HYDROFORMING OF SUPERCONDUCTING TESLA CAVITIES

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Abstract

Seamless fabrication of single-cell and multi-cell TESLA shape cavities by hydroforming has been developed at DESY. The forming takes place by expanding the seamless tube with internal water pressure while simultaneously swaging it axially. Tube radius and axial displacement are being computer controlled in accordance with results of FEM simulations and the experimentally obtained strain-stress curve of tube material. Several Nb single cell cavities have been produced. A first bulk Nb double cell cavity has been fabricated. The Nb seamless tubes have been produced by spinning and deep drawing.

Surface treatment such as buffered chemical polishing, (BCP), electropolishing (EP), high pressure ultra pure water rinsing (HPR), annealing at 800°C and baking at ca. 150°C have been applied. The best single cell bulk Nb cavity has reached an accelerating gradient of Eacc>42 MV/m after ca. 250µm BCP and 100µm EP.

Several bimetallic NbCu single cell cavities of TESLA shape have been fabricated. The seamless tubes have been produced by explosive bonding and subsequent flow forming. The thicknesses of Nb and Cu layers in the tube wall are about 1 mm and 3mm respectively.

The RF performance of NbCu clad cavities is similar to that of bulk Nb cavities. The highest accelerating gradient achieved was 40MV/m after ca.180µm BCP, annealing at 800°C and baking at 140°C for 30 hours. The degradation of the quality factor Qo after repeated quenching is moderate, after ca. 150 quenches it reaches the saturation point of Qo = $1{,}4\text{x}10^{10}$ at low field. This indicates that on the basis of RF performance and material costs the combination of hydroforming with tube cladding is a very promising option.

1 INTRODUCTION

The hydroforming of a seamless bulk niobium cavity of the TESLA shape, with a ratio of equator diameter to iris diameter about three, is a challenging task and requires special development. It is to be expected, that this technology will not only reduce the production costs, but also improve accelerating performance of the cavities.

One starts with 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 followed by expansion of the tube in the equator area.

For the choice of the initial tube diameter two aspects should be taken into consideration. On the one hand the work hardening at the equator should be moderate and during the expansion remain below the yield strength of the material. Therefore a larger initial tube diameter is preferred, easing the second stage of hydroforming. On the other hand enlargement of the tube diameter increases the roughness at the iris area. According to our experience a tube diameter between 130 and 150 mm is close to optimal. The seamless cavities have been successfully fabricated starting both from ID=130 mm and ID=150 mm. Comparison of the hardness distribution HV of the hydroformed single cell cavity (figure 1) with its inside surface roughness (figure 2) gives a hint for the choice of the tube diameter for hydroforming.

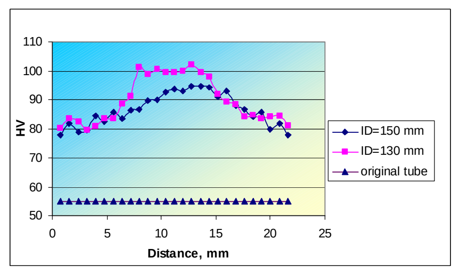

Figure 1: Hardness HV as a measure of the work hardening along the cavity contour - starting from the iris - compared to the HV of the original tube. Cavities are hydroformed from tubes of ID= 130 mm and ID=150 mm. Reduction of the tube diameter increases the work hardening at the equator area.

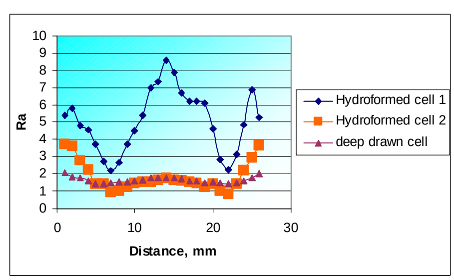

Figure 2: Arithmetic mean roughness Ra along the cavity surface inside of the hydroformed and deep drawn cavities. Enlargement of the tube diameter increases the surface roughness at the iris area.

The hydroforming experiment consists generally of three steps:-Determination of the strain-stress properties of the tube material, computer simulation of the forming and the hydroforming test itself.

The hydraulic two-dimensional bulging of the disk into the spherical form was applied to receive a strain-stress diagram [1]. The values of the stress σ and the strain ε can be found by measurement of the pressure p, radius of the curvature r and thickness t in the zenith of the sample during the deformation procedure.

The numerical simulation of the hydraulic expansion of the tube is done with the finite element code ANSYS. Nonlinear elasto-plastic behavior in accordance with stress-strain curve and isotropic hardening rules are taken into account [2]. 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 of applied internal pressure against axial displacement and radial growth (path of the expansion) for the hydroforming process.

During hydroforming experiments an internal pressure is applied to the tube and simultaneously an axial displacement, forming the tube into an external mold.

2 HYDROFORMING EXPERIMENTS

The experiments have been done by a machine for hydroforming built at INR institute [3] within the scope of the TESLA collaboration. At DESY it was provided with a water hydraulic system for the internal pressure in the tube and with a oil hydraulic system for the cylinder movements. The developed computer control system for the hydroforming allows the hydraulic expansion in stepwise as well as in continuous regime. The main criterion for the hydraulic expansion is the theoretically determined relation between internal pressure and axial displacement. Further correction of the expansion parameters can be done on the basis of comparison of the theoretical and experimental growth of the tube diameter.

The main part of the set up of the hydroforming machine can be seen in figure3. A periodic stress fluctuation (pulse regime) was applied. The previous tensile tests have shown, that elongation before necking can be almost 30% higher by application of a pulse method in comparison with monotonic increase of stress.

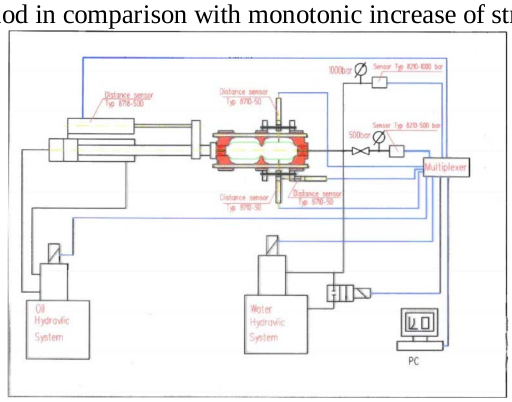

Figure 3: Set up of the hydroforming machine

In addition, the strain rate during the hydraulic expansion of Nb was taken into account. The experiments have shown, that the deformation procedure should be rather slow. By keeping the strain rate below $10^{-3}\,s^{-1}$ a 10% gain of strain before necking can be realized.

3 SINGLE CELL BULK NB CAVITIES

Several single cell cavities have been manufactured so far. Four single cell cavities were formed at DESY from 134x2mm mm thick spun RRR100 tubes without intermediate annealing and with an intermediate cylindrical constraint. Finally the cavities were calibrated in their hydroforming mold by increasing the internal pressure to 1000 bar after the hydroforming was complete. Subsequently, some of them were post purified at a temperature of 1400°C for 1 hour and 1350°C for 3 hours in the presence of Ti as a getter material; this process increased the RRR - value to RRR >300.

Three single cell cavities were made from a deep drawn RRR200 niobium tube of dimensions 156x3 mm without any intermediate constraints or annealing steps (one of them was fabricated at the company BUTTING with a similar technique). The post purification annealing was not applied in this case.

Some of the best results of hydroformed bulk Nb single cell cavities can be seen in figures 4 and 5.

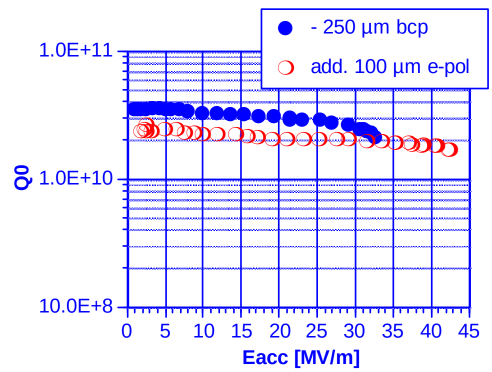

Figure 4: Q vs Eacc for cavity 1K2 after Buffered Chemical Polishing BCP and Electropolishing EP.

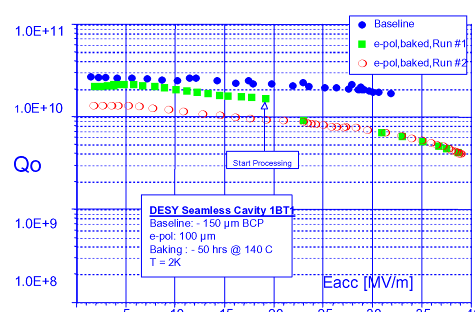

Figure 5: Q vs Eacc for cavity 1BT1 after BCP and EP.

Cavity 1K2 exhibited excellent performance after the removal of app. 250 µm of material from the surface; an accelerating gradient of Eacc = 33 MV/m was measured. At this point the cavity was baked at T ≈ 140°C "in-situ" for app. 24 hrs, a process, which had in previous investigations shown on several occasions an improvement in cavity performance. Here, the Q vs Eacc behavior did not change, however, as often observed [6], the BCS surface resistance improved by 50 %; a residual resistance as low as 3 nΩ was extrapolated from the temperature dependence of the surface resistance.

After this test series, cavity 1K2 was electropolished at KEK by 100 µm and returned to JLAB under vacuum. For the initial test after EP the cavity was only high pressure rinsed and showed field emission loading starting at Eacc ≥ 20 MV/m. In a subsequent surface preparation the cavity was thoroughly cleaned with a surfactant and ultrasound, and high pressure rinsed at 80 bar for 1 hour prior to standard assembly as mentioned above. After this treatment the accelerating gradient had improved to Eacc ~. 43 MV/m at a high Q-value of > 1.5 x 10^{10} as shown in fig. 4 . During the measurement the cavity showed a multipacting level at app. 25 MV/m, which could be passed rather quickly, but never disappeared completely : it sometimes showed up as a burst of x-rays during a decay- measurement, when its level was passed and also the decay time constant showed a "jump" as the stored energy from the cavity passed through that level. The measured accelerating field of Eacc ≈ 43 MV/m in cavity 1K2 is one of the highest ever achieved with a single cell cavity.

After ca. 150µm BCP and additionally 100µm Ep the electrical accelerating field of the cavity 1BT1 reached about 39 MV/m even without post purification annealing (figure5).

So the development of seamless cavity fabrication has demonstrated that high performance levels in both Q - value and accelerating gradient can be achieved with hydroformed seamless cavities.

4 MULTI CELL CAVITIES

The developed technology allows to fabricate not only single cell but also multi cell cavities.

Figure 6: Example of tube necking at the iris area

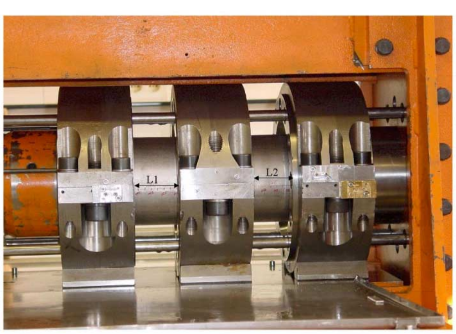

Figure 7: Hydroforming of double cell cavity in progress

The main problem in the multi cell fabrication was so far the reduction of the tube diameter in the iris area (necking). In a joint development program with industry this obstacle was overcome. The necking of Nb and NbCu-clad tubes of ID=130 mm and ID=150mm was developed as a 'teach and playback' procedure. Some necked tubes are shown in figure 6.

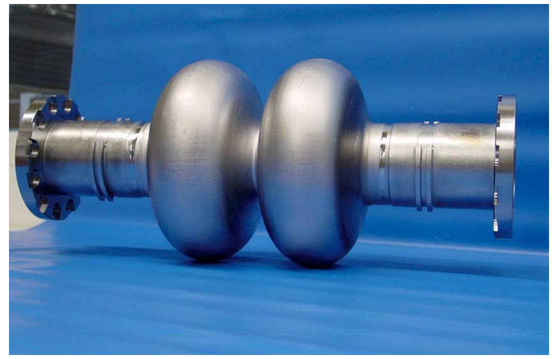

Figure 8: First Nb double cell cavity produced at DESY by hydroforming

Several two and three cell Cu cavities of the TESLA shape and first bulk Nb double cell cavity were recently successfully produced at DESY. Figure 7and 8 show the hydroforming in progress and the final shape of double cell Nb cavity, respectively.

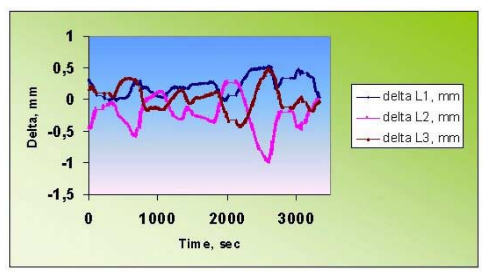

Figure 9: Variation of the value delta Δi=Li-L (i=1,2,3, L - the average value of Li) for Cu three cell cavity during of hydroforming process.

It is worthwhile to emphasize that in the multi cell case the cells have been hydroformed simultaneously. It is not evident that the hydroforming of each cell will be symmetrical during simultaneous forming of cells (the intern pressure is equal in all cells, but the axial force is applied at one end). A difference in the gaps between axially moving molds will appear as indication of asymmetrical hydroforming (L1≠L2≠ L3 for three cells forming for example, see figure 7 too) ANSYS simulation have shown that the gaps decrease in synchrony. The absolute value delta |Δi|=|Li-L | (i=1,2,3, L - the average value of Li) can not change dramatically. If Δi deviates from 0, a force acting to return the system to the balanced state appeared. This result is in a good agreement with the experiments. The variation of Δi versus hydroforming time can be seen in figure 9. Delta remains rather small and does not exceed a value of 0,5-1 mm.

The dimensional inspection of the Nb double cell has shown that during the hydroforming process the radius of the iris decreases by ca. 1 mm. The understanding of this phenomenon was the subject of ANSYS computer simulations and of a series of experiments on Cu-double cells. It turns out, that the iris reduction can be mostly avoided by sharply increasing the pressure at the initial stage of hydroforming. The increase of the internal pressure has an influence on the iris diameter only up to the stage where the iris area contacts the mold; after that further alteration of the iris is prevented.

The results of computer simulations for Nb can be seen in figure 10. The calculations were done for a tube with an internal diameter of 150 mm and wall thickness of 2,8 mm. The initial pressure vs-axial displacement employs minimal pressure acceptable for hydroforming. In other options the pressure was increased by a factor K between 1,75 and 2,5. Increasing of the pressure by a factor of two can reduce the effect of the iris reduction, but further increase of pressure has no big influence on it. The experiments are in good agreement with this conclusion. The possible iris reduction should be additionally taken into consideration at the stage of the tube necking.

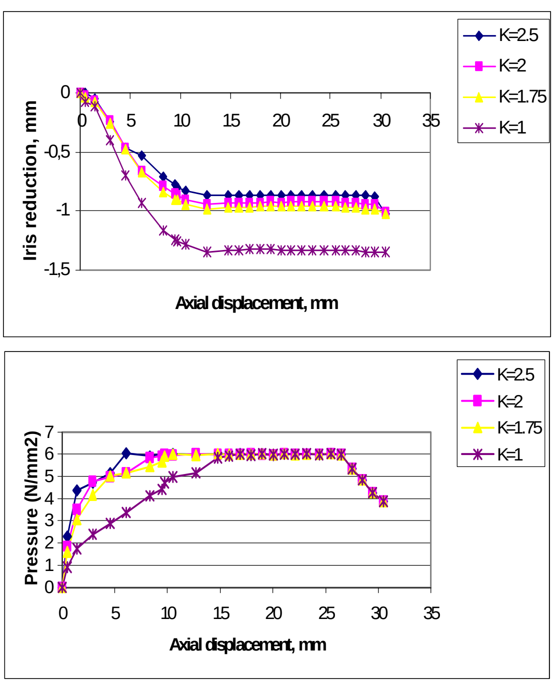

Figure 10: ANSYS simulations of the iris behavior dependence on the internal pressure. Sharp enlargement of internal pressure at the initial stage of hydroforming suppresses the reduction of the iris diameter.

5 NBCU CLAD CAVITIES

Fabrication of bimetallic Nb Cu cavities is an attractive option and a lot of efforts was exerted in this direction. On the one hand the material combination saves expensive niobium, on the other hand high thermal conductivity of copper can increase the thermal stability of the cavity against the quench. Especially the first aspect is important in the context of the TESLA project, which will need about 500 tons of high purity Nb. Cladding of 0,5-1-mm thick Nb layer with a 3-4 mm thick copper layer allows to retain almost all treatment procedures of bulk Nb as BCP, EP, Annealing at 800°C, Bake out at 150°C, HPR, HPP (excluding only post purification at 1400°C). The competing sputtering technique do not have such advantages. In addition the stiffening against Lorence Force Detuning can be easily done by increasing of the Cu layer thickness. On the other hand some open questions remains such as degradation of Qo after quench or fast cool down (frozen magnetic flux) or the role of thermal resistivity of NbCu interface in the cavity performance.

The combination of a tube based hydroforming technology with NbCu cladding may open new perspectives in cavity fabrication. Some first results of the hydroformed NbCu clad cavities are presented below.

Five single cell cavities 1NC1-1NC5 were fabricated. Both the necking and the expansion were done at DESY without of intermediate constraint. The calibration at 1000 bar was done supplementarily. Two of the cavities were additionally annealed at 560°C for 2 hrs. before calibration in order to make them softer.

Figure 11 shows the principle of the welding of 0,7-1 mm thick Nb layer of the cavity with the 2 mm thick wall of Nb of the cut - off tube. The Cu was turned away from the cylindrical part of the cavity before welding and the rests of Cu was etched away.

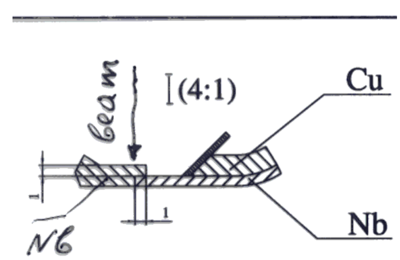

Figure 11: Principle of the welding of NbCu clad cavities

Some of the NbCu cavities can be seen in figure 12.

Figure 12: NbCu cavities 1NC1-1NC4 hydroformed from explosive bonded tubes of 4 mm wall thickness. Resonance frequency: 1NC1-1,3051GHz, 1NC2-1,3038GHz, 1NC3-1,3025GHz, 1NC4-1,3039GHz.

At the moment most of the hydroformed cavities are in preparation for the RF-tests (fitting of the cut off tubes and flanges, chemical polishing and electropolishing).

Some preliminary tests have been done at DESY and KEK. After some preparation steps an excellent result has been achieved at Jefferson Lab with cavity 1NC2 even without electropolishing (figure 13). At the achieved accelerating gradient, Eacc = 40MV/m, the Q value is ca. 10^{10}. A degradation of the quality factor Qo after quenches at ca. 40 MV/m was observed in the cavity 1NC2 , nevertheless Qo remains rather high.

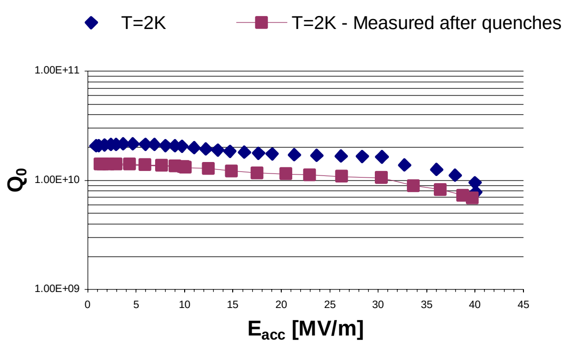

Figure 13: The best result achieved in single cell NbCu clad cavity. Preparation and RF tests done at Jeff. Lab: 180 μm BCP, annealing at 800°C, baking at 140°C for 30 hours, HPR.

6 SEAMLESS TUBES FOR HYDROFORMING

Development of the production of seamless Nb tubes for hydroforming was done and is being continued in collaboration with several companies. The tube production by spinning, back extrusion, flow forming and deep drawing were investigated. Uniform, small grain and homogeneous texture are required to provide high plastic deformation of the tube during hydroforming.

At first sight it seems that the fabrication by backward extrusion of the pill turned from the Nb ingot in combination with flow forming is favorable from the costs saving point of view. Despite all efforts and after two campaigns of tube fabrication we have to conclude that the properties of back extruded tubes are not adequate for hydroforming of bulk Nb cavities. Areas with rather big grains (500-1000 μm) dramatically reduce the elongation before necking and cause a rough inside surface after hydroforming. It is very difficult to reduce the few cm big grains of the ingot to small and uniform grain of ca. 50μm size required for hydroforming. The degree of deformation is not sufficient for getting an acceptable micro structure after annealing. Much better results can be achieved by starting from a thick sheet having already rather small and uniform grain structure. Such tubes can be produced by deep drawing or spinning. These tubes show much higher strain before onset of necking.

The combination of spinning or deep drawing with flow forming allows to improve the surface and significantly reduce the wall thickness variations. Flow forming over a cylindrical mandrel gained in the last years in importance. Machines with three work rollers employed for flow forming in either forward or reverse direction are available. This method allows to produce very precise tubes from spun, deep drawn, forged or sintered thick walled cylindrical parts. The ratio of the length to diameter can exceed 20, the ratio of diameter to wall thickness can exceed 500 for such tubes. The flow forming of high purity Nb- and NbCu-clad tubes was developed at a German company. After optimization of several parameters shiny surface and small wall thickness variations (less then +/-0,1 mm) have been achieved.

The experience with bulk Nb seamless tubes for hydroforming are summarized in table 1.

Table 1: Seamless bulk Nb tubes for hydroforming

Production procedure	Advantages	Disadvantages	Status of the hydroforming
Deep drawing	Weak anisotropy of mechanical properties	Relatively high wall thickness variation	Single cells 1BT1, 1K4, 1K7, double cell 2H1 produced
Spinning	Weak anisotropy of mechanical properties	Relatively high wall thickness variation	Single cell 1K2, 1K3, 1K5, 1K6 produced
Backward extrusion	Few production steps (ingot-pill-tube)	Big anisotropy of mechanical properties, areas with big grain. Reserve of plasticity is not sufficient	Single cell 1K1 produced. Hydroforming only in steel jacket possible

Table: 2 Seamless Nb/Cu bimetallic tubes for hydroforming

Production procedure	Advantages	Disadvantages	Status of the hydroforming
Explosive bonding + flow forming (Nb/Cu composite tube)	- Low wall thickness variation -rather high plasticity	Low recrystallization temperature of Cu.	Single cell 1NC1, 1NC2, 1NC3, 1NC4, 1NC5 produced
Co extrusion (Nb/Cu composite tube)	- High bonding quality	-Relative high wall thickness variation - protection of Nb from oxidation is necessary	Single cell 1NC6 produced

Back extruded and flow formed seamless Nb tubes can be tolerated from a mechanical properties point of view because the plastic properties of Cu plays a dominant role during hydroforming of such bimetallic tube.

Fabrication of seam less NbCu clad tubes was a subject of special efforts. The tubes have been produced in the following way.

1 Explosion bonding of seamless Nb tube of ID=130 mm and ca. 4 mm wall thickness (RRR=250) with oxygen free Cu tube of ID ca. 140 mm and wall thickness 12 mm.

2 Calibration of the bonded tube to diameter ID=130 +0,5/-0 mm

3 Flow forming into NbCu tube of 4 mm wall thickness (ca. 1mm Nb, 3 mm Cu)

4 BCP and heat treatment of tube at 560°C for 2 hrs. Nb was not totally recrystallized after annealing, but annealing at higher temperature was limited due to grain growth in Cu.

Another possible way for fabrication of bimetallic NbCu tubes is a joint extrusion of seamless Nb and Cu tubes (co extrusion). The examination of this option is going on at DESY now.

Table 2 summarized the current situation of the NbCu tubes evaluation.

Explosion bonding is an effective procedure for joining different metals. It uses a controlled detonation of ammonium nitrate and fuel oil. 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 intense pressure fuses the metals and turns a few atomic layers of each to plasma. The metal surfaces always contain some level of oxidation. The plasma spurts out ahead of the angled collision zone effectively cleaning the surface prior to bonding. The metallurgically pure surfaces are pressed into very close contact, allowing even valence electron sharing and an atomic level bonding. Bonds appear wavy because metals behave as viscous liquids under these conditions. Heating is highly localized and extremely short.

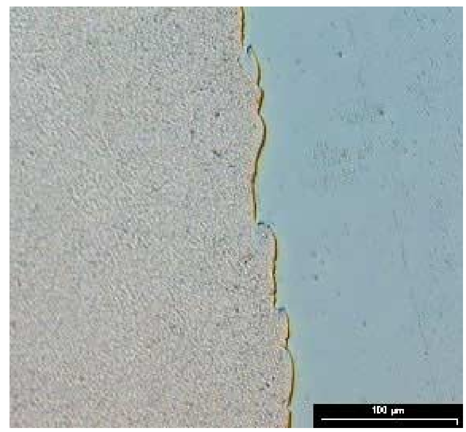

Figure 14: Microstructure of the interface between Cu (left) and Nb in NbCu explosion bonded tube.

Figure 15: Explosion bonded NbCu tube

Metals keep most of their original properties, even at the bond line [4]. Careful control of plasma flow and the resulting wave pattern at the bond line are the key to quality bonds. This is accomplished by optimization of detonation velocity explosive load and interface spacing.

An example of the wavy microstructure at the interface and of an explosion bonded tube is shown in figures 14 and 15, respectively.

7 CONCLUSIONS

Several bulk Nb and NbCu clad cavities have been fabricated at DESY by hydroforming. The technique is developed so far that it allows the production of multi cell cavities. A first Nb double cell cavity has been produced. A good reproducibility of the cavity shape can be easily reached. The arithmetic mean roughness Ra inside the cavity is a few µm larger compared to that of deep drawn cells, but this difference becomes negligible after standard BCP or EP treatment. The technology gives a real chance for the low cost mass production of the seamless cavities.

High RF performance was achieved with hydroformed seamless cavities. The measured accelerating field of ca. 43 MV/m in the cavity 1K2 is one of the highest ever achieved with a single cell cavity. The TESLA specification can be met and even significantly exceeded.

Special attention was devoted to fabrication of seamless bimetallic NbCu cavities. The combination of hydroforming with tube cladding is a very promising technology. It reduces significantly the material costs, which is of special importance for large projects like TESLA.

The RF performance of hydroformed NbCu clad cavities is comparable to the best bulk niobium cavities: with the cavity 1NC2 a gradient of Eacc = 40MV/m with a Q value of ~. 10^{10} was measured. A degradation of the quality factor Qo after quenches at ca. 40 MV/m was observed in the cavity 1NC2 , nevertheless Qo remains rather high.

8 ACKNOWLEDGMENTS

The authors wish to thank all our colleagues of the TESLA collaboration who supported the development of hydroforming technology at DESY. We are especially grateful to L. Lilje, A. Matheisen, D. Reschke, J. Wojtkiewicz for cavity preparation and treatment, and to G. Kreps for measurements of the resonant frequency.

9 REFERENCES

[1] K.Lange, Umformtechnik, Band 2: Massivumformung, Springer-Verlag 1990.

[2] I.Gonin, H.Kaiser, D.Proch, W.Singer, Finite Element Simulation of the TESLA-Cavity Hydroforming Process. Proc of the 7th Workshop on RF Superconductivity, October, 1995, Gif sur Yvette, France.

[3] H.Kaiser, D.Proch, W.Singer, S.Esin, L.Kravchuk, I.Jelezov, V.Samohvalov, A.Stepanov, Some Technological Methods for Superconducting Cavity Manufacturing. EPAC-96, Abstracts, P. 129.

[4] L. Kren, Big-bang bonding, Machine design, November 16, 2000, p. 67-69.