R&D OF Nb/Cu CLAD SEAMLESS CAVITIES AT KEK

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Abstract

We are proposing Nb/Cu clad seamless superconducting rf cavities as a cost effective mass production for TESLA [1]. This way can eliminate electron beam welding by applying spinning or hydro-forming in cavity fabrication, at the same time it reduces material cost remarkably by using rather thin niobium material. It keeps the niobium bulk property. We can use present high gradient preparation methods, e.g., electropolishing, therefore this approach will guarantee the high gradient performance (> 30MV/m).

Since the first successful feasibility study by spinning technique in 1999 [2], we are making hard efforts on the R&D. Recent international collaborative works with INFN-LNL, DESY and Thomas Jefferson Lab have developed the excellent potential on high performance.

For a mass production, we have successfully developed Cu/Nb/Cu sandwiched tubes for hydro-forming, and 1300MHz mono cell cavities were successfully hydro-formed from the tubes in the collaborative work with Toshiba. KEK own hydro-forming technique is also under developing.

1 INTRODUCTION

Many laboratories have successfully developed high gradient superconducting (sc) niobium cavities at various frequencies. In these cavity fabrications, they are made by deep drawing of half-cell cups from high pure niobium sheet material with RRR ~ 200, trimming, electron beam welding. Consider about future large-scale production like TESLA, however, this procedure looks to cost too much. Therefore, R&D of seamless cavity fabrication has recently been started in INFN-LNL [3] or DESY [4]. 1300 MHz seamless niobium bulk cavities were successfully fabricated in both mono-cell and multi-cell cavities by spinning (INFN-LNL) and hydro-forming (DESY). The performance has been confirmed by international matrix collaborations: INFN-LNL / Jlab / KEK and DESY / Jlab / KEK. Both methods produced the high gradient of 40 MV/m after electropolishing [5].

On the other hand, since 1994 KEK is also making R&D of seamless cavities. KEK's proposal is not seamless niobium bulk cavity but seamless Nb/Cu clad cavity, in which one uses clad materials bonded rather thin niobium material (maybe 0.5 – 1 mm thick) on thicker copper material (2 - 5 mm thick) [1]. The cavity will be fabricated from sheet material (spinning), or tube material (spinning, hydro-forming), therefore electron beam welding is eliminated, and at the same time a rather much amount of niobium material is reduced. This method will be cost effective cavity production. As other technology close to this, copper-spraying method developed in CNRS-IN2P3 in France is there [6]. This method has two processes: bulk niobium cavity production and the afterward copper spraying on it. It looks no cost effective.

Nb/Cu clad cavity is close to the niobium film coated cavity developed at CERN [7], but keeping the niobium bulk property is definitely different. It will be able to eliminate the steep Q-dropping [8] seen in film sputter coated cavities. Nb/Cu clad cavities can use present high gradient preparation techniques, e.g. electropolishing, then high gradient will be guaranteed. This method will have both benefits in production cost and high gradient performance.

However, there may be critical opinions against Nb/Cu clad cavity because it has been the abandoned technology by several reasons. It was used in low β cavity fabrication but welding was not reliable between clad material and other materials [9]. In our future, we will actually have to weld beam tubes with ports or flanges on clad cavity-cell, however we are optimistic to develop new reliable welding method. DESY has been to fabricate a 500MHz single cell cavity from Nb/Cu clad sheets and they observed serious Q-droppings due to bimetal effect [10]. This problem is understood as following: when there is a temperature difference, thermoelectric voltage like a thermo-coupler is induced (bimetal effect), then electric current flows and is trapped into superconducting state (frozen flux). The flux is moved by microwave and results in an additional heating loss. This problem appears in two cases: in fast cool down around superconducting critical temperature (T_C), and after quenching. However, there is no detailed study about this issue as long as we know. As seen latter, it might depend on niobium thickness. This is a further R&D issue. We expect this

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problem will be understood well and some cures will be found.

In this paper, recent feasibility studies done in international collaborations are presented on Nb/Cu clad cavities. KEK original Nb/Cu tube production method is described. The status of KEK own hydro-forming is also reported.

2 SUCESFUL FEASIBILITY STUDY WITH INFN-LNL

2.1 Collaboration with INFN-LNL

As mentioned above, there are two techniques on fabrication of Nb/Cu clad cavities. In 1997 we had no way to fabricate seamless cavities in Japan, therefore feasibility study was started with spun seamless cavities by collaboration with V. Palmieri in INFN-LNL. Nb/Cu clad planks 430mm x 430mm x 4mm in size were sent to INFN-LNL. The clad materials were explosively bonded and reduced the thickness from 10 mm to 4mm by rolling. RRR of the niobium material was 100. INFN-LNL successfully fabricated three Nb/Cu clad cavities. The cavity wall thickness was 0.5 mm with niobium and 2mm with copper. The clad cavities were electropolished and cold tested in KEK. One of them achieved 25 MV/m in accelerating field gradient (Eacc) without any steep Q-dropping [2]. This field limit was higher than our niobium bulk cavity with RRR=100 (Eacc, max =19 MV/m). To improve the field gradient, another Nb/Cu clad cavities were fabricated from better niobium material with RRR=200 by the further collaboration.

2.2 Cavity Performance

The cold test result on the Nb/Cu clad cavity with RRR=200 is shown in Fig.1. By the way, spun niobium bulk cavities were sent us from V.Palmieri to take electropolishing and to evaluate the performance. Both cavity performances are compared in this figure. As seen in the figure, in first excitation curve measurement at 1.5K (△), multipucting appeared around 18 MV/m. RF processing was needed. During the rf processing, unloaded Q (Qo) was dropped rapidly after the initial several quenches and came down Qo = 4 x 10^9. After processed out the multipacting, Qo-values still stayed at the lower value. This phenomenon is due to frozen flux. During the processing multipacting electrons bombard cavity wall and heat the place and a temperature difference occurrs. As a result thermo-electric voltage is generated and results in frozen flux. After processing the gradient was achieved Eacc=27.5 MV/m. At low fields Qo value still stayed at the low level (▲). After the measurement, this cavity was warmed up 10K just above T_C of niobium and the frozen flux was released into the normal conducting state. Then it was slowly cooled down around this temperature and re-measured at superfulid liquid temperature (1.5K). Qo value recovered due to releasing the frozen flux (●). No multipacting appeared. Once multipacting was processed out, its processed effect is still remained for the warming up to 200 - 250K [11]. In this second measurement the gradient achieved 29.5 MV/m. This performance is not so different compared with other spun niobium bulk cavity with RRR = 200 (▼). Spinning has a lot of miro-crakes on the surface [12]. To get high gradient of > 30 MV/m we has to remove material more than 300 µm. This clad cavity is removed only 90 µm. Further material removal will improve the gradient. However, we had a problem about it. We designed to have the thickness of niobium is 0.5 mm but the resultant wall thickness is too thin in some places, and the thinnest aria (at iris section) was only 0.3 mm thick with niobium. This aria is more removed by electropolishing because it is close to cathode [13]. If we remove material of 300µm, copper will appear perfectly at iris section. Present design has no margin for material removal.

Another problem in spun cavities is fluctuation in wall thickness as seen in Fig.2. From the point of cavity operation, each cell in multi-cell (future cavity production) must be in a regular distribution for cavity mechanical tuning. This will be a further R&D issue in seamless spun cavities.

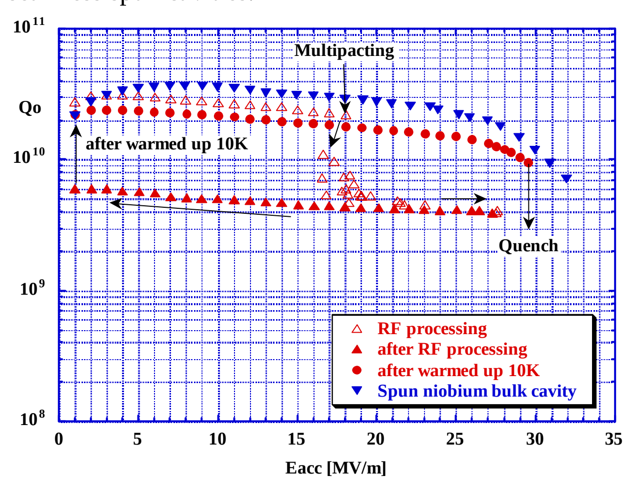

Figure 1: Result of the new Nb/Cu clad spun cavity from RRR = 200 niobium material

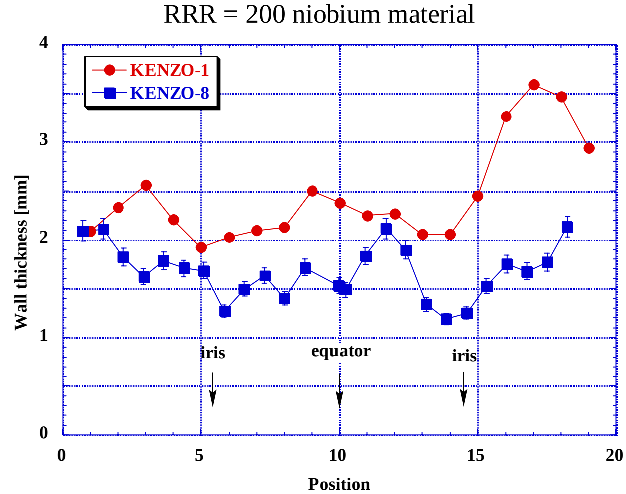

Figure 2: Wall thickness distribution of Nb/Cu spun cavities

3 HYDRO-FORMED Nb/Cu CLAD CAVITY IN DESY COLLABORATION

3.1 Fabrications and Preparation

DESY has successfully developed the hydro-forming technology for L-band niobium bulk seamless cavities. This technology was applied to Nb/Cu clad seamless cavities production. W.Singer fabricated 1300 MHz Nb/Cu clad mono cell cavities from explosive bonded Nb/Cu clad tubes out of 1 mm thick seamless niobium inner tube and 3 mm thick outer copper tube as seen in Fig.3 [14]. As the clad tubes are not so long as to have beam tubes, he formed cells without beam tubes, and then welded niobium tubes on them. In KEK, one of cavities was mechanically ground by centrifugal barrel polishing [15], then taken chemical polishing (110μm). Successively 750°C annealing and final electropolishing (50μm) were done.

Figure 3: 1300MHz Nb/Cu clad cavity cells fabricated at DESY by hydro-forming

3.2 Cold Test Result

The first cold test result is presented in Fig.4. This cavity was cooled as fastly as for other niobium bulk cavities, however, Q-dropping did not appear so seriously comparing with spun clad cavities [2]. But in the Q-Eacc excitation cure measurement, multipacting happened and resulted in Q-dropping (△→▲) as same as spun Nb/Cu clad cavities due to frozen flux. However, Eacc=31MV/m was achieved with Qo = $7x10^9$. After this measurement, it was warmed up 75 K and retested (○). In this test, Qo-value did not changed even after quenching (●) and Eacc=33.5 MV/m was obtained. Another similar experiment was repeated again (after warming up 25 K). Qo-value was dropped after quenching but it was not so much (▽→▼). The frozen flux effect looks to be small in the 1 mm Nb clad cavities. An optimisation of niobium thickness will be very important against the effect.

The other very excellent result on high gradient was obtained in Jefferson Lab. Another clad cavity was sent to Jlab from DESY. P.Kneisel made chemical polishing (130μm) and got Eacc = 28.5 MV/m without Q-slope. After several tests it was made annealing at 800°C, a light CP, then baking at 140°C. Eacc = 40 MV/m was achieved without electropolishing as seen in Fig.5.

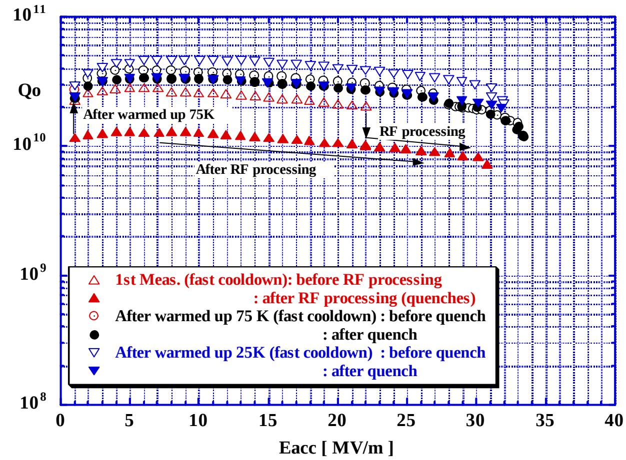

Figure 4: First result in KEK of a Nb/Cu clad cavity fabricated by hydro-forming at DESY

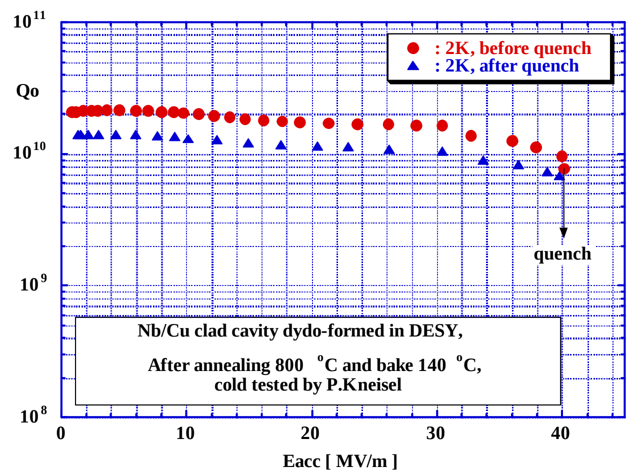

Figure 5: Excellent high gradient performance of Nb/Cu clad cavity.

3.3 Merits and demerits in Nb/Cu cavities

From the cold tests in KEK and Jlab, we found several benefits in Nb/Cu clad cavities. P.Kneisel suggested the Lorentz detuning coefficient: $\kappa = \Delta f/\Delta Eacc^2 = 1.5$ $[Hz/(MV/m)^2]$ is rather small comparing with niobium bulk cavities. Value of the coefficient depends on the cavity wall thickness and is inversely proportional to square of the thickness [16]. The large part of the rigid stiffening in the clad cavity comes from the thicker copper wall. Copper material is cheaper than niobium material by a factor of 1/30. Nb/Cu clad cavity has a benefit in the rigid stiffening using cheaper and thicker cavity wall.

The other merit in Nb/Cu clad cavity is to have a possibility to compensate the disadvantage of chemical polishing with high gradient. The better thermal conductivity by the thicker copper wall will help for heat transfer in the Q-slope problem.

As pointed out from previous experiences, Q-dropping happens after quenching. This is a demerit of the clad cavities. Similar problem is sometimes observed in niobium bulk cavities [16]. In our feeling, however, this kind of Q-dropping in Nb/Cu clad cavity is not so large at least as long as one uses thicker niobium material (~1 mm). It is very large in thin niobium cavity (~0.5 mm) [2]. This effect will be rather relaxed by optimisation of niobium thickness. Other point on this Q-dropping will be pinning effect. It will be very important for the flux trapping because the degradation appears as a result of flux motion. The pinning strength may depend on the material.

4 HYDROFORMED NB/CU CLAD CAVITIES IN COLLABORATION WITH TOSHIBA

Spinning technique is a candidate for future seamless cavity production, however, it has a lot of micro crakes on the surface [12]. Hydro-forming could be a better surface because it uses a liquid (oil or water). From such a consideration, we have started to develop hydroforming in collaboration with Toshiba Co. Ltd in 1998. They successfully developed this technology with copper cavity [17]. We applied their technology to fabricate Nb/Cu clad seamless cavities.

4.1 Nb/Cu clad tubes

A clad tube 460mm long and 132mm inner diameter is needed to make a 1300 MHz single cell cavity with both beam tubes. One problem was how to make such a long clad tube. We made long tubes using hot isostatic pressing (IHP) technology [18]. A niobium tube (0.5mm thick x 132mm inner diameter x 460mm long), for which a 0.5mm thick sheet was rounded and electron beam welded, was sandwiched between an outer 2.50mm thick copper seamless tube and an inner 1.0 mm thick copper tube. The set of three tubes was electron beam welded at both ends and the gaps between tubes were vacuum-sealed (canning). It was pressed for 2 hrs in argon gas at a temperature of 800°C and at a pressure of 2000kg/cm^2. After this HIP process, the inner copper tube was resolved chemically with nitric acid after hydro-forming.

4.2 Performance of the clad cavities

Toshiba successfully formed four clad cavities. Two (BC-1, 2) of them were fabricated by directly hydro-forming the HIP bonded tubes, but other two were made from the elongated clad tubes as described in next section. Cavity wall thickness distributions by hydro-forming were seen with BC-2 and BC-3 in Fig.6. It is not uniform but expects us a regular distribution in each cell for future multi-cell cavity fabrication.

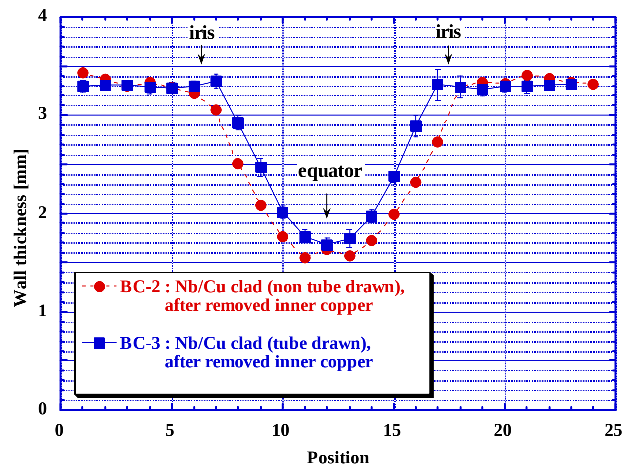

Figure 6: Distribution Wall thickness in hydro-formed Nb/Cu clad cavities

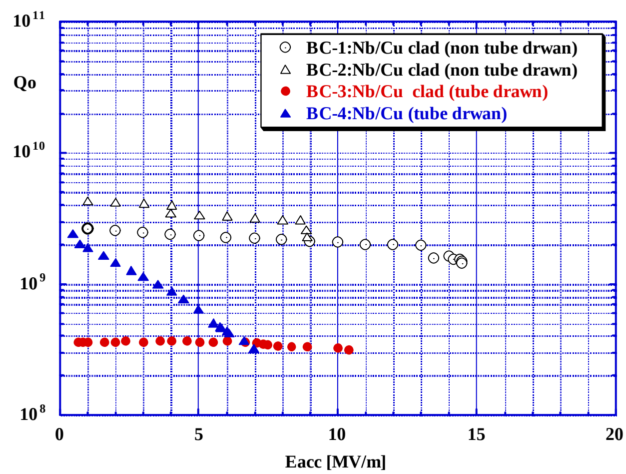

Figure 7: Excitation curves with Nb/Cu clad cavities hydro-formed in Toshiba

These cavities were barrel-polished by 33 mm in average, removed 3µm by electropolishing to make the surface, clean, annealed at 750°C for 3 hrs, then electropolished by >100µm, rinsed with HPR, and tested. Every cavity has very low Qo values as seen in Fig.7. The cavities from tube drawing seem to have worse Qo values. By our CCD camera inspection, corrosive arias were detected on the EBW seam of the BC-4 cavity. The outside copper was removed, then two cracks appeared on the welding seam as seen in Fig.8 (circle markers). The reason why is such a low Qo value in our clad cavities will be by the imperfections on electron beam welding seams.

Figure 8: Cracks on beam welding seam in BC-4 cavity

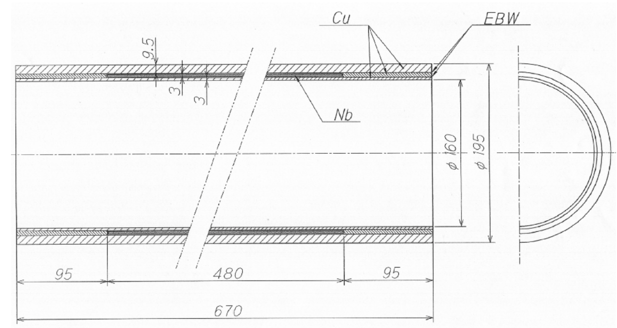

Figure 9: Primary clad tube design for HIP

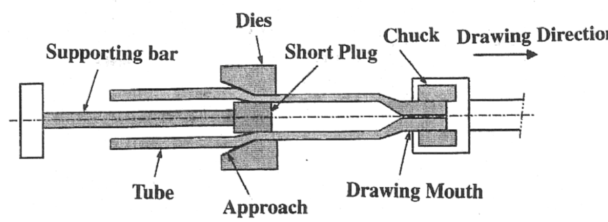

Figure 10: Principle of tube drawing technology

5 SANDWICHED TUBE PRODUCTION

As shown in the sections 2 and 3, Nb/Cu cavity is very promising for both good performance and cost effective production. Now it is the time to develop clad tube production method for mass production. If one fabricates a TESLA-type 9-cell cavity by hydro-forming, the needed tube-size will be a 2500 mm long. We have developed a method to make such a long clad tube by combination of HIP technology [19] and conventional copper tube drawing technique. Use of welded niobium tubes will have a benefit in cost effective production, although one has seen a problem at the moment in Fig. 8. However, it will be solved by use of thicker niobium tubes and by upgrading electron beam welding. Here, we will demonstrate that the long clad tubes could be successfully produced by our idea.

We made primary clad tubes by HIP bonding. The structure is presented in Fig.9. A welded niobium tube in size 480mm long x 170mm inner diameter x 2.5mm thick was sandwiched between copper tubes. The three tubes are welded at both ends by electron beam welding (canning), and then taken a HIP process (800^{o}C x 2000 kg/cm^2 for 3 hr). The primary clad tube has a size 670mm long x 165mm inner diameter x 20mm thick.

Tubes were elongated up to 3000 mm long using an industrial copper tube drawing machine. Principle of tube drawing is illustrated in Fig.10. Fig.11 shows the drawing machine. In this process, annealing is needed but a gas atmosphere annealing can be used similar to copper case because niobium is perfectly surrounded by thick copper materials. The elongated tube was cut into 5 pieces to fabricate L-band single cell cavities. The completed tube are seen Fig.12. The averaged thickness of the completed clad tube was 2.99 mm and the variation was within 0.3%.

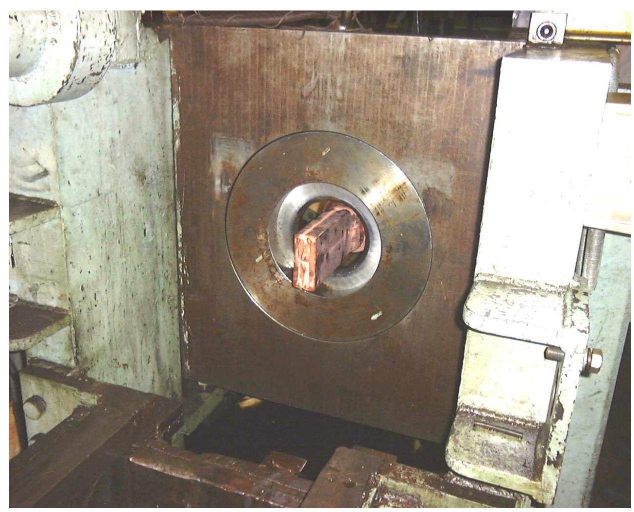

Figure 11: Tube drawing machine

Thickness of niobium was scattered from 0.327mm to 0.707mm due to the wavy structures. These tubes were hydro-formed to 1300 MHz single cell cavities by Toshiba technology. After the forming, the inner copper was resolved chemically with nitric acid. It took a half of day.

5.2 Material degradation in HIP process

Niobium material degradation in RRR by HIP process was investigated. Results are summarized in Table 1. HIP condition is 800^{o}C, 2000kg/cm^2 for 2 hrs. The niobium covered perfectly with copper (sandwiched) was degraded to 78% in RRR. Naked niobium in HIP was reduced to

Figure 12: Completed Cu/Nb/Cu sandwiched tubes by drawing technology

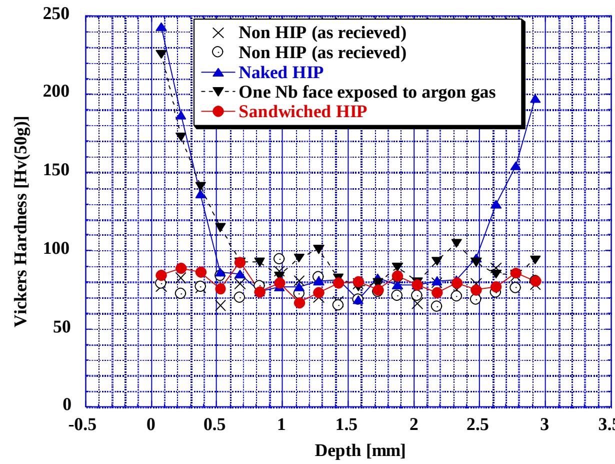

Figure13: Hardness (Vickers) in cross-section of materials after HIP process

45%. On the other hand, one-niobium-surface faced HIP degraded to 78%, which is about one half of the naked case. The degradation seems to depend on a degree of the initial RRR. The higher RRR gets the larger degradation.

The effected surface depth was estimated by micro-Vickers hardness measurement. Results are presented in Fig.13. The niobium surface faced to Argon gas was degraded in a rather deep depth 0.7 - 0.8 mm thick, but the sandwiched HIP is no difference from non-treated niobium material.

The concentrations of elements; Cu, H, N, O in niobium material of the clad tubes which were used for cavity production, were evaluated. Copper on the clad niobium material was chemically resolved by nitric acid, and then a little bit etched the niobium specimens. The analysed results are summarized in Table 2. From these results, the followings are concluded: 1) copper migration is not observed, 2) hydrogen is picked up in the nitric acid dipping but is degassed perfectly by 750°C annealing, 3) nitrogen, maybe came by HNO_3 dipping exists only on the surface layer, 4) oxygen looks to increase. It seems to be no serious degradation after 750°C annealing.

Table 1: RRR-value degradation by HIP process

Naked HIP	Sandwiched HIP	One-side naked HIP
170 → 77 45 %	253 → 198 78 %	170 → 133 78 %

Table 2: Analysed results (ppm)

	Cu	H	N	O
Non treated	10 <	1.3±0.3	4±0.4	23±2
HIP, HNO_3 dipping,	22 28	70±1 67±2	6±1 28±2	65±45 59±11
HIP, HNO_3 dipping, CP10μm	10 <	-	6±1 8±2	-
HIP, HNO_3 dipping, CP 120 μm	-	76±1 88±3	-	29±1 30±1
HIP, HNO_3 dipping, CP 120 μm, Annealing 750°C	-	0.9±0.06	4±1	29±1

6 KEK OWN HYDRO-FOMING

6.1 Hydro-forming

We have successfully developed clad tubes. Next R&D is to have KEK own hydro-forming technology. It has been started getting helps from a small company. Fig.14 shows the picture of the hydro-forming. Swaging technology is also very important as well as hydro-forming. We have developed cold swaging method by spinning. Recently we have succeeded in forming 1300MHz copper single cell cavities as presented in Fig.15.

6.2 Cost estimation of 9-cell structure

From this clad tube production, we estimate roughly the fabrication cost of a TELA type 9-cell structure. In the mass production, price of the clad tubes will be less than 4.5k US$ (as 1$ = 130 yen). In the future cavity production, a 9-cavity-cell with beam tubes having

Figure 14: Hydro-forming of a copper tube

Figure 15: Successfully hydro-formed Cu cavity (left) and swaged tubes for hydro-forming (right)

extruded ports will be formed in the same fabrication process by hydro-forming or spinning + other techniques. This forming price will be a 1.5 k$ or less. Other costs: flanges and welding the flanges on the beam tube ports are not clear at the moment. However, we expect it will be less than 4 k$. The total cost will be a 10 k$, which is a half of the price DESY estimated in the TESLA TDR.

6.3 Near future plan

As described above, our tube drawn technique has not yet succeeded in good sc performance. We have developed that 0.5 mm niobium tube design has cracks on welding seams after forming and has no margin to material removal. As seen in the *5.2*, any serious degradation was not found out in HIP bonding. It will have no responsibility for the bad performance. However, we have to more investigate it. From these points, the following investigations are undergoing: 1) explosive bonding from 1 mm welded niobium tube, and the afterward hydro-forming from the clad tubes. 2) clad tube drawing with 1mm niobium thick and the afterward hydro-forming. In these clad tube production we will use the same way presented here. We still keep the welded niobium tubes. We will use raster beams in the electron beam welding in order to upgrade the reliability.

The welding method of ports is other R&D issue. We will start the R&D soon.

7 CONCUSION

As presented is this paper, the excellent potentiality of Nb/Cu clad cavities has been confirmed in both good performance and cost effective production. Now it is the time to develop a clad tube production. Sandwich tube production and the afterward tube drawing technology will be a very promising way.

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