FULLY HYDROFORMED RF CAVITIES

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Abstract

Niobium coated copper cavities are an attractive solution for RF superconducting structures. The copper parts are usually obtained by spinning and subsequent weldings. But the defects of welded surfaces may create local coating problems. One way to minimize them is to hydroform monolithic cavities starting from OFHC copper tubes. Manufacturing procedures are presented. The very encouraging results obtained on multicell pieces for frequencies of 2.1 GHz and 1.5 GHz are correlated with theoretical computations. Extrapolation to the hundreds MHz range frequency is discussed from the technical and financial points of view.

Introduction

In order to achieve the best possible performances e.g. electrical field gradient, radio-frequency structures built or planned for new particle accelerators are superconducting. For two decades, niobium has been used both as superconducting and as structural material. Various fabrication techniques have been tried more or less successfully to obtain satisfactory bulk niobium cavities[1]. In particular, circular/elliptical cavities in the decimetric range (300 MHz to 3 GHz) are now usually manufactured by spinning shells and subsequent electron beam welding. But besides their high cost, the relatively poor thermal conductivity of niobium could create thermal breakdown.

A way to improve the situation is to coat a high thermal conductivity metal like copper with a thin superconducting niobium film. Development conducted at CERN has shown the viability of this approach[2]. Among advantages, one can mention the lower price of copper, the insensitivity of thin films to trapped magnetic field and a possible use of pipe cooling which leads to a simpler cryostat. However, the first arising technological problem is the production of copper parts suitable for a good coating. Hydroforming monolithic cavities starting from copper tubes has given very encouraging results presented below.

Manufacturing techniques

General

Besides machining, which should practically be excluded for these shell-like structures, a series of techniques are possible, in particular spinning, deep drawing, hydroforming, hot forming, explosive forming, electroforming.

The latter three solutions have not gone much further than feasibility studies or limited prototyping :

- hot forming should be done in vacuum with a costly and complicated tooling and may lead to a large increase in grain size:
- as the yield point of copper expectedly increases with strain rate, explosive forming does not allow any secondary creep and is therefore avoided for large deformations:
- electroformed prototypes of small size have been built but extrapolation to larger dimensions is doubtful : copper quality. thickness variations.

Spinning - Deep drawing

The most popular and extensively used technique is the production of cups by deep drawing and (or) spinning which are then joined together by electron beam welding. This manufacturing method is that used for bulk niobium. Whereas the forming dies represent a limited investment, welding of OFHC copper is much more difficult to master than that of niobium. Extensive studies have led to huge improvements of the welds quality : minimisation of voids creating vacuum leaks, decrease of surface roughness, control of shrinkage[3].

These solutions lead however to large investments for internal EB welding source and precise adjustment toolings. All manufacturing steps must still be carefully followed : dimensional checks at each step, precise fitting of the individual cups, careful welding of the whole length of the joints : more than 12 meters for a 352 MHz 4-cell cavity. And despite all these costly precautions, the final pieces of series production may still lack reproducibility.

Hydroforming

Hydroforming means pushing a piece against a rigid die by applying a large pressure through a deformable medium, liquid or polymer. Large volume changes are achieved with the former and the latter allows to solve easily tightness problems.

Hydroforming is a manufacturing procedure already extensively used for vacuum chamber elements like bellows and transparent thin wall experimental chambers in materials as different as stainless steel. titanium, nickel and aluminium alloys. It has the advantage to suppress welding in critical regions, limiting it to the connections with end pieces. If the tooling is expensive, on the other hand reproducible parts are obtained straightforward. Therefore, it is attractive to hydroform a material with a large ultimate elongation like copper to obtain radio-frequency cavities.

Hydroforming monolithic cavities

Method

In the present case. the cavities are exclusively made from Oxygen Free High Conductivity (OFHC) copper.

These cavity cells are axisymmetric with a ratio between maximum (D) and minimum (d) diameters up to 3. Consequently. if the initial piece is a seamless tube of diameter d, the radial elongation is then 200%. This value is largely greater than ultimate elongation of OFHC copper at room temperature (45%), but a multistage process, theoretically four steps with intermediate annealing, is possible. However, according to the volume conservation law. the wall thinning is equal to or larger than the diameter ratio and this leads to structural problems or heavier (thicker) pieces.

A better way to solve this problem is to start with a larger diameter (Do) tube and apply a combination of swaging, thus creating toroidal grooves and reducing the diameter to its minimum value, and subsequent expansions by inflation to obtain the required shape.

Swaging

The principle of swaging is shown in figure 1. A high resistance polyurethane membrane blocked by a rigid support is pressurised. It pushes the annealed tube onto an internal core creating a toroidal groove.

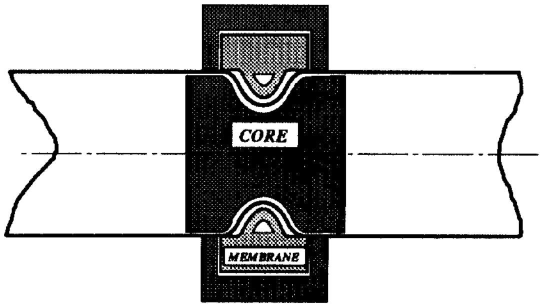

Figure 1

During this process however, the resulting compressive stresses may lead to an instability by plastic buckling, creating ripples and spoiling the tube with no possibility of recovery. This phenomenom has been modelled using BOSOR 5 software [4] and verified by tests.

After optimisation of the process, a reduction up to 40% of the diameter has been achieved in only one stage with a pressure up to 650 bars.

After the swaging, radial deformation to reach the maximum diameter is still much larger than the copper ultimate deformation, but the complete number of steps for the process is now minimized as well as with the wall thinning.

Expansion

The principle of the expansion phase is shown in figure 2 (final configuration). The tube is placed into a multi-part die with the external shape of the final cavity. This precise die is equipped with dowel pins in order to avoid any mismatching. It is initially opened in order to suppress the axial elongation and it follows the axial movement of the tube to its closing. The high internal hydraulic pressure (up to 200 bars), controlled manually, deforms the copper plastically against the mould. Each expansion phase is monitered by simply measuring the maximum diameter: the pressure increase is stopped when it reaches the value corresponding to the specified maximum elongation.

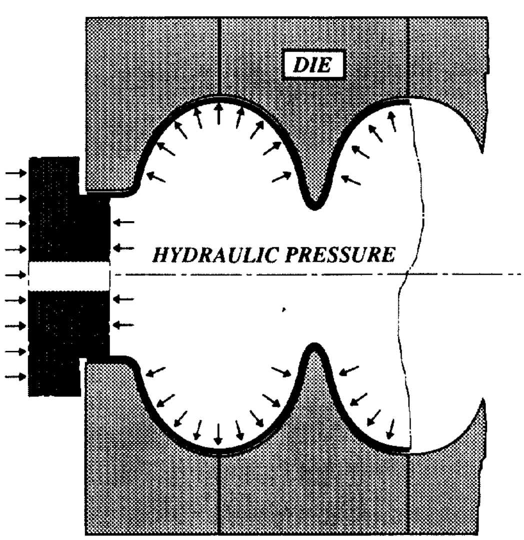

Figure 2

As for swaging, the expansion phase has been computer modelled. CASTEM software [5] allows to study the complex phenomena of hydroforming : plasticity, large displacements, variable boundary conditions and contacts. Modelling predicts precisely the behaviour of the piece during all the stages and, in particular, the rapid diameter increase above 20% elongation. Computed values agree very well (better than 5%) with the measured ones for all steps.

Heat treatment

After each expansion stage, the tube is annealed under vacuum. Parameters for this operation have a drastic influence on grain size increase but the optimal temperature-time combination is not well determined : it lays between a low temperature (350°C) - long duration and a high temperature (650°C) - short duration ! The present choice is 650°C for one hour but more investigation in this field is clearly needed.

Manufactured cavities

Hydroforming has been applied successfully to two types of mono and multicell cavities : model pieces of about 2.1 GHz and 1.5 GHz cavities for the GECS group at CEA-Saclay [6] are shown in Figure 3.

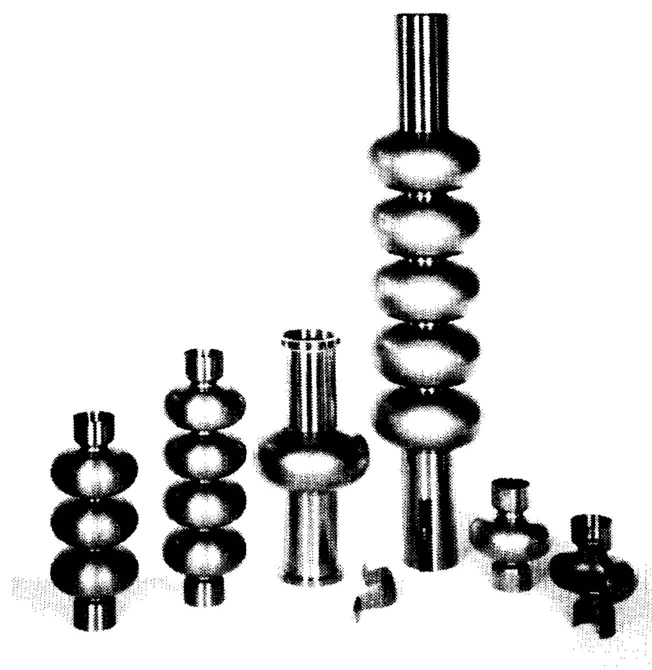

Figure 3

Their main geometrical characteristics (in mm) are shown below :

Frequency	Diameters (internal value)			Thickness	
	Tube Do	Cavity min d	Cavity max D	Tube	Cavity min
2.1 GHz	55.0	35.3	124.0	2.15	1.04
1.5 GHz	80.0	70.0	181.4	3.0	1.36

A correct design of the expansion die considers the thickness variation, the elastic strain and die movements under pressure. In this case, the internal shape of a raw cavity is accurate to some tenths of a millimeter. Repetitivity on a small series production has been measured to be in the range of one tenth of a millimeter.

Grain size and the resulting surface roughness increases with the number of annealings. All the present cavities have been manufactured with two annealings. Final surface roughness depends also on the initial tube quality (Ra between 0.02 and 0.2 µm). On the corresponding raw piece just after forming, Ra ranges from 0.5 µm and 1.0 µm and after chemical polishing, Ra decreases down to 0.1 - 0.15 µm.

Monocell 1.5 GHz cavities (figure 4) have been coated with niobium by magnetron sputtering.

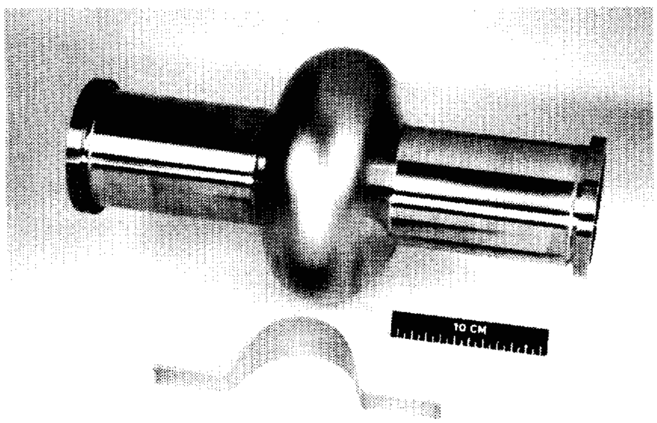

Figure 4

Whereas a "spinned" cavity exhibits an almost uniform wall thickness, this varies for a hydroformed cavity is inversely proportionally to the diameter change. A study of the mechanical behaviour of 1.5 GHz cavities in the elastic range has shown that, due to a better thickness repartition, a hydroformed cavity exhibits smaller peak stress under pressure or own weight load, higher eigenfrequencies in axial, torsion and flexion modes and higher buckling values under external pressure.

Extrapolation to other frequencies

Theoretical approach

The feasibility of hydroformed 1.5 and 2.1 GHz cavities being demonstrated, one should examine a possible extrapolation to lower frequencies, i.e. larger pieces.

Taking into account,

.that, in the considered frequency range, superconducting RF cavity shapes are very similar to each other,

.and that loads applied during hydroforming are only pressure loads,

by applying laws of similitude to the equations of mechanics, it can be shown that the pressure leading to similar deformations is the same for any frequency.

Therefore, any cavity with dimensions proportional to the ones already hydroformed could be hydroformed.

Practical application

Whereas hydroforming has theoretically no limits, some drawbacks appear at low frequency :

- The first and main one regards the dimensions : they vary with the inverse power of the frequency. The tooling, proportional to the third inverse power of frequency, becomes huge and expensive in the 300-500 MHz range. For 350 MHz, it will weigh about 6 tons. The same scaling applies also to the vacuum oven.
- Large and accurate OFHC seamless tubes have to be especially manufactured: for 350 MHz, their dimensions are about 3.5 meters long, 10 millimeters thick and 300 mm in diameter.
- Metallurgical and mechanical behaviour change with the part thickness : grain size, surface hardening,...
- Shape defaults will lower the critical pressure during swaging.

However, it is believed that none of these drawbacks create problems which cannot be solved, at least for frequencies higher than 300 MHz.

Conclusion

On the technical side, the main advantages of hydroforming over the present manufacturing technique are the suppression of the critical welds, a better geometrical accuracy and better thickness repartition. On the financial side, the proposed fabrication is easier and shorter per cavity and the large initial investment is quickly amortized even in the case of a small series production.

In the perspective of LEP energy upgrading, studies on the tooling and manufacturing procedure have now started at CERN to hydroform 4-cell monolithic 352 MHz radio-frequency cavities.

Acknowledgments

The development of monolithic hydroformed cavities results from the collaboration of several workers within LEP division, in particular W. Jeker for initial development and J. Genest and R. Jaggi for design and accurate manufacturing, and G. Bachy for his support.

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