FIRST RESULTS OF SRF CAVITY FABRICATION BY ELECTRO-HYDRAULIC FORMING AT CERN

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Abstract

In the framework of many accelerator projects relying on RF superconducting technology, shape conformity and processing time are key aspects for the optimization of niobium cavity fabrication. An alternative technique to traditional shaping methods, such as deep-drawing and spinning, is Electro-Hydraulic Forming (EHF). In EHF, cavities are obtained through ultra-high-speed deformation of blank sheets, using shockwaves induced in water by a pulsed electrical discharge. With respect to traditional methods, such a highly dynamic process can yield valuable results in terms of effectiveness, repeatability, final shape precision, higher formability and reduced spring-back. In this paper, the first results of EHF on copper prototypes and ongoing developments for niobium for the Superconducting Proton Linac studies at CERN are discussed. The simulations performed in order to master the embedded multi-physics phenomena and to steer process parameters are also presented.

INTRODUCTION

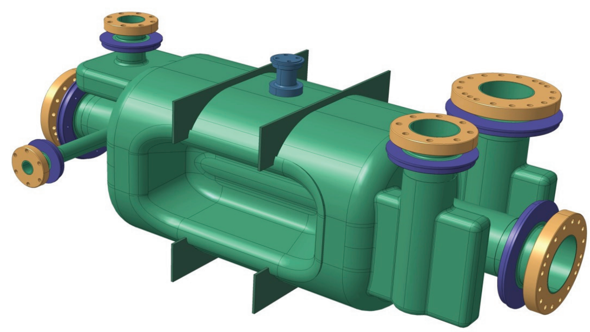
Several projects at CERN require developments of new or spare superconducting RF cavities, in particular for the LHC consolidation, the LHC High Luminosity upgrade (HL-LHC), the Superconducting Proton Linac (SPL) and the Future Circular Collider (FCC) studies. CERN has in recent years increased its effort into SRF technologies R&D as well as the related infrastructure.

SPL is an R&D study aiming at developing key technologies for the construction of a multi-megawatt proton linac based on state-of-the-art RF superconducting technologies, which would serve as a driver in new physics facilities. Amongst the main objectives of this R&D effort, is the development of 704 MHz bulk niobium beta=1 elliptical cavities (see Fig. 1), operating at 2 K with a maximum accelerating gradient of 25 MV/m, and the testing of a string of cavities integrated in a machine-type cryomodule.

HL-LHC relies on the availability of new technologies such as superconducting RF crab cavities, which would be installed in the interaction region (IR) of the upgraded ATLAS and CMS experiments. This requires the development of superconducting RF cavities of complex, non-axisymmetric shapes.

Superconducting RF (SRF) structures are traditionally fabricated from sheet metal formed using a wide range and combination of techniques: spinning, deep drawing, necking and hydroforming.

Figure 1: SPL 704 MHz elliptical cavity.



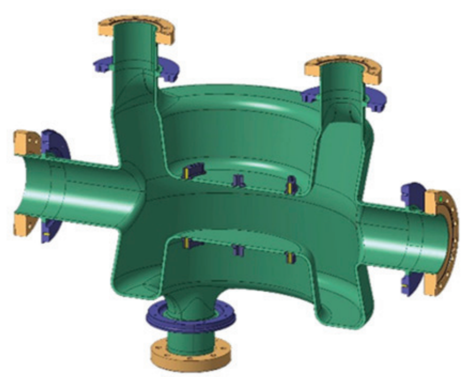


Figure 2: Special shapes 400 MHz crab cavities for HL-LHC upgrade.

The metals involved are pure niobium as well as oxygen free OFE copper typically used for preliminary trials and as substrate for niobium sputtered cavities. Geometries used for SRF cavities can be axisymmetric (e.g. LHC, ILC, SPL) or non-axisymmetric (e.g. HL-LHC crab cavities, Fig. 2). Electron-beam welding is typically used to join formed structures to obtain the final geometry.

The possible forming techniques can be compared along different characteristics of merit: complexity of set-up, equipment and dies, precision of formed geometry, regularity of formed thickness, metallurgy, reproducibility of results and cost.

High-velocity forming processes are potentially alternative solutions to traditional methods. They involve high-strain rate forming, through a process lasting less than a millisecond. Applications to copper and niobium have only recently started using EHF. Advantages are expected in metallurgy, geometrical precision, reproducibility and suitability for economic and large series production.

A collaboration between CERN and an industrial partner, Bmax, has been set up to study and apply this technology for SRF applications at CERN.

MOTIVATION FOR HIGH STRAIN RATE SHAPING

Due to their efficiency in terms of processing time and material usage, sheet metal forming processes represent the method of choice for fabrication of superconducting niobium cavities. However, the plastic deformation phenomena characteristic of standard forming processes, entail mechanical property limitations which directly lead to thickness reductions, formability limits and springback. Such issues hinder the achievement of required dimensional tolerances, increase the difficulty of assembly and, most critical for RF performance of accelerator cavities, affect shape quality of the components.

Amongst the above-mentioned drawbacks of metal forming, springback is the known phenomenon in which a component partially reverts to its previous form, as the applied loads are suddenly removed. To a first approximation, springback can be associated to the relaxation of the elastic stress field inside the part; in reality, also plasticity of the loaded material must be taken into consideration. Therefore, an accurate springback prediction must consider both elastic and plastic material properties such as the variation of elastic modulus with strain, strain rates and the Bauschinger effect; complexity in material interpretation further rises in case of anisotropic properties such as the ones pertaining to rolled sheets.

Given the importance of such a phenomenon, many studies have been performed on its effects both in accelerator technology and in other domains. The production of SRF cavities by deep-drawing has proven to be prone to springback-induced deviations in the final geometry causing important fluctuations in resonating frequency [1]. In the case of spinning of stainless steel [2] and aluminium alloy [3] sheets, experiments have resulted in the observation of considerable springback, even though in the latter study it was concluded that the phenomenon could be reduced by varying the feed rate to a certain interval. In [4], the authors have shown the advantage of flexible spinning, where the working roller can move beyond the target shape, in order to compensate for springback without colliding with the mandrel.

The constant search for improvement in the production quality and throughput of such processes is ultimately leading the scientific community into exploring the industrial application of known alternative forming techniques such as Magnetic Pulse Forming (MPF) and Electrohydraulic Forming (EHF).

These high strain-rate forming processes have the potential to overcome some of the standard processes' limitations by inducing interesting material behaviours such as, for instance, increased elongation and significant springback reduction [5, 6, and 7]. These advantages are related to the materials' viscoplastic behaviour during forming and to the high velocity impacts on the die, even though the forming occurs at room temperature.

Consequently, in some cases, this increase in ductility makes it possible to avoid heat treatments, enabling the forming of parts directly from sheets in their final temper state. An important feature of these forming technologies is also the level of fine details and sharp angles that can be achieved; this increases design flexibility, making it possible to perform with metal, what was previously possible only with manufacturing techniques greatly different from metal sheet forming (e.g. injected plastic).

One of the key contributing factors in the recent success of these decades-old processes is the ability to rely on new improvements in multi-physics simulation tools. These allow a much better understanding of the concerned physical phenomena, the design of long lifetime tools and a significant increase in the predictability and control of these remarkable high-speed forming processes.

A final positive note for these high peak power processes is in fact their low overall energy consumption.

ELECTRO-HYDRAULIC FORMING PRINCIPLES

Generally speaking, High Pulse Power (HPP) forming processes refer to the brief discharge of high voltage capacitors into either a coil for the MPF process or an arc in water for the EHF process. The main elements composing these HPP generators are shown in Fig. 3.

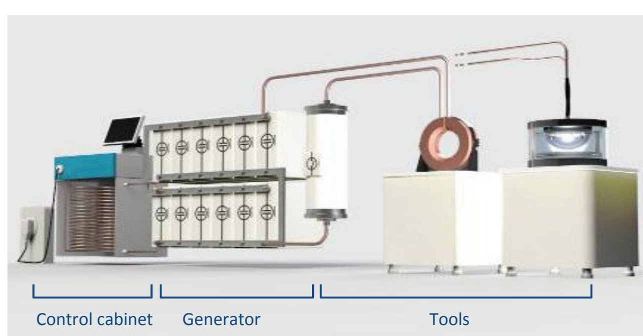


Figure 3: Principle of HPP forming generators [8].

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The discharge is controlled by a Programmable Logic Controller (PLC) that triggers the system in order to release the energy in tens of microseconds. The operating voltages typically range from 2 kV to 50 kV.

In EHF, the transient current coming from the pulse generator is discharged through an arc created between two electrodes located in water.

The energy deposition is made through Joule heating by the plasma that creates a fast bubble expansion, and therefore a shock wave which propagates in water and causes the plastic deformation of the workpiece at high speed against the die. Impact velocities are commonly in the range of 50 m/s to 200 m/s, thus much higher than conventional high velocity stamping (< 20 m/s). Fig. 4 explains the basic industrial sequence.

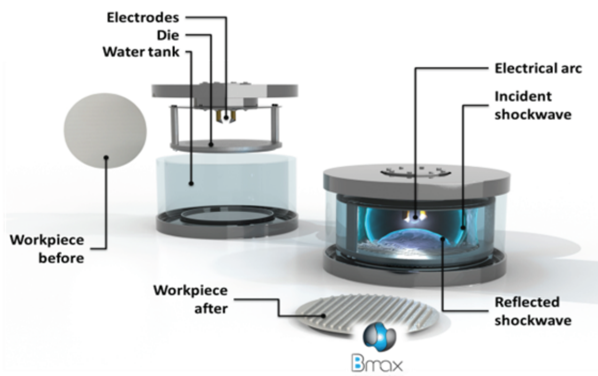

Figure 4: Electrohydraulic forming principle [8].

Two examples of EHF formed parts are shown in Fig.5. This shows the ability of EHF to achieve sharp fine details and sharp angles (very high local deformation) which, as mentioned, is very useful in increasing design possibilities. On the right hand side, a 400 mm diameter oil deflector for a helicopter engine made of Aluminium EN AW-6061 is shown. While the conventional forming process consisted of 7 steps including 2 thermal treatments, the EHF process achieves the same goal in a single operation: forming on the same die, using a blank with the required final tempered state (T4), and no need for thermal treatments. 35% elongation has been measured in the groove of the parts, while the elongation at break measured in uniaxial tensile tests is given at 15% [9].

Figure 5: Example of Electro-Hydro Formed parts.

MATERIAL CHARACTERISATION

When submitted to EHF, the workpiece's material deforms at strain-rates between 100 s^{-1} and 10 000 s^{-1}. In this range, the mechanical behaviour can be significantly different from the one experienced in quasi-static conditions [6].

To obtain predictive simulations, complementary material characterisation has been performed in quasi-static conditions at CERN, as well as in dynamic conditions at Bmax.

Behaviour under Quasi-static Loading

For the preliminary EHF tests, OFE copper annealed sheets were used. They were cut to Ø 550 mm circles keeping the original 3 mm thickness. The high purity niobium (Residual Resistivity Ratio, RRR>300), has been supplied by Ningxia Orient Tantalum Industry Co. Prior to utilization, material has been controlled via ultrasonic testing. No continuity defects were detected and the attenuation of the back wall echo was always lower than 20%, meaning a very homogeneous grain size across the plates. The results of the tensile tests carried out for both materials are summarised in Table 1.

Table 1: Mechanical Properties of OFE Cu and Nb

Material	OFE Copper	Niobium
Rp0.2 (MPa)	51.5 ± 0.5	122.0 ± 7.0
UTS (MPa)	224.3 ± 3.2	203.8 ± 1.2
A %	52.8 ± 0.0	46.7 ± 3.6

The characterisation of the material included a metallography to assess the recrystallization of the material and to measure the grain size. Fig. 6 shows an example of one plate of each material.

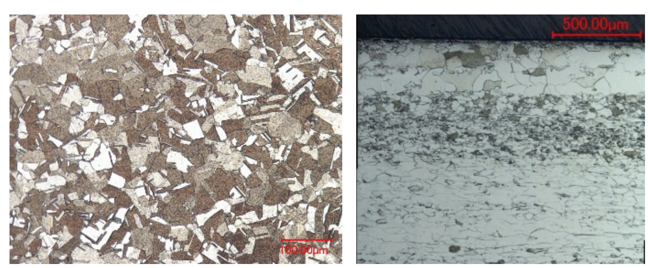

Figure 6: Metallographies of a copper plate (left) and a niobium plate (right) showing uniform equiaxial grains for the copper and slightly elongated grains in the core for the niobium plate.

Additionally, the strain hardening exponent (n) for both materials was obtained, which can add valuable information for the forming process and also for the simulations. The magnitude of this parameter reflects the ability of the material to resist further deformation in the plastic domain. For its determination, true stress and associated true strain have to be plotted on log-log scale.

A straight line should result with a slope equal to the strain hardening exponent.

For the niobium, 5 plates were tested both in rolling and transverse direction making a total of 10 samples. For the copper, 3 samples in the rolling direction and 3 samples in transverse direction from a single plate were tested. Fig. 7 shows all the results which were obtained for both materials.

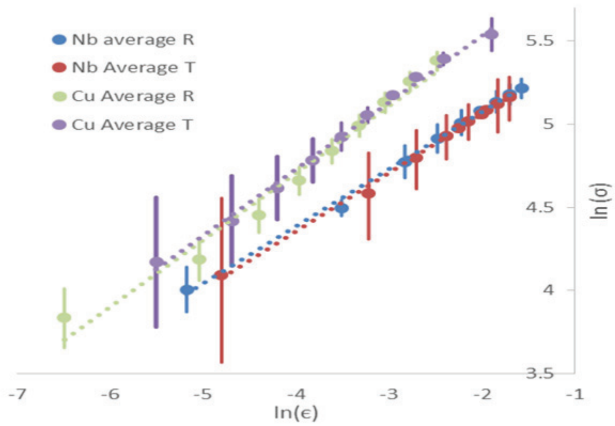

Figure 7: True stress vs true strain in log – log scale for Nb and Cu plates. The slopes of the curves determine the strain hardening exponent.

For niobium, the average obtained values are n = 0.40 for the rolling direction and n = 0.35 for the transverse, which is slightly higher than the reported values [10]. This value decreases with the amount of cold work and vice versa [10] so the values are in good agreement with the temper state of the material. For the OFE copper, the average obtained values are n = 0.35 for the rolling direction and n = 0.40 for the transverse direction, slightly lower than the 0.54 value reported in [11]. These lower values can be attributed to an incomplete annealing of the material.

To the extent of the mechanical properties which were assessed, copper and niobium show similar formability. Nevertheless, it has to be noted that the properties are measured in a quasi-static uniaxial tensile test.

Behaviour at High Strain Rates

More complex tests aiming to determine the mechanical properties of materials at high strain rate ($\varepsilon > 10^3\ s^{-1}$) are more suitable in order to predict material behaviour during the EHF process. To meet this need, a specific methodology has been set up. It is used to identify the constitutive behaviour of the workpiece material in conditions specific to EHF and MPF.

The methodology consists in a parameter identification strategy based on the electromagnetic free expansion of a metallic tube or sheet. This test is derived from the ring expansion test described in [12, 13, and 14].

The approach is based on a reversed analysis method allowing the identification of the parameters of the constitutive law and is presented in [14]. The diagnostic techniques are a key element required to obtain sufficiently precise predictive models. The uncertainties become low enough to get reliable models only with precise velocity measurements such as Photon Doppler Velocimetry developed by Bmax in collaboration with Ohio State University, as well as a careful calibration of the current measurement.

As an output of this methodology, a strain rate dependent constitutive law is obtained, like the Johnson-Cook one shown in (1) [15], in order to model with sufficient accuracy the material plastic behaviour in the range of strain rates of interest:

$$\sigma = \left[A + B \cdot \overline{\varepsilon_{pl}}^{n}\right] \cdot \left[1 + C \cdot ln\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)\right] \cdot \left[1 - \left(\frac{T - T_0}{T_m - T_0}\right)^{m}\right] \quad (1)$$

where σ is the effective von Mises stress, $\overline{\varepsilon_{pl}}$ is the effective plastic strain, $\dot{\varepsilon}$ is the effective strain-rate, $\dot{\varepsilon}_0$ is a reference strain-rate, T the material temperature, T_0 the room temperature, and T_m the melting temperature. *A*, *B*, *n*, *C* and *m* are material constitutive parameters.

Applying this methodology [14] gives typical velocity graphs as shown in Fig. 8

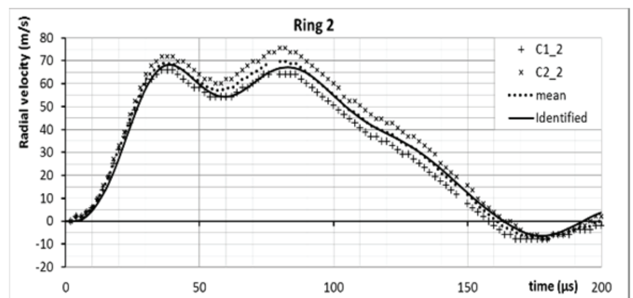

Figure 8: Measured ring expansion velocities (dots) and identified curves (lines).

Figure 9 shows a comparison of the stress-strain relation for copper in static and dynamic conditions at 2500/s, the latter obtained through the described technique.

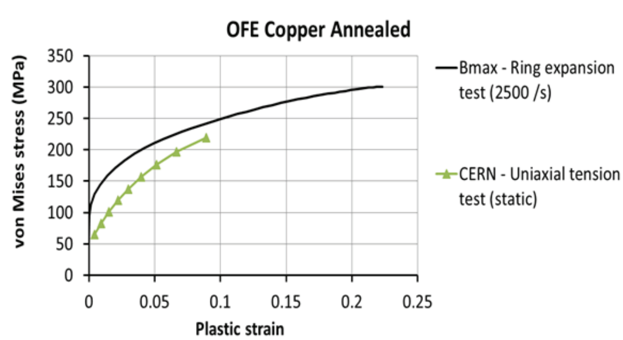

Figure 9: Stress-strain relation comparison for OFE copper between static and dynamic conditions.

This methodology has also been applied at Bmax on different copper alloys, aluminium and its alloys, steels and is being applied to niobium. The precise definition of the material model is instrumental in simulations to coherently model the deformation of a complex part.

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NUMERICAL SIMULATIONS OF CAVITY SHAPING

Objectives

Numerical simulations bring many advantages to efficiently fulfil the prediction requirements for high strain rates processes such as EHF. Provided proper material models are implemented, simulations make it possible to predict the point at which tearing could occur in the material while forming. They also help to identify the main parameters having a significant influence on the efficiency of the process, as well as to understand the important physical phenomena involved. When appropriately used, simulations can also significantly reduce development time and costs, as feasibility of complex projects can be numerically checked, thus limiting the physical testing endeavour.

EHF Simulations

The EHF process is modelled by a fluid-structure interaction and a time dependent energy deposition to generate the pressure waves resulting from the discharge. The fluid is represented by an Arbitrary Lagrangian Eulerian (ALE) formulation, an adapted equation of state to produce potential shock waves and a Lagrangian formulation is chosen to calculate the mechanical response of the structure (blank, die, wall of the discharge chamber).

Simulations can be used to define the number and position of discharges and to select the energy level. It allows also the optimization of the chamber (mold) geometry, which has a large influence on process efficiency, as typically two thirds of the forming effect comes from reflected waves.

Fig. 10 shows the simulation of the forming of a copper cavity starting from a flat sheet.

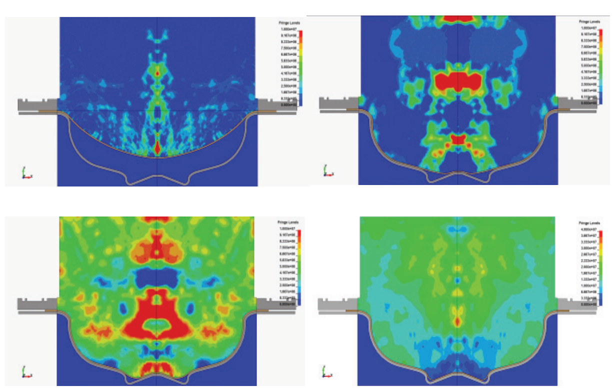

Figure 10: 2D-axisymmetric EHF simulations of a copper cavity using four different EHF discharges.

Springback Reduction

It has been widely observed that high velocity impact forming processes can greatly reduce springback. [6, 7, and 16].

When the blank velocity reaches several 10's of meters per second on impact, it creates a pressure wave travelling first across the thickness of the blank and possibly sufficient to generate plasticity by compression throughout the thickness. It produces a new stress distribution in the blank in all directions, efficiently relaxing those stresses which are the main cause of springback.

To optimize the spring back reduction, simulations can be of great help to validate and understand the importance of each parameter.

Practically, while forming a real 3D part, the best way to minimize the distance between the sheet and the die is generally to create a re-acceleration of the sheet onto the die. In EHF, the reflected waves perform this work quite naturally.

EXPERIMENTAL RESULTS ON HALF CELLS OF ELLIPTICAL CAVITIES

Several half-cells of 704 MHz SPL elliptical cavities have been produced and analysed. Three copper half-cells have been first optimised to qualify the shaping process. First trials on Nb half-cells have also been started Fig.11.

Figure 11: Half-cells in copper and niobium by EHF.

Shape Accuracy

A significant shaping error arises after forming OFE copper and niobium sheets in half-cells by deep-drawing or spinning. Springback can cause serious deviations from the nominal shape due to internal material stresses, when the pressure and dies are released after the forming process.

To quantify prevalent springback induced errors by EHF, three nominal SPL mid cells made from OFE copper sheets (3 mm thickness) have been shaped, while obeying usual procedures and using existing die sets. Subsequently, inner contours have been measured for each half-cell with a Coordinate Measuring Machine (CMM) at different planes.

The measured contours (eight per half-cell) have been plotted showing the deviation from the ideal cell shape for each contour. The data reveals average errors in the range of ± 200 μm.

Table 2: Summary of the Achieved Shape Accuracies for Copper Half-Cells Formed by EHF

Half-cell ID	Shape µm	Circularity iris µm	Circularity equator µm	Iris deviation. µm	Equator deviation. µm
OFE 1	± 200	88	80	693	235
OFE 2	± 200	90	190	354	193
OFE 3	± 200	58	144	288	213

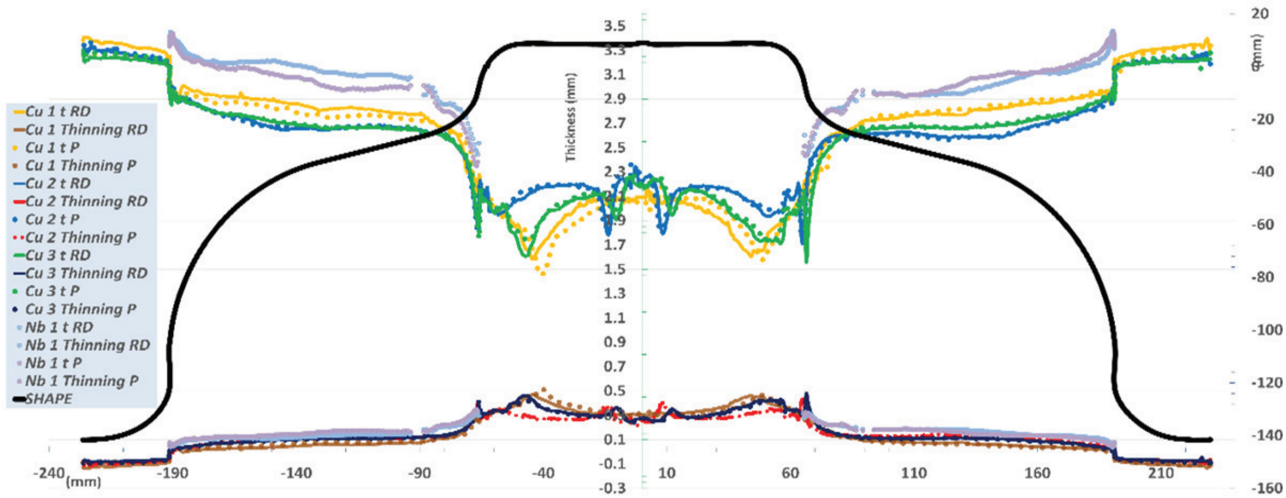

Figure 12: Final shapes of OFE copper half-cells thickness and thinning ε_3 distributions in sheet rolling and perpendicular direction.

The CMM revealed that the area close to the cell iris is pushed inwards resulting in the largest errors, while the equator area is comparably less affected. The differing errors indicate that cells are circular. The summary of the achieved shape accuracies is shown in Table 2.

Thinning

Processes like EHF belong to the methods of impact forming with elastic media, they thus differ from traditional punch-and-die forming by mechanism of sheet deformation. With a traditional deep-drawing process, a rigid punch is tightly pressed into the sheet surface. This creates large friction forces preventing deformation of the central zone of the sheet. Therefore, the central zone is only slightly deformed at the end of the forming process. When forming with elastic media, the sheet blank is not supported by rigid surfaces and so it is subjected to tensile stresses, larger in the central zone, while periphery is under tensile and compressive stresses.

This results in large sheet thinning ε_3 along radius with a maximum in the central point, thus reducing the maximum deformation of the blank material. Such peculiarities of these two principal methods of forming (with rigid tools and elastic media) are obvious at production of hemispherical components.

The produced half-cells presented no fractures and satisfactory thickness distribution (Fig. 12). Maximum thinning ε_3 in correspondence of the shape of interest reached acceptable values of 0.3, while maximum thinning of up to 0.4 is located near to the bottom of the half-cell (non-functional zone). Here also the effect of superplasticity should be taken into account.

Roughness

The resulting roughness at the inner surfaces has been measured and compared to the initial sheet roughness before forming. Subsequently, inner half-cell surface roughness does not show any degradation due to the fact that these surfaces are in contact with water during the shaping process. The results are shown in Table 3.

Table 3: RF Surface Roughness before and after Shaping

Cell	Ra sheet µm	Rt sheet µm	Ra HEF µm	Rt HEF µm
OFE	0.2	3.5-5.8	0.2	2-12
Nb	0.8-0.9	7-11	0.9-1	8-11

These findings, i.e. conservation of surface roughness and the relatively low wall thickness variation, could lead to an important reduction of post forming related surface

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treatment, as buffered chemical polishing (BCP) and electropolishing (EP).

SUMMARY AND FUTURE PLANS

The major advantages of high strain rate forming processes are the increased material formability, reduced wrinkling, ability to impose detailed surface features thanks to high-pressure impacts, reduced springback and reduced manufacturing cost.

For all of the above-mentioned reasons, EHF is being investigated for SRF applications. The development work carried out at CERN and Bmax has shown that EHF indeed represents a very promising technology for the shaping of SRF cavities.

The methodology and the characterisation have been successfully applied to the shaping of copper half cells for SRF 704 MHz elliptical cavities. This ongoing study is expected to yield a thorough understanding of the process and to extend to niobium the investigation on the main process parameters already applied to copper. In particular, characterisation will be performed on the orthotropic and non-linear behaviour of the typical raw material used for production, both in quasi-static and high-strain velocity regimes.

Further investigation will focus on the development of material microstructure and of physical (e.g. RRR) and mechanical properties induced by the strain rates and temperatures ranges associated to the EHF process. The influence of the main process parameters will be evaluated in terms of cavity performance.

The know-how gained on this high-speed forming technique will be used and optimised as an alternative/advanced fabrication method for more "conventional" superconducting cavities such as LHC mono and multi-cell elliptical cavities in the framework of SRF R&D projects such as SPL. At a later stage, the technology will be applied to cavities with much more complex shapes, such as the crab cavities for the future upgrade of the LHC.

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