HYDROFORMING OF NBCU CLAD CAVITIES AT DESY

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Abstract

Several bimetallic NbCu single cell cavities of the TESLA shape have been fabricated at DESY. The cavities have been hydroformed by expansion of seamless tubes with internal water pressure while simultaneously swaging them axially. Tube radius and axial displacement are being computer controlled according to results of FEM simulations and experimentally obtained strain-stress curve of tube material. The tube ends were necked before hydroforming. The seamless tubes have been produced by explosion bonding and flow forming. The thickness of the Nb and Cu layers in the tube is about 1 mm and 3 mm, respectively.

Surface treatments such as buffered chemical polishing, (BCP), high pressure ultra pure water rinsing (HPR), annealing at 800°C and baking at ca. 150°C have been applied. The RF performance of NbCu clad cavities is similar to that of bulk Nb cavities. The highest accelerating gradient achieved was E_{acc} = 40MV/m with a Q_o-value of ~ 10^{10} after ca.180µm BCP, annealing at 800°C and baking at 140°C for 30 hours. The degradation of the quality factor Qo after "quenches" of the cavity is moderate; after ca. 150 quenches it reaches the saturation point of $Q_o = 1.4\ 10^{10}$ 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

Fabrication of bimetallic NbCu clad cavities is an attractive option and it was a subject of a lot of efforts [1]. On one hand the material combination allows to reduce the costs for the expensive Niobium, on the other hand the high thermal conductivity of Copper can increase the thermal stability of the cavity against the quench. The first aspect become especially important in context of TESLA project, that will demand about 500 tons of high purity Nb. Bonding of a 0,5-1-mm thick Nb layer with a 3-4 mm thick Copper layer allows to retain all treatment procedures of bulk Nb such as BCP, EP, annealing at at 800°C, bake out at 150°C, HPR, HPP (High Power Processing) except post purification at 1400°C. In addition increased stiffening against Lorentz Force detuning can be easily done by increasing the thickness of the layer. The sputtering technique has more limited advantages.

Unfortunately some peculiarities of bimetallic NbCu cavities behavior remain open. For example the degradation of Q_o after quench or fast cool down (frozen-in magnetic flux) or the role of thermal resistivity of the NbCu interface, and Kapitza resistance in the cavity performance is not completely understood up to now.

In case of NbCu clad cavities TESLA will need only one third of Nb (ca. 170 tons) and the material costs of each cavity can be reduced by factor of two.

The combination of hydroforming technology with NbCu cladding may open new perspectives in cavity business. Some first results of hydroforming of NbCu clad cavities at DESY are presented here.

2 FABRICATION AND RF BEHAVIOR OF NBCU CLAD CAVITIES

Six single cell cavities 1NC1-1NC6 have been fabricated. The hydroforming procedure is described in details in [2]. Both the necking and the expansion were done without intermediate constraint. The calibration at 1000 bar was done supplementary. Two of the cavities were additionally annealed at 560°C for 2 hrs. before calibration in order to make them softer.

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

Some of the NbCu cavities can be seen in figure 1. The cavities have been fitted with standard Nb end tubes and NbTi flanges. Figure 2 shows the principle of the welding of 0,7-1 mm thick Nb layer of the cavity with 2 mm thick wall of Nb cut off tube. The Cu was machined off from the cylindrical part of the cavity and the rests of Cu were carefully etched away before welding.

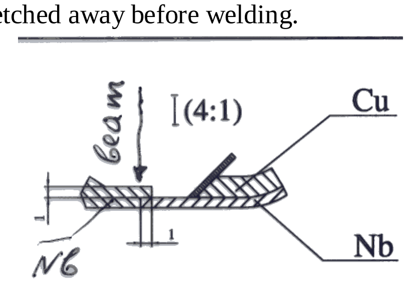

Figure 2: Principle of the welding of NbCu clad cavities

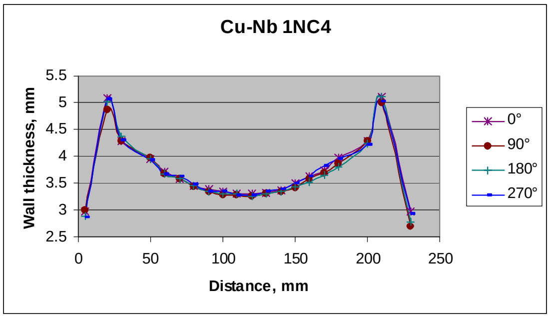

Figure 3: An example of wall thickness distribution in the NbCu clad cavity. The wall thickness is measured ultrasonically along the cavity axis in four lines, separated azimuthally by 90°.

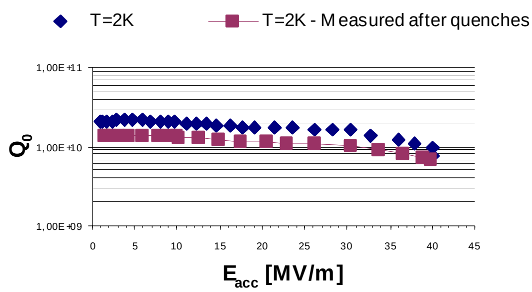

Figure 4: The best result achieved in single cell NbCu clad cavity. Preparation and HF tests done at Jeff. Lab: 180 µm BCP, annealing at 800°C, baking at 140°C for 30 hours, HPR.

The initial tube has the wall thickness of 4 mm and an inside diameter of 130 mm. The wall thickness distribution after hydroforming is represented in figure 3. The wall thickness reduction is maximal at the equator area where it reaches about 20%. It can be seen that the circumferential variation of the wall thickness is not high. The difference of the resonant frequency from cavity to cavity was less then 2,5 MHz, each cavity could be easily tuned to 1,3 GHz. The cavities shape is rather precise and the forming procedure can be repeated with a good reproducibility.

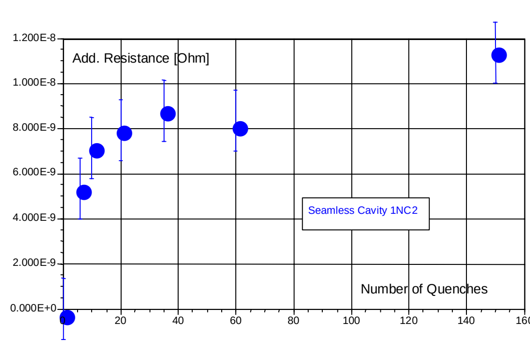

Figure 5: Additional surface resistance after quenches at ca. 40 MV/m.

At the moment most of the hydroformed cavities are being prepared for the RF-tests (fitting with cut off tubes and flanges, annealing, BCP and EP). Some preliminary tests have been done at DESY and KEK.

An excellent RF result was achieved at Jefferson Lab at the cavity 1NC2 even without EP treatment (figure 4). The accelerating gradient is 40 MV/m, the Q_o value is ca. 10^{10} . The degradation of the quality factor Q_o after quenches at 40 MV/m was observed, however, Q_o remains rather high. The additional resistance caused by frozen-in flux can be seen in figure 5.

3 NBCU CLAD SEAM LESS TUBES

Fabrication of seamless NbCu clad tubes is a subject of special efforts. The following way of tube production was the most successful:

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 of 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.

Explosion bonding is an effective method for joining of 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 speed 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.

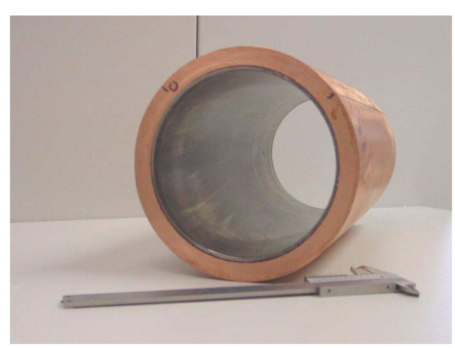

Figure 6: The NbCu explosion bonded tube

Heating is highly localized and of extremely short duration, so metals keep most of their original mechanical properties, even at the bond line [3]. 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.

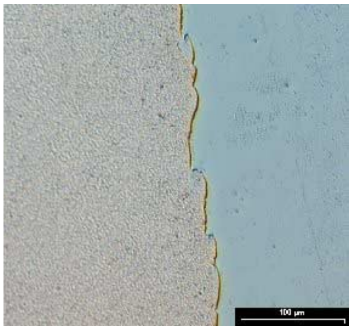

Figure 7: Microstructure of the interface between Cu (left) and Nb in NbCu explosion bonded tube.

The explosion bonding of the NbCu tubes for hydroforming was done by industry. A small non bonded area at the edge was detected only in one of the tubes by means of ultrasonic inspection. The example of an explosion bonded tube and wavy microstructure at the interface is shown in figure 6 and figure 7.

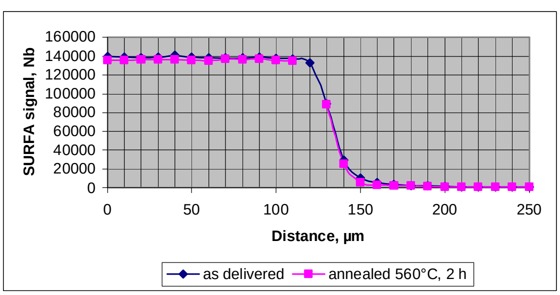

Figure 8: SYRFA line scan over the NbCu interface

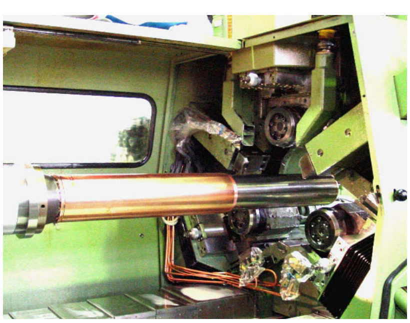

Figure 9: Flow forming of NbCu clad cavities

The profile of the interface between Cu and Nb after flow forming was explored by synchrotron radiation analysis. The distribution of the Nb signal over the Nb/Cu boundary can be seen in figure 8. The boundary area is not bigger than 20-30 µm and did not change after annealing.

Flow forming over a cylindrical mandrel was selected as the method to extrude the bi-metal tubes, since machines with three work rollers for flow forming in either forward or reverse direction are available. It allows to produce a very precise tubes from spun, deep drown, forged or sintered thick walled cylindrical part. The ratio of the length to diameter can exceed 20, the ratio of diameter to wall thickness can exceed 500 for such parts. One can imagine that the high local pressure created by rollers during flow forming can additionally improve the bonding quality.

The flow forming of NbCu-clad tubes was developed at a German company (Figure 9). After optimization of several parameters shiny Nb surface and small wall thickness variations (less then +/-0,1 mm) have been achieved.

Another possible way for fabrication of bimetallic NbCu tubes is a joint extrusion of seamless Nb and Cu tubes (co extrusion). This option is being explored at DESY now. A single cell cavity 1NC6 was recently produced from such type of tube at DESY.

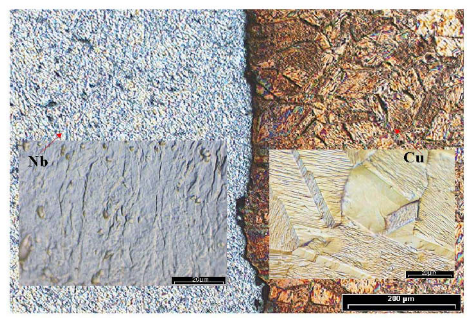

Figure 10: Microstructure of NbCu explosion bonded tube after annealing at 560°C for 2 h.

The softening annealing has a special meaning for hydroforming and deserves attention. Figure 10 shows that the Cu is fully recrystallized after annealing at 560°C for 2 hours, the grain size is about 30µm and is acceptable for the hydroforming, the elongation before rupture remains high (about 35-40%). In contrast to copper, niobium has after such annealing a deformed structure without pronounced grains. The recrystallization temperature of Nb is rather high (ca. 800°C), 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. It is following the Cu during forming because of the tight bonding. Nevertheless, unwanted effects cannot be completely avoided. For example, several cracks appeared in Nb during necking at iris area and damages one of the single cell cavities produced at DESY.

The situation can be improved by suitable alloying of the Cu. It is well known that small additions of some metals (Zr, Hf, Ti, Cr, Mg, Sn, Mn, Al) increase the recrystallization temperature of Cu. Two alloys for possible replacement of pure Cu have been checked. The results of tensile tests can be seen in figure 11. It seems that the alloy Cu0,15%Zr is not a bad compromise. It demonstrates desired mechanical properties (rather small grain about 20-30µm and high elongation ca. 40%) after annealing at 800°C for 2 hours and can be a good candidate for use in clad tubes. The alloy CuAl is not acceptable for our aim as indicated in figure 11.

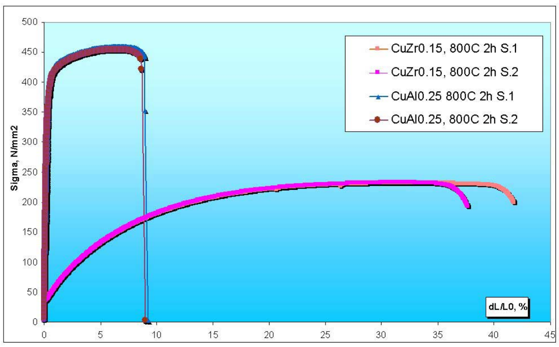

Figure11: Strain-stress behavior of samples from the Cu tube with 0,15%Zr or 0,25%Al after annealing at 800°C for 2 hours. The Cu0,15%Zr shows a high elongation after annealing, small and rather uniform grain.

Unfortunately each alloying addition to 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 at cryogenic temperatures (comparable with that of high purity Nb). In addition the thermal conductivity can be increased by special thermal treatment of the clad cavity.

4 SUMMARY AND OUTLOOK

At first sight the idea to fabricate sc cavities from a bimetallic composite material is very attractive. But there are also caveats and several new aspects appeared in this connection caused by difference in physical properties of two metals.

The main problem areas are listed below:

- the difference in the thermal expansion coefficient between Cu and Nb (more than by factor of two) will produce stress in the interface during cooling or annealing and in the worst case can destroy the bonding
- the diffusion of the gases or impurities from the Cu into Nb can cause a detoriation of the niobium material properties important for cavity performance
- the generation of thermo-electric currents during cooldown or quenches can lead to frozen-in magnetic flux [after quench] and reduce the quality factor of the cavity. This phenomena was in details investigated on Nb_3Sn coated cavities [4]
- insufficient bonding can caused enhanced thermal resistance at the interface
- the softening annealing is a problem because of big difference in the melting temperature of Nb and Cu.

The impact of each of these items on the performance of the cavities depends on the kind and quality of the bonding. The interface of the tubes fabricated by explosion bonding in combination with flow forming is not sufficiently investigated so far. Nevertheless some of our preliminary experiments and calculations have shown that the performance of the cavity should not be affected and one can expect that the RF properties will be similar to the bulk Nb cavity.

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