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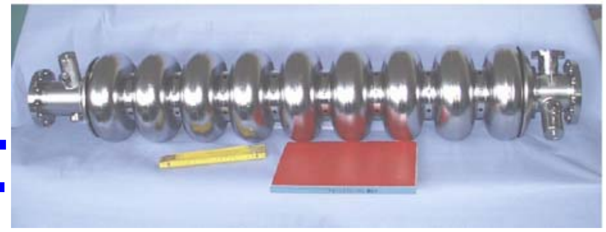

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**Fabrication of hydroformed 9-cell cavities**

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DESY

## Abstract

The technological aspects of seamless cavity production by hydroforming are presented. The problems related to the fabrication of seamless cavities from bulk niobium are mainly solved. Two cell-, three cell- and a 9 - cell TESLA shape niobium cavities are produced.

Fabrication of NbCu clad cavities from bimetallic tubes is an interesting alternative option. On the one hand it allows a reduction of the niobium costs; on the other hand it increases the thermal stability of the cavity. The fabrication of NbCu cavities clad by special copper and fabrication of multi cell NbCu cavities by hydroforming is demonstrated.

**Acknowledgements**

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# I. 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 the welding areas of conventional cavities can be critical for the performance. In the last few years improvements 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).

Nevertheless a fabrication method which will avoid the welding is very welcome from two reasons. Firstly the seamless cavity does not have the risk of equator weld contamination and therefore could improve the reliability for reaching high gradients. It is expected that the performance statistics of in series produced seamless cavities will be better. Secondly a lower cost of fabrication can be expected, especially for large series.

An additional advantage 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 effectiveness: 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 the microstructure and properties of bulk Nb (the competing sputtered niobium layers do not have these 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 the thermal stabilization;
- stiffening against Lorentz - force detuning and microphonics can be easily done by increasing the thickness of the Cu layer.

The hydroforming technique (Innenhochdruckumformen) was worldwide developed in the passed 40 years [1]. It is an established procedure now with serial application mostly for fabrication of light parts in the automobile industry. Nevertheless 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 have been necessary to build multi-cell cavities.

This report presents the current status of the hydroforming development and contains the fabrication technique, tube fabrication, some fabrication examples, remaining problems and perspectives.

# II. HYDROFORMING OF BULK NIOBIUM CAVITIES

## II. 1 SEAMLESS BULK NIOBIUM TUBES FOR HYDROFORMING

Seamless Nb or NbCu tubes suitable for hydroforming are not available on the market and a special development is necessary. Standard small and uniform grain Nb material has not the required elongation of greater than 30%. Several fabrication methods [2] (spinning, back extrusion, forward extrusion, flow forming and deep drawing) were analyzed.

The experience has 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 µm) 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 µm size in the final tube as required by hydroforming [3].

Much better results can be obtained starting from the thick sheet with the grain size of ca. 100 µm. The tubes can be produced by deep drawing or spinning and show much higher strain before onset of necking. Combination of spinning (Fig. 1a, b) or deep drawing with flow forming (Fig. 2a, b) allows to improve the surface and to significantly reduce the wall thickness variations. Shiny surfaces and small wall thickness variations can be achieved.

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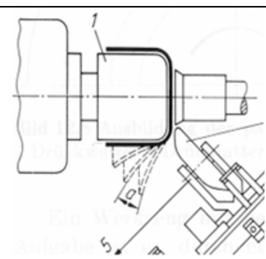
|  |  |
| Fig. 1a: Principle of spinning [2] | Fig. 1b:Spun tubes |

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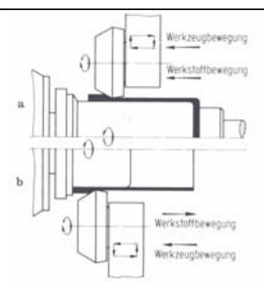
|  |  |
| Fig. 2a: Principle of flow forming [2] | Fig. 2b: Flow formed tubes |

The main principles for the production of seamless Nb tubes for hydroforming are developed in cooperation with industry. The seamless tubes built starting from the 10 mm thick sheet have already a rather small and uniform grain structure (grain size of ca. 100 µm) and the required mechanical properties (Fig. 3,4). Tubes are produced by combination of spinning and flow forming (Fig. 1b, 2b). The combination of spinning with flow forming allows to improve the surface and to significantly reduce the wall thickness variations. Flow forming was done in forward direction. This method allows producing a tube with a wall thickness tolerance of +/- 0.15 mm sufficient for subsequent hydroforming [4].

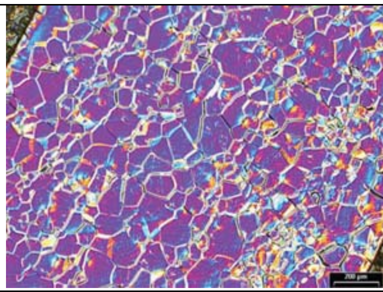


Fig. 3: Microstructure of Nb tubes produced by combination of spinning and flow forming

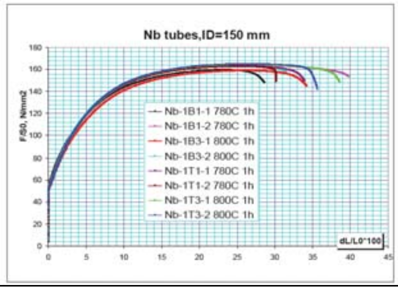



Fig. 4: Stress-strain curves of Nb tubes produced by combination of spinning and flow forming. Tensile tests done in circumferential direction.

## II.2 NECKING PROCEDURE

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

Two facts should be taken into account for the choice of the initial tube diameter. On the 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 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 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 obtained by using a specially profiled ring moving in radial and axial directions. The radius of the ring profile touching the tube is roughly the same as the outside radius of the cavity iris. Plates with holes and ball bearings prevent the tube from bending (Fig. 5a, 5b), but at the same time do not disturb the tube rotating. Combination of radial and axial movement allows to ensure circumferentially a uniform wall thickness at the iris area without remarkable reduction of the wall thickness.

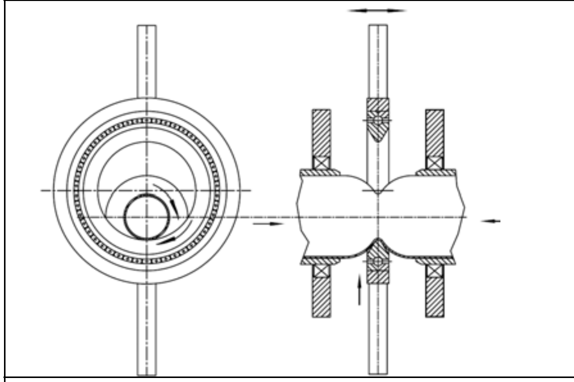


Fig. 5a: Principle of the reduction at the iris

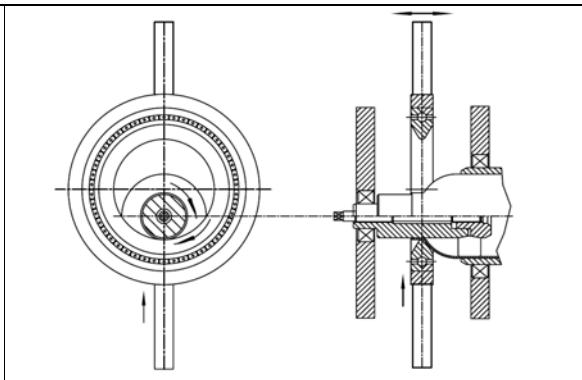


Fig. 5b: Principle of the reduction at the tube end

Principles of the reduction at the iris and tube end are shown in the figures 5a, 5b and 6a, 6b.

The axial movement occurs continuously from position one to position two; from position two to position three etc. following the declined trajectory. At the same time the tube is compressed axially. The compression value depends on the contact angle between the necking ring and the tube. These developments are summarized in the patent [5].

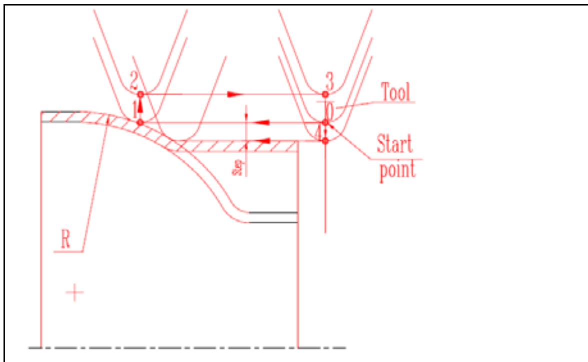



Fig. 6a: Principle of the end cell necking

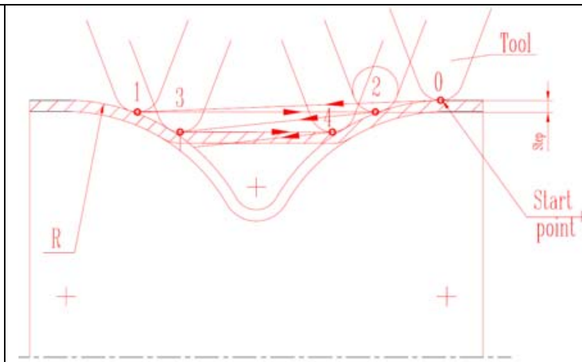



Fig. 6b: Necking between two cells (iris)

A tube necking device for experiments on a laboratory level based on this principle was developed and constructed (Figure 7).

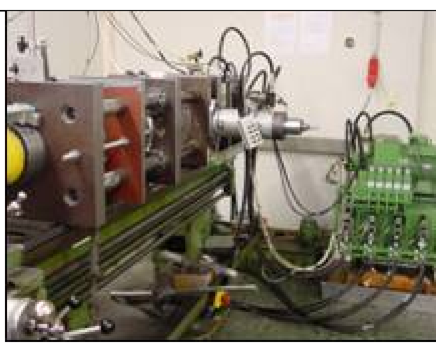


Figure 7: The tube necking machine

Fig. 8: Example of the Nb three cell unit after necking

The device is built for necking of Nb tubes with an inside diameter of 130 or 150 mm and is foreseen for single cell, double cell or three cell cavities of ILC like shape (TESLA, Low Loss LL, Re-entrant RE). The machine consists of several transversally oriented plates. Two plates do not disturb the tube rotating, but at the same time prevent the tube from bending. Two hydraulic cylinders provide the axial and radial movement of the profile ring. The cylinders are equipped with position and pressure sensors. The PC control of the device allows a reproducible repeat of the necking parameters. The experience has shown a good functioning of the machine. The necking of the bulk niobium tubes at the tube ends as well as at the tube middles (iris) can be routinely done.

Combination of radial and axial movement allows to reach the uniformity of circumferential wall thickness at the iris area without remarkable reduction of the wall thickness (not more that 20%). One example of the necked niobium tubes can be seen in Fig. 8

## II.3 HYDROFORMING PROCEDURE

During hydraulic expansion of the equator area an internal pressure is applied to the tube and simultaneously an axial displacement is needed to form the tube into an external mold. The challenge is to correlate both movements such that the Nb material does not fracture.

A special machine for hydroforming experiments on a laboratory level was designed and built previously [6]. 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. A picture of the hydroforming machine can be seen in Fig. 9.

Figure 9: The hydroforming machine

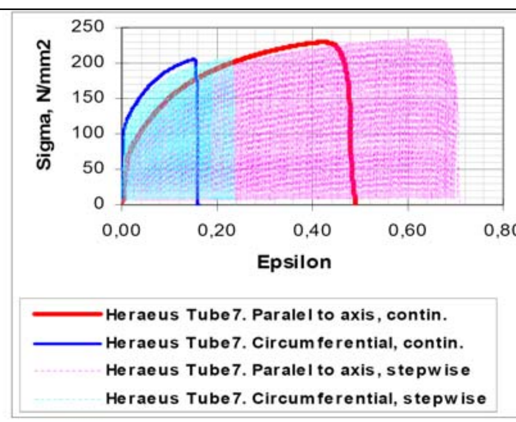



Fig. 10: Comparison of the tensile test result in continues and pulse regime

Two additional aspects contributed to the success in the hydraulic forming of the Nb cavities. The first one was the application of a periodic stress fluctuation (pulse regime). Previous tensile tests have shown that elongation before necking can be increased almost by 30% by applying a pulse regime, compared with a monotonic increase of stress (see Fig. 10).

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.

## II.4 NUMERICAL SIMULATION OF NECKING AND HYDROFORMING PROCESS

A numerical simulation of the hydraulic expansion of the tube is very useful. At the beginning of the seamless development, a lot of simulation was done with the finite element code ANSYS, assuming the elasto-plastic behavior in accordance with the stress-strain curve and isotropic hardening rules [7]. The calculations were carried out on the basis of the experimentally determined strain-stress characteristics 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.

The real geometry of the tubes after end reduction was taken into account. The stress distributions and wall thickness after the necking process is shown in the Fig. 11a, b. The comparison with experimental results was made for Cu tubes. For comparison the tube thicknesses were normalized to 4 mm.

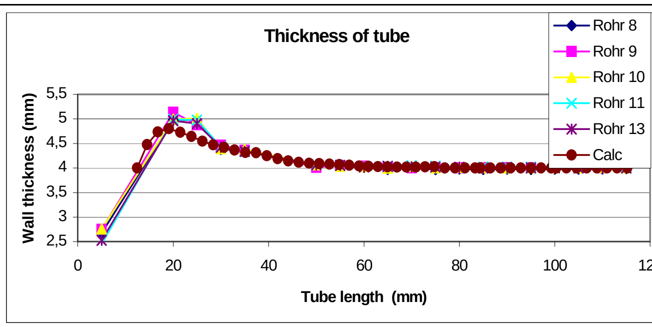



Fig. 11a: Comparison of simulated (calc) with experimental wall thicknesses (Rohr 8-11,13) after necking

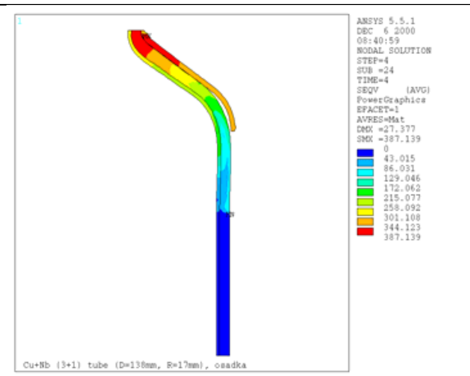



Fig.11b: Calculated stress distribution (in $N/mm^2$) after necking

The thickening of the tubes in the region between iris and equator agrees with dimension measurements of tubes with necked ends.

During the simulation of hydroforming process the tube form and stress distribution after necking was taken into account. The results are compared in Fig. 12. The prediction of experimental data is acceptable.

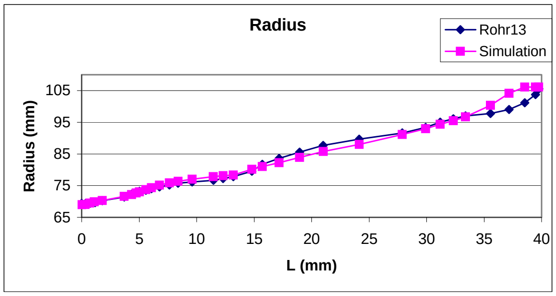



Fig. 12a: Simulation of radius growth during hydroforming in comparison with experiment (Rohr 13)

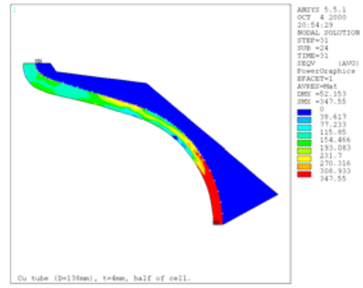


Fig. 12b: Calculated stress distribution (in $N/mm^2$) after hydroforming

## II.5 FABRICATION OF BULK NIOBIUM MULTI CELL CAVITIES

One of the main tasks was to demonstrate that the technology allows the fabrication of 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 a 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 in the iris area of up to 1-2 mm caused a hole during material removing by EP or centrifugal barrel polishing in some multi cell cavities. Therefore the development of a special necking procedure and the construction of a special necking device as described above was necessary.

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.

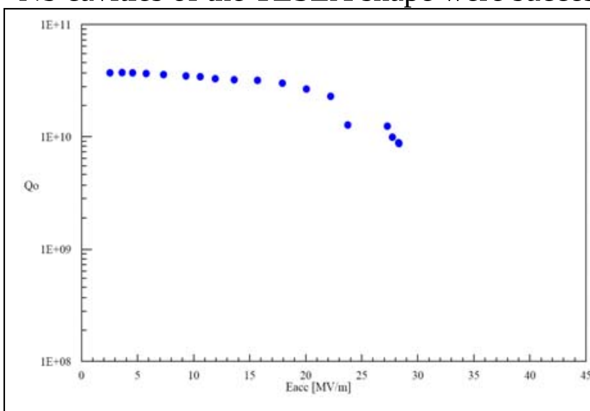



Fig. 13a: Q(Eacc) of hydroformed 2-cell bulk niobium cavity 2H3

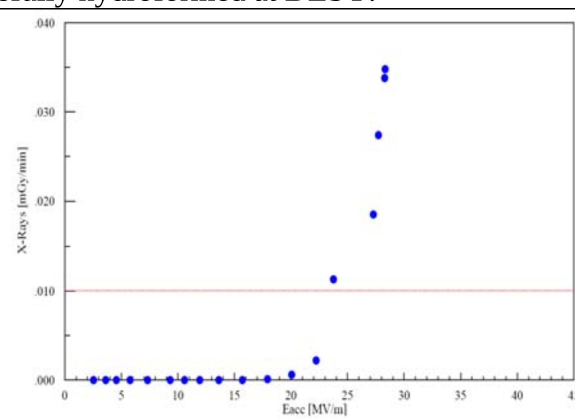



Fig. 13b: Field emission of hydroformed 2-cell bulk niobium cavity 2H3

It was proven that expansion at the equator area can be done in two different ways: all cells simultaneously or successively one cell after another. Both options were realized for three cells.

Unfortunately the preparation and RF tests of hydroformed cavities had no high priority in the DESY test program. Therefore only one multi-cell resonator was tested at DESY. The cavity reached almost 30 MV/m after removal of ca. 220 µm by electropolishing and annealing at 800°C for 2h. The performance was limited by strong field emission which started at 22 MV/m (Fig 13a, 13b). Two three cell cavities are at the preparation for RF tests at JLab at the moment.

A seamless 9 cell cavity of TESLA shape was fabricated on the basis of 3-cell units [8, 9, 10]. Three 3-cell units for the 9 cell cavity have been fabricated by hydroforming from seamless tubes of dimensions: ID 150mm, wall thickness 3 mm of bulk Nb. The hydroforming is done on the hydroforming machine in two stages with an intermediate constraint in order to achieve the correct shape, rather uniform wall thickness of the complete cavity and to suppress the instabilities in the tube expansion.

Completing of a first 1.3 GHz nine cell hydroformed resonator is underway at the company ZANON.

Completing included the following steps:

- Fabrication of the long and short end groups connected with three cell units
- Machining, preparation and welding of three units together to a 9 cell cavity (two iris welds done from outside);
- Machining, preparation and weld on the stiffening rings.

The completing is successfully done and the seamless resonator delivered to DESY can be seen in Fig. 14.

Prior to tuning the cavity was “softened” by a 800 °C annealing step after removal of 40 µm by BCP. A “traditional” surface treatment of electropolishing (170 µm), ethanol rinsing, 800 °C heat treatment, electropolishing (48 µm) and HPR at DESY preceded the cryogenic test.

The performance of the 9-cell cavity is shown in Fig. 15: the cavity reached a maximum gradient of Eacc = 30.3 MV/m, limited by the Q-drop without field emission and Q-disease. From mode measurements it was determined that individual cells had fields between 30 MV/m and 39 MV/m [10]. The cavity is foreseen for the assembly into the accelerating cryomodule, the He-vessel is welded onto the resonator.

Fig. 14: Hydroformed 9-cell TESLA cavity Z145

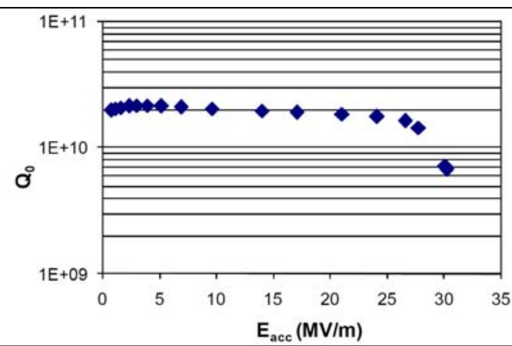



Fig. 15: Performance of 9-cell TESLA cavity Z145

## III NBCU CLAD CAVITIES

The fabrication of seamless bimetallic NbCu cavities deserves special attention. The combination of hydroforming with tube cladding is a promising technology. It reduces 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.

Two issues of NbCu clad cavities have been pursued in the frame of the CARE JRA1:- cladding by special copper and fabrication of multi - cell cavities.

### III.1 FABRICATION OF SEAMLESS NBCU CLAD TUBES

Fabrication of seamless NbCu clad tubes is a subject which also needs special efforts. The demands on the mechanical properties of bulk Nb tubes are not so challenging in this case because the plastic properties of Cu play a dominant role during hydroforming of such bimetallic tube. Back extruded seamless Nb tubes [5] can be tolerated from a mechanical properties point of view. The main question is how to make the cladding of Nb with Cu without reducing the Nb purity and cladding quality.

Different cladding procedures were checked earlier. First of all the explosive bonding was applied [11]. 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 [12] (hot bonding) and at DESY together with Fa. NuTech (Canada) [9]. The main idea is to protect the Nb from contamination at high temperatures by an additional Cu shield. The leak tight connection between the outer Cu shield and the inner NbCu pipe has to be welded under good vacuum conditions ($10^{-5}$ - $10^{-6}$ mbar). This procedure results in a concentric tube of Cu/Nb/Cu. After that a tube with smaller wall thickness can be produced from such a “sandwich” using hot rolling or hot extrusion procedures providing at the same time the cladding. A combination with standard procedures such as spinning or flow forming allows getting the required tolerances in the wall thickness. Accelerating gradients up to 40 MV/m were reached in several NbCu clad single cell cavities [13].

### III.2 CLADDING BY SPECIAL COPPER

Softening by annealing deserves special attention for the 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°C for 2 hours with the grain size about 30 µm. After this procedure Niobium has a deformed structure without pronounced grains. The recrystallization temperature of Nb is rather high (ca.

800°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 [14] 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 will reduce the thermal conductivity. However, experiments have shown that the thermal conductivity of Cu0.15%Zr remains high enough ca. 150 W/mK at 4.2 K (comparable with that of high purity Nb). In addition the thermal conductivity can be increased by special heat treatment. The Nb Cu0.15%Zr clad tube based on described upper principle has been produced at the company NuTech (Canada) and can be seen in Fig. 16.

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| Fig. 16: Bimetallic tube clad by niobium and Cu0.15%Zr alloy | Fig. 17: Single cell cavities produced from Nb Cu0.15%Zr tube | Fig. 18: Two cavities in preparation for tests |

Four single cell NbCu clad cavities were fabricated from bimetallic tube clad by niobium and Cu0.15%Zr alloy (Fig. 17). The calibration at 500 bars 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 end tubes 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 problems and provides 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.

At the moment two single cell NbCu clad cavities are within of the preparation for the RF test at JLab (Fig.18).

## III.3 FABRICATION OF MULTI-CELL NBCU CLAD CAVITIES

The hydroforming technique developed for fabrication of bulk niobium cavities allows also fabrication of multi-cell cavities from Nb/Cu clad tubes without any restrictions. Four double-cell cavities were produced from four sandwiched Cu/Nb/Cu tubes delivered from KEK (Fig. 19). The wall thickness distribution (see Fig. 20) did not meet the required tolerances of +/-0.15 mm. Nevertheless the hydroforming was curried out without any problems. A rather small frequency deviation from cell to cell (within of one MHz) was achieved, what indicates the high accuracy of the cell shapes.
At the moment two double cell NbCu clad cavities are ready for the RF test at KEK.

Fig. 19: Double cell NbCu clad cavities produced at DESY by hydroforming from KEK tubes

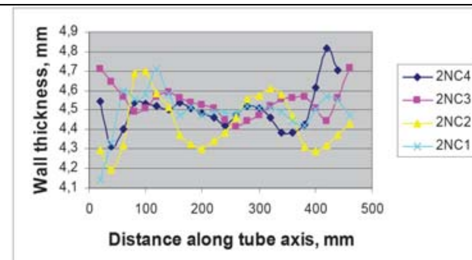


Fig. 20: Wall thickness distribution in the four Cu/Nb/Cu tubes delivered from KEK

## IV CONCLUSIONS AND OUTLOOK

The hydroforming technique was developed so far that allows fabrication of multi-cell cavities.

Problems related to the fabrication of seamless cavities from bulk niobium are mainly solved. Several two cell- and three cell- bulk niobium cavities are produced by hydroforming at DESY. A 9-cell cavity of TESLA shape has been completed from three sub-sections at the company ZANON. The cavity was EP treated and successfully RF-tested. This cavity will be completed with a LHe vessel and finally it will be installed in TTF. The main task left of the hydroforming fabrication technique is the transfer to industry.

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. Experiences 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 are missing at the moment.

The application of hydroforming a bimetal NbCu tube is a very promising technology that reduces the cavity material costs. Prototypes of single-cell and multi-cell NbCu clad cavities by hydroforming from bimetallic tubes have been built. No sever problems for extending this technique to 9-cell cavities are expected.

## V ACKNOWLEDGMENTS

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