

SEAMLESS/BONDED NIOBIUM CAVITIES*

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Abstract

Technological aspects and performance of seamless cavities produced by hydroforming are presented. Problems related to the fabrication of seamless cavities from bulk niobium are mainly solved thanks to the progress of the last years. The highest achieved accelerating gradients are comparable for both seamless and welded versions (ca. 40 MV/m.) Nevertheless further development of seamless cavities is desirable in order to avoid the careful preparation of parts for welding and get reliable statistic.

Fabrication of NbCu clad cavities from bimetallic tubes is an interesting option that gives new opportunity to the seamless technique. On the one hand it allows reducing the niobium costs contribution; on the other hand it increases the thermal stability of the cavity. The highest accelerating gradient achieved on seamless NbCu clad single cell cavities (ca. 40 MV/m.) is comparable to the one reached on bulk Nb cavities. Fabrication of multi cell NbCu cavities by hydroforming was recently proven.

1. INTRODUCTION

The traditional fabrication procedure of elliptical SRF cavities consists of deep drawing and electron beam welding (EB) of the half cells. This procedure is well established and has about 30 year of industrial fabrication experience. It is well known that RRR degradation in welding areas of conventional cavities can be critical for the performance [1]. In the last few years improvement of the material quality control, preparation for EB welding and the welding parameters allowed to reach accelerating gradients close to the theoretical limit by applying advanced cavity treatment techniques such as electropolishing (EP) [2].

Nevertheless a fabrication method which will avoid the welding is very complementary from two aspects. First the seamless cavity does not have the risk of equator weld contamination and therefore could improve the reliability towards achieving high gradients. It is to expect that the statistic in performance of seamless cavity for the series will be better. Second a lower cost of fabrication can be expected.

Especially interesting is the combination of the seamless technique with NbCu bonding, i.e. the fabrication of cavity from bimetallic bonded NbCu tube by seamless technique.

The advantages of this option can be easily pointed out.

- cost effective: allows saving a lot of Nb (ca. 4 mm cavity wall has only ca. 1 mm of Nb and 3 mm Cu). This can be essential for large projects like ILC
- the bonded Nb layer has still microstructure and properties of bulk Nb (the competing sputtered niobium layers does not have such advantages)

- the well developed treatment of the bulk Nb such as buffered chemical polishing (BCP), EP, annealing at 800°C, bake out at 150°C, high pressure water rinsing (HPR), high power processing (HPP) can be applied (excluding only post purification at 1400°C).

- high thermal conductivity of Cu improves thermal stabilization

- stiffening against Lorentz - force detuning and microphonics can be easily done by increasing the thickness of the Cu layer.

The development of the seamless technique mostly for the TESLA shape cavity was pursued in the last years at INFN by V. Palmieri (spinning) [3,4] and at DESY (hydroforming) [5]. Fabrication of a seamless cavity of the TESLA shape, with a ratio of equator diameter to iris diameter of about three, is a challenging task and several years of development were necessary to build the multicell cavities. The spinning fabrication technique and performance of the spun cavities is described in details in ref. [3]. A 9-cell cavity was produced. A new spinning machine was introduced recently [4].

This paper presents the current status of the hydroforming development and contains the fabrication technique, first RF test results, remaining problems and perspectives.

2. FABRICATION TECHNIQUE

For hydroforming one starts with a tube of a diameter intermediate between iris and equator. The forming procedure consists of two stages: reduction of the tube diameter in the iris area and expansion of the tube in the equator area.

Two aspects should be taken into consideration for the choice of the initial tube diameter. On one hand the work hardening at the equator should be moderate. Therefore a larger initial tube diameter is preferred, easing the second stage of hydroforming. On the other hand enlargement of the tube diameter will increase the roughness at the iris area after diameter reduction. Comparison of the hardness distribution HV10 with the inside surface roughness of the hydroformed cavities gives a hint for the choice of the tube diameter for hydroforming. Experience shows that a tube diameter between 130 and 150 mm is close to optimum. The single cell and multicell seamless cavities have been successfully fabricated starting both from ID=130 mm and ID=150 mm.

The arithmetic mean roughness, Ra, inside the cavity is normally several μm larger compared to that of deep drawn cells. In many cases the surface roughness was reduced to acceptable values after standard BCP or EP treatment. Generally the combination of hydroforming with successive centrifugal barrel polishing (CBP) before EP or BCP would be complimentary. CBP reduces the surface roughness and is a good pretreatment for EP. It is well known that the EP is more successful when starting from a smoother surface. CBP is more cost effective and

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environmentally friendlier than EP or BCP. If CBP as pretreatment is applied, thinner Nb layer can be removed by EP or BCP (ca. 50 μ m instead of 150-200 μ m). CBP was successfully applied by KEK as cavity pretreatment procedure [6]. The new machine for 1-3 cell cavities with improved technological process was developed at DESY [7].

The development of the tube diameter reduction at the iris area (necking) demanded even more efforts than its expansion (hydroforming itself). Several necking methods (hydraulic necking, electromagnetic strike necking, round knead, spinning) were tested before the current necking procedure was established. The best necking results were achieved by using a specially profiled ring moving in radial and axial directions. A tube necking device for experiments on a laboratory level based on this principle was developed and constructed at DESY (figure 1)

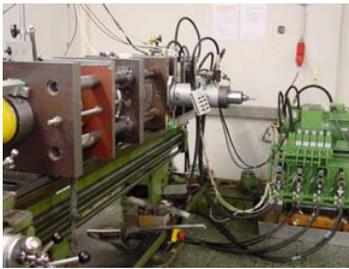


Figure 1: The tube necking machine.

The device is built for necking of Nb and NbCu tubes and is foreseen for single cell, double cell or three cell cavities. The machine consists of several transversally oriented plates. Four hydraulic cylinders are fixed on the plates. All cylinders are equipped with position and pressure sensors. The computer control of the device allows reproducibility of the necking parameters. The first experiences have shown a good operation of the machine. The necking of the NbCu and bulk niobium tubes at the end as well as at the tube (iris) of the tube can be routinely done.

During hydraulic expansion of the equator area an internal pressure is applied to the tube and simultaneously an axial displacement, forming the tube into an external mold. The hydraulic expansion relies on the use of the correct relationship between applied internal pressure and axial displacement, assuming that the plastic limit of the material is not exceeded.

The hydraulic two-dimensional bulging of a disk into the spherical form is very helpful[8], especially because it gives the opportunity to check the anisotropy of plastic properties. However, taking into account that during hydroforming the main elongation occurs in the circumferential direction, a conventional tensile test on samples following this orientation can be sufficient.

A numerical simulation of the hydraulic expansion of the tube is very useful. At the beginning of the seamless development, a lot of simulations were done with the finite element code ANSYS, assuming the elasto-plastic behavior in accordance with stress-strain curve and isotropic hardening rules[5]. The calculations were carried out on the

basis of the experimentally determined strain-stress characteristic of tubes to be hydroformed and resulted in the relation between the applied internal pressure as a function of the axial displacement and radial growth (path of the expansion) for the hydroforming process. The FEM simulation gives the starting point for the hydroforming parameters, which can be additionally tuned on the base of hydroforming tests, from comparison between the theoretical and experimental growth of the tube diameter.

A special machine for hydroforming experiments on a laboratory level was designed and built[5]. It has a water hydraulic system to apply the internal pressure in the tube and an oil hydraulic system for the cylinder movements. The computer control system for the hydroforming was developed to allow a stepwise as well as a continuous hydraulic expansion.

Picture of the hydroforming machine can be seen in figure 2.



Figure 2: The hydroforming machine.

Two additional aspects contributed to success in the hydraulic forming of the Nb cavities. The first one was the application of periodic stress fluctuation (pulse regime). Previous tensile tests have shown that elongation before necking can be increased almost by 30% applying a pulse regime, in comparison with a monotonic increase of stress.

The second one was the use of the correct strain rate for niobium during the hydraulic expansion. The experiments have shown that the deformation procedure should be rather slow. By keeping the strain rate below 10⁻³ s⁻¹, a 10% higher strain before necking can be obtained.

3. SEAMLESS TUBES FOR HYDROFORMING

Seamless Nb or NbCu tubes suitable for hydroforming are not available on the market and a special development is necessary. Required elongation at break greater than 30%, small and uniform grains in the final shape are challenging.

Development of seamless Nb tubes for hydroforming was done and is being continued in collaboration with scientific institutes and industrial companies. Several fabrication methods (spinning, back extrusion, forward extrusion, flow forming and deep drawing) were analyzed.

The experiences have shown that properties of tubes back extruded from the ingot pills are not adequate for hydroforming of bulk Nb cavities. Areas with rather big grains (500-1000 μ m) dramatically reduce the elongation before necking and yield a rough inside surface after

hydroforming. It seems that the amount of deformation is not sufficient to reduce the few cm-size grains of the ingot to small and uniform grains of ca. 50 μ m size in the final tube as required for hydroforming.

Much better results can be achieved starting from the ca. 10 mm thick sheet having already rather small and uniform grain structure. The tubes can be produced by deep drawing or spinning and show much higher strain before onset of necking. Combination of spinning or deep drawing with flow forming allows improving the surface and significantly reducing the wall thickness variations. Shiny surfaces and small wall thickness variations (less than ± 0.1 mm) can be achieved.

Fabrication of seamless NbCu clad tubes is a subject of special efforts. Requirements to mechanical properties of bulk Nb tubes are not so challenging in this case because the plastic properties of Cu plays a dominant role during hydroforming of such bimetallic tube. Back extruded seamless Nb tubes can be tolerated from a mechanical properties point of view. The main question is how to make the cladding of Nb with Cu without reduction of the Nb purity and cladding quality.

Different cladding procedures were checked. First of all the explosive bonding was applied. The bonding takes place by an explosively driven, high-velocity angular impact of two metal surfaces at very high speeds creating huge contact pressure.

The tubes have been produced in two steps:

- Explosive bonding of back extruded seamless Nb tube (ca 4 mm wall thickness) with oxygen free Cu tube (wall thickness ca.12 mm).
- Flow forming into NbCu tube of 4 mm wall thickness (ca. 1mm Nb, 3 mm Cu)

Another cladding way of bimetallic NbCu tubes was developed at KEK together with the industry (hot bonding) [9] and at DESY together with Fa. NuTech. The main idea is to protect the Nb from contamination at high temperatures by a Cu shield; the vacuum of $10^{-5} - 10^{-6}$ mbar is created between Nb and Cu layers and is air tight welded (canning). It can be three concentric tubes Cu/Nb/Cu or three plates Cu/Nb/Cu. After that, a tube with smaller wall thickness can be produced from such "sandwich" using hot rolling or hot excursion procedures providing at the same time the cladding. Combination with standard procedures like spinning or flow forming allows getting the required tolerances in the wall thickness.

Excellent results in the cavity performance were reached for both kinds of tubes: explosively bonded and hot bonded. We do not have enough statistics for comparison of explosive bonding with hot bonding. It seems that the quality of hot bonding is more reliable; better statistic in the cavity performance should be expected.

Softening by annealing deserves special attention for NbCu clad option. Because of the large difference in recrystallization temperature, it is not possible to reach during appropriate annealing, an optimum for the hydroforming plastic properties in both materials. For example, Cu can be fully recrystallized by annealing at 560 $^{\circ}$ C for 2 hours with the grain size about 30 μ m and acceptable for hydroforming elongation before rupture

(about 35-40%). Niobium has after such annealing a deformed structure without pronounced grains. The recrystallization temperature of Nb is rather high (ca. 800 $^{\circ}$ C), and annealing of NbCu bimetallic composition at this temperature will lead to significant 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. Nevertheless, undesired effects cannot be completely avoided. The tendency of cracks forming at iris area during necking is especially dangerous.

The situation can be improved by 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. It seems that the alloy Cu0.15%Zr available on the market could be 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 Nb recrystallization.

Unfortunately the alloying of Cu will increase the number of scattering centers for electrons and reduce the thermal conductivity. However, experiments have shown that the thermal conductivity of Cu0.15%Zr remains high enough ca. 150 W/m K at 4.2 K (comparable with that of high purity Nb [1]). In addition the thermal conductivity can be increased by special heat treatment. The Nb Cu0.15%Zr clad tube has been produced and is ready for hydroforming.

4. BULK NB CAVITIES

Several single cell cavities have been manufactured so far, without intermediate annealing from spun or deep drawn tubes with ID 130 or 150 mm (one of them was fabricated at the company BUTTING with a similar technique).

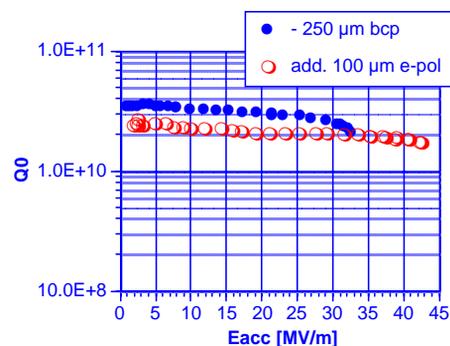


Figure 3: Q vs Eacc for cavity 1K2 after BCP and EP. (Nb100, post purified at 1400 $^{\circ}$ C).
 Filled circles – Jlab (P.Kneisel) [5]
 Open circles – KEK (K.Saito) [5]

It turned out that the forming is possible without intermediate constraint (mould of the intermediate shape between the tube and final cell). Nevertheless an

intermediate constraint is desirable in order to reach stable and reproducible cavity fabrication taking into account variation of plastic properties within the tube. Finally the cavities were calibrated by increasing the internal pressure up to 500bar after the hydroforming was completed.

One of the best results of hydroformed bulk Nb single cell cavities can be seen in figure 3 [5]. Cavity 1K2 demonstrates excellent performance. Accelerating field (E_{acc}) is ca. 43 MV/m with a high Q-value of $> 1.5 \times 10^{10}$. The accelerating field of the cavity 1BT1 reached about 39 MV/m without post purification annealing.

The development of hydroformed cavity fabrication has demonstrated that high performance levels in both Q - value and accelerating gradient can be achieved.

One of the important steps of the seamless development is to demonstrate that the technology allows fabricating not only single cell but also multi-cell cavities.

The main problem in the multi-cell fabrication was the reduction of the tube diameter in the iris area (necking). In the first stage the necking was done by spinning using an industrially available spinning machine and a 'teach and playback' procedure. For single cell cavity this procedure works. Necking of the multi-cells was less successful. For the long tube it was difficult to achieve the uniform wall thickness at the necking area. The irregularity in the wall thickness on iris area up to 1-2 mm even caused a hole during material removing by EP or centrifugal barrel polishing in some multi cell cavities. Therefore we had to develop a special necking procedure and constructed a special necking device described in sec. 2. The wall thickness variation reachable with this device does not exceed 0.2 mm.

Expansion of the necked tubes caused less problems. Several double and three cell bulk Nb cavities of the TESLA shape were successfully hydroformed at DESY. The expansion at the equator area can be done in two different ways: all cells simultaneously (see ref. [5]) or successively one cell after the other. Both options were realized for three cells. The second option is probably more realistic for hydroforming of a nine cell cavity from one piece. It allows making such fabrication more reliable even if some variation of tube mechanical properties will take place.

5. NBCU CLAD CAVITIES

Few single cell NbCu clad cavities were fabricated. Both the necking and the expansion were done at DESY without intermediate constraint. The calibration at 500 bar was done afterwards. Some of the cavities were additionally annealed at 560°C for 2 hrs before calibration in order to make them softer.

The endtubes with the flanges were connected with the Nb layer of the cavity by EB welding. The welding of 0.7-1 mm thick Nb layer of the cavity with the 2 mm thick wall of Nb of the end tube in principle does not cause any problem and provide sufficient stiffness for the single cell cavity. The Cu should be very carefully removed from the cylindrical part of the cavity before welding otherwise a leak tight welding is not guaranteed. The stiffness of the connection can be

additionally increased by using Cold Gas Dynamic Spray System developed at University of the Federal Armed Forces in Hamburg (H. Kreye). The small purity degradation of Nb during spraying (from RRR=300 to RRR=250), the microstructure and properties of sprayed Cu layer being close to bulk Cu (porosity ca. 1%, small oxidation, electr. conduct. ca.80% of bulk Cu), make this technique very attractive for applying to NbCu cavities.

The hydroforming technique allows also to fabricate multicell cavities from Nb/Cu clad tubes. Several double-cell cavities were produced recently at DESY from sandwiched Cu/Nb/Cu tubes delivered from KEK. Rather small frequency deviation from cell to cell (within 1 MHz) was achieved.



Figure 4: Double cell NbCu clad cavities recently produced at DESY from KEK tubes (no cracks on the inside surface).

Some NbCu clad cavities were already prepared and RF tested at 2K.

An excellent result was achieved at Jefferson Lab with cavity 1NC2 from explosively bonded tube even without electropolishing (figure 5). At the achieved accelerating gradient, $E_{acc} = 40$ MV/m, the Q value is ca. 10^{10} [5]

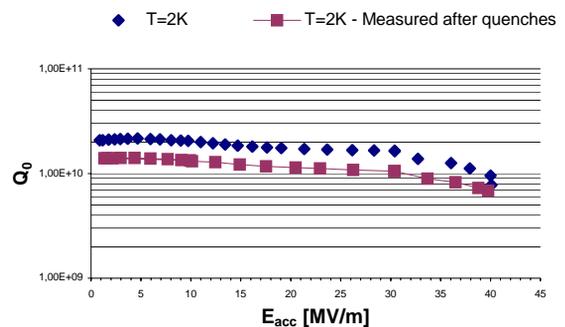


Figure 5: The best result achieved in a single-cell NbCu clad cavity produced at DESY from explosively bonded tube. Preparation and RF tests done at Jeff. Lab: 180 μ m BCP, annealing at 800°C, baking at 140°C for 30 hours, HPR. (P. Kneisel) [5].

One of the NbCu cavities (NSC-3) produced at DESY from sandwiched hot roll bonded tube (Nippon Steel Co.) was prepared and RF tested at KEK (figure 6). Excellent result of

ca. 39MV/m shows that very good cavities can be fabricated not only from explosively bonded but also from hot roll bonded tubes.

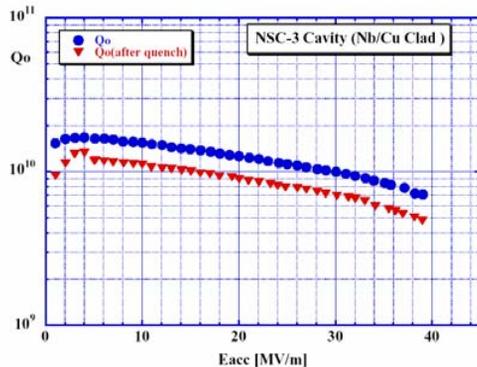


Figure 6: Q(Eacc) curve of the NSC-3 cavity: Barrel polishing, CP(10 μ m), Annealing 750°C x 3h, EP(70 μ m) (K.Saito) [9].

Unfortunately one peculiarity of bimetallic NbCu cavities behaviour remains open, namely Q degradation during fast cool down, RF processing or quench (trapping of magnetic flux caused by thermo - coupling effect). The phenomenon is not completely understood. Similar effect was observed on Nb₃Sn cavities and in sputtered NbCu cavities. The Q degradation is relatively moderate (less than one order of magnitude in fig. 5 and fig. 6) especially for rather thick Nb layers of ca. 1 mm thickness. The degradation can be cured by warm up above T_c and slow cool down. It seems that annealing and hot bonding should contribute to the reduction of the thermal coupling effect due to diffusion.

6. CONCLUSIONS

Several single-cell and multi-cell bulk Nb and NbCu clad cavities have been fabricated at DESY by hydroforming.

The technique developed so far allows the production of multi-cell cavities. A good reproducibility of the cavity shape can be easily achieved. The main task left in the fabrication technique is its industrialization.

It is shown that very good RF performance can be achieved with hydroformed seamless cavities. The measured accelerating field of ca. 43 MV/m in cavity 1K2 is one of the highest ever achieved in a single-cell cavity. The aim of the development is the fabrication of a 9-cell cavity of the TESLA shape. The DESY hydroforming machine is a laboratory equipment built to check the perspectives of hydroforming for cavity applications. The size of this machine is not sufficient to hydroform a nine cell cavity from whole tube. We proposed to fabricate a 9-cell cavity assembled from 3 pieces of three cells. Extension of the hydroforming procedure to the 9-cell fabrication from one piece does not have any particular problems; especially because it was proven that the hydroforming can be done cell by cell. We still don't have enough experience in the fabrication of seamless Nb tube of the length about 1.8 m required for hydroforming of the 9 cell cavity from whole piece.

The fabrication of seamless bimetallic NbCu cavities deserves special attention. The combination of

hydroforming with tube cladding is a very promising technology. It reduces significantly the cavity material costs. A rough estimate shows that the NbCu clad cavities of TESLA shape will be 30% cheaper than standard bulk Nb cavities, assuming equal cost of the end groups. The RF performance of the best hydroformed NbCu clad cavities is comparable to the best bulk niobium cavities. Degradation of the quality factor Q₀ due to thermocurrents is an open issue and needs further investigation.

7. ACKNOWLEDGMENTS

The development continues in tight collaboration with KEK, JLab, INR and INFN. A significant contribution to the success of hydroforming development was done by P. Kneisel and K. Saito due to state of the art preparation and RF tests of the hydroformed cavities. I would like to express gratitude to my colleagues at DESY who worked with me in the last years and significantly contributed to the development of hydroforming technology, especially to I. Jelezov, X. Singer and G. Weichert.

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