

HYDROFORMING MONOLITHIC CAVITIES IN THE 300 MHz RANGE

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Abstract

Superconducting accelerating structures made of niobium coated copper cavities are now being built in various laboratories. The standard manufacturing technique for the copper shells associates spinning and welding. But a parallel method, hydroforming of monolithic parts which leads to a better surface quality, has also been investigated at CERN. Parts have previously been produced in the 1-2 GHz range, but this technique has now been extrapolated up to the 300 MHz range. Manufacturing procedures, in particular optimisation of the forming and heat treatment sequence, is presented together with the characteristics of the final product. The advantages of the present solution are discussed from the technical and financial points of view.

Introduction

A possible method of upgrading energy in particle accelerators is to use superconducting radio-frequency structures. The advantage of superconducting cavities stems from the fact that RF losses are reduced enormously in comparison with the conventional copper version. In the past SC cavities were made entirely from niobium, but the version made from copper with a thin internal layer of sputter-deposited niobium has been developed [1]. It permits not only to reduce the price owing to the lower cost of the raw material, but also to decrease the RF losses because of the high thermal conductivity of copper, which prevents eventual dramatic quenches (thermal breakdown). This latter version implies the production of copper parts with a good surface quality, suitable for coating.

Hydroforming of monolithic cavities from copper tubes presents advantages compared to the standard manufacturing technique of spinning and welding: better geometrical accuracy and surface quality, lower cost, and shorter manufacturing time. However this innovative technique requires thorough studies of the mechanical and structural behaviour of copper submitted to successive heat treatments and forming phases.

Hydroforming has been successfully applied to pieces in the 1-2 GHz range [2], and is now extrapolated up to larger cavities, in the 300 MHz range, for mono and multicell cavities. The tooling, the manufacturing procedure deduced from the study of the behaviour of copper, and the final products and their performances will be presented successively.

Hydroforming

Principle

Hydroforming is a manufacturing procedure which allows the achievement of large volume changes. The principle is to push the part against a rigid die by applying a large pressure through liquid or polymer.

This method has the advantage of producing monolithic pieces, and therefore suppressing the need for welding, particularly in critical regions.

Cavities are obtained from a copper tube, which has to withstand very large deformations, typically up to about 200%. Because the ultimate elongation of annealed copper is only of the order of 50%, the process must be multistage, including preliminary swaging and several expansions with intermediate annealing. During expansion, the decrease of the tube thickness is virtually proportional to the increase of the diameter. Therefore swaging permits procedure using a larger initial tube diameter and a smaller initial tube thickness, and minimizing the number of expansion phases. The manufacture of the tubes includes extrusion, drawing and machining. Thus, at their reception, the tubes are in the as-drawn condition, and must be annealed before swaging.

Swaging

The principle of swaging is shown in figure 1: a steel internal core is introduced into the initial annealed tube. Then the tube is slid inside a high resistance polyurethane membrane embedded in a steel support of internal diameter equal to the outer tube diameter. The oil-pressurised membrane pushes the tube onto the internal core, the annealed copper taking a toroidal shape. The core is made of eight identical parts for easy dismantling after the deformation process. According to the number of cells of the final cavity, several swagings are carried out on the same tube.

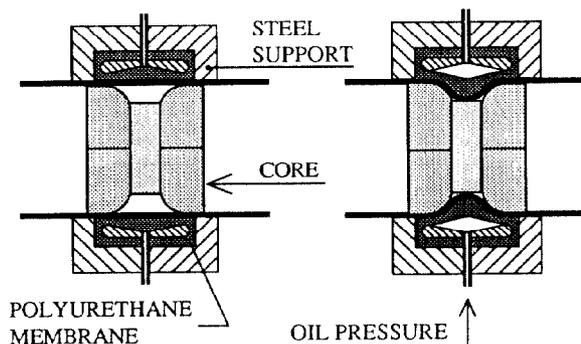


Figure 1

The tangential deformation is based on the dimensions of the final cavity; a maximum reduction of 40% has been obtained with a pressure of 650 bars. The problem is to prevent plastic buckling due to high compressive stresses, creating irreparable ripples.

Expansion

Figure 2 shows the expansion principle : the tube is put into a multi-part die, which is initially open and will close progressively during expansion, while the length of the tube decreases. This process allows virtually no axial elongation while keeping a reasonable thickness. The closed die (all parts in precise contact and located with pins) has the exact external shape of the final cavity.

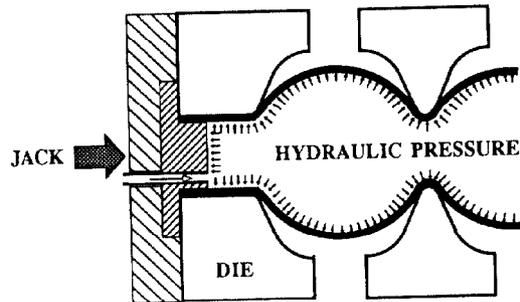


Figure 2

A progressive internal hydraulic pressure up to 200 bars pushes the tube against the die. The expansion of each cell is controlled by dial gauges, which measure the increase of the maximum diameter.

After swaging, the tube is only locally hardened, and it can be directly submitted to the first expansion stage. The total number of expansion steps depends on the total radial deformation and on the behaviour of the annealed copper.

After each expansion stage, the hardened tube is annealed so that it can recover its structural properties. The characteristics of heat treatment have been determined from studies of the mechanical and structural behaviour of copper.

OFE copper and heat treatment

Because of its purity and its high conductivity, OFE (Oxygene Free Electrolytic) copper [3] is used for the cavities. To determine the influence of the heat treatment parameters, i.e. the temperature and the duration, several tensile tests have been realised with samples annealed under vacuum at different temperatures, from 300°C to 600°C and then at different duration times, from 30 to 90 minutes. The main results are presented below. Heat treatment only starts to influence mechanical properties at 400°C, particularly the ultimate elongation and the hardness.

An important observation is that no particular relation has been found between hardness and grain size. Heat treatment does not affect the grain size, but roughness increases by a factor of 1.4 for any temperature. After a tensile test, grains are elongated but their size remains virtually unchanged; roughness increases by a factor of 4 to 10 according to the annealing temperature. A chemical polishing in a special bath improves the surface quality, reducing the roughness by a factor of 3. The duration of the heat treatment has a relatively slight influence, compared with that of the temperature.

In order to simulate the most difficult conditions of hydroforming, samples have been submitted to successive annealings and tensile tests, during which the maximal deformation of the corresponding expansion phase is reached. After each annealing, the copper recovers almost all its mechanical properties with a small decrease in its elastic limit and its strength.

Manufactured cavities

Three sizes of mono and multicell cavities have been successfully hydroformed : 2.1 GHz model pieces, 1.5 GHz cavities for the GECS group at CEA-Saclay, and 352 MHz cavities for the LEP 200 project at CERN. Figure 3 is a photograph of three different types of multicell cavities, the geometrical characteristics of which are grouped together in Table 1.

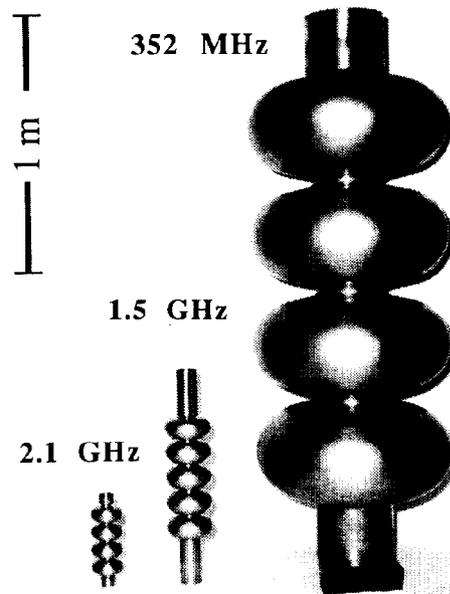


Figure 3

Frequency	Initial Ext. Ø (mm)	Max. Ext. Ø (mm)	Min. Ext. Ø (mm)	Max. Ø Min. Ø (%)	Initial Thicken. (mm)	Min. Thicken. (mm)
2.1 GHz	59.3	126.1	39.6	218	2.15	1.04
1.5 GHz	86	184.1	75	145	3.00	1.36
352 MHz	304	759.9	259	193	9.00	3.67

Table 1

Dimensional controls show that the shapes of the cavities are accurate to some tenths of a millimeter. For all types of cavity, the measured thicknesses are a slightly larger than the calculated ones (calculation made from the volume conservation law, supposing a null axial elongation). In fact, the jack creates an axial force, leading to an axial deformation of a few percent. Therefore the developed length of the final cavity is smaller than the length of the initial tube.

Calculations on 1.5 GHz and 352 MHz cavities [4] show that hydroformed pieces exhibit a better mechanical resistance under pressure or under own weight load than the welded ones. Moreover, frequency measurements on a series of 1.5 GHz cavities present a dispersion of only 1%.

Hydroformed 352 MHz cavities

The main problem for such large cavities is to obtain accurate OFE tubes in suitable dimensions. The tubes used have a length of 3000 mm, an internal diameter of 286 ± 0.5 mm, and a thickness of 9 ± 0.3 mm. The tubes are extruded, drawn, and machined. Each one weighs 223 kg. The initial grain size is large, about 200 μm , and the roughness Ra is between 0.16 and 0.38 μm . The tooling for 352 MHz fourcell cavities is a ten-part steel die weighing about 6 tons for a price of about 100 KCHF.

A four-phase expansion process (after swaging) has been chosen, with intermediate annealing at 500°C for 30 minutes. Figure 4 shows the tube at each stage of its manufacture. Swaging reduced the diameter by 14.8%. During expansion, the maximal tangential deformation was 37% for the first phase, 30% for the second, 25% for the third and 12.5% for the last one.

After each expansion, geometrical and structural measurements are made on the cavity. Table 2 shows the main characteristics of each phase of hydroforming.

	INITIAL	SWAGING	1st PHASE	2nd PHASE	3rd PHASE	4th PHASE
ext. diameter (mm)	304	259	416.5	541.5	676.9	759.9
tangential def. (%)		-14.8	37	30	25	12.3
max. σ / min. σ (%)		0	67	109	161	193
min. thickness (mm)	9 ± 0.35		7.2 ± 0.27	5.7 ± 0.23	4.61 ± 0.31	3.67 ± 0.23
tube length (mm)	3403	3403	3106	2772	2409	2130
max. pressure (bar)		500	140	90	90	95
intern. roughness Ra (μm)	0.16/0.38		1.82	3.2		4.27

Table 2

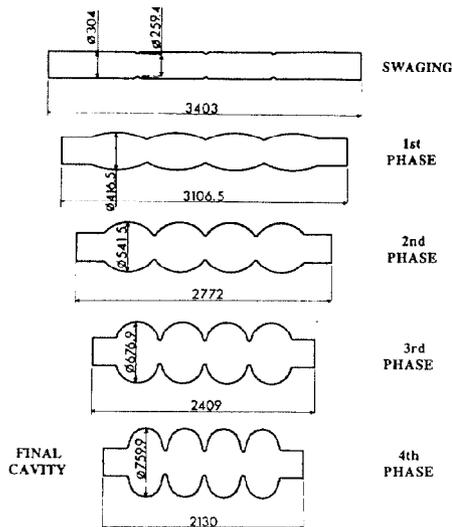


Figure 4

Geometrical measurements on the first cavity have shown that the external diameters are 0.2% smaller than expected, owing to a too low pressure during the final phase.

The final developed length of the cavity is 3297 mm, whilst the initial length was 3403 mm, corresponding to an average axial deformation of 3%. The final minimal thickness was of between 3.4 and 3.9 mm, dispersion resulting from the inaccuracy of the initial tube (not to required specifications) and an average value 2% higher than computed. As a consequence, the inner diameter is too small. In fact, the measurement gives an absolute frequency of 353.557 MHz, whilst the desired one was 352.209 MHz. This will be corrected by thinning the initial tube down to 6 mm and, if necessary, remachining the die.

The increase of roughness during the hydroforming process is very marked, but tends towards a finite value. The surface quality will be improved by chemical polishing and/or tumbling, but intermediate treatments between expansion phases are also to be considered.

In order to reduce cost and manufacturing time, an hydroforming process with only three expansion phases is now being tested. Niobium coating and RF measurements (quality factor and accelerating field) will follow.

Conclusion

It has been demonstrated that the hydroforming technique is applicable down to cavities in the 300 MHz range. The main advantages of this process, related to cost and to technical quality, are the suppression of welding, followed by obtaining of a better geometrical accuracy. The production of elliptical (instead of axisymmetric) cavities can also be envisaged. The expensive tooling, which is quickly amortized should permit the manufacture of up to one cavity per day. Improvements to and optimisation of this technique are in progress.

It seems to be impossible to manufacture larger tubes and therefore larger cavities, but hydroforming could be applied to the whole range of superconducting copper cavities. It could be a cheap way of manufacturing very large series in the GHz range.

References

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