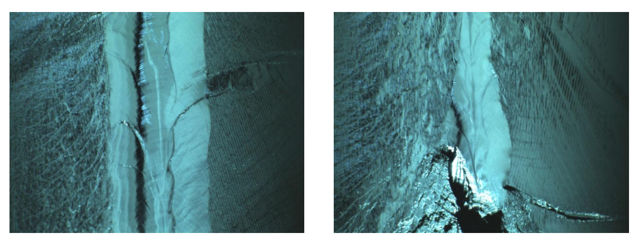

Figure 8: Stable (left) and unstable (right) welding beads for the R-1 cavity.

Figure 9 shows other specific phenomena observed during the fabrication of the R-5 cavity. One is cracks, which were observed at grain boundaries. They weaken cavity strength, so it is rather critical for SRF cavities. Fortunately, cracks were only outside and we could perform vertical tests without vacuum leaks. It is noted that rather small grains are gathered around equator area of CBMM disks. Bend test may help to understand the reason for cracks. Another one is spattering, which occurred during EBW. This is also only observed at the outside surface of the cavity. To see this kind of spattering at our EBW machine is very rare. No spattering was observed during EBW tests on CBMM plates. The reason for this spattering is not clear.

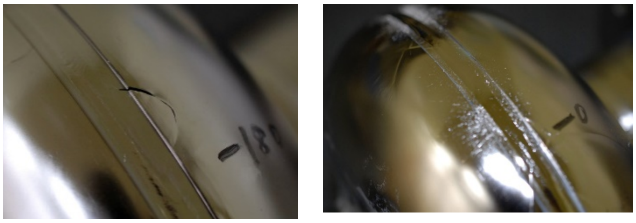

Figure 9: Cracks (left) and spattering (right) observed for the R-5 cavity.

Vertical Test Performance

The same surface treatment procedure as for fine grain cavities was applied for large grain single-cell cavities and vertical tests were carried out to investigate cavity performances.

Figure 10 shows vertical test results for large grain single-cell cavities. Vertical tests were performed three times for the R-1 cavity, which is made from Tokyo-Denkai large grain disks. Results are shown only for the measurements at less than 1.5 K. The accelerating gradient exceeded 40 MV/m. High Q_0 values, close to 1 x 10^{11}, was observed at the first measurement. It may suggest an advantage of large grain cavities. It could not be, however, reproduced. This is probably because our vertical test system is not enough optimized for high-Q measurement, at present.

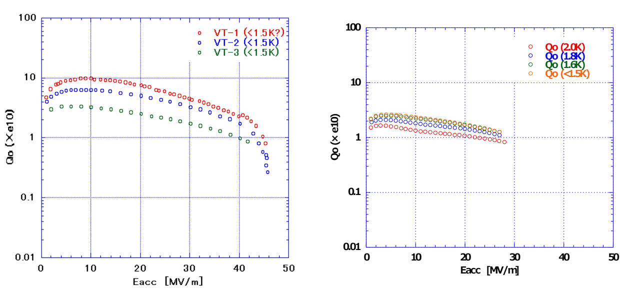

Figure 10: Vertical test results for the R-1(left) and the R-5(right) cavities.

The quench field of the R-5 cavity was 28 MV/m. After the vertical test, a defect was found around equator by surface inspection. This defect is not originated from the material. We have a plan to remove this defect by local grinding and carry out a vertical test again. A higher accelerator gradient might be achieved.

SEAMLESS SINGLE-CELL CAVITIES

Seamless Nb tubes were prepared by Wah Chang with the cooperation of Fermilab, and ULVAC. Seamless cavities were fabricated by using a hydro-forming technique [9].

Fabrication Procedure

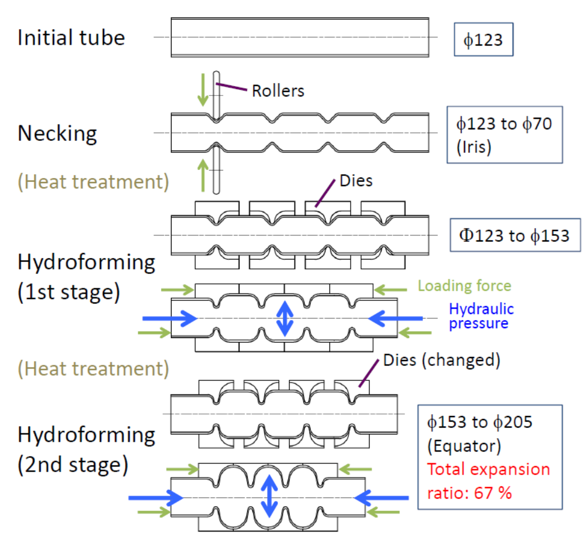

Figure 11: The fabrication process of hydro-formed seamless cavity from a seamless Nb tube.

The fabrication process of hydro-formed seamless cavity is shown in Fig. 11 and a necking machine and a hydro-forming machine are shown in Fig. 12.

Figure 12: Necking machine (left) and hydro-forming machine (right).

Fabrication was started from the fine grain Nb tube with the inner diameter of 123 mm. First, the irises were produced by using a necking machine and a heat treatment at 750 C for 3 hours was applied. Then, the first stage hydro-forming was carried out. The hydro-forming procedure should be divided into two stages, since the total expansion ratio of 67 % is required, from initial diameter of 123 mm to final equator diameter of 205 mm. Figure 13 left shows a cavity after the first stage of hydro-forming. Another heat treatment at 750 C for 3 hours was applied to release stress, and finally the second stage hydro-forming was carried out. Figure 13 right shows the successfully formed cavity after the second stage hydro-forming.

Figure 13: After first stage (left) and second stage (right) of hydro-forming.

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Both ends of hydro-formed structure were cut off and the cell part, shown in Fig. 14 left, was EB welded to end groups. The completed seamless cavity is shown in Fig. 14 right.

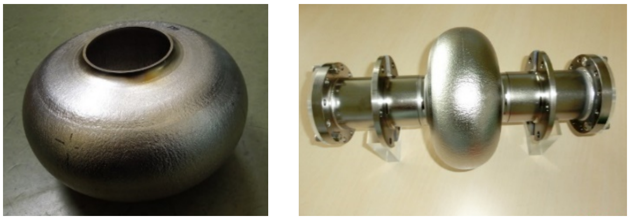

Figure 14: The cavity cell before being welded with end parts (left) and the completed seamless single-cell cavity (right).

Burst During Hydro-Forming

The major difficulty in fabricating hydro-formed seamless cavity comes from large expansion ratio. Sometimes, hydro-formed cavity suffers from burst, as shown in Fig. 15.

The required total expansion ratio is 67 %, while typical elongation of Nb is 50 to 60 % with a suitable heat treatment. Therefore, in order to avoid bursts, hydro-forming was held in two stages and an annealing after each forming was also applied to recover elongation.

Figure 15: An example of burst during hydro-forming process.

The quality of the initial seamless tube is also important. Uniform and small grains are essential for uniform expansion. To lower the expansion ratio, Nb tubes with larger diameter would be helpful.

Cavity surface

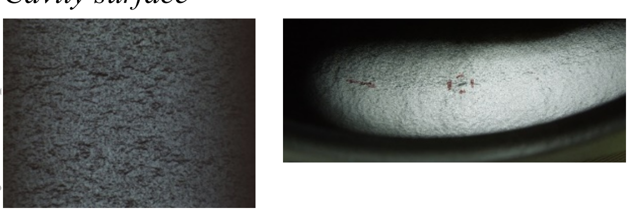

Figure 16: Inner surface of hydro-formed cavity for the W-1 cavity (left) and the U-4 cavity (right) after fabrication.

Another specific issue for hydro-formed cavity is rough inner surfaces. The left and right photos in Fig. 16 show the inner surface of the W-1 cavity, made from Wah Chang tube, and the U-4 cavity, made from ULVAC tube, after fabrication, respectively. The roughness of the surface can be clearly seen. In order to obtain a smooth surface, we had to apply centrifugal barrel polishing for both cavities.

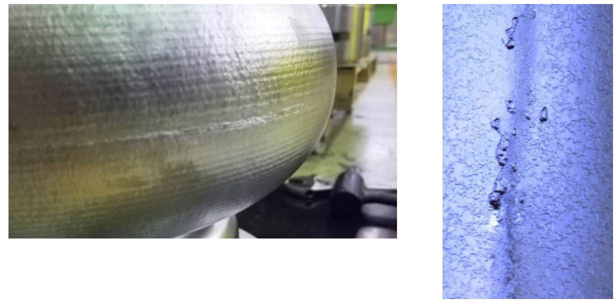

Figure 17: The outer surface (left) and inner surface (right) after barrel polishing of the W-1 cavity.

Another problem we found is a valley appeared around equator region. Figure 17 left shows the outer surface of the W-1 cavity. In the picture, it may not be so clear, but a step can be seen as a white line around equator. This position is recognized as the area where two dies meet. Figure 17 right shows the inner surface of the equator region after barrel polishing. Clear defects can be seen. This is a deep valley. It was removed by local grinding. It was hard to get a smooth surface. This kind of defects, however, should be avoided by optimizing fixtures and / or parameters of hydro-forming process.

Since the potential advantage of hydro-formed seamless cavities is a defect-free smooth surface around equator region, these issues should be addressed to realize this potential.

Surface Treatments for Seamless Cavities

Because of rough surfaces, centrifugal barrel polishing (CBP) was applied. For the case of the W-1 cavity, it was sent to Fermilab and CBP was applied. Its surface became as mirror finished after removal of about 120 µm. Then cavity was sent back to KEK. Surface treatment procedure, without EP-I, was applied before vertical tests.

For the case of the U-4 cavity, barrel CBP was carried out at a Japanese company. Surface became much smoother than before, but still some roughness remained. A surface treatment, including 100 µm of EP-I, was applied to the U-4 cavity.

Vertical test performance

Vertical test results for the W-1 and U-4 cavities are shown in Fig. 18. The accelerating gradients of

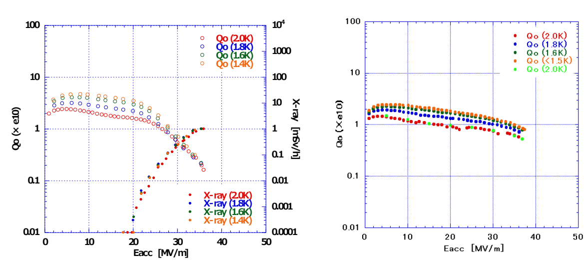

Figure 18: Vertical test results for the W-1 cavity (left) and the U-4 cavity (right).

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> 35 MV/m were achieved for both cavities. Also reasonable Q_0s were obtained for both cavities. A field emission was observed for the W-1 cavity as shown in Fig. 18 left, but this was found out to be due to poor welding at the boundary to the beampipe and not related to the hydro-formed cell.

SUMMARY

We prepared fine grain, large grain and seamless single-cell cavities to investigate fabrication procedure and their performances. Nonuniform deformation around grain boundaries cause difficulty in large grain cavity fabrication. It leads to unstable EBW bead, spattering and cracks around boundaries. Hydro-forming of Nb tubes was tried to produce seamless cavities. In order to avoid bursts, several steps of hydro-forming and annealing were needed. Rough inner surfaces of seamless cavity need to be improved. Vertical tests results were fine for all the cavities. Most of them reached an E_{acc} of > 35 MV/m.

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