# HYDROFORMING SRF CAVITIES FROM SEAMLESS NIOBIUM TUBES

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## Abstract

The authors are developing the manufacturing method for superconducting radio frequency (SRF) cavities by using a hydroforming instead of using conventional electron beam welding (EBW). We expect higher reliability and reduced cost with hydroforming. For successful hydroforming, high-purity seamless niobium tubes with good formability as well as advancing the hydroforming technique are necessary. Using a seamless niobium tube from ATI Wah Chang, we were able to successfully hydroform a 1.3 GHz single cell cavity and obtained an $E_{acc}$ of 36 MV/m confirming that the hydroforming technique developed at KEK is applicable for the SRF cavity.

## INTRODUCTION

The major manufacture method for SRF cavities which have elliptical cell shape are the press forming of rolled niobium sheet to the cell shape and the assemble of them by a EBW. Although the inner surface of cavity should be smooth, the penetration welding is provided from outside of cavity because the electron gun of EBW is big, and a smooth rear-welding bead with small bump is required. This is very difficult welding work, which needs skills. Moreover, a chemical polishing of a groove before welding, a prevention of contamination during welding, and sometime a remove of defect occurred by welding as a post process, are required. The initial cost of an EBW machine is high and the EBW is the main factor of cost rise for cavity manufacture.

Although the welding is provided at the equator (maximum diameter) and the iris (minimum diameter) of cells where the magnetic and electric fields are largest respectively, there should be no bump like a welding bead ideally. To keep a high reliability of cavity production, very careful process control in the EBW is required. A hydroforming is one of a plastic working and applied to cavity fabrication instead of the EBW. This manufacture method is well known for a long time, and widely used for manufacture of automobile and hydraulic parts. The hydroforming involves expanding a tube with internal hydraulic pressure while simultaneously swaging it axially. The die is placed around the tube, which is formed along it. Singer has provided the study of applying the hydroforming to the cavity fabrication energetically at DESY. 1.3 GHz TESLA cavities were fabricated using a 150 mm inner diameter (ID) and 2.7 mm thickness seamless niobium tube, and the 9-cell cavities were manufactured by joining three 3-cell cavities by the EBW. The maximum accelerating gradient

attained to 30 to 35 MV/m [1]. The series of research in DESY and activities at other laboratories are introduced in detail in Ref. [1], and please refer to it. KEK started the research of hydroforming since 1994. Fujino, et al. developed the seamless tube using a clad material, which joined thin niobium and fat copper sheets for the cost reduction, and manufactured 1-cell cavity by the hydroforming. The maximum accelerating gradient attained to 40 MV/m [2-4]. Afterwards, Ueno, et al. developed the necking and the hydroforming machines [5-6], and KEK can provide series of process from the seamless tube to finish the cavity in the laboratory.

It is necessary to manufacture more than 17000 1.3 GHz 9-cell cavities in the International Linear Collider (ILC) project. The cost reduction of cavity fabrication is indispensable subject. Its method by the press forming and the EBW using a high-purity (residual resistance ratio: RRR > 300) niobium is shown in the technical design report (TDR) completed in 2013 as the baseline design [7]. The authors are examining whether the cavity fabrication by the hydroforming can replace the baseline design method from the viewpoint of the cost reduction. The material is fixed as the high-purity niobium shown in the TDR. The above-mentioned method, which three 3-cell cavities are manufactured by the hydroforming and joining them by the EBW, is not sufficient for the cost reduction. The hydroforming 9-cell cavity from one long tube is significant. At present, this is not realized. The purpose of this study is the hydroforming 1.3 GHz 9-cell cavity and showing the performance of hydroformed cavity is equivalent to the cavity manufactured by the conventional method, then take a measure that the hydroforming is effective in the cost reduction. In this report, the result of manufacture of 1-cell cavity and the evaluation of performance for the first time.

## SEAMLESS NIOBIUM TUBE

For successful hydroforming, high-purity seamless niobium tubes with good formability as well as advancing the hydroforming techniques are necessary. Although KEK could not obtain a good niobium tube until now, has got it manufactured by ATI Wah Chang in U.S. by cooperation of FNAL this time.

The equator ID of 1.3 GHz TESLA-like cavity is approximately 205 mm. Since the iris part is 70 mm. If we only use hydroforming from 70 mm ID tube, required elongation is 200%. Since the maximum elongation with niobium tube is 50 to 60% with suitable heat treatment and grain size. Therefore, we use a combination of necking (iris) and hydroforming (equator) from 123 mm ID tube [5]. A 2.6 mm thickness niobium sheet is used in ordinary press forming for cells; however, that of

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**SRF Technology - Cavity**

**E04-Seamless Technology**

seamless tube is set to 3.5 mm, a little largely. Because the thickness at the equator part is expected to become thin by hydroforming, the thickness of the tube is increased to secure 2.6 mm there. The tube length required for 1-cell cavity is 450 mm. It contains the length of the portion chucked by the processing machine. The beam pipes joined to both ends of cavity by EBW is separate part, and not included in above length. The tube length for 3-cell and the 9-cell cavities are 800 mm and 1700 mm, respectively in the same manner. The RRR of niobium ingot, which is the start material of this tube, is 387. The hardness of the tube as received from the builder is 46 HV.

## MANUFACTURE OF CAVITY

### Necking and Hydroforming

The processes of the necking and the hydroforming are shown in Fig. 1. The figure shows the case of 3-cell cavity. First, the iris parts are formed by the necking. The state of necking is shown in Fig. 2. The neck is formed by plunging the two counter rollers into rotating niobium tube. The roller rotates due to contact rounding. A lubricant is not used between the roller and the tube. The necking process is provided by each neck. In the case 1-cell cavity, two necks are formed. After the necking process, the tube is annealed using a vacuum furnace. The heat treatment condition is 750 degree for 3 hours.
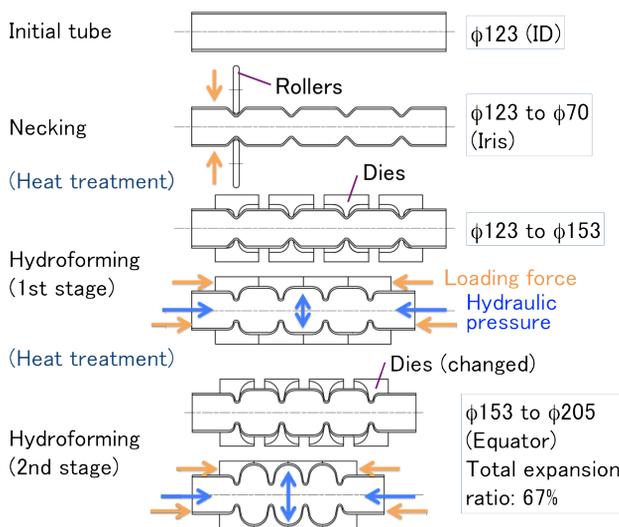


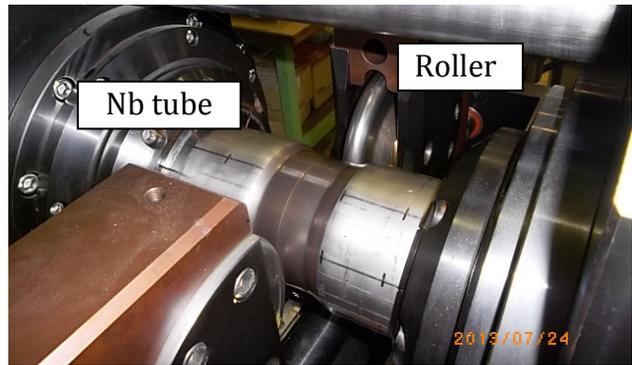Figure 1: Process of necking and hydroforming.



Figure 2: Necking machine.

Next, the equator part is hydroformed. It is provided in two stages as shown in Fig. 1. In the 1st stage, 123 mm ID is expanded to 153 mm. The die is placed outside and the internal hydraulic pressure is applied to the tube while simultaneously swaging it axially. The outer shape of the die is a cylindrical. The dies placed in a long cylinder and can move in longitudinal direction. This dies are swaged until they stick together. The internal pressure is rise to 25 MPa and held for a while to make the tube fits to the die. Then, the dies are removed and the tube is annealed again. The longitudinal length of the tube becomes short as shown in the figure. The appearance of the hydroforming is shown in Fig. 3. A hydraulic piston generates the longitudinal loading force. The hydraulic pressure for this piston and the inner tube are supplied from independent hydraulic pump, and the amount of pressure is controlled, respectively. In addition, a fluid is oil. In the 2nd stage, the die is changed for the final shape, and the hydroforming is provided again. The niobium tube which forming is completed is shown in Fig. 4. The photograph near the equator part of inner surface is shown in Fig. 5. The equator part is the most expanded part in 67%. It is a mating face of die and some unevenness occurred and the surface became rough a little. The cell shape is the center cell of TESLA-like, which KEK developed.



Figure 3: Hydroforming machine (Final hydraulic pressure: 25 MPa).

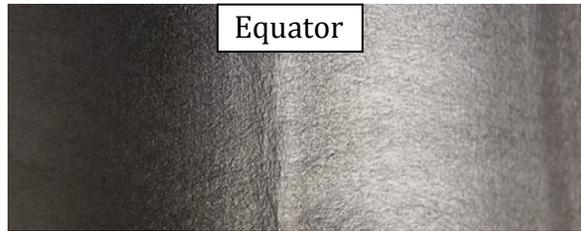Figure 4: Niobium tube just after hydroforming.



Figure 5: Cross view at equator area (inside).



Figure 6: Finish to 1-cell cavity.



Figure 7: Barrel polishing machine[8].

## *Finish to Cavity*

The both iris parts of tube shown in Fig. 4 were cut and the 70 mm ID beam tube was joined to both ends by the EBW. The beam tube was manufactured by rolling a niobium sheet and the EBW. The flanges made from niobium titanium alloy were attached to both ends by the EBW. Figure 6 shows the completed 1-cell cavity. In the ordinary procedure, the inner surface observation is achieved after finishing the cavity. If the defects, which should be removed, were found, they are removed using the special device. Then, it proceeded to the electrolytic polishing (EP) process. However, in this cavity the inner surface became rough after forming, we decided a mechanical polishing is required before the electrolytic polishing. The barrel polishing which has the achievement in mechanical polishing for the SRF cavity is adopted. KEK don't have the facilities of the barrel polishing, and asked to FNAL for this treatment [8]. The barrel-polishing machine used is shown in Fig. 7. It is a centrifugal barrel-polishing machine and polishes inside cavity with a polishing media and water put into it by rotating. This machine can treat four 9-cell cavities (length: 1.3 m) at one time. The process was provided with changing the media type, and the surface became mirror finish finally. The details of barrel polishing are shown in Ref. [8]. Please refer to it.

## PERFORMANCE EVALUATION

### *Result of Vertical Test*

The finish of inner surface after the barrel polishing was so good that the EP for approximately 100 mm treated for the conventionally manufactured cavity was skipped and the EP of finishing surface for 15 mm was treated. Then the vertical test was carried out at Superconducting Test Facility (STF) in KEK. The result of the vertical test was shown in Fig. 8. The maximum accelerating gradient attained to 36 MV/m confirming that the hydroforming technique developed at KEK is appreciable for the SRF cavity.
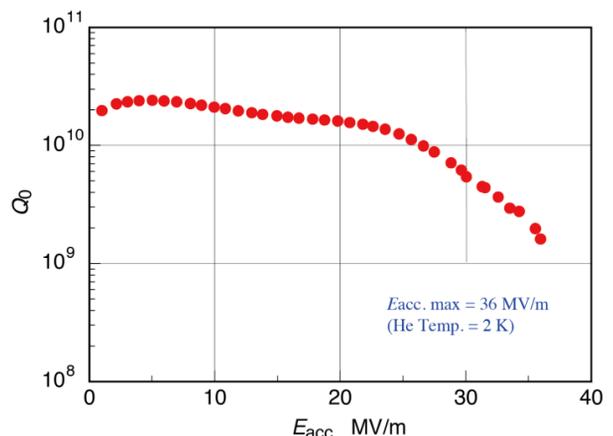


Figure 8: Result of vertical test (Q-E curve).

*Measurement of Inner Shape of Cavity*

The inner shape of cavity is given as a design value. The shape of die must be designed considering a distribution of thickness of the cavity. Since the thickness at the equator part was expected to become thin, the die shape was designed in consideration of this. The error of inner shape for the designed value was examined. It was difficult to measure the inner shape of cavity directly, so that the outer shape and the thickness distribution of cavity were measured using a coordinate measuring machine (CMM) and an ultrasonic thickness measurement device, respectively as shown in Fig. 9. The inner shape was estimated by these measurement results (Fig.11).Figure 10 shows the measurement result of thickness. It was measured at four points on the circumference. The equator was the thinnest part. It is thinner than expected; therefore, an improvement to reduce the thinning is required by modifying the forming conditions. A circle at the equator, an ellipse at the iris and a tangent between them construct the curve of cavity shape, so that the estimated curve was approximated using the circle, the ellipse and the tangent to obtain actual parameter. The TM01 mode frequency was calculated using the Superfish and above parameter, then 1273.0709 MHz was obtained. The actual measured value was 1274.4375 MHz, and well in agreement. The inner diameter is 2 mm larger than the designed value due to the thinner wall. Therefore, the measured frequency became high by 10 MHz than the designed value.



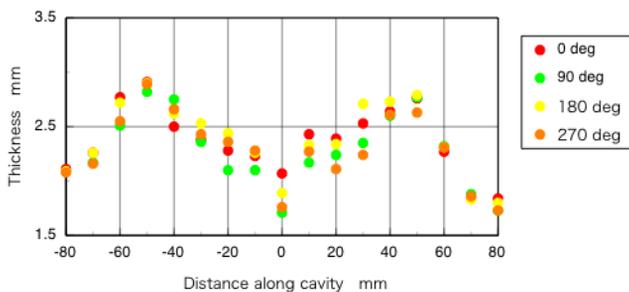Figure 9: Measurement using (left) CMM and (right) ultrasonic thickness measurement device.
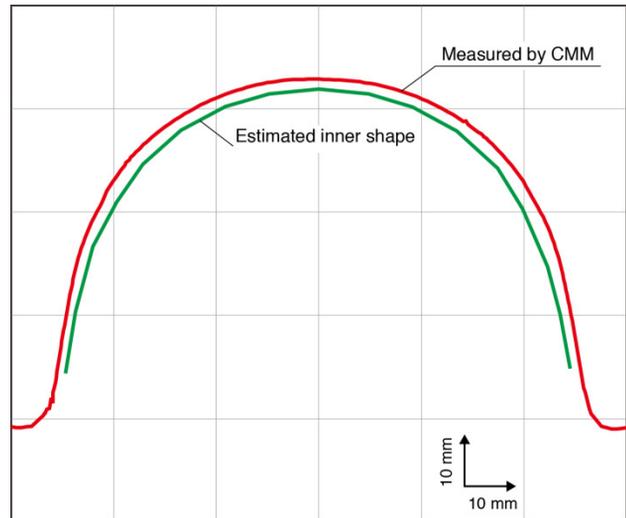


Figure 10: Thickness distribution along cavity shape.



Figure 11: Estimation of inner shape.

## SUMMARY

It succeeded in the manufacture of the 1.3 GHz 1-cell cavity by the hydroforming. From the result of the vertical test, the maximum accelerating gradient attained to 36 MV/m confirming that the hydroforming is appreciable for the SRF cavity. We will continue the study to successfully hydroform a 9-cell cavity.

## ACKNOWLEDGMENT

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