

ADVANCES AT DESY IN HYDRO FORMING OF TESLA CAVITIES

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Abstract and Introduction

Development of hydro formed superconducting rf-cavities is being pursued at DESY. Advantages of such design with respect to the usual eb(electron-beam)-welded construction from deep-drawn half cells are seen in conservation of niobium, lower fabrication cost, and perhaps better rf-performance.

Cavities are being hydro formed from niobium seamless tube by expanding the tube with internal pressure while simultaneously swaging it axially. Tube radius and axial displacement are being computer controlled according to results of FEM simulation of forming based on measured stress strain characteristic of tube material. Forming difficulties arise from inhomogeneity of mechanical properties and texture, causing the tube to deviate from rotational symmetry during forming. Four TESLA mono-cells have been successfully hydro formed from seamless niobium tube made by back extrusion and flow forming(1K1), spinning(1K2 and 1K3), and deep drawing(1BT1). 1K1 and 1BT1 have RRR near 300, the others equal to about 100 with capability of reaching RRR=400-500 via purification heat treatment with titanium getter. Only 1K1 has been rf-tested so far and reached 23.3MV/m cw accelerating voltage.

1 WHY HYDRO FORM CAVITIES?

Development of hydro forming of TESLA cavities from seamless niobium tube has been pursued at DESY for about 4 years. Expected advantages relative to the established eb-welded version are **lower costs** and **improved performance**.

1.1 Lower Costs

Starting from the purified Nb ingot of RRR≈300 and fabricating welded cavities from it, about 65% of ingot mass will go to scrap. For the hydro-formed cavity made from back-extruded tube the loss to scrap is only about 35%. A substantial saving on niobium cost will result.

For the hydro formed cavity there will also be a saving on fabrication cost, since in the undulated region no machined edges and eb-welding are needed. Further, the stiffening rings may be eliminated by thickening the cell walls in the conical part sufficiently (to 5...6mm) so that Lorentz force detuning will be tolerable. Finally, calibrating a cavity by forcing it against the mold with internal pressure substantially higher than that used for hydro forming, may render the cell form accurately enough to eliminate the need for warm tuning (cf. 3.3).

1.2 Improved Performance

The weld-less cavity does not have risk of foreign material and gases diffusing into equator welds to reduce RRR at the place where the magnetic field is highest and where it is needed the most. Some welded cavities in the past have required substantial deformation of individual cells to achieve correct tune. In such cells one may expect unwanted higher order modes and deviation of frequency shift from that of cells of correct shape when the cavity is being cold-tuned. We also think that tube- and subsequent hydro forming contains less risk of embedding particles of foreign matter into the rf-surface, since the rather "dirty" rolling of sheet and contact of tools with rf-surface, characteristic for welded construction, are avoided.

2 DEVELOPMENT WORK TO DATE

The development of seamless niobium tubes with satisfactory material properties has delayed progress much more than the computer simulation of forming operations and the hydro forming experiments.

2.1 Study and Improvement of Material Properties of Niobium Tubes

The rather extensive work is the subject of a separate report [1], and will only be summarized here. Back extruded tubes, 0.6 scale in wall thickness and diameter relative to the 138x4mm tube for full size cavities, have been fabricated in 3 different ways from 2 qualities of niobium (RRR=300 and RRR=100). The less pure RRR100 tubes, without any intermediate anneals before re-crystallization in the final form, were found to have a grain structure most favorable to hydro forming. On the basis of stress-strain characteristics found by bulge testing, a computer simulation of forming was made and the tubes were hydro formed to 0.6 scale TESLA cells. No intermediate anneals or -constraints were needed.

Further, it was found in bulge tests and conventional traction tests, that the stress strain behavior in tubes is very anisotropic and that strain before onset of necking will be increased by almost 30% by deforming the sample with *pulsed* stress. This new method has also proved to be advantageous for hydroforming.

Bulge tests were carried out to determine the stress-strain relationship on which the computer simulation of hydro forming is based.

2.2 Computer Simulation of Forming Process

With the measured stress-strain characteristic of tube to be formed, a computer simulation of the hydro forming process is made. The forming process is optimized so that the least maximum strain in niobium results at end of the hydro forming. The calculation neglects inhomogeneities of stress/strain characteristic of tube. The mechanical forming of iris grooves and end-reductions of tube have also been studied with computer simulation. Further work was directed towards design of continuous radial constraint, and minimizing Lorentz-force detuning effects on the overall cavity.

2.3 Hydro Forming Experiments

In hydro forming, a tube of ideal mechanical properties deforms through a succession of shapes, a few of which are shown in Fig.1. The functions $r(d)$ and $p(d)$ (Fig. 2), with

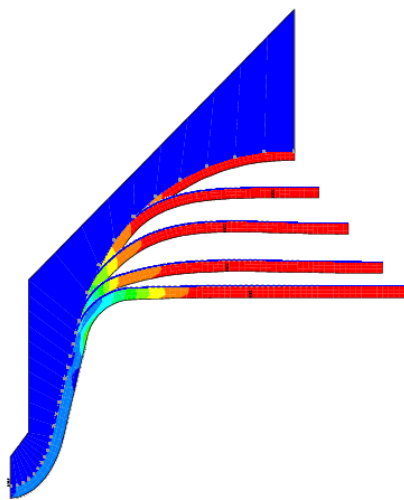


Fig. 1 Simulation of succession of tube shapes during hydro forming (a quarter of cell shown)

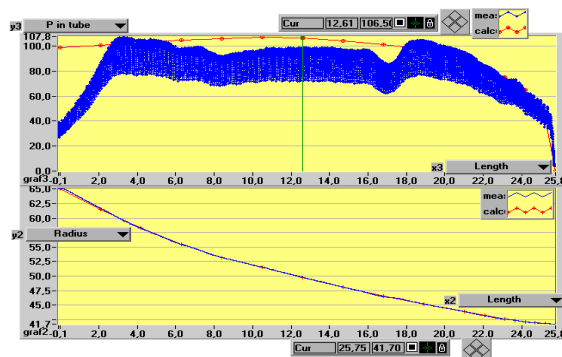


Fig. 2 Pressure (upper curve) and radius as function of displacement

r =tube radius in equator-plane, p =internal pressure and d =axial swaging displacement, are the output of the computer simulation.

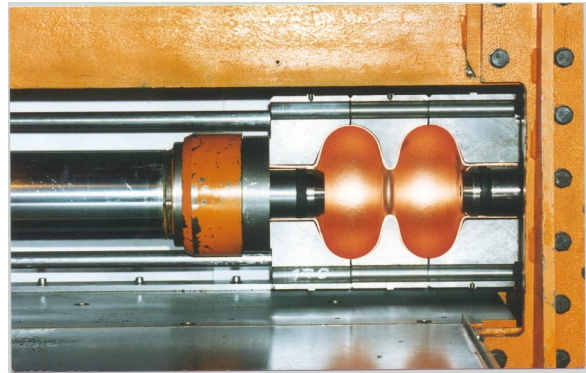


Fig. 3 Hydro forming apparatus set up for two cell resonator

The hydro forming in our apparatus (Fig. 3) strictly computer-controls r , d , and the $r(d)$ curve by suitably adjusting the pressure and allowing some deviation from the calculated $p(d)$ curve. This method differs from industrial practice, where d and r are controlled by applied axial force and internal pressure, respectively. Our method was chosen because the forming process can be adapted to the actual mechanical properties of tube being hydro formed, which generally will differ from those of sample on which the simulation was based.

In practice, mechanical properties of tube will be inhomogeneous, as mentioned, and various forming problems are the result. Generally, the tube will become plastic first at a place of minimum yield strength. This leads to local thinning of wall and stress enhancement producing more local deformation. This self-enforcing process will continue until fracture unless stopped either by strain hardening (not very pronounced in Nb) or contact with the mold wall.

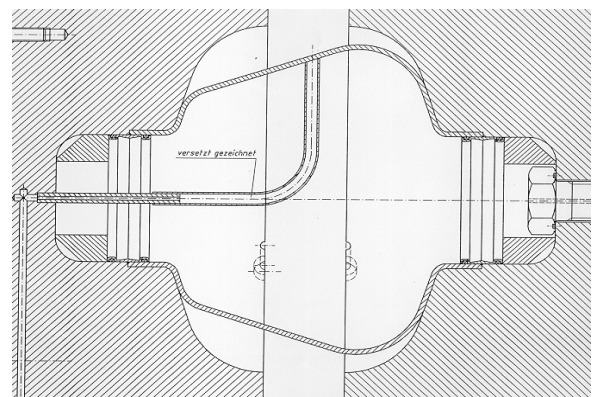


Fig. 4 Conical anomaly of intermediate tube shape

Two special situations will now be discussed. If the yield strength of the tube monotonically varies from one end of tube to the other, a conical type of intermediate tube shape will result (Fig. 4). Tubes often show this effect, because many fabrication processes, like deep drawing, spinning, and back extruding of the cup-shaped tubes will produce a deformation-degree increase from bottom to rim, leading to the above mentioned anomaly on re-crystallization. While

this effect is systematic, a random strength variation can also occur. One such deviation is a change in the of yield strength over the tube circumference. Shapes like in Fig. 5 will result.

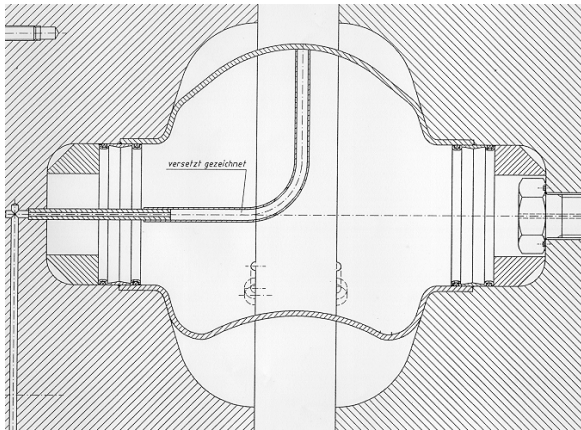


Fig. 5 Anomalous tube shape for circumferential variation of yield strength

Another stability problem can occur in thin tubes. The axial swaging may cause tube buckling in form of waves like in a bellows (Fig. 6).

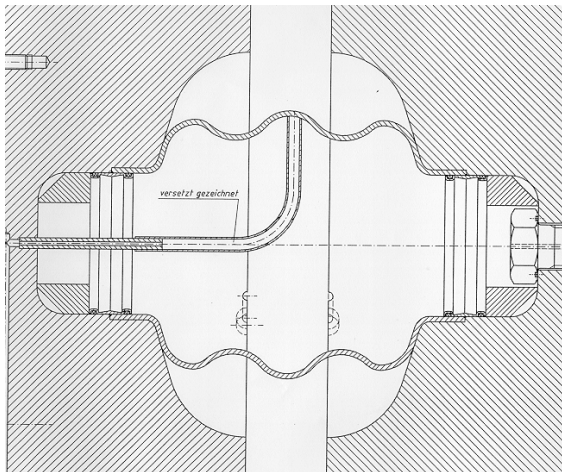


Fig. 6 Buckling anomaly in thin walled tube

All three effects were present in varying degrees in the hydro forming of the four mono cells (Fig. 7 and Fig. 8), made so far. Cavity 1BT1 was made from deep drawn Nb300 tube, 3mm thick, without any intermediate constraints, -anneals or other aids. It showed, however, local thinning of the wall, just short of fracture. 1K1 was made from a special tube. The wall of back extruded Nb300 tube was sandwiched between an outer and an inner tube of 1mm thick stainless steel. The very homogeneous mechanical properties of the stainless steel resulted in good overall forming performance, only negligibly disturbed by the poor forming characteristics of the niobium. An intermediate constraint of 168mm ID was used, but no anneals were needed. The stainless steel later was etched

away. After a purifying heat treatment it reached an accelerating voltage of 23.3MV/m.

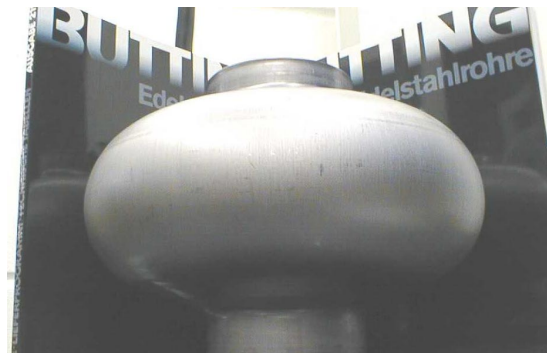


Fig. 7 DESY made TTF mono cells 1K1 1K2 and 1K3 (from left to right)



Fig. 8 First BUTING made TTF cell 1BT1

This rather good result indicates, among other things, that no serious damage was done to the niobium by the fabrication process. 1K2 and 1K3 made from spun Nb100 tube, 134x2mm, also required the intermediate tubular constraint of an inner diameter of 168mm to symmetrize tube form, which suffered from all three aberrations of form discussed above. Finally the cavities were calibrated in their hydro forming mold by increasing pressure to 1300bar after hydro forming was complete. These two cavities will receive a purifying heat treatment to bring RRR to about 400... 500, and then be rf-tested along with 1BT1.

3 CURRENT AND FUTURE WORK

3.1 Tube Improvement

Currently a few spun and subsequently flow-formed tubes 138x4mm are being produced from RRR300 material. Tube development will further be focussed on the more economical production routes, such as extrusion of thick walled tube, subsequently reduced in wall thickness and extended in length (for instance by drawing). Any intermediate anneals will be avoided, in order to get maximum possible deformation degree prior to re-

crystallization. To this end, starting the tube fabrication from larger ingots will also be pursued. Thin-walled tubes will also continue to be produced on small scale for practice in making cavities for possible cladding with copper or for other means of re-enforcement.

In parallel it is planned to continue the work with tubes from a niobium quality with $RRR \approx 100$, with chemical analysis allowing increase of RRR to about 500 by a purifying heat treatment with getter. Per kilo price of such tubes should be below that for Nb300 tubes because fewer purifying remeltings of ingot are needed, and they will hydro form better.

Tube fabrication methods that allow us to hold the wall thickness constant to about 0.1mm will be favored.

3.2 Improvements of Hydro Forming Apparatus

The discussed aberrations of tube form, developed during hydro forming, need to be kept under control in order to be able to hydro form tubes of varying forming quality with an adequate safety margin for the process. The intermediate 168mm ID radial constraint, used to form the K-series mono cells, served this purpose, as described. However, a *continuously* active radial constraint would provide greater process safety and better lend itself to series production. To this end, a modified type of mono-cell hydro forming apparatus has been designed and will be built, which provides a continuously acting radial constraint for tube growth in the form of 12 equally spaced bars. The radial position of these constraint-bars is controlled as function of axial displacement, as optimized by the simulation calculation. Fig. 9 shows computer simulation of tube growth being controlled by optimized radial constraint motion. The concepts used allow their extension to multi-cell hydro forming after having been proven to function properly on mono cells.

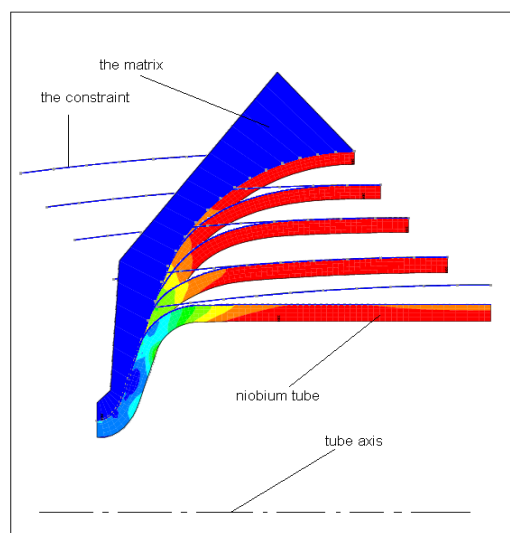


Fig. 9 Simulated hydroforming with continuous radial constraint

3.3 High Pressure Calibration of Hydro Formed Cavities

A calibration device with fortified matrices for the purpose of achieving assured gap-free contact of cavity wall against mold everywhere, especially in the difficult-to-hydro-form iris region, has been designed. It is now under construction and will consist of matrices from 7075 T6 Aluminum alloy supported by a massive steel tube. The device will stand pressures up to 1500bar and have capability to calibrate resonators with 1 to 9 cells (Fig. 10).

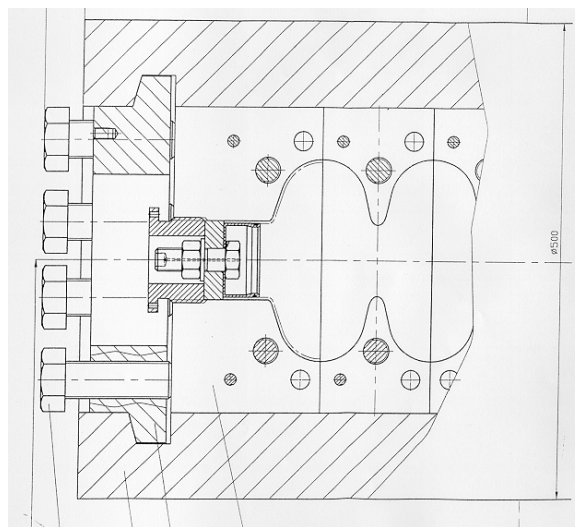


Fig. 10 High pressure calibration device

High-pressure calibration can produce resonators, which will exactly fit the mold when calibrated and hold their shape when the pressure is relieved. This works due to spring back of mold and relatively low yield strength of Nb. With the pressure rising, the cavity will grow plastically with the mold, which remains elastic. When pressure is turned off again, the mold springs back to practically its initial stress-free form (only hindered by cavity inside). The resonator will be slightly squeezed plastically to the shape of mold. This process will provide a highly accurate resonator with a straight axis. The "squeezing" will tend to relieve peak stresses in Nb and thus give the resonator increased stability of shape during subsequent handling. Inside shape of cells will depend almost exclusively on wall thickness, and it may be hoped, that warm tuning of cavity will not be necessary.

4 REFERENCES

- [1] I. Gonin, et al, DESY, "Hydroforming of Back Extruded Niobium Tubes", this workshop