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NOVEL APPROACHES IN CHARACTERIZATION AND MODELLING OF FABRICATION PROCESSES FOR SRF COMPONENTS*

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Abstract

In the past years, Finite Element Methods have been increasingly applied at CERN, with the aim of modelling fabrication processes for SRF components. Currently, many large deformation processes such as deep drawing, forging, hydroforming, and spinning, are being simulated. Taking the initial trials out of the workshop via simulation has proven very efficient for steering fabrication strategy, avoiding unnecessary trials, and helping to reduce time and costs. This contribution will present a novel approach for studying fabrication process feasibility and failure prediction using numerical tools, based on the Forming Limit Diagram method, developed for OFE copper sheets. This contribution will show the application of the mentioned method on the study of tubular hydroforming, as an alternative way to produce seamless elliptical RF cavities. Analysis of past hydroforming trials is also discussed, together with the comparison of different fabrication strategies.

INTRODUCTION

The manufacturing of SRF cavities, as key components for particle accelerators, poses many challenges due to opposing requirements such as large ratio deformations, tight tolerances, and low surface roughness. In view of the current study for CERN's Future Circular Collider (FCC), seamless cavities are of interest, since they would allow to elude circular welds in correspondence of the cavity equator; the latter allowing to improve RF performance. Current R&D activities at CERN are focused on production of seamless OFE copper substrates for niobium coating, with hydroforming being one of the suitable processes. Nowadays, the presence of more reliable fabrication techniques, advanced calculation methods, and novel material characterization techniques, allows Hydroforming (HF) process to be better understood and optimized, providing a fast and repetitive fabrication method [1]. In this article the novel approach of characterization and modelling methods are being presented in the context of HF. The study focuses on 1.3 GHz OFE copper substrates, used as proof of principle, in view of production of the larger 400 MHz cavities, needed for FCC.

FAILURE MODELS

To properly assess the feasibility of a given process through FEM, an appropriate failure criterion needs to be defined. A commonly used failure criterion is maximal principal strain, which is based on the material elongation at break. However, this method proves conservative and inaccurate when modelling of large deformation behavior is needed. Other measures can be maximal equivalent plastic strain or maximal allowable thinning. These failure criteria, if calibrated based on uniaxial tensile (UA), are equivalent with respect to the simple UA deformation conditions but are significantly different when considering three directional forming conditions. To obtain more accurate material' formability limits for sheet-like products, the Forming Limit Diagram (FLD) approach was thus adopted.

Forming Limit Diagram

FLD is a standard approach to predict ductile failure in metal sheet forming, being valid for proportional loading conditions. FLD correlates the minor vs major principal true strains (ε_2 and ε_1) for every volume in the formed piece. The Forming Limit Curve (FLC) indicates the onset of necking for different strain paths (i.e., uniaxial (UA), pure shear, plane strain (PS), ...) [2]. The preferable forming area is on the left branch of the graph, in between pure shear, and UA. The lowest point of the FLC, representing lowest formability, corresponds to the PS condition (ε_2=0). FLD can also indicate failure by rupture thanks to the implementation of the Fracture Forming Limit (FFL) and of the Shear Fracture Forming Limit (SFFL). Figure 1 shows a part of FLD developed at CERN for Cu OFE 4 mm thick sheet [3].

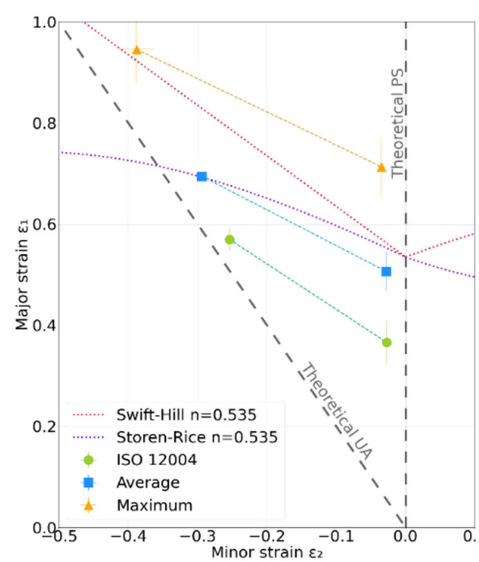

Figure 1: FLC for OFE-copper, 4 mm thick sheet [3].

Material Characterization

To build a complete FLD, Nakashima or Marciniak sets of tests need to be done. The material characterization campaign at CERN, was firstly focused on the left side of the FLD plot ($\varepsilon_2 \leq 0$) since this region is of interest for HF simulations [1]. For such region, tensile tests were performed

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for two types of the specimens, corresponding to the UA and PS samples. Three methods ('ISO', average, and 'Maximum' from the most to the least conservative) were used to postprocess the data and to draw FLC. Such strategy has been implemented to minimize the testing campaign, with respect to a full Nakashima or Marciniak set. The obtained curves, based on experimental results, were compared with two analytical models: Storen-Rice and Swift-Hill, which are also plotted on the FLD in Figure 1.

Benchmark Pieces

Two parts were hydroformed from a straight tube into T- and X- like shapes. An extensive experimental campaign was conducted to benchmark the real process with simulation and to validate the material and failure model.

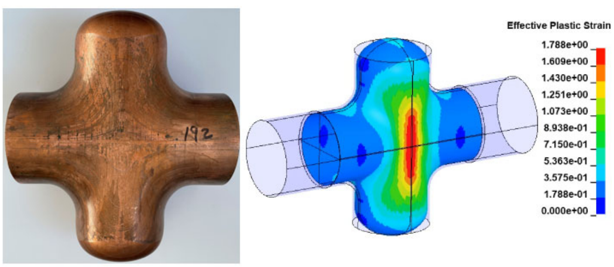

Figure 2. X-shape formed vs simulated piece.

The fabrication process was simulated using LS-Dyna explicit code, as presented in Figure 2. The simulation outcome was compared with metrology results, showing very good match in the piece final geometry, thickness, and deformation level. For both shape types, the most stressed area is found in the central part of the piece, corresponding to the furthest FLD points, as plotted on Figure 3.

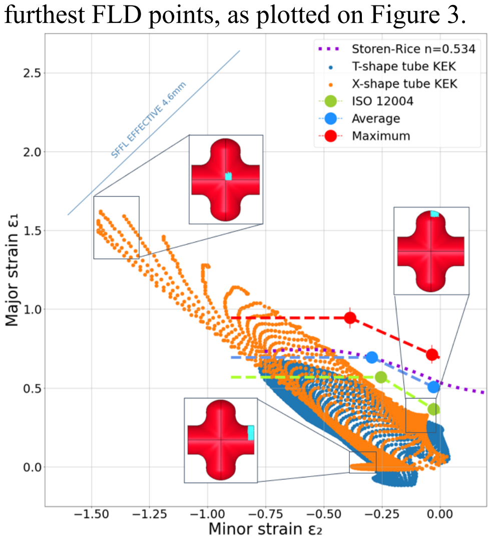

Figure 3. T-shape, X-shape simulation results (elements minor vs major strain) plotted on FLD.

For what concerns the X-shape, this undergoes very high deformations in such central part (more than 150 % of effective plastic strain), which corresponds to a much higher limit than what an elongation at break limit would predict (around 40 % for Cu-OFE). This is due to the biaxiality type of loading which the parts experience during HF. The analysis of in-plane true strains on the FLD (Figure 3) shows how such forming process reproduces "pure shear"-like deformation, thus allowing such extensive feasibility to be reached, together with very little thinning (zero thinning for a theoretical pure shear condition). The analysis of T-shape confirmed that the necking limit (FLC) is well represented, when using "average" method of data postprocessing, which matches well the Storen-Rice model. Such analytical model was thus used for future assessments. This benchmark study showed the possibility to proficiently explore the material formability limits, using relatively low sets of material tests.

THE USE OF FLD TO EXPLAIN THE HISTORY OF HYDROFORMING FOR SRF CAVITIES

Hydroforming

Historically, several trials of HF elliptical SRF cavities have been made at KEK [4], DESY [5, 6] and CERN [7]. Over the years, many different HF strategies were tested, starting with the simplest approach of hydroforming an initially straight tube, just by applying a pressure inside the tube, pushing material against a fixed, rigid die. However, this required many forming steps with intermediate material heat treatment, resulting in significant thickness reduction at the cavity equator. Further on, the process strategy evolved, and axial force at the tube extremities was added, to facilitate material flow during forming. Additionally, the mold was divided in two separate parts, serving as movable dies during forming. In this article, four different types of HF processes are simulated and compared: i) internal pressure is applied inside the tube, mold is closed and fixed with respect to the tube movement; ii) axial force on both ends of the tube is also applied simultaneously with the internal pressure, mold is closed and fixed; iii) internal pressure, no axial load, open separate dies being displaced; iv) simultaneously with the internal pressure, axial force on both ends of the tube is applied, the opened separate dies are being displaced. For the sake of simplification, just one HF step, starting from an initially straight tube was considered. In this paper, the focus is given to HF of 1.3 GHz cavity shape, with the inner diameter of the beam axis d=78.1 mm and the inner diameter at the equator D= 206.6 mm.

Numerical Modelling Techniques

FEM setup LS-Dyna explicit solver is used as FEM code. A quarter of the full geometry is modelled, including the tube, die, and a side punch providing axial force. Two different FEM models are used, considering movable and fixed mold as presented in Figure 4. Fully integrated shell elements (ELFORM 16) are applied. The model contains 5668 elements in total and 2178 elements for the tube. HF is performed starting from a 262 mm long straight tube with an initial thickness of 4.6 mm, and with the initial inner diameter corresponding to the beam axis diameter. A contact: *CONTACT_FORMING_ONE_WAY_SURFACE_TO_SURFACE is defined between the tube and the

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mold. The pressure is defined on the segment which is the internal surface of the tube. Axial force is simulated by a boundary displacement applied on the side punch. In case of a forming strategy with the moving dies and feeding force (strategy number iv), the same boundary axial displacement is applied on the side punch and on the die**.** The concurrent die-punch movement mimics the presence -in the actual process- of two rigid flanges: each flange being joint to one side of the clamp and providing movement to the corresponding tube side.

Input process parameters To define a multilinear loads' evolution, four parameters are introduced: the intermediate and the final value of the internal pressure, the intermediate and the final value of the punch displacement. The values of these four parameters are used to define the load curves vs. time for a given analysis as presented in Figure 5. The final value of the displacement- when needed, as per case iii) and iv)- is fixed by geometrical characteristics, since it depends on the initial distance between the clamps (length of the tube). While the other three parameter values may vary; the intermediate value may also be higher than the final value.

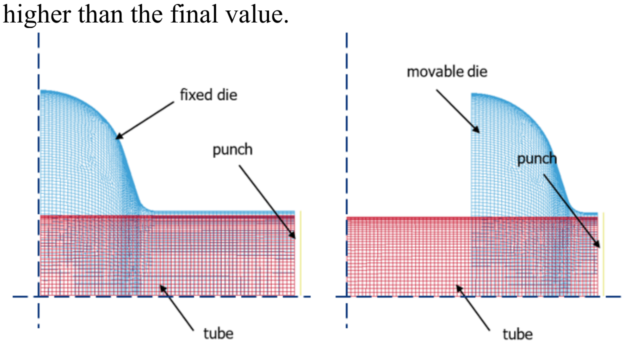

Figure 4. FEM setup, model with fixed die for HF case i) and ii), model with movable die for HF case iii) and iv).

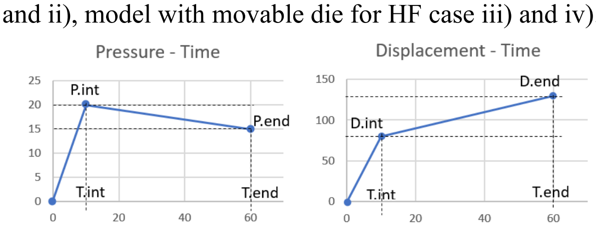

Figure 5. Input process parameters for simulation.

Material models and failure models The molds are assumed to be bulk Stainless Steel, thus defined as Rigid Body through use of *MAT-RIGID. The tube is made of OFE Copper. The material model defined for the tube is *MAT-PIECEWISE-LINEAR-PLASTICITY, assuming isotropic material properties. This model represents an elastic-plastic material with an arbitrary stress versus strain curve. Strain rate dependency is not defined, after being checked and found non-relevant for this analysis.

FLD Application, Use of FLD to Validate Efficiency of a Process

Figure 6 presents the comparison of the straining paths -plotted on FLD- for different hydroforming strategies. Only in one case- strategy iv) (purple curve)- the full cavity forming could be reached in one step without elements becoming highly distorted. It can be observed that if the tube is deformed only by pressure, strains fall in the region between plane strain and biaxial tension; the part is thus exposed to excessive thinning, that can provoke a failure. Providing an axial force during the process allows for moving from the 1st to the 2nd quadrant of FLD, where formability is improved. Simulations show that the most effective way to form a cavity is obtained by applying a pressure together with the axial displacement and with the moving molds. In such case, if parameters are correctly chosen, a linear strain path can be maintained all along the process, which follows UA-like strains.

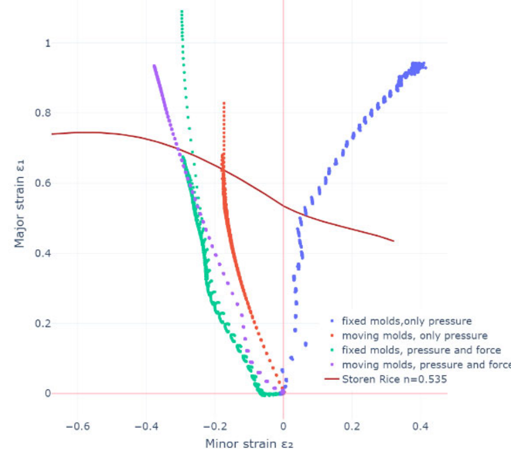

Figure 6. Comparison of the straining paths for different hydroforming strategies.

A key parameter for this kind of HF is the space between the molds, that will define the maximum provided displacement. Increasing the initial tube length (i.e., the distance between the molds) moves the strain paths from PS conditions towards UA ones. The longer the tube, the more displacement is applied, and the less pressure is needed because more material is available for forming of the cavity. This strategy guarantees better flow of material (less stretching) for the tube to reach its final shape. However, there is a limit to the allowable space between the molds because the minimum value of pressure needs to be maintained to avoid buckling: Also: if the tube is too long, it tends to reach large diameters too soon, and thus form out of the molds while these are still separated and still coming into contact (causing a 'pinching' phenomenon in the region of the cavity equator). Figure 7 shows the resulting strain paths for one-step HF from a straight tube (strategy iv), for a given pressure-displacement set of parameters. It can be observed how by just changing the process parameters slightly, the straining paths change significantly. In other words, process feasibility is highly dependent on the process parameters (pressure and displacement), which can be optimized through FEM. This observation highlights once more the advantage of FE process modelling prior to workshop trials. Simulation shows that a sharp increase of a pressure at the beginning of the process is beneficial, to initiate the bulging of the tube; pressure should then be de-

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creased to avoid runaway effects: the bulged shape provides increasing surface for pressure, thus becoming even more prone to bulge.

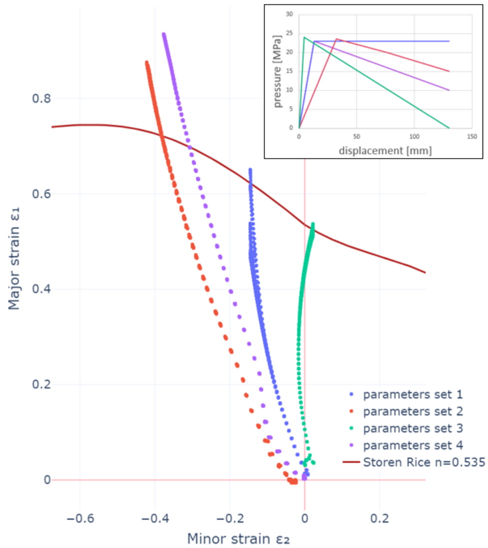

Figure 7. Results of HF with different set of parameters.

STRATEGY FOR HYDROFORMING

As previously stated, the most efficient way to hydroform the cavity shape is by applying internal pressure simultaneously with axial displacement of each end of the tube, and with coinciding closing molds. This procedure was chosen as baseline fabrication. Simulations showed that -if feasibility w.r.t. failure and equatorial thickness must be optimized- two hydroforming steps with one intermediate heat treatment are needed to form a 1.3 GHz cavity shape from a straight tube (d=78 mm, length=285 mm, thickness=4.6 mm). The initial space between the molds has been optimized and set to ~150 mm.

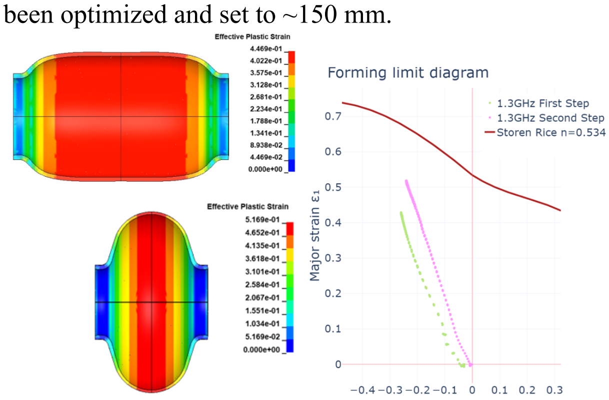

Figure 8. Feasibility studies on two-step hydroforming process, starting from a straight tube.

In most cases, the optimal process was obtained with displacement increased linearly during the forming. A balanced approach was chosen, meaning that in each of the two forming steps, similar levels of the deformation are reached. Figure 8 presents the results of the process simulations for each step of HF, showing that strains experienced during both forming steps are well below the FLC. The calculated effective plastic strain values are around 44 % and 53 % for the first and second hydroforming step respectively. The minimum thickness at the cavity equator at the end of the process was simulated at 2.9 mm (so 37 % of total thinning).

A second fabrication strategy has also been studied, which foresees obtaining the 1.3 GHz copper substrate starting from a bigger tube (inner diameter equal to ID=131.2 mm), initially deformed into an intermediate shape by spinning, and then hydroformed to its final shape. In this way, one can avoid excessive stretching of the material in the cavity equator and provide less thinning. The target necked shape after spinning was carefully studied and optimized, in terms of flat part length and external radius size. The inner radius of the necked tube corresponds to the cavity iris and the small diameter to the beam axis. This strategy could potentially elude the need of any intermediate heat treatment, since it is not the same portion of material which is being deformed during each forming step. On the other hand, two different fabrication processes are being involved (spinning, HF) so dedicated equipment and know-how is required for in-house production, or components subcontracting need to be considered. Figure 9 provides the results of the one-step HF simulation, starting from the necked tube. The maximum effective plastic strain is 45 % (being below FLC) with 22.5 % of thinning.

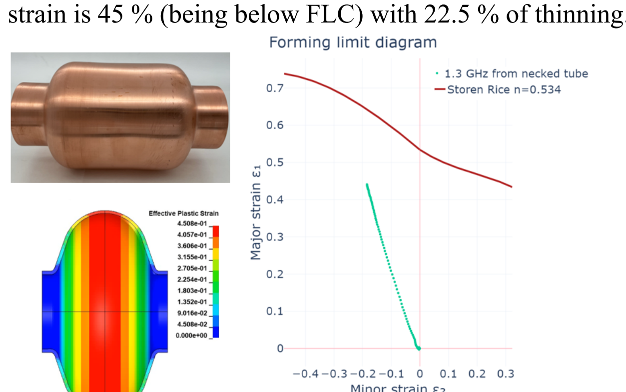

Figure 9. Feasibility studies on necking-hydroforming process.

NOVEL CRITERION FOR FAILURE IN SRF APPLICATIONS: SRFLD

Recent advancements at CERN in the field of fabrication modelling and feasibility studies have been directed towards expanding the scope of the standard FLD to accommodate SRF applications. This is achieved through the introduction of a novel framework named SRFLD, which aims to provide not only the 'standard' forming limit failure model, but also a comprehensive tool for predicting key parameters of interest, including final surface roughness and thinning, thus embedding failure considerations for both fabrication processes and for SRF scenarios, within the same set of visual forming limit diagrams.

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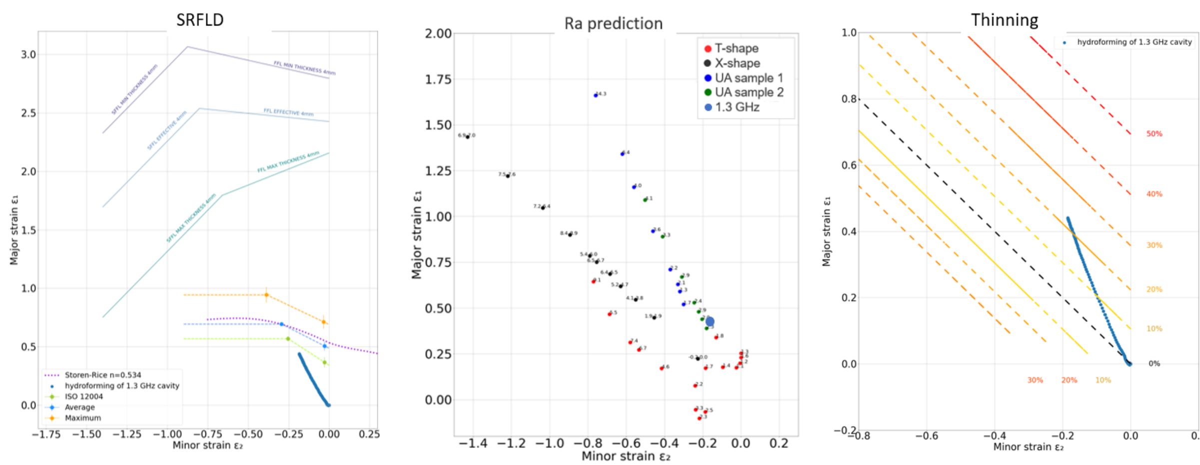

Figure 10. Use of SRFLD to assess feasibility and predict final parameters of a cavity, for a given HF process.

Roughness and Surface Aspect

One of the key parameters in RF performance is the general concept of surface condition, which encompasses surface roughness, presence of voids and/or microcracks, presence of embedded macro or micro-scale elements such as foreign material debris or atomic-scale elements like hydrogen. During HF the internal surface is exposed to high deformation, while not being smoothen by a rigid mold, as in other processes like deep drawing. A study correlating the roughness increase with respect to the deformation path is ongoing. Experimental data was collected from the set of tensile tests and from the hydroformed pieces (T- and X-shape), allowing to relate the expected strain value of the material elements with the corresponding roughness measurements. The roughness results were then plotted on the FLD-like graph (Figure 10), providing an indicative value of Ra roughness increase, as function of the in-plane strains. It must be noted that the roughness increase during a process is also presumably linked to the initial material grain size. With the current results, it can be appreciated how the roughness increase appears to follow iso-lines, exhibiting a somehow pseudo-elliptical pattern. This observation suggests that the evolution of roughness may be governed by underlying phenomena linked to equivalent volume distortion. The addition of further experimental data is foreseen, so that the plot may be further populated and improved; the current segmentation is thus expected to be smoothened, together with the clarification of eventual underlying phenomena and trends.

Application of SRFLD for Prediction of Final Parameters of the Hydroformed Cavity

Figure 10 exemplifies the application of SRFLD to assess feasibility of a given process and to predict roughness increase and final thickness of a formed piece. In this case, the HF step from a necked tube was plotted (belonging to the spinning-hydroforming 1.3 GHz hydroforming strategy, as in Figure 9). It can be observed how the process follows the UA strain path, and how the resulting major vs minor strains -plotted on FLD for OFE Cu- are below the forming limit curve (even looking at the most conservative line); this means that this process falls within the formability region. The numerical model predicts no failure or necking in the material. Based on the simulation results, one can expect an internal surface roughness increase of ~2 µm, and 22% of thinning at the end of the process.

CONCLUSION

This study gives an overview of the numerical methods for modelling large deformation processes, focusing on the HF seamless substrates. HF, as for other large deformation processes, can be optimized, by exploiting advanced simulation and novel material characterizations. It has been shown that HF is highly dependent of the combination of its main input parameters: axial load and internal pressure. Their values as well as their evolution in time will determinate the flow of the material during the expansion, the final shape of the formed piece, and the thickness distribution after forming. Two strategies were identified for manufacturing 1.3 GHz copper substrates. Their feasibility was proven through simulations and FLD failure model. Considering manufacturing of 400 MHz cavity as final goal, two-step HF was chosen as the baseline strategy and has been successfully applied for fabrication of 1.3 GHz; these results will be presented in the future. A novel approach of studying failure in view of SRF application was also presented, the SRFLD, thanks to which the formed part final parameters, can be predicted numerically; such promising tool can be used for any large deformation metal sheet forming process and will be further developed by the authors.

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