HYDROFORMING OF MULTI-CELL NIOBIUM AND NBCU-CLAD CAVITIES *

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Abstract

Technological aspects of multi-cell cavity production by hydroforming are presented. Problems related to the fabrication of seamless cavities from bulk niobium are mainly solved. Several three cell units have been produced by hydroforming at DESY. A 9-cell cavity of the TESLA shape completed from three sub-sections at company ZANON has been treated by electropolishing (EP) and successfully RF-tested.

Three 3-cell units equipped with niobium beam pipes are being RF-tested after buffered chemical polishing (BCP) surface treatment at JLab. The cryogenic test results are discussed in this contribution.

Of special interest is the combination of the seamless technique with NbCu cladding, i.e. the fabrication of a cavity from a bimetallic clad NbCu tube by hydroforming. This process has been successfully developed. Several single cell cavities have been fabricated, using a special Cu0.15%Zr alloy for cladding. They will be tested in the near future. The actual status of the manufacturing process will be presented below.

INTRODUCTION

Although it was demonstrated that welded cavities can achieve very good performance, elimination of welds in critical locations is very desirable. Firstly, a seamless cavity avoids the risk of weld contamination; and it can be expected that an improved statistic in performance of seamless cavity can be achieved. Secondly, lower cost of fabrication - especially for a big series - seem to be possible.

SEAMLESS BULK NIOBIUM TUBES FOR HYDROFORMING

Seamless tubes suitable for hydroforming are presently not available on the market and a special development is necessary.

The required percentage elongation before necking of > 25% is challenging. Several fabrication methods [1] (spinning, back extrusion, flow forming and deep drawing) were evaluated to reach this goal.

The best results have been achieved by starting from a thick sheet combined with deep drawing or spinning with flow forming. For the three cell units the seamless tubes have been fabricated from 10 mm thick discs of approximately 500 mm in diameter. “Beakers” with 5 mm wall thickness and a length of app. 500 mm were produced by spinning (at Co. Thate, Germany). Subsequent flow forming in forward direction (done at Co. MSR, Germany) reduced the wall thickness of the tubes to 3 mm and increasing the length to 950 mm .Wall thickness tolerances of +/- 0.15 mm have been achieved, sufficient for subsequent hydroforming [2]. The microstructure and crystal orientation distribution was acceptable (Fig. 1). In tensile tests done in circumferential direction elongations of 27-35 % before necking were measured.

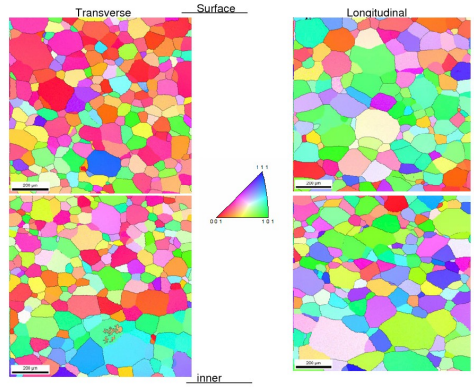

Figure 1: Orientation Imaging Microscope [OIM] figures of the RRR niobium used for hydroforming of seamless [Nb] tubing.

FABRICATION OF MULTI CELL NB CAVITIES

The details of the fabrication technique developed at DESY over several years are described in earlier publications [1-3]. Here we will present only a short summary and some aspects leading to successful manufacturing of multi- cell cavities.

The fabrication of the resonator starts from a seamless tube of intermediate diameter between cavity equator and iris. In a first step the tube diameter is reduced in the iris area and at the end of the tube, called “necking”; in a second step the tube diameter is expanded in the equator area.

Several necking methods (hydraulic necking, electromagnetic strike necking, round knead, spinning) were tested. Most satisfactory necking results were achieved by using a special ring and moving it in radial and axial directions (Fig. 2a). The ring profile touching the tube is similar to the outside profile of the cavity iris.

The combination of radial and axial movements ensures circumferentially a uniform wall thickness at the iris area without significantly reducing the wall thickness. The axial movement occurs continuously from position one to position two; from position two to position three etc. (Fig. 2b) following the declined trajectory. At the same time the tube is compressed axially.

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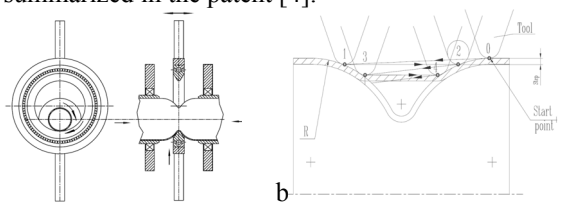
The expansion of the tube diameter in the equator area is accomplished by applying an internal water pressure and simultaneously the axial displacement. A well defined relation between applied internal pressure and axial displacement (path of the expansion) has to be followed. A rough value of the pressure is derived from numerical simulations. It can be further corrected on the basis of hydroforming experiments.

The hydroforming of multi cells is done in the two stages as described above in order to form all cells simultaneously, to achieve the correct shape, rather uniform wall thickness and to suppress any instabilities in the tube expansion. At the first stage the expansion of the necked tube reaches a value app. half way between initial and final diameter. The tube diameter grows until it touches the specially shaped mould (intermediate constraint). The mould shape is chosen on the basis of FEM simulations (Fig. 3). In the second stage the final expansion into the external mould, which has the final cavity shape, takes place.

A special mechanism synchronizes the movement of the moulds and allows the stable forming of many cells simultaneously (see figure 3). The synchronisation is applied for both stages of expansion. The developed ideas are summarized in the patent [4].



a b

Figure 2a,b: Principle of the necking between cells.

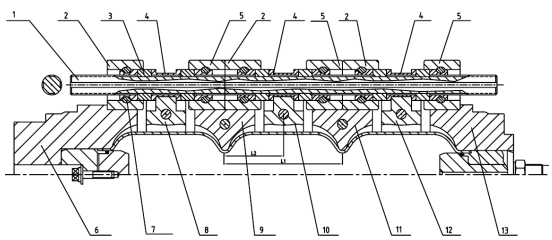


Figure 3: Shape of the intermediate constraint. Schematic of the synchronization mechanism.

Nine three cell units have been produced at DESY by applying the described technique without any ruptures of the walls.

The first three 3-cell units have been sent to JLab for completion with beam pipes and for evaluation of their performance. A 9-cell cavity was completed at Zanon, Italy, from the second three 3-cell units by electron beam welding from the outside at the irises, then by adding stiffening rings and end-groups as for the conventional cavities. The third 3- cell unit is planned for completion into a conventional cavity of the XFEL type.

FABRICATION OF NBCU CLAD CAVITIES

Different cladding procedures were checked in previous investigations[2]. Softening by annealing plays an important role for the NbCu clad option. Because of the large difference in recrystallization temperature between both materials, it is not possible to reach an optimum in plastic properties in both layers needed for the hydroforming. For example, Cu can be fully recrystallized by annealing at 560°C for 2 hours with a grain size of about 30 µm , which is acceptable for hydroforming (percentage elongation before necking > 30%). Niobium however has after such annealing a deformed structure without pronounced grains. The recrystallization temperature of Nb is rather high (ca. 800°C); an annealing of the NbCu bimetal at this temperature will lead to significant, undesired grain growth in Cu.

The high plastic properties of Cu play a leading role in the forming process of NbCu clad cavities. The hard and less plastic Nb layer is much thinner. Nb follows the Cu during forming because of the tight bonding. However, undesired effects cannot be completely avoided. There is a tendency of crack formation at the iris area during necking and this is especially dangerous.

This drawback can be excluded by a suitable alloying of the Cu. It is well known that small additions of some metals (Hf, Ti, Cr, Zr, Mg, Sn, Mn, Al) increase the recrystallization temperature of Cu. The alloy Cu0.15%Zr available on the market is a good candidate for replacing the pure Cu in NbCu clad tubes. This alloy has the desired mechanical properties after annealing at temperatures required for the Nb recrystallization.

Unfortunately, the alloying of Cu will increase the number of scattering centres for electrons and reduce the thermal conductivity. However, experiments have shown that the thermal conductivity of Cu0.15%Zr remains high enough : 150 W/mK at 4.2 K (comparable with that of high purity Nb). In addition, the thermal conductivity can be recovered by aging at app. 400°C for one hour. During this step, Zr leaves the solid solution and creates precipitates of Cu5Zr distributed in the Cu matrix that do not influence the thermal conductivity.

A clad bimetallic tube app. 2 m long of niobium and Cu0.15%Zr alloy has been produced by the process described above at the company NuTech (Canada) using forward extrusion.

Figure 4: Two Nb Cu0.15%Zr clad cavities in preparation for tests.

Four single cell NbCu clad cavities were fabricated. The beam tubes with the flanges were connected with the Nb layer of the cavity by EB welding. Presently, two single cell NbCu clad cavities are in preparation for the RF test at JLab (Fig. 4).

RF RESULTS

Single 3-Cell Units

For the cryogenic RF testing the cavities have been treated by BCP removing the niobium in several steps. A high pressure rinsing (HPR) for two passes of 2 h each from the top of the cavity to the bottom followed after the BCP and subsequently the cavities were dried in a class 10 (ISO 4) clean room for several hours. The cavities were evacuated on the cryogenic test stand to a vacuum of typically $< 10^{-8}$ mbar prior to cool-down to liquid helium temperature. Some RF results were previously reported for cavity #1 and cavity #2 [3].

Additional RF tests were carried out on both cavities after post-purification at 1200°C for 3 hrs with titanium and subsequent removal of 50 µm by BCP. Cavity #1 exhibited some field emission loading starting at $E_{acc} \geq 20$ MV/m, but reached a gradient of $E_{acc} \sim 30$ MV/m without quench. The Q degradation at higher fields is caused by a combination of "Q-drop" and field emission (Fig. 5).

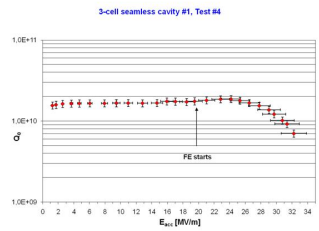


Figure 5: Last test result (test 4) at 2 K of cavity #1 after post purification at 1200°C for 3h. The total material removal is 270 µm.

The performance of cavity #2 before and after post-purification is shown in Fig.6. After post-purification a gradient of $E_{acc} \sim 32$ MV/m was measured, limited by the available rf power; no quench was detected.

The cavity #3 is presently equipped with beam pipes and will undergo the same treatment procedures as cavity #1 and #2.

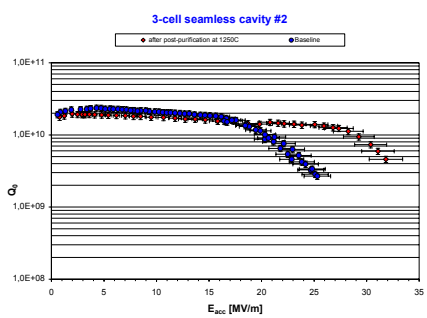


Figure 6: Last test result (test 7) at 2 K from cavity #2. The total material removal is 275 µm.

9-Cell Cavity

The 9-cell cavity reached a maximum gradient of $E_{acc} = 30.3$ MV/m, limited by the Q-drop after electropolishing [EP] (170 µm removed), ethanol rinsing, 800 °C heat treatment, EP (48µm) and HPR [3]. Individual cells have shown performance between 30 MV/m and 39 MV/m. After "in-situ" baking at 120 °C for 48 h. the Q-drop almost disappeared, but the accelerating gradient was not increased in contradiction to well known behaviour of baked EP cavities (Fig. 7). Even some field degradation was observed in pass band mode measurements. The E_{acc} of individual cells is now only between 29 and 30 MV/m. It is difficult to say whether this degradation is due to a non-understood phenomenon of hydroformed cavities or the baking itself was not sufficient.

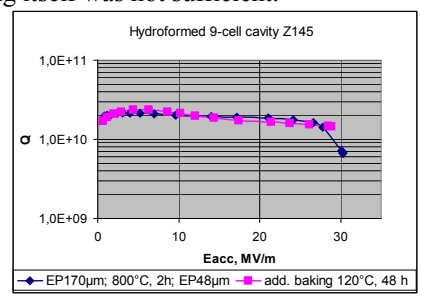


Figure 7: Performance of hydroformed 9-cell TESLA cavity.

SUMMARY AND OUTLOOK

The development of the hydroforming technique achieved the industrially applicable level; the developed procedures can be automatized for series fabrication. Several 3- cell units have been fabricated and successfully tested. Extension of the hydroforming procedure to 9-cell cavities from a sufficiently long piece of tubing seems possible without any particular problems. NbCu - cladding and cavity fabrication by using special Cu0.15%Zr copper alloy is proven.

Individual 3- cell units and 9-cell cavity completed from three cell units reached a respectable performance of ~ 30 MV/m. The 9-cell cavity is welded into the He vessel in order to be installed in one of next accelerating cryo modules at DESY.

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