HYDROFORMING AT C.E.A. SACLAY : FIRST RESULTS

C. Z. ANTOINE, J. GAIFFIER
CEA,DSM/DAPNIA/Service d'Etude des Accélérateurs,
H. CHALAYE
CEA/CEREM
CE-SACLAY, F-91 191 Gif-sur-Yvette Cedex
J. F. ROCHE
BOURGOGNE HYDRO, ZI LES BLETTRYS, F-71530 Champforgueil

SUMMARY

The development of an industrial hydroforming process has been undertaken at Saclay, with the help of experts in forming material. In a first step, finite element program "Forge 2" was modified and tested with copper and niobium tubes on the CERN hydroforming bench. In a second step, we have designed with the help of "BOURGOGNE HYDRO" company an hydroforming machine able to form 1.3 GHz cavities in few steps according to the calculation. In the same time, calculations were performed by the CEREM (CEA Material Research Center) to optmize the forming process of large high RRR niobium tubes as required for 3-cells fabrication. The "FORGES-DE-BOLOGNE" company carried out the effective production. of seamless bulk tubes.

First attemps of hydroformed monocells with RRR 30 and RRR 200 Niobium will also be described in this paper, and compared the results of simulation calculation.

INTRODUCTION

The actual way of cavities fabrication, with welded half cells cannot be considered for building such large accelerators projects like TESLA. Firstly, any defective welds could constitute a dissipative part, preventing us to get high accelerating gradients, secondly we need to finalize an industrial fabrication process, in order to save time and money. Hydroforming is an attractive forming process as it works at room temperature. This avoids any oxygen contamination of the material, because it could easily get polluted at temperatures as low as 250-350°C.

Hydroforming cavities using seamless tubes with few intermediate thermal treatments presupposes at least three conditions :

- the furniture of seamless bulk tube of high purity Nb with adequate dimension.
- the simulation of the deformation process in order to optimize the number of steps.

• the fabrication of a hydroforming machine able to follow with precision the simulated path.

These points oblige us to get a very good knowledge of the mechanical behavior (rheology) of the niobium : first to be able to master the production of seamless tubes of large dimensions ; secondly, to be able to measure with precision the mechanical properties needed for the finite elements code.

In this work, we have explored the feasibility of 1.3 GHz monocells. This includes:

- Large niobium tubes fabrication.
- Mechanical characterization.
- Simulation with Forge 2.
- Studies of the forming limits.
- Validation of the simulation.
- Experimental results.
- Discussion and prospective.

NIOBIUM TUBE SUPPLY

Large tube of high RRR material are not commercially available.

A new fabrication scheme was developed in collaboration with an industrial company specialized in refractory materials : " Forges de Bologne".

In view of forming 1.3 GHz cavities the initial diameter was chosen to be intermediate between final cavity and irises diameters with approximately 20% reduction to be insured by swaging and 80% expansion by hydroforming. The part of the deformation kept for swaging was voluntarily low because of the folding risks, as we already observed experimentally on welded tubes Ref.[1].

The tubes are formed in three steps :

- reverse extrusion of Nb billiet
- spinning of the tubes
- swaging of the ends of the tube to adapt to the 1.3 GHz monocell tooling.

Note that this process can be easily adapted for the production of longer tubes as the ones needed for the fabrication of nine-cells for instance.

Figure 1 : Raw Nb tube and Nb tube prepared for 1-Cell hydroforming

The first produced tubes exhibit at visual observation a very good aspect : although the micrographies show a slight dispersion in grain sizes (80-120mm) the tensile curves show a fairly isotropic behavior (see figures and discussion below).

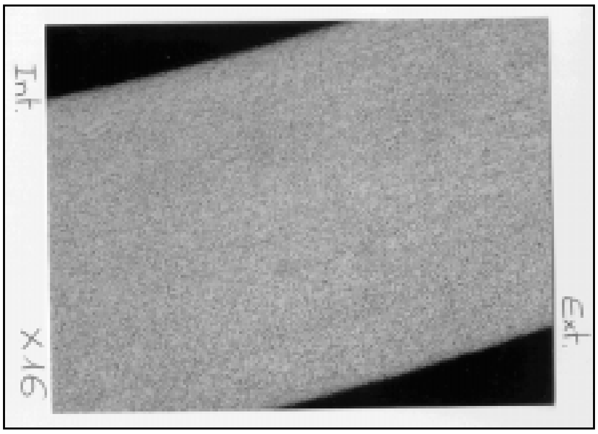


Figure 2 : Micrography of the tube

MATERIAL CHARACTERIZATION

These characterizations allow us to determine mechanical properties of Niobium and to check the following assumptions :

- isotropic material
- no effect of the deformation speed on mechanical characteristics.

With a stress-strain curve (tensile test), we can determine elastic properties, the consistency K, and the strain hardening coefficient n of the Hollomon law : $\sigma = K\ \varepsilon^n$ chosen to fit the hardening of the material (i.e. elasto plastic rheology) [2].

From these curves Niobium has also been characterized by tensile strength, yield strength which are the parameters which allow to determine the power necessary to hydroform niobium. The determination of percent elongation A% and reduction area is an indication of the ductility of the material. These two last parameters give us a first idea concerning the ability of the material to be hydroformed.

SIMULATION BY FINITE ELEMENTS METHOD

For this work we use a finite element code : FORGE 2 especially adapted for hydroforming problems. The calculation in plasticity is based on an incremental updated Lagrange procedure by using the principle of virtual work. For constitutive equations the generalized Prandtl-Reuss formulation for large deformations is used [3]. Moreover we suppose the material is following the Von-Mises criteria given in principle axes by :

$\frac{1}{\sqrt{2}}\left[\left(\sigma_1-\sigma_2\right)^2+\left(\sigma_2-\sigma_3\right)^2+\left(\sigma_3-\sigma_1\right)^2\right]^{\frac{1}{2}}=\bar{\sigma}$ where $\bar{\sigma}$ is the equivalent stress. A curve $\bar{\sigma}=H.(\bar{\varepsilon}_p)$ is extrapolated from the experimental true stress / true strain curve, where $\bar{\varepsilon}_p=\int d\bar{\varepsilon}_p$.

This calculation is coupled with a friction law chosen as Coulomb law in the case of Niobium.

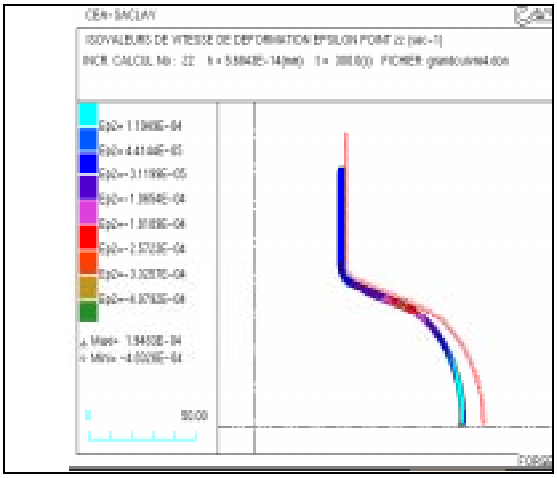


Figure 3 : exemple of simulation with FORGE2

FORMING LIMIT CURVES

Hydroforming is governed by the forming limit due to plastic instability and fracture. That's why it is necessary to establish a forming limit curve. Generally during the forming of sheet metals there is a first sequence of homogeneous deformation. In a second step a plastic instability appears in form of a diffuse necking followed by localized necking which causes final failure.

The simplified rheology ($\sigma=K\varepsilon^n$) introduced into FORGE2 takes only into account the strain hardening behavior of the material. Indeed no information about necking or rupture are considered. We need to define an additional criteria for the prediction of rupture. A limit curve must take into account all these phenomena.

It is known that a strain curve limit is quite dependent from strain path [4].

In order to establish theoretical curve we have made the following hypothesis :

- isotropic material.
- homogeneous material.
- the ratio between the bigger principal stress and the lower one must be constant.
- the hardening is supposed to respect the Hollomon law.

According to this hypothesis the equation of the forming limit is given by :

$$\sigma_\theta = \frac{K(2n)^n \left(1 - \alpha + \alpha^2\right)^{\frac{n-1}{2}}}{(1+\alpha)^n}$$

where K is the strengh coefficient,

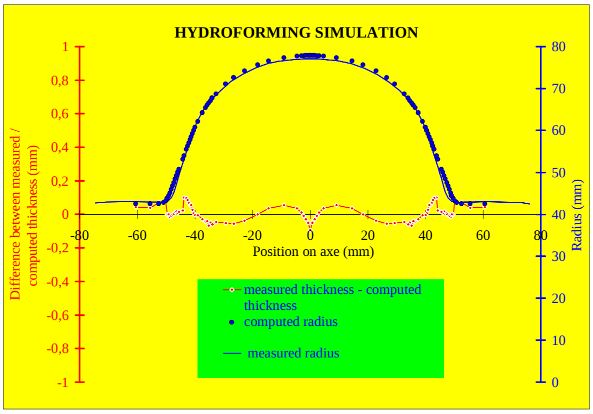
n is the strain - hardening exponent.

α is the ratio between principal strains ; $\alpha = \dfrac{\sigma_z}{\sigma_\theta}$

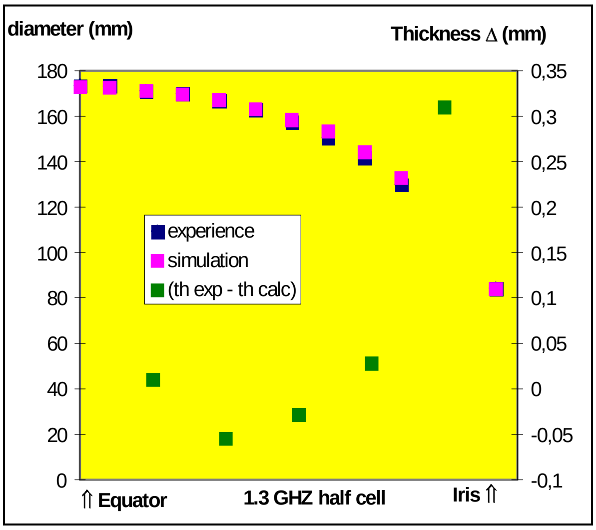
Respect to this criteria, we have to extrapolate a strain path in order to hydroform the tube without failure, avoiding geometric configuration as wrinkling. The initial ratio between pressure and tools displacement is very important in order to initiate a nearly spherical shape.

VALIDATION

The validation of the simulation was undertaken with copper and niobium tubes. They were deformed at several deformation paths (predetermined with Forge 2), then cut and very precisely measured with a 3D coordinate measuring machine (ZEISS).



5a) for Cu : here ∅final/∅initial = 181%



5b) for Nb : here ∅final/∅initial =206%.

Figure 5 : Comparison between experimental and calculated thickness an diameter for copper (a) and for niobium(b)

The difference between the calculated and the experimental values was less than 3% either for the general geometry as for the thickness variations, as shown in fig 5

The simulation allows a good prediction in term of geometry, but this type of calculation (Hollomon law) does not allow prediction about necking and/or rupture. One has to introduce a forming limit to stop the experiment before the apparition of localized necking.

In fig 6 two experimental points are plotted versus the Hill criteria formulation in the case of copper. We can see that this criteria can be used to prevent rupture.

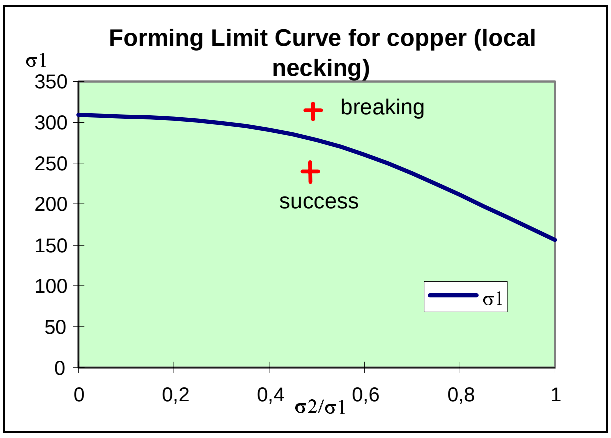


figure 6 : Application of the Hill criteria as a forming limit for copper

Unfortunately, this behavior was not systematically reproduced with niobium, depending on the origin and the thermomechanical treatment of the material. This point will be discussed in the next chapter.

HYDROFORMING

The unit developed with Bourgogne Hydro is a fully automated testing device which allows a precise control of inner pressure and tools displacement. Monocells and 3 cells can be formed on this unit.

The chosen shape for tooling is presently the same as for the end cells of the TESLA 9-cells at 1.3 GHz. This geometry, starting with tubes of ϕ = 98 mm asks for a total expansion of ∅final/∅initial = 216% which is very demanding to the material; this leads us to foresee intermediate annealings. Note that any cavity shape with a smaller expansion ratio like it is proposed for instance in ref[5] can be then reached with less intermediate steps.

The pressure unit is designed for high RRR material forming. Some difficulties may arise in the case of lower ductility material forming which needs some additional annealing treatments.

Hydroforming of copper does not give rise to any problem, neither in the choice of the simulation parameters (rheology, necking parameters), as for the realization of 1.3 GHz cavities of constant thickness. (See Fig 3). Note that due to the large ∅final/∅initial ratio, one to two intermediate annealings are necessary. Nevertheless, the deformation path can be further improved allowing to get fewer steps.

A similar deformation process can be applied to niobium. The application of the Hill criteria predicts a two steps process for RRR 200 and five steps for RRR 20 (due to insufficient pressure available). In Fig 7 we can see a RRR 20 Nb cavity which undertook 5 deformation steps (4 annealings) and which presented a rupture at ∅final/∅initial = 208% instead of the required 216%. In this case, the Hill criteria and the chosen rheology appeared to be relevant, at least for the first 3 steps. But after several steps of {deformation + annealing}, some damaging occurred (i. e. modification of the necking , appearance of micro-cracks, …) and cannot be cured by a standard annealing.

Figure 7 : Nb RRR 20 : rupture at 208% expension (instead of 216 %)

For Nb of higher purity, the rupture appeared often under the Hill criteria. Microscopic observations led us to the hints that rupture was due to localized defects, mainly grain size dispersion and micro-damaging.

Moreover, first texture studies also showed some difference of behavior between RRR 20 and RRR 200. It is known that some required texture can favors forming while some are hindering ref [6].

A study about the influence of texture on damage of the material is starting and should allow us to define better either the rupture parameters for niobium, either the evolution of the rheology upon several deformation steps.

In parallel with these studies, optimization of the deformation path can lead us to define a systematic and reproducible hydroforming process.

REFERENCES

[1] Unpublished results
[2] JF FRIES, PhD Thesis, Orsay, (1972)
[3] HJ BRAUDEL, M ABOUAF, JL CHENOT Computers and structures, Vol.24, N°6, pp.825-843, (1986)
[4] ARRIEUX, PhD Thesis, Lyon, (1990)
[5] W. SINGER et al, TESLA Report 96-03, DESY Ed, Hamburg (1996).
[6] P.COULOMB, Les textures dans les métaux de réseaux cubiques, Dunod , (1972).