SEAMLESS CAVITIES: the most creative topic in RF Superconductivity

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Abstract - In the RF Superconductivity field, the technology of seamless cavities is, among all other topics, perhaps the one that mostly requires a creative approach. More than elsewhere, this is the right place where researchers can give free rein to their imagination. The R&D on seamless multicell cavity is pushed forward in order to face the problem of a possible mass production at lower costs than those resulting from the traditional approach. After an outline of the basic mechanism under plastic deformations, several approaches to the problem are reviewed. Potentialities, advantages, and disadvantages of hydroforming, explosive forming, electroforming, and spinning are reported and compared. From a critical analysis of the current status of the art, the need for seamless tube fabrication appears compulsory. Even if there is a long way to go, there are research groups that lead the way, just by simply applying to cavities the already existing forming technologies. The reader will immediately realize that the problem of a low cost mass production is a difficult task, but at the same time definitely possible to solve.

Keywords: Seamless cavities, rf superconductivity, Niobium, cold-forming, hydroforming, explosive forming, spinning, deep-drawing, extrusion, flowturning.

1. The need of a new technology for large scale production

The new generation colliders require mass production of multicell superconducting cavities. Just 20.000 ninecell resonators would be required for TESLA. The standard fabrication technique consists in cutting circular blanks from bulk Niobium sheets, deep-drawing halfcells and Electron Beam (EB) welding them at the equator and at the iris under U.H.V.. There is a physicist wing believing that a so huge amount of resonators could be manufacturable in a traditional way [1]. In parallel there is a trend to research on alternative fabrication technology.

If we just stop to crude cost considerations, and consider deeper the TESLA case, we will see that the bare bulk Niobium cavity costs can be roughly shared in a) material costs and b) fabrication costs.

a) Material costs: the weight of a TTF resonator is a little less than 25 Kg. If we assume as 100% the fraction of successful resonators over the number of fabricated ones, and if we neglect the swarf coming from cutting disks from slabs, at least 500 Tons of high purity Niobium will be needed. At the moment it is difficult to buy "RRR > 250 Niobium" for less than 500 DM/Kg. However, it must be kept into account that if, by improving the construction technology reliability, the success probability can be rather close to 1, the scrap Niobium is far away from being zero.

b) Fabrication costs: Equipment, tooling and man-power constitute the main fabrication costs. Still considering the example of TESLA nine-cell cavities, each resonator requires nineteen EB welds in critical regions. Especially the equatorial ones are welds not easy to perform. Generally it is preferable to execute all the EB welds by an internal gun, since the weld surface is always nicer and smoother at the beam side rather than at the opposite one (nicer and smoother in this framework mean a weaker probability to occur for micro-cracks, craters and material projection). Internal welding however, becomes a severe limitation on the construction of high frequency cavities due to the difficulty of inserting the welding gun and the beam deflection magnet in the cell narrow bore. Moreover, because of the resonator wall much thinner than the equator diameter, not only scrupulous circularity tolerances must be respected when forming the half cells to weld, but also strong attention must be paid to the relative contractions of the halves in the meanwhile welding; this is particularly true in the case of textured sheets.

At the present nobody at the moment executes all the welds in just one run of the EB machine. Therefore the welding chamber must be opened around twenty times and each time the parts to be welded must be positioned within strict tolerance values. Ultra High Vacuum (UHV) must be created twenty times. In the best case maybe in future, welding times can be limited to ten pumping runs, being possible to align all the nine cells welded at the equator, and then execute the welds at the iris in only one run. In the case of bulk Niobium, the RRR values at the weld strongly depend on the vacuum reached in the EB machine. This implies that even in the most favourable case, pumping times cannot be much less than 100 hours per resonator, for a total of 2 millions of hours, that is more than two centuries working night and day, working with only one EB machine. The hypotheses of making 10 EB machines working in parallel, is no more comforting, since still more than 20 years would be required, and we have neglected the time needed for maintenance of the equipment. Of course we skip formulating any consideration about the possible cost of two centuries of man-power.

2. Some history about seamless resonators

Seamless resonators have come into the limelight only in recent years due to the mass production requirement for TESLA. However first attempts to form seamless resonators are dated to already almost twenty years ago. Maybe the first attempt of seamless cavity fabrication is referable to a patent application in 1973 for the construction of superconducting devices as AC transformers and gyroscopes, by electroplating Niobium in a fused salt bath onto a copper die that had to be removed at the end of the forming process [2]. The Niobium film is externally coated with porous tungsten by plasma spray. The refractory coating has the function of supporting the Niobium during the purification process by high temperature outgassing in UHV. In addition the porosity of the tungsten coating enables a more effective cooling in superfluid Helium.

First investigations about seamless cavities for particle accelerators were carried on at Cornell and at CERN where respectively Niobium [3] and Copper tubes [4,5] were bulged by hydroforming. The main limitation of such an approach has always been the need to perform hydroforming in multiple stages, because only by intermediate annealings one could avoid wall thinning and the consequent fracture at the equator during bulging.

The above mentioned research is satisfactorily covered by literature, while not much is known about the investigation on hydroforming carried around 15 years ago in Japan. In 1984 the Furukawa Electric Co Ltd patents the bulging of a longitudinally weld Niobium tube [6]. The tube is compressed in length during the bulging operation. The weld structure is recrystallized by repeated intermediate annealings.

Two other patents [7-8] are dated on the same year. In the former a Niobium thin film is deposited onto an Alluminum tube; subsequently the niobium surface is coated by a thin copper film onto which a thick Copper layer is applied. The multilayer is bulged by hydroforming, then the Alluminum die is removed. The latter is even simpler, since the same process is applied onto an Alluminum die having already the definitive internal resonator shape, avoiding in this way all the possibility of crack induced in the film during bulging. Of course two main drawbacks immediately leap to the eye: the die removal operation is not risk free. The step of dissolving Alluminum by acid can cause hydrogen embrittlement of Niobium, while melting it can cause an irreversible Alluminum migration across Nb grain boundaries.

Q-factors up to 5×10^9 and accelerating fields up to 9 MV/m are reached in the work reported in the Furukawa El. Co patent in 1986 [9]. A die is constructed by bulging an Alluminum tube and machining and lapping its external surface in order to reproduce the same shape of the cavity interior. The die is then coated with a thin nickel film acting as a diffusion barrier in order to prevent hydrogen (developed by the Alluminum chemical dissolving) from reaching the 10 micron thick niobium film that is subsequently deposited by ion plating. A thick copper layer is then electroplated onto Niobium. The multilayer is then reinforced by applying fiber-reinforced metal layers as composite fibers cloths of tungsten, carbon, and silicon carbide plated with copper. A copper pipe for liquid helium flow cooling is point-bond soldered to the structure external surface and then copper plated. The core is then dissolved and the first film is removed. The niobium is then electrochemically and chemically polished up to provide a mirror-like surface.

3. Forming by plastic deformations

Forming of a seamless cavities from a blank or a tube presupposes the possibility to apply plastic deformations to the material to shape. Under an acting stress caused by external forces, the material must deform like plastics without undergoing losses in cohesion. Stress and strain are correlated by a relationship, observable in tensile tests, that for convenience is graphed as in fig. 1, the so called stress-strain curve, that somehow characterizes the material intrinsic properties.

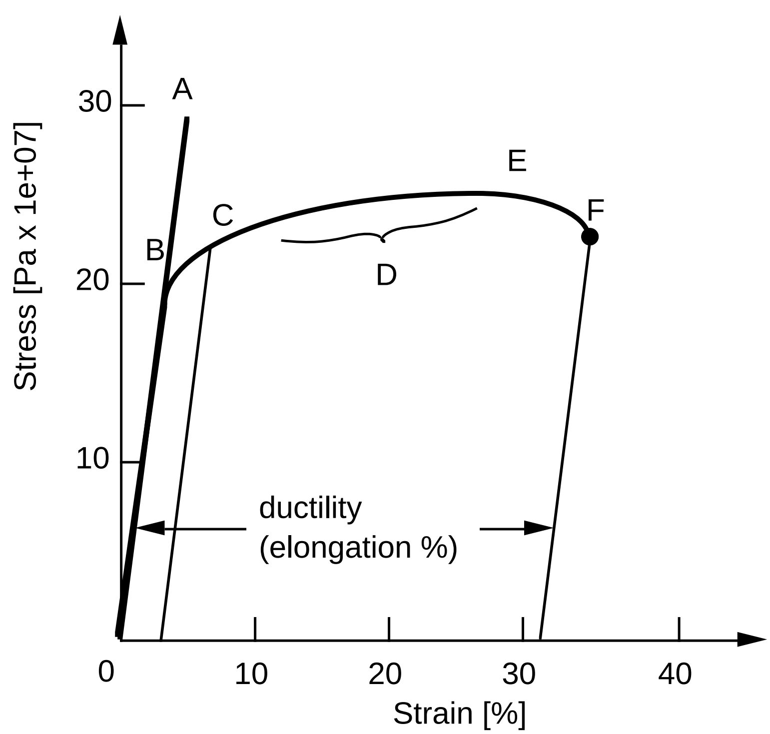

Fig. 1 A typical stress-strain curve for metallic materials

No permanent deformations are achieved in the elastic range of the curve where stress and strain are proportional and the Hooke's law $s = \mathbf{E}\ \varepsilon$ holds. The constant **E** is the Young modulus that is a parameter indicating the material rigidity. The curve is reversible up to the point B, after which the material starts to flow like plastics, showing permanent non-proportional elongation even after the stress is removed. The stress corresponding to the point B is named yielding stress. However it is often more handy to define the test stress (point C), as the stress required to produce the 0.5 % of plastic deformation. As the stress is increased, the material hardens (region D), up to when the maximum tensile stress is reached (point E), after which the material gets an area reduction or fractures. The total plastic deformation achieved by the sample at the fracture point is the material ductility and it is generally expressed in % elongation.

If a crystal is examined after a plastic deformation, one or more sets of thin parallel lines can be observed on the surface. At a better magnification, it will appear that such slip lines are caused by crystalline plane shifts of tens or hundreds of atomic layers. At low temperature the deformation will continue creating new slip planes, without changing the pre-existent lines. At higher temperatures, however, the slip lines will collect in rougher bands, between which lines can slip repeatedly.

If we take a monocrystal, the most relevant mechanism ruling plastic deformations is the slipping of atomic planes along certain planes and direction of the crystal lattice. As displayed in fig. 2, the atoms of the first line, stressed by a tangential force leave their equilibrium positions respect the ones of the second line, the displacement being proportional to the applied force strength. For overcoming the elastic regime, the force applied must be higher than the slip tangential tension. If this value is overcome, the atoms will fall in the attraction domain of the first neighbors. A new equilibrium configuration establishes, and the displacement is permanent.

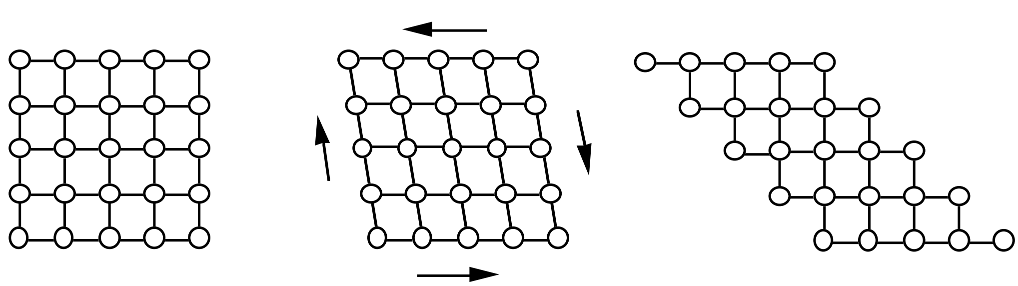

Fig. 2 Ideal model representation of plastic deformation of a crystal lattice by slipping, where all the atoms on both sides of the lattice planes are moved at the same time.

Slipping takes place preferably along certain planes and directions of the crystal lattice. The slip system is formed by a slip plane together with a slip direction lying therein. The number of slip systems has an effect on the plastic behaviour of metals. Just for example, due to a restricted number of slip systems, hexagonal cell metals can be deformed in a reduced manner.

The slip direction is however always the one encountering the highest atomic packaging density in the lattice, since slipping is favourite if associated to the minimum displacement energy. With its FCC crystal structure, Copper is one of the most plastic metals. The most common slipping system in a FCC metal is generally made of the plane (111) and the direction [101] and it is displayed in fig. 3a. There are however other 11 equivalent slip systems, since there are 4 equivalent planes in a cell and each of it has 3 slip directions. Among the slip systems of BCC metals, the most recurrent is the one characterized by the slip plane (101) and by the direction [11<u>1</u>] represented in fig. 3 b. The slip systems are 12 also for BCC metals. The case of Niobium is very interesting [10] because it is an exception among BCC metals, showing the system (101) [010].

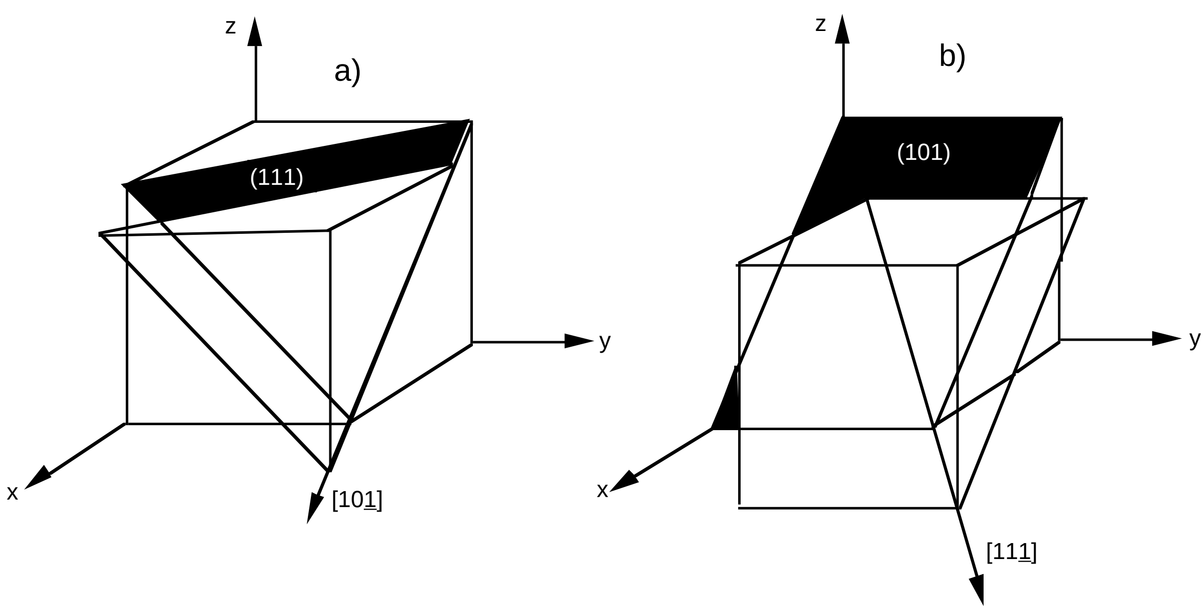

Fig. 3 a) Slipping system (111) [10<u>1</u>] for FCC metals; b) slipping system (101) [11<u>1</u>] for BCC metals. Among BCC metals, Niobium is a lucky exception since its anomalous slip direction [010] requires less energy for displacement if compared to the [11<u>1</u>].

The process can be compared to the slipping of a pack of playing cards one on each other. However all that is true for perfectly ordered monocrystals. In polycrystalline materials, the process is more complex, since each grain must deform in coherence with the deformation of the most neighbor grains. That means that a grain must be able to slip in any direction, but a slipping system yields only along a characteristic direction. Therefore a certain number of systems will slip simultaneously: some grains will slip in natural system under little stress applied, some others will require a higher strength, since less favourable slip systems are involved. This is the reason why polycrystalline metals require a yielding stress higher than monocrystals.

In ordinary life the real slip process however is different from the one foreseen by the binding energy calculations. The real needed forces are about a thousand times lower than theoretical values. The reason for that resides in the presence of dislocations that make the slip of atoms incremental, rather than simultaneous. Movement of the dislocations is the basic mechanism of plastic deformations (figure 4).

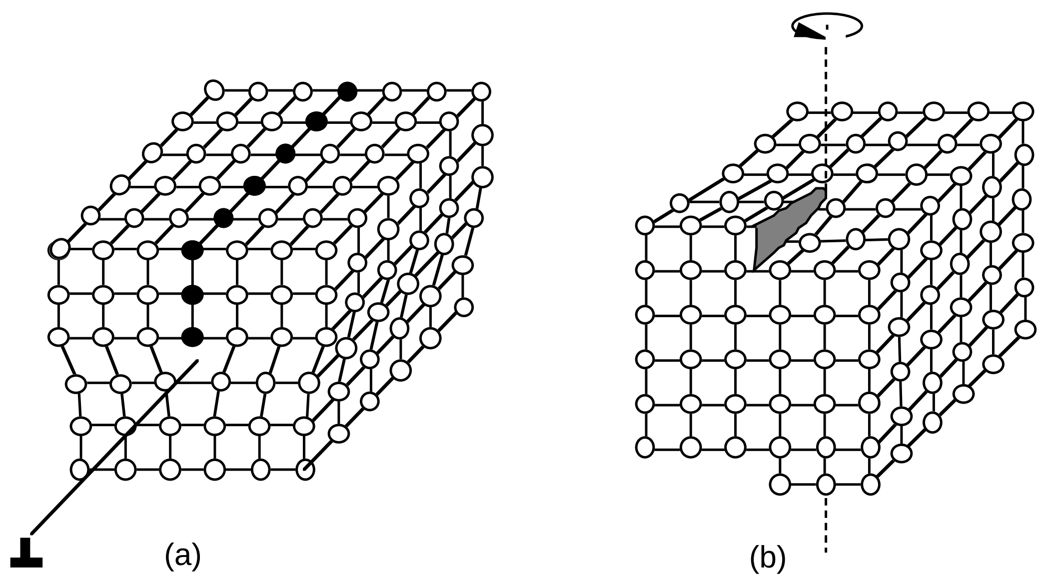

Fig. 4A dislocation can be split in two simpler components: a linear one (a), and a helicoidal one (b).

A hole in the lattice will propagate in the lattice as a wave, making that only a limited portion of coordinated atoms will slip, without involving all crystal planes. A rough model to represent plastic deformation by dislocation motion can be the motion of a caterpillar. An even more fitting example is the displacement of an heavy carpet: instead than dragging it bodily, one can create a longitudinal fold and making it flowing from one side to an other.

In a undeformed metal the dislocation density is typically of 10^{11} m^{-2}.

Forming increases definitely dislocations density (cold-rolled Copper can have up to 10^{16} m^{-2} dislocations). Dislocations produced by plastic deformations interact with dislocations moving along self-intersecting slipping systems, up to forming a bundle. This corresponds to the work hardening in the curve stress-strain. The higher the dislocation density is, the stronger the work hardening. Helicoidal dislocations must be only annealed in order to be recovered. Linear dislocations instead, whenever of opposite sign, can annihilate when encountering each other on the same plane.

Grain boundaries and impurities are obstacle to dislocations, since they destroy the crystal continuity. A dislocation can move only inside the grain in which it has been created. Hence, the smaller the grain size is, the more difficult the plastic deformation will be. An empirical relation, called the Petch equation, indeed holds:

$$\sigma_y = \sigma_i + \quad d^{-1/2}$$

being σ_y the yielding stress, **d** the grain size, a constant and σ_i the intrinsic interplane slipping resistance.

4. Superplastic forming

One of the most significant emerging technologies in metal forming is superplasticity, i.e. the capability of certain polycrystalline materials (at elevated temperatures and under controlled rates of deformation) to undergo extensive tensile plastic deformations. While a conventional metal or alloy in an ordinary tensile test would develop perhaps 30-40 % tensile elongation, elongations of several hundreds of percent are commonly documented in literature. For instance, elongation values up to 8000 % are found in commercial Alluminum bronze [11]. This is achieved at elevated temperatures and controlled strain rates. The other characteristic normally observed concurrently with the high tensile deformation is a substantial reduction in the flow stress of the material: the forces required can be as little as 1/2 to 1/20th that of the material under the same conditions. Are these two factors (high formability and low flow stress) that provide the exceptional potential of superplastic forming.

The most fundamental requirements for superplasticity are i) the fine or even ultrafine grain size, ii) the deformation temperature usually higher than one-half the absolute melting point, iii) the strain rate control, since superplasticity is observed only in a specified strain rate range.

Superplastic deformation of metallic materials has one primary feature: the flow stress σ is highly sensitive to the strain rate ε. The relation between them can be expressed through the equation

$$\sigma = k\ \varepsilon^{m}$$

where **k** is a material constant depending upon the test temperature, microstructure and defect structure, **m** is the so-called strain rate sensitivity exponent describing the capability of the material to suppress necking.

The index m is defined as $d(\log \sigma)/d(\log \varepsilon)$, and it is generally graphically determined by the slope of a $\log \sigma$ versus $\log \varepsilon$ plot. For non superplastic materials **m** values range from **0.02** to **0.25**, even at temperatures up to $0.9\ T_m$. For heated polymers **m** ranges from **0.3** to **1**. For hot glass $m = 1$. For metallic materials clear indications of superplastic behaviour exist when $T > T_m$ and $m \geq 0.3$.

At the current status of the phenomenon knowledge, pure niobium is not known to be superplastic. However no fundamental limitations seem to exist preventing superplasticity, although the main problem to solve would be the stability of a fine grain size, difficult to retain at elevated temperatures. In fact unless the grain growth is inhibited by some microstructural feature, this grain size would normally increase beyond the limit of superplasticity, once the temperature achieves more than one half the melting point. This is the reason why relatively few materials exhibit superplasticity. Nevertheless it would be definitely worthwhile launching a focused research program aiming to investigate if Niobium is superplastic or not. The advantages coming from superplastic forming of TESLA cavities would be incommensurable. Multicell cavities would be formable in one shot at relatively low pressure (usually < 300 PSI), by means of inexpensive tooling and single configurational dies.

5. The current forming situation

Nevertheless a plethora of forming processes [12] would be successfully applicable to the fabrication of seamless cavities, only a few among the most common are currently investigated.

5.1 Hydroforming

What is commonly named hydroforming is more rigourously reported in literature under the name of hydrostatic bulging. It consists in expanding a tubular part by applying internal pressure to the inside of the workpiece contained in an external die split in two parts for extracting the piece after forming. Pressure can be applied by compressing a fluid, by pressing lead balls or a rubber, usually polyurethane.

Cavities of the reentrant type have diameters at the equator around two-three times that of cutoffs, but even tubes of Copper (that is definitely the most plastic metal) can be enlarged with difficulty to more than 30 % of the blank diameter, unless of progressive workpiece annealings. Of course, the method is competitive with other cold forming methods as spinning, only if the number of annealings can be kept to the minimum or ideally to zero. In order to achieve this, one can devise a stratagem such as:

• acting directly on material structure defining purity, grain size and texture of the blank tube.

• sizing conveniently the original starting diameter. The tube is indeed initially swaged at the ends and then bulged.

• designing in clever way the external die, since the reduction of wall thickness is minimized by freedom of the workpiece to shorten during bulging.

• investigating the effect on material formability of such parameters as forming temperature, temperature of the intermediate annealing (whenever needed), and forming rate. The forming temperature of a resonator is kept to room temperature for simplicity and in order to avoid oxidation. The annealing temperature must be kept as low as possible, in order to avoid grain growth and the consequent orange peel. The OFHC copper hardness falls already to 45 HV after a 1 hour annealing at 200°C. So it is unneeded to go higher, just because grain growth starts to be significant already once overcame 250°C. Forming rate is a more controversial parameter, since high values can extend elongation limits, but the risk of buckling and fracture becomes sensitively higher. Forming rate in hydroforming depends on internal pressure. Forming velocities can change appreciably compared to the theoretical values during loading, because of the compressibility of the fluid medium and the elastic deformation of the punch. Hydroforming by internal pressures up to 2500 Bar, for example allows to obtain commercial seamless bicycle frames of a geometry unachievable in conventional way. At so high pressures water is substituted by more proper fluids.

Problems can even arise by the expansion of the fluid medium during the steep force drop. Moreover, for very high pressures, safety considerations become more and more strict. Indeed in order to prevent a danger of sparking a fire in the hydraulic oil in the event of leak, special antideflagrable fluids are advised. At very high pressures mineral oil can spark. If burning, fluids form gases which put out the flame. Besides to water, media commonly used in commercial hydrostatic bulging are oil in water and water in oil emulsions, water glycol solutions, Chlorinated carbohydrates, pure phosphoric acid, silicone and fluorocarbohydrates. At more moderate pressures, polyurethane is used as expanding medium. The force to deform polyurethane and move the metal is transmitted to the punch by the ram of either a mechanical or hydraulic press. The punch can be indifferently on the press bed or on the slide. In order to compensate the equator wall thinning by the piece shortening during the stroke, the two die half-sections must be moved toward each other. In operation polyurethane acts as a solid when deflected, the volume remaining constant, while changing the shape. During bulging the rubber changes the vertical force of the ram to uniform multidirectional force on the blank. When the force is removed on the upstroke of the ram, polyurethane returns to its original shape, permitting easy withdrawal of the punch. During forming, the amount of tube bulged is determined by the degree of deflection of the urethane punch. The main advantage of polyurethane over fluids, consists in getting rid of seals and leakage problems. Moreover it is economical, highly wear, abrasion resistant and will not mar the inside of the workpiece. However, care should be taken to avoid cutting the polyurethane.

The advantage of hydroforming is the high speed production since for a large number of pieces, the equipment is readily adaptable to be automated. Hydroforming of multicell cavities can mean a significant economy over alternative manufacture methods. In addition to the relative economy of tooling and equipment, it must be mentioned the enhanced strength and the high dimensional stability and consistency of shape. Referring to superconducting resonators, one limit of hydroforming instead consists in the use of an external die, that insures the strict control of tolerances for the cavity exterior, but not for the interior (that instead defines the frequency).

Since coming after the pioneering work done with hot forming at Cornell in 1983 [13,14], hydroforming has not been the first attempt to produce seamless multicell cavities for beta 1 particles. However, if not the first, it has been certainly the most investigated, as pursued by several institutions and companies.

Copper cavities for Niobium sputtering have been hydroformed at CERN by Hauviller [5] with only two intermediate annealings by preliminary swaging of the tube at the iris, then expanding it at the equator (fig. 5).

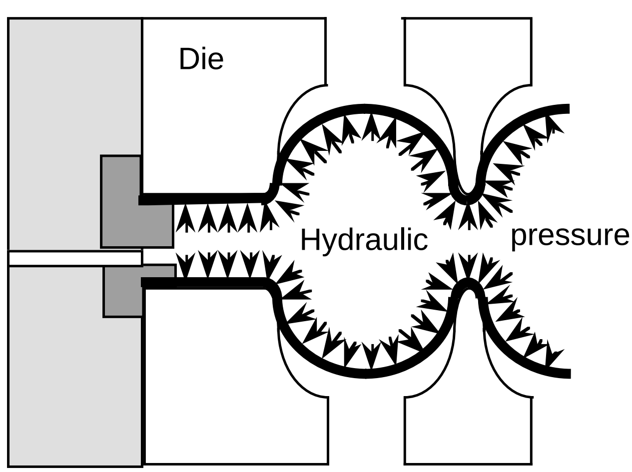

Fig. 5. Principle of Copper multicell hydroforming at CERN [15]

No annealings were instead required by Butting, a German Company, that has hydroformed a Copper 1.3 GHz TESLA-shape two cell cavity [14]. Recently also at DESY a research program aiming to hydroform Niobium has been launched. Seamless Niobium tubes are produced by back extrusion from Niobium billet. In forming tests hydraulic expansion ratios up to 53% have been achieved without annealing [16], being the expansion ratio defined as

$$\psi[\%] = \frac{D_1 - D_0}{D_0} .100 \; ; \qquad D_0 = \text{initial diameter, } D_1 = \text{final diameter.}$$

The studies carried on 1.3 GHz geometry by Antoine at Saclay [17], even if not yet completed, are certainly noteworthy. Niobium seamless tubes are produced by flow turning short cups back extruded from Niobium billets. Tubes are swaged by 20% then bulged. Only two steps, hence one annealing, are calculated as necessary for 200 RRR material, while five steps are predicted for 20 RRR Niobium. Up to now expansion ratios of 208% instead of the 216% longed-for have been achieved (fig. 6). Fractures are imputed to grain size dispersion and microdamaging of the tube.

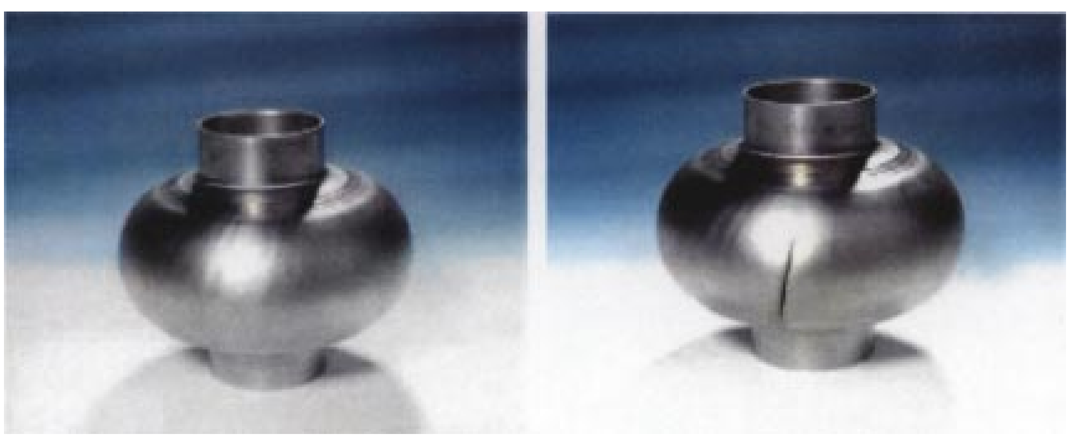

Fig. 6. Hydroforming tests performed at Saclay: rupture happened at 208% expansion instead of the 216% aimed [courtesy C. Antoine].

5.2 Explosive forming

This process is generally known as shock wave forming. A water filled tube can be instantaneously bulged by the high pressure that results from the detonation of an explosive. Pressure is built up steadily but irregularly: it is transmitted as either pressure wave or a shock wave generated by the conversion to kinetic energy of the chemical energy available in the explosives. The explosive compounds serve as energy-transmitting media when they are ignited under water to explode, producing a large quantity of gaseous products from the violent combustion. Due to the very short time for the energy conversion, the mass inertia of the water hardly allows an increase in volume enlargement. Thus the pressure built up propagates in the form of a shock wave. As water is relatively incompressible, the pressure is equal in all directions. When a shock wave propagating through water reaches a metal, then two waves are spread from the transition front water-metal, one propagating through the metal and the other reflected back through water. As the shock wave reaches the workpiece surface, the part of kinetic energy which is not lost in reflection of the wave, is transferred over. During this phenomenon the workpiece is accelerated to high velocity. Efficiency increases with the density of the medium, Therefore water is used instead of air. Molten Alluminum is used some times for special application at high forming temperatures.

In most cases the spacing between the die and the workpiece has to be evacuated because the air located there cannot escape completely during the forming operation. Otherwise the highly compressed air quantity would create undesirable bulges or fractures on the workpiece, and the die surface can paradoxically even melt locally because of the intense heat generated by compression of the trapped air.

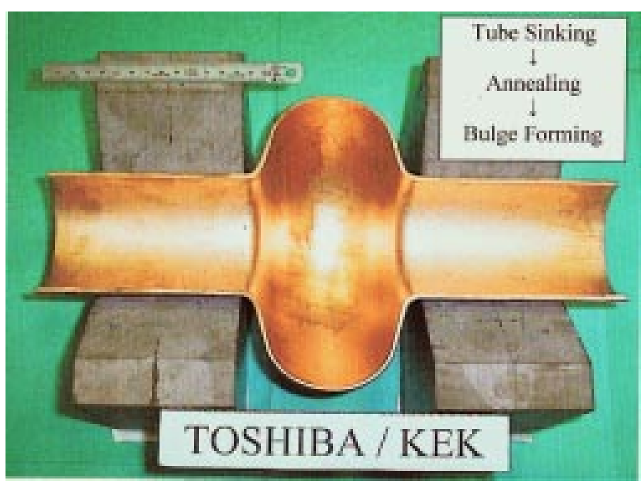

Fig. 7 Cut of a resonator formed by explosive bulging. The die consists of four sections, each divisible into half [courtesy K. Saito].

Explosive forming has been partly investigated by the author in 1992 for 1.5 GHz prototype fabrication. Some experiments were required in order to arrive at the optimum in dosing explosive and provide the escape of unwanted air between tube and die. One Copper monocell with an expansion ratio of 145% was produced in five steps (four intermediate annealings) starting from a longitudinal welded tube of 70 mm diameter. Of course, less annealings would have been needed whenever starting from an end-swaged tube as for hydroforming. The die was made in tempered low carbon steel set into a armoured matrix with stiffening ribs. The adopted explosive was Pentaerytritol tetranitrate (PETN) in pressed granules inserted into a small plastic bag. One unsolved problem was the contamination due to such plastic particles embedded onto the cavity internal surface during the explosion. However, this research plan was abandoned due to the need of concentrating on the spinning program in parallel launched at LNL, but showing results much more promising and easy to obtain.

Much more complete results have been obtained at KEK (fig. 7), where even a TESLA shape Copper three cells has been explosively formed in only two steps [18]. This means only one intermediate annealing, being the expansion limited to 60 %.

Limiting ourselves to the pure forming point of view, and not considering other problems, as the impossibility to perform 1400°C firing of the cavity, the Japanese have a big advantage on the others: the technology of Nb/Cu Copper. With such a material, if the Copper thickness is larger than that of Niobium, the difference in mechanical properties between the two materials is overcome. One can form Niobium using almost Copper forming parameters.

In parallel KEK has developed in collaboration with the Japanese industry also tests on hydrostatic bulging, in order to combine the two techniques, using hydroforming as an intermediate step before the final explosive forming. In the author opinion, the combination of the different forming techniques is often a more expensive approach, since double equipment, double tooling and double expertise are required. However, recently the same KEK group, in collaboration with TOSHIBA [19], has succeeded in hydroforming a L-band Copper single cell, by sinking the beam pipes and hydroforming the central part. Unfortunately intermediate annealings were necessary for sinking.

The main advantage of applying explosive forming to cavities resides in the inexpensiveness and in the high efficiency of the process. Compared to many metal-working process, machines needed for explosive forming require little investment, consume less energy, and die costs are low. However, explosive forming releases all its potential when dealing with tricky shape workpieces having large areas for which nominal forming forces of the conventional machines do not suffice, or when forming materials which can be formed easily in no other way. It must be emphasized moreover that the embossing and coining accuracy achieved by the process is certainly superior to any other conventional process. However, given the simple geometry of cavities, in the author opinion there are a few contingencies which tend to prefer other forming technologies to explosive forming: the possibility to execute this job only in authorized bunkers and strict safety regulations, handling and storing explosive, hazard of fire, uncontrollable noise, and loss due to deterioration of explosives.

5.3 Electroforming

Galvanoplastic is a well known technique in the field of seamless cavities [20, 21] since it has been tried both for Niobium and for Copper bases for Niobium sputtering. Thick layers of Niobium can be deposited by Organometallic CVD* and by electroforming in bath of fused salts [22, 23]. The preferred salt composition of depositing niobium consists of potassium fluoride, Sodium fluoride, Lithium Fluoride and Potassium Niobium Fluoride. The proportions of fluorides in the melt, the temperature of the melt and the electrolyzing current density are adjusted to produce a dense, fine grain, structurally coherent deposit. The main problem to solve is the growth of a porous dentritic structure. In order to avoid it one can add to the solution moderators or to throw current in pulsed mode. The cavity must be necessarily titanified in UHV at about 1400°C according the standard procedure.

Copper is easier material to electroform; moreover a widespread industrial experience exists. Mainly four different recipe families can provide thick coherent Copper layers: fluoborate, pyrophosphate, amine or sulfammate-based baths [24].

However, additives are almost not less important than Copper salts. There are striking effects on electrocrystallization processes due to the adding of small concentrations of addition agents, ranging from a few mg/l to a few percent.

The function and mechanism of additives in electroforming solutions have not been clearly understood and their discovery has been so far <u>mostly empirical</u>. Nonetheless their use is extremely important for the structure of the deposit. In such a framework it is maybe worthwhile to report the early sixties anecdote of SLAC electroformed low Oxygen Copper deposits for NASA's space shuttle main engine [25]. The SLAC people experienced much difficulty in attempting to electroform a good deposit, although exactly the same recipe of a German firm capable of producing low Oxygen deposits was used. The only appreciable difference was that in Germany, the plating solution was kept in an oak tank, while at SLAC plastic lined metal tanks were used. With time, the German solution was leaching something from the oak that gave to the solution a greenish colour unlike the bluish colour of copper sulphate solutions. Later on, the need for a deeper understanding showed that a very small amount of sugar was leached from the wood [26]. It turns out that all the pentoses are suitable for use in the copper sulphate solution, e.g. xylose, arabinose, ribose and lyxose. These materials act as oxygen scavengers in the solution by pickling up oxygen. This prevents the anodes from being oxidized and leading to this oxygen being incorporated in the deposit.

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* Up to now literature displays only examples of reduced area coatings moreover with a purity not enough high for our application.

Many other examples can be found, and very often the common theme is that some very minor ingredient and in very small concentration provide the difference between the success or the failure of a given process. For Copper indeed some of the most effective additives used in the past contain glue, dextrose, phenosulphonic acid, molasses and thiourea. Many of the present day commercially available brighteners contain carriers, or levelers and brighteners. Carriers are typically polyalkylene glycol type polymers with a molecular weight around 2000, levelers are typically alkane surfactants containing sulphonic acid and amine or amide functionalities, and brighteners are typically propane sulphonic acids derivatized with surface active groups containing pendant sulphur atoms [27-29].

Additives are often high molecular weight organic compounds or colloid since small ions or molecules are generally not very effective. They can be classified into four main categories [30]: grain refiners; dentrite and roughness inhibitors; leveling agents; wetting agents and surfactants.

Normal electrodeposition accentuates roughness by putting more deposit on the peaks than in the valleys of a plated surface since the current density is higher at peaks, because of a stronger electric field. Leveling agents are preferentially adsorbed on the high points of the substrate where they inhibit deposition working as insulator [31]. The effects of additives are also displayed by changes in polarization characteristics of the cathode. There is an effect of absorption on the substrate or by forming complexes with the metal. The investigation of the curve of developed cathodic overpotential versus additive concentration is a good tool against porous and dentritic deposits [32]. Although empirically, the role of additives in Copper electroforming is an intensively studied subject.

For Copper cavities done by electroforming it will be unavoidable incorporating even a small part of the additive. Niobium sputtered films however need an absolute pure substrate, in order to prevent diffusion of contamination from the substrate to the film. Additives are avoided by means of pulsed plating, as in the research launched at CERN [33] on 1.5 GHz electroformed Copper monocells. High purity dense Copper cavities have been deposited on a previously metallized glass die, having the exactly shape of the cavity interior and that goes chemically dissolved after forming. Due to the optical finishing of the glass surface, cavities with practical no internal roughness have been produced. The sputtering of Nb films into such cavities is under investigation [34].

5.4 Spinning

Spinning is a chipless production method of forming axially symmetrical hollow parts of almost any shape. It is a point deformation process by which a metal disc, or a cylindrical preformed hollow component is plastically deformed by axial or radial motions of a tool or rollers acting onto a workpiece clamped against a rotating chuck. It is a characteristic of this process that the movement of tools onto a rotating piece, acts upon a very localized area where plastic flow takes place.

Spinning belongs to the tension-compression forming process since tangential compressive and radial tensile stresses are generated in the deformation zone just as in deep drawing. In contrast, flow turning (spinning with wall thickness reduction) is a compressive forming process like rolling. Under flow forming the standard draws a further distinction between shear forming (US: flow turning) where the starting piece is a blank or a cup, and cylindrical flow forming where a short thick wall tube or a bush is plastically ironed to a longer and thinner one.

Many process variables have to be considered when spinning from a disk blank, in order to achieve good trueness of shape, dimensional accuracy, surface finish and wall thickness profile and tolerances. On the basis of empirical considerations, the following parameters have been recognized to govern the final result [35-37].

Workpiece parameters: blank diameter and thickness; shape and size of the final piece to spin.

Material parameters: Flow curve; anisotropy; compressive modulus; compressive yield strength.

Tooling parameters: Shape, size and finishing of the mandrel; diameter, nose radius and shoulder radius of the roller; type and quantity of lubricant.

Machine parameter: Positional accuracy; machine rigidity, operational distance between headstock and tailstock, maximum radius of acceptable blank.

Process parameters: Number of rollers; roller feed speed; angular speed of the rotation chuck; forming force (tangential, axial and radial components); blank support force;

After some spinning practice, the role of each of those parameters can be learned without big difficulties. It is needed only a certain systematic approach in making several tests in which all parameters are kept unchanged and only one parameter is varied. There are instead a few parameters requiring test over test even from the most skilled spinner. They are: the design of preforms (intermediate shape mandrels), the roller path and the number and the direction of forming passes.

As the roller passes on the workpiece, the blank gets smaller and smaller in diameter, until the diameter of the spinning chuck is reached. This is possible only by inducing tangential compressive stress in the material. As a consequence, the material is compressed in tangential direction, particularly towards the edge of the blank. There are strict limits, however, to this process. As the load increases, the resistance to buckling is overcome, leading to the formation of wrinkles [38-40]. The aim is to keep the applied load within limits by progressively forming the blank in a series of steps rather than in one pass.

Figure 8 shows typical shapes at the different stages, whereby a distinction must be drawn between movements towards the blank outer edge and movements back towards the blank support.

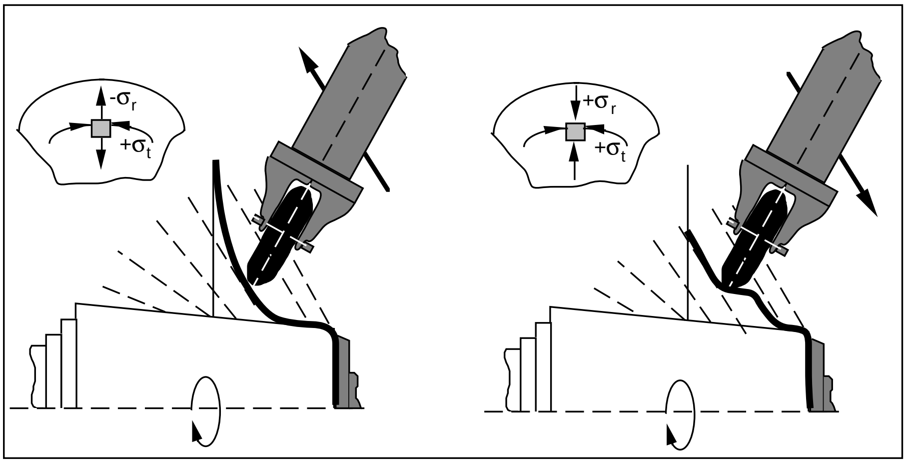

Fig. 8 Development of work zone and material stress during intermediate stages of spinning. The workpiece is shaped with a roller in several increments until the final shape is reached. A material element in the deformation zone is loaded by radial tensile and tangential compressive stresses. Let's define $+\sigma_t$ = tangential stress, $-\sigma_r$ = radial tensile stress, $+\sigma_r$ = radial compressive stress.

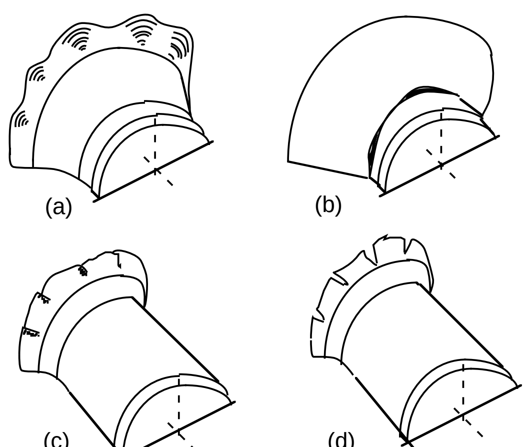

Fig. 9 Typical failures in spinning [12]: a) buckling due to tangential compressive strain; b) splitting due to radial tensile strain; c) splitting due to tangential compressive and bending strain; d) splitting due to tangential tensile strain after flipping the edge of the blank over.

Basically the tendency to wrinkle is dependent on the relationship between metal thickness and the area of the blank which, being to be formed, is not clamped. Also material strength has a direct effect on the limits to tangential loading: a thin large diameter blank will require definitely more intermediate steps than a smaller diameter thick blank. The critical parameter is however the ratio **(v/ω)** between the feed speed **v** and the angular speed of the rotating part ω. Increasing **v** or decreasing ω will favour wrinkles appearing. For a given material and assigned the cinematic conditions, lowering the angle a between lathe axis and mandrel surface or increasing the roller nose radius will also provide a higher wrinkles probability.

Subsequently radial cracks can form in the outermost portion of the workpiece at the end of the process when wrinkles removed by continued spinning (fig. 9).

Spinning and flow turning are applicable to almost any cold-formable material. After superplasticity, spinning is the only deformation process able to achieve elongations more than 1000%. Surprisingly the elongation limit, the starting of necking regions and all what is a limitation in hydroforming, become not important for the elongation limits of fig. 1.

Fig. 10 The first two seamless multicell bulk Niobium cavities ever done. Spun in LNL they will be characterized in DESY.

At LNL spinning has been applied by the author to the construction of seamless TESLA-shape cavity prototypes [41-45]: Niobium multicell cavities can be cold-formed starting from a circular blank, with a production rate of one-cell per hour and without any annealing (fig. 10).

The quality of the final result depends on the tenacity and viscosity of the lubricant used and its ability to adhere to the rotating blank. The lubricant is applied to the blank with a swab or a brush before loading it into the lathe. Additional lubricant is added during spinning as judged necessary to avoid the tool from scraping the surface or jamming, and to limit the amount of heat generated. Animal fat and soap have been experienced by the author as the more performant and the less contaminant. Niobium has been experienced to be not more difficult than Copper to spin. The shape of rollers is different. Steel tools cannot be used for copper, since Steel tends to gall with Niobium. The feeding velocity is lower, due to the fact that Niobium has a tendency to shrink less than Copper.

In Figure 11 and fig. 12, some moments of the spinning process are displayed.

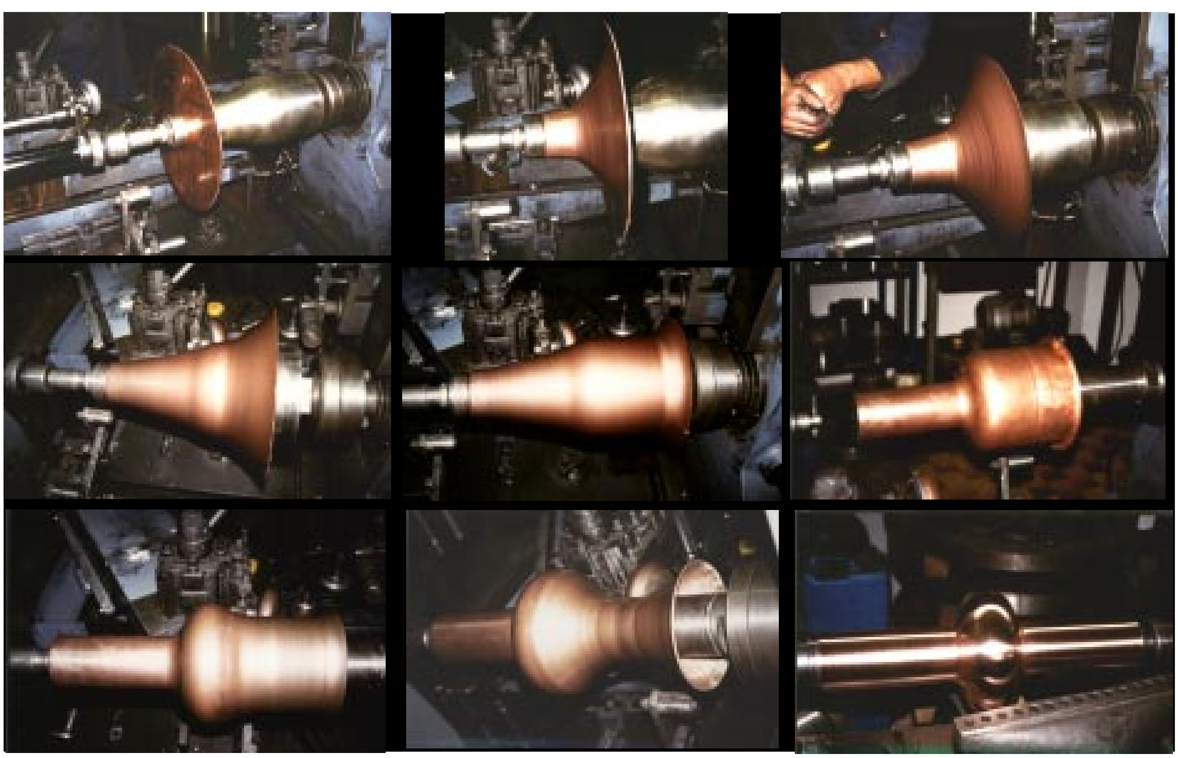

Fig. 11 Spinning of a 1.5 GHz copper multicell from a circular blank.

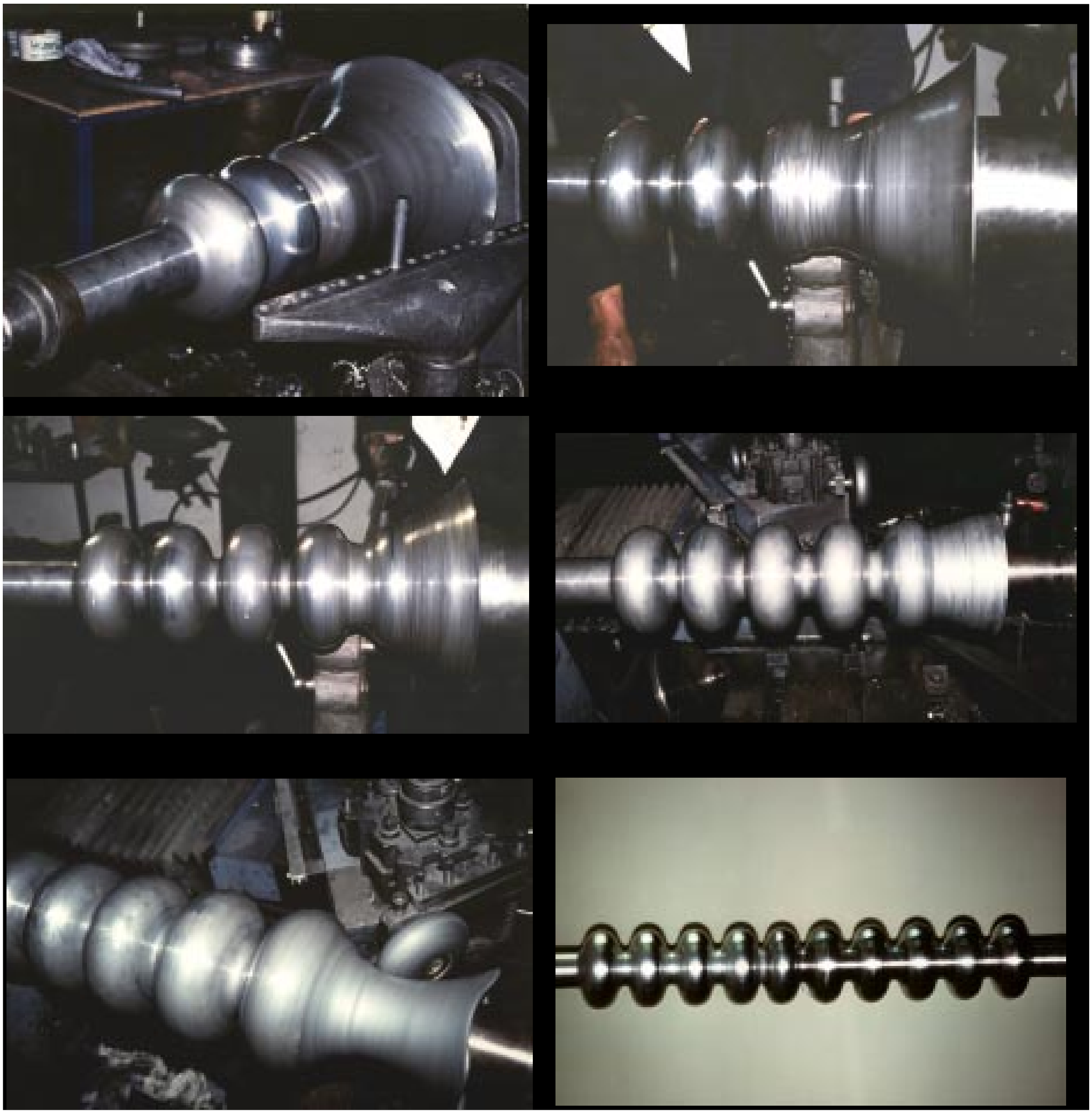

Fig. 12 Spinning of a 1.5 GHz Alluminum multicell prototype from a circular blank.

Cavities of both frequencies 1.5 GHz and 1.3 GHz can be spun. Just starting from the simple blank, the fabrication time of a monocell, is of about one hour, while the time needed for a multicell is of the order of one hour per cell. Both Copper and Niobium are cold worked. That means that <u>no intermediate annealings are required during forming</u>. The great advantage of spinning consists in the possibility in fabricating one ninecell in only one day. The most evident drawback is that at the moment a manual process is adopted, so the fabrication is subject to the worker skill, concentration and mood. However at regime, every thing can be automatized without big difficulty and the fabrication time can be much more decreased.

Spinning is performed in two set-ups and requires the use of two mandrels: a truncated cone pre-form mandrel and the final mandrel in the shape of the finished resonator. The cells of the mandrel are collapsible, consisting in an assembly of sectors held in place by some key-sectors. When the keys are removed, the mandrel collapses and the remaining sectors can be removed from the spun resonator one by one (fig. 13).

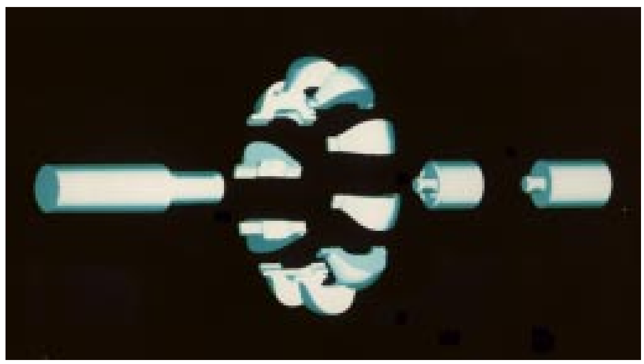

Fig. 13. Exploded view of the collapsible mandrel for 1.5 GHz cavities.

Multicell cavities can be equally spun both from a circular blank and from a tube. Spinning a tube is simpler and it guaranties a more uniform wall thickness. Cell by cell, the forming operation is always the same except for the final half-cells. Spinning from a planar disk is equally feasible, but it requires greater attention. The blank is first spun into a conical preform, then into a cavity. Cell by cell, the material required for the cells still to form, is shaped in a frustum that changes in thickness and shape as more cells are spun.

The first two spun 1.3 GHz seamless monocells fabricated by the author from a RRR 300 Niobium slab have been chemically processed then RF characterized at DESY by Pekeler [46]. The cavity 1P3 was spun with a thickness reduction, greater than the one called 1P4.

The 1P3 resonator has been tested twice up to now after a total of 50 mm and 120 mm etching of the inner surface. The 1P4 was tested twice, after a 130 mm etching, after heat-treatment at 800°C plus additional 100 μm, and after additional etching of 60 μm. The cavity improved from 20 MV/m to 23 MV/m to 25 MV/m (fig. 14). In both cavities the measured Q-slope in not accompanied by field emission. Moreover, there is a clear evidence that spun cavities require a much deeper chemical etching of the inner surface than standard equatorially weld cavities.

Both the monocells are in queue for further chemical processing and rf measurement. Also the seamless four-cell and the five-cell of fig. 10 have been sent from LNL to DESY, for EB welding of cut-off tube, processing and RF characterization.

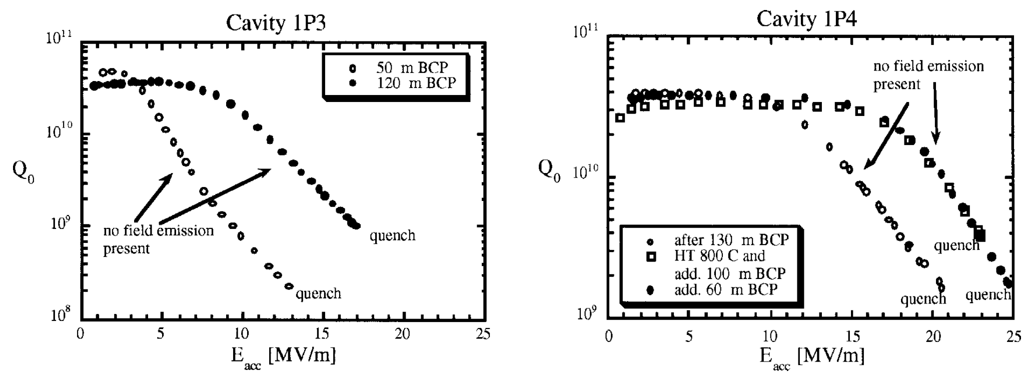

Fig. 14. Performances of first bulk Niobium 1.3 GHz monocells spun in LNL and characterized in DESY [46].

Accelerating gradients up to 25 MV/m have been measured also by Kneisel [47] at TJNAF on a bulk Niobium spun 1.5 GHz seamless monocell. This cavity, spun at LNL by the author from a 250 RRR Niobium blank, was heat-treated at 1000°C then sputtered at CERN with a Niobium film onto the Niobium substrate** , then it was send to TJNAF, were the film was removed together with additional 20 µm. The cavity reached 22 MV/m, then, this value was brought to 25 MV/m, but with some Q-decrement, after grinding of some rough areas (fig. 15). The lower Q-value is suspected to have been caused by an insufficient removal of the grinding particles embedded into Niobium.

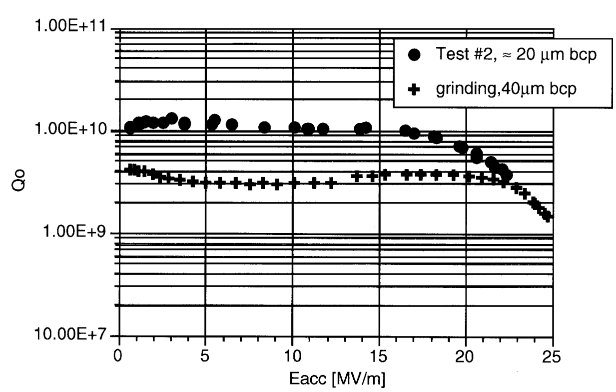

Fig. 15. Performance of a seamless 1.5 GHz cavity spun in LNL, sputtered at CERN and chemically processed and characterized in TJNAF [47].

** The reason for sputtering Niobium onto Niobium lays in the framework of CERN investigation of Niobium sputtered cavities. The ideas is to distinguish the role of the film by that of the substrate, by comparing Niobium sputtered copper cavities with Niobium sputtered Niobium cavities. Of course the substrate needed to be fabricated in identical way by the same technique [34].

Spun seamless cavities have given also surprising results in the field of sputtered Nb/Cu resonators. At CERN indeed Niobium film has been sputtered onto Copper cavities, both those hydroformed by Hauviller [4,5] and those spun by the author. Spun cavities exhibit on average definitely better results than hydroformed cavities, being the latter affected by a more evident Q-degradation versus accelerating field than the former [34]. Fig. 16 displays the Q-slope at 1.7 K plotted as a function of residual resistance. It can be observed that spun cavities (round symbols) lie closer to the origin of hydroformed ones (square symbols).

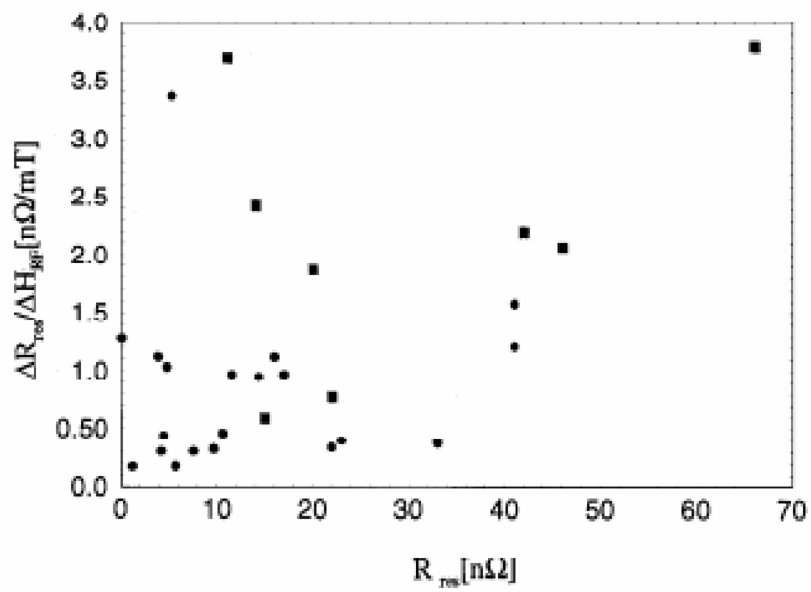

Fig. 16. Q-Slope versus residual resistance for Niobium sputtered Cu cavities. The round symbols refer to spun cavities, the square ones to hydroformed [34].

In the author opinion, the reason why spun cavities behave better than hydroforming lays in the grain structure resulting from the different forming technique. It must be kept into account that spinning works in compressive stress regime, while hydroforming in tensile stress regime. Looking for example at grain boundaries: in one case they are smashed one onto the other in a strongly compact structure; in the other case grain boundaries are dilated. Even if specific measurements have not been done, it is intuitive that, during the sputtering process, any impurity diffusing across grain boundaries from the bulk to the Niobium film, will find a more difficult path in a “compact” structure where grains are compressed one onto the other, rather than in a “dilated” structure.

Up to now all delivered spun cavity have provided high level results. From the reported data, it is evident that forming cavities by spinning is a technology to keep into account for mass production, both because of promising results, and for the fabrication cost abatement.

5.5 Stiffening of thin-wall Nb cavities by Cu plasma spray.

Proposed by the Orsay group [48], this approach is not a fabrication method of seamless cavities, but it can be directly connected to the improvement of seamless cavities. By this method cavities thinner than the standard ones can be externally Copper coated by plasma spray.

A series of 3 GHz cavities has been fabricated by deep drawing and EB welding using 40 RRR Niobium sheets of 0.5 mm thickness. The cavities were heat treated at 1200°C with a titanium getter before Cu plasma spray. The first two tested cavities (fig. 17) have a Q in the range 10^9 at 1.8 K and are limited by quench at field values around 15 MV/m. Taking benefit from the thermal conductivity and porosity of the sprayed copper layer (resulting in an increase of the heat transfer surface in superfluid helium), the quench fields measured before and after Cu plasma spraying are the same. Tests with high purity Niobium and at 1.3 GHz are in programme.

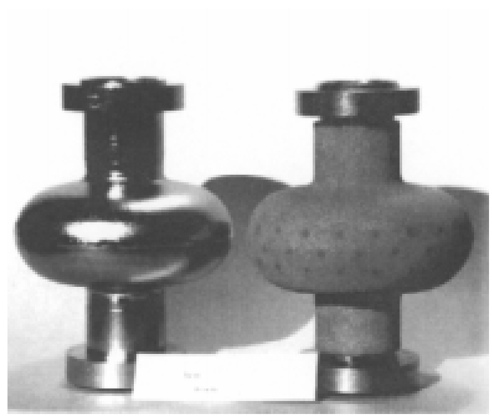

Fig. 17 A 3 GHz thin Niobium wall resonator [48] without and with Copper plasma spraying [courtesy M. Fouaidy].

Stiffening thin wall Niobium resonators is a technique becoming particularly interesting to apply to seamless cavities, where the search for uniform wall thickness is just the most difficult and time consuming problem to solve. Hence it would be worthwhile to apply the technique to hydroformed cavities and to spun cavities, where a few tenths of millimeter cavities already exist and are easy to do.

6. Seamless tube forming

Disposing of seamless Niobium and/or Copper tubes is of great help for spinning seamless multicell resonators, while it is definitely a need for the other forming techniques.

The most easy way for fabricating a tube consists in rolling one sheet and E.B welding it longitudinally. In this regard it has been experimented by the author that the spinning of a welded tube is a problem easy to solve. The welded tube should be recalibrated by spinning onto a cylindrical mandrel of little lower diameter: after spinning, EB welds result tenacious and even invisible to the naked eye. Of course proper rollers must be used. The best results can be obtained by longitudinally welding a tube of higher thickness and reducing it to a thinner one, by flowturning on a three roller machine. The only problem lays in the danger of incorporating dust and all the other contamination (lubricant or even air) trapped in the weld due to the presence of roughness, craters and other imperfections.

If such a tube must be hydroformed or even explosively formed or any other tensile stress based method, the problem become more severe. In order to avoid fractures, then the grain structure of the weld and its close zone must be carefully retreated in order to get uniform grain structure. Of course, all these problems vanish when using seamless tubes.

Although many techniques can be applied for seamless tube forming, only few of them have been tested for cavities.

6.1. Cold forming seamless tubes by backward extrusion

A Copper or Niobium billet of shorter length but of identical diameter of the final piece, can be converted into a much longer tube, by forcing the metal to flow plastically around the punch through the die-punch opening in direction opposite to the punch travel.

The backward extrusion of a tube is characterized by a quasi-stationary material flow. Therefore the velocity field determined from the path of the material particles remains more or less unchanged throughout the deformation process. The deformation process starts with a non stationary zone in which the die cavity is filled with the material, and the material begins to flow out of the die. A near-ideal stationary velocity field is important because it helps to avoid material hardening

The process is usually done under hydraulic press having good rigidity and a minimum of deflection. Press slides must be well guided with long, close-fitting, adjustable gibs, and the frame must minimize bending of the extruding punches. In order to minimize friction, even if one loses a little on dimensional tolerances, the punch is never cylindrical, but it has a nose contour on the edge. The contour of the punch nose is critical and varies with the material to be extruded. Other parameters that must be carefully controlled are: the viscosity of lubricant, the roughness of the die inner surface, the reduction in area required, the speed of extrusion and the pressure employed.

High quality backward extruded Niobium tubes have been produced by HERAEUS in collaboration with DESY [16]. The required pressure to backextrude Niobium scales with the square of tube diameter, so the diameters achieved at the moment are relatively small, just good for hydroforming, but not for spinning where larger tubes are required. For large diameters, too powerful presses are required and dies are too expensive to be economically convenient.

6.2. Seamless tubes by deep-drawing,

Forming seamless tubes by deep-drawing is one of the most common sheet-metal forming operations. The rather complex relations between the numerous variables which influence this process have been intensively studied for a large number of metals and alloys. The rules governing this operation are fairly well known. That means that the deep-drawing of a tube involves a number of problems which can be solved either by calculation or on the basis of experimentally established relations rather than trial and error.

Deep drawing is a process in which the central portion of a flat blank is forced by means of a punch into a die opening to form a tubular part in which the thickness is substantially the same as that of the original material (fig. 18).

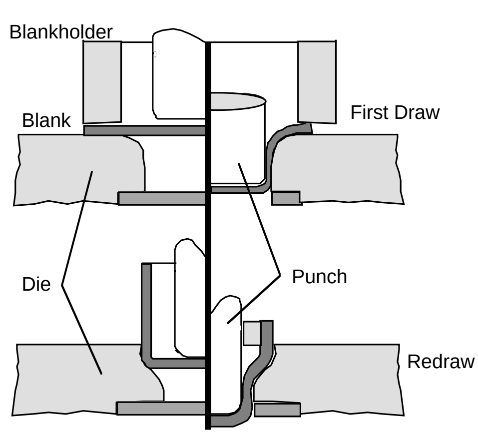

Fig. 18. Schematic diagram of the deep-drawing process with first draw (top) and first redraw (bottom), before starting the process (left) and during the process (right).

During the first stage of the deep drawing process the blank is bent around the punch nose (fig. 19 b), and this process is usually completed after a small stroke. Simultaneously and subsequently, the outer portions of the blank move radially towards the center. The various volume elements of the blank decrease correspondingly in circumferential length until they reach the die opening (fig. 19 a). Then they bend to conform to the die radius. When they become tangent to the wall of the tube, they again unbend

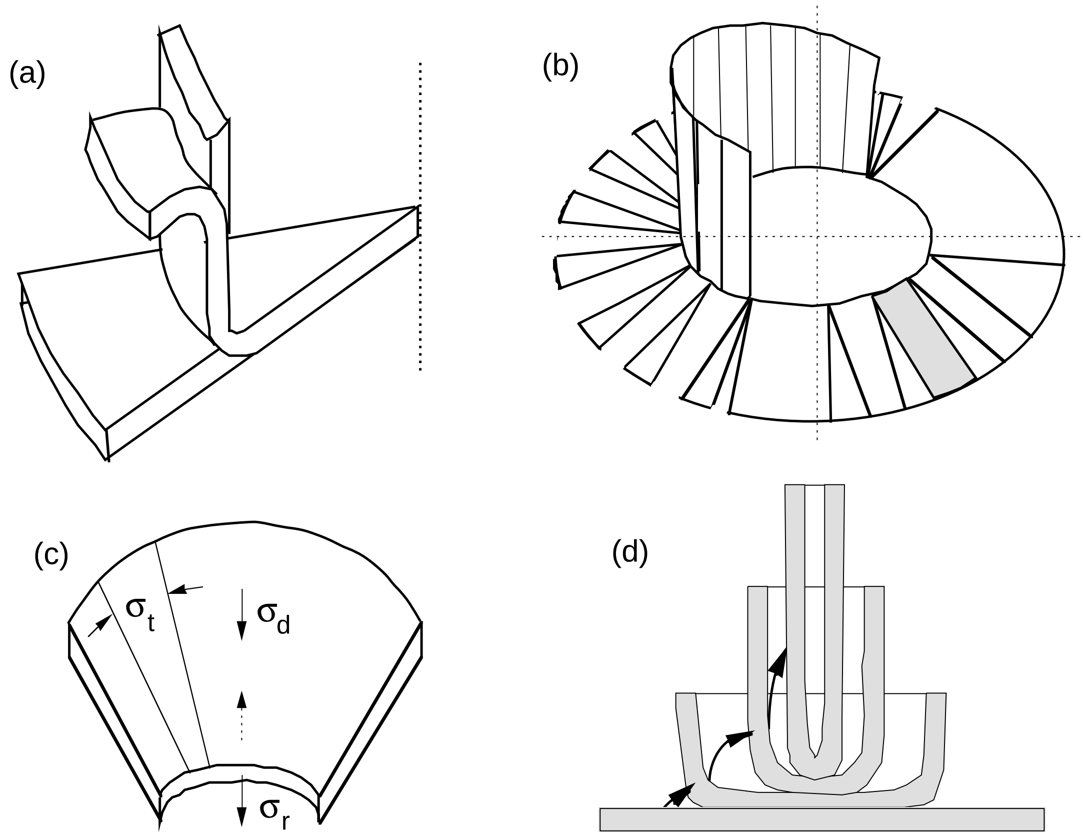

Fig. 19. Features of a cup deep-drawing from a flat blank: a) Segment illustrating the progressive development of a cup from a blank; b) While the tube bottom remains unchanged, the tube mantle is formed by a set of rectangles among which are the characteristic triangles; c) Stresses on the flat part during drawing: sr is the radial tensile stress exercised by the plate center forced between punch and die, σ_d is the compressive stress exercised by the blankholder, s_t is the stress exercised by the drawn mantle rectangles onto the characteristic triangles; d) After each redraw, the circumferential region that has been subject to bending is now only circumferentially compressed, while it is a new virgin region that will undergo bending.

The punch force is transferred from the part bottom into the wall of the part, which is thus subjected to axial tension stresses. These tensions produce reactive stresses which i) circumferentially compress and radially stretch the metal in the flange, ii) bend and unbend the metal flowing from the flange into the wall of the part, and iii) overcome the frictional resistances under the blank holder and at the die radius.

Besides some die-punch geometrical factors, the success or failure of the operation depends on whether the axial tensions in the wall, developed when the punch force is at maximum, remain below the tensile strength of the wall metal, or whether they reach this limiting value.

Parameters influencing the thickness uniformity and more general the quality of the drawn tube are: the punch pressure and the drawing speed, the pressure of the blank holder, the die opening angle and the punch nose radius, the redrawn number needed to arrive to the final length, the lubricant effectiveness.

Various types of failures can be encountered in tube drawing. A common failure is the separation of the bottom from the part. This happens whenever a reduction is made which requires a force exceeding the strength of the part wall near the bottom. Indeed the cup bottom is subjected to tensions in all directions, while the lower portion of the wall (particularly the radiused portion connecting the bottom with the wall) is subjected primarily to a longitudinal tension during the entire drawing process. The circumferencial crack probability will be decreased by reducing the frictional forces as well as by smoothing the punch radius or lowering the pressure of the blank holder.

Another common failure type is the tendency of a blank to buckle under the influence of the tangential compressive forces exercised by the drawn mantle rectangles onto the characteristic triangles of figure 19 c. The buckling at the edges is called “wrinkling”, while that at the die curvature or at the punch nose is usually called “puckering”. Both kinds of failure can be prevented by setting the right pressure of the blank holder. However a blank is not susceptible to any buckling under certain geometrical conditions. A plethora of other geometrical factors are more or less important in the further redrawing operations after the first step.

Forming of Seamless tubes by deep drawing is under investigation at Legnaro. Copper seamless tubes 208 in diameter, 750 mm long and 3 mm thick have been produced by the author in four steps, without any intermediate annealing. An 800 mm diameter copper blank is first drawn into a cup then three times redrawn with no significant difference whether the starting blank is hard or annealed. Niobium is more difficult to draw: both die and punch nose angles must be smoother than for Copper and other three redrawing passages have been added.

In the author experience, the above mentioned technique is a cold forming method suitable for producing tubes within thickness tolerances of the order of 200 microns and with excellent formability.

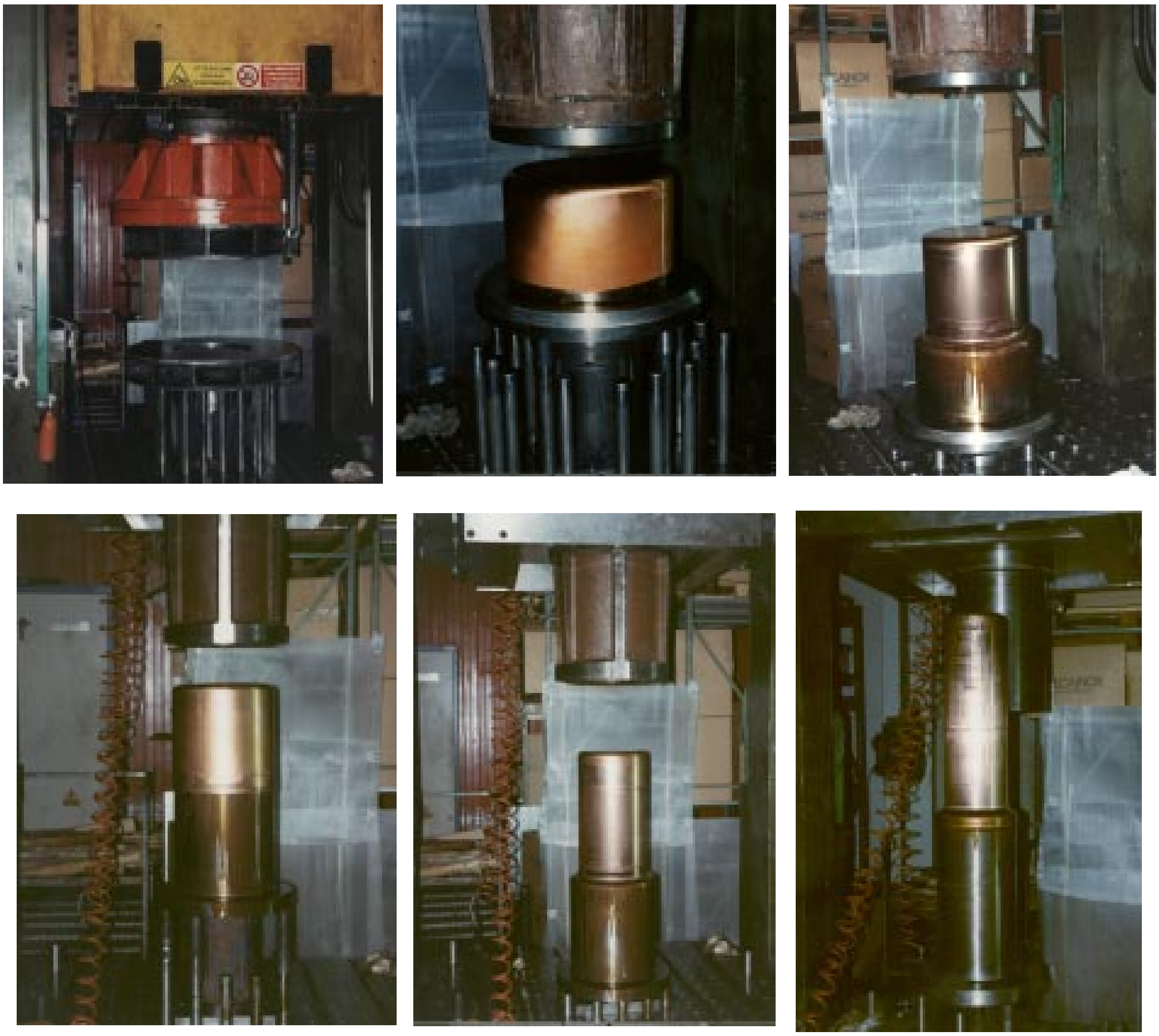

Fig. 20 First drawing and redrawing of the seamless copper tubes under investigation at LNL.

On the other side deep-drawing presents several disadvantages: i) The ensemble of dies is extremely expensive especially if more and more redrawn steps are needed; ii) Dies are in tempered steel and any little improvement or retouch of die angle or punch nose generally requires long time to be made; iii) Little changes in drawing parameters can result in a huge increasing of failure occurrence probability; iv) Too large slabs (out of rolling capabilities of main RRR Niobium suppliers) are required for forming tubes long enough to spin a ninecell cavity; v) Any change in the starting disk thickness requires irreversible and a time consuming changes of dies. On the other side in a prototyping phase it can easily happen to introduce some changes to the developed forming method. For example forming a multicell by spinning can require thicker wall tubes whether the welding of stiffening rings has to be avoided.

6.3. Seamless tubes by flowturning

All the disadvantages mentioned for deep-drawing vanish when forming tubes by flowturning. In the author opinion this is the most suitable one to apply to tube mass production for seamless cavities forming.

A short and thick cup can be easily formed by a thick flat disk, by spinning or deep-drawing. Then the wall thickness of the cup is reduced and the tube elongated by spinning on a multispindle machine (usually by three or four rollers). In this way, reductions in wall thickness of 90 % and increases in length up to 1000 % are achievable without any intermediate annealing.

Tube flowturning is particularly cost effective for the production of precision tubes, both for the process simplicity and because of almost no swarf. The relatively low power consumption, the short forming time, the possibility of cold working as well as the simple tool design and extended tool life, make this process definitely superior to any other seamless tube forming technique.

Two distinctly different techniques (fig. 21) are used for tube flowturning, namely backward and forward.

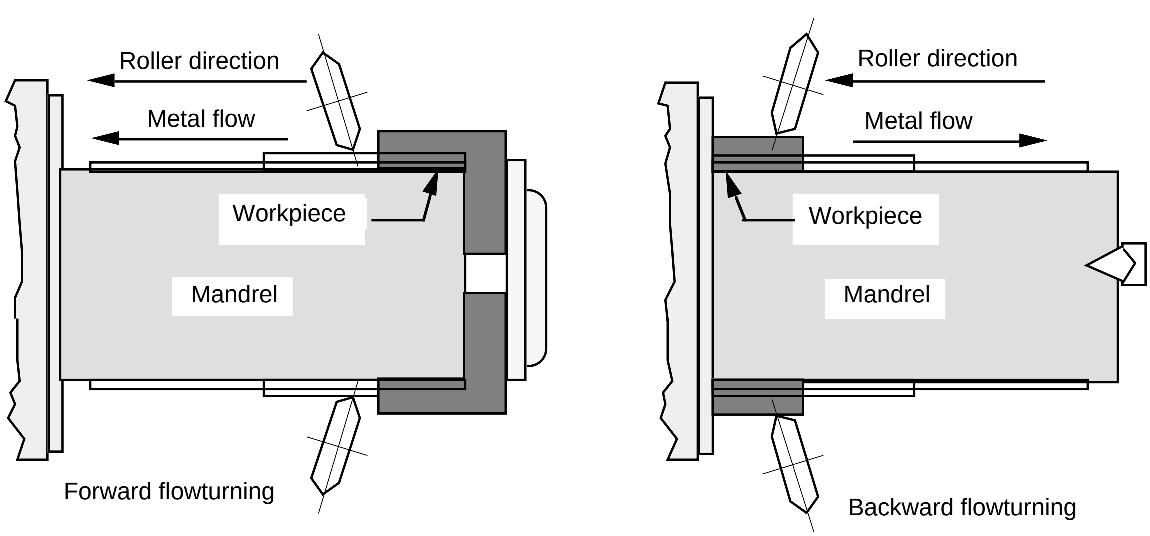

Fig. 21. Metal flow and roller travel in forward and backward flowturning.

In the forward tube spinning method, the preform is clamped to the mandrel at the tailstock. Metals flows ahead of the roller in the same direction as the roller feed, usually from the fixed end of the workpiece toward the headstock of the machine. Forward spinning is particularly advantageous when a closed-end preform is being worked. Closer control of tolerances is possible in forward spinning: as metal is formed under the roller, it is not required to move again. Moreover any variation caused by the variable wall thickness of the preform is continually pushed ahead of the rollers and eventually trimmed off.

In the reverse or backward method, the metal, which implies slides over the mandrel and does not require an internal flange for clamping, is extruded beneath the rollers in the opposite direction of the roller feed usually toward the machine tailstock. The disadvantage of backward tube spinning is that the first portion of the spun tube must travel the greatest distance and is therefore the most susceptible to distortion. Good diameter control can be obtained, regardless of the tolerances on the preforms, in spite of a lower accuracy in thickness uniformity automatically resulting from the forward method.

Flowturning has been proposed by Antoine [17] and by the author for the preparation of seamless tubes. Thanks to the high potentialities of such a method, Saclay disposes of Niobium tubes (98 mm in diameter formed from a backextruded cup) for hydroforming, while the LNL disposes for the moment of Copper tubes (208 mm in diameter formed by forward flowturning from a spun preform) for spinning (fig. 22).

Fig. 22. Seamless tubes formed by flowturning: the Saclay Niobium tubes [courtesy C. Antoine] are on the left; the LNL flowturned Copper tubes are on the right.

In the author opinion, if a cavity mass production will be ever done, flowturning is definitely the most suitable technology for producing low price and high standard seamless tubes in the shortest time.

7 Cold-forming of seamless Quarter Wave Resonators.

The technology developed for beta 1 multicell cavities can be extended also to low beta cavities and in particular to Quarter Wave Resonators (QWRs)

At the moment QWRs are being constructed by coupling and UHV brazing the central “mushroom” to the external cylinder (fig. 23). An alternative technique consists in excavating the full resonator by machining an OFHC Copper billet.

Fig. 23. The traditional fabrication way of a QWR. The resonator sizes are: 200 mm the external diameter, 80 mm the diameter of the central shaft, 600 mm the piece length.

The author has proposed the possibility to cold-form a complete resonator, by backward extrusion of a short billet. Compared to machining, backextruded cavities have the advantage of shorter fabrication times (a few minutes instead than days) and of material saving (only one third of the billet used for machining).

The technique has been successfully tested onto a QWR 1 : 2.5 scaled model (80 mm in diameter) and it is under study for full size cavities. An annealed copper pill is kept into a tempered steel die. An hollow punch is forced under 260 Tonn onto the pill surface. Under pressure the copper flows in one shot around and inside the punch up to the desired height. The shape of the punch nose determines the height ratio between the central shaft and the external cylinder. Being the punch axial section area just the double of the cavity section area, it is enough to push the punch of one third of the desired height, being the material flowing for two thirds out of the die.

As shown in fig. 24, the scaled model tests were immediately successful. Nevertheless a certain number of technological devices must be taken into account for designing the extrusion machine for full size resonators.

Fig. 24 Backward extrusion of a QWR 1:2.5 Copper model.

8. Conclusions

The field of superconducting cavities is certainly the right topic where enthusiastic researchers can better unbridle their imagination and creativity.

Several techniques seem to be the favourite ones for a large scale production: among them hydroforming and spinning seem to have all the makings for being the technology of the future. In this framework it is evident that disposing of seamless tubes is a must. Several tube forming technologies are still under investigation, since the variables to study are not only formability, but also morphology and microstructure. In this contest however flowturning is a simple and well-established technique. Time is running and the number of good experimental results is in continuous growth. All this lets understanding that the scientific community is not far from the final solution of the problem.

9. Acknowledgements

Whatever fabrication technology is adopted, it is undeniable that the preparation and characterization of a high performance superconducting cavity is a complex experiment. The establishment of a new technology, like that of forming of seamless cavities cannot disregard also all the other aspects connected such as the flanging operation, barrel finishing, chemistry, electrochemistry, cryogenics and radiofrequency. Sometimes a leak at superfluid helium can be responsible for loosing long time. In such a variegate world, the success of any enterprise depends not only on the personal motivation or competitiveness of the single researcher. There is something often more precious that makes running faster: a collaborative spirit. In this framework the author cannot exempt from expressing his gratitude to D. Proch, M. Pekeler, L. Lilije of DESY and P. Kneisel of TJNAF that took care of spun resonator characterization.

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