Development of numerical tool for hybrid manufacturing process for titanium sheet metal forming

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Abstract:

The use of titanium in the aerospace industry has grown considerably in recent years in conjunction with the development of composite aircraft. In this way, improving titanium forming has become an important issue for the industry, both for productivity objectives and the ability to deliver basic parts according to the needs imposed by aircraft delivery rates, as well as for cost objectives. Currently, hot forming of titanium parts can be achieved through two processes: Super-plastic forming (SPF) or Hot Forming (HF). The aeronautical industry wanted to develop an innovative process for the manufacture of titanium parts by coupling the HF and SPF processes in order to exploit the advantages of these two technologies. The development of a mixed HF / SPF process will thus not only improve the rates and allow better control of the quality of the formed parts (thickness homogeneity), but also, by allowing forming at lower temperatures, this hybrid process presents a large interest at the energy plan. The study was devoted to the development of a hybrid HF/SPF process, carried out at a common temperature, allowing the "pre-forming" of the part in HF mode and the "calibration" of the part in SPF mode, while respecting a global cycle time compatible with the objectives of the aerospace industry and guaranteeing the quality expected for the final complex part. Improving the performance of the final part requires a development of numerical simulation tool of the forming process. The available simulation tool (ABAQUS/ Standard) must be adapted to define the best simulation strategy according to the simulated parts; moreover, it remains imperative to determine the input data (material behavior laws of titanium alloys) adapted to the cases to be treated (strain rate and process temperature).

Keywords: Hot forming, Super Plastic forming, Hybrid process, Titanium alloys, Numerical simulation, Behavior laws.

Note: for confidentiality reasons, some information will not be communicated.

1. Introduction:

Super Plastic Forming (SPF):

Superplasticity is a plastic deformation property of a material which results in very high elongations at break (typically several hundred percent). This phenomenon occurs at temperatures typically higher or equal to half the absolute melting temperature, for some materials only, and for rather low strain rates only.

Industrially, the so-called superplastic process most often consists in applying a gas pressure on a blank blocked at its periphery and heated up to a temperature suitable for superplasticity. The sheet is then gradually deformed until it fits the mold. The presence of blank holders preventing slipping of the sheet, the elongation also causes a thinning of the part, especially during the free bulging stage.

The main advantage of superplastic forming is the ability to fabricate parts having complex geometries that are impossible to produce with other forming processes. These parts therefore have a high added value and are currently destined mainly to the aviation industry. However, this method has the disadvantage of presenting long cycle times due to the low strain rates required (typically between thirty minutes and two hours to produce a part). Therefore, it is impossible to use it in the context of mass production. A second disadvantage is the elevated costs resulting from these high temperatures needing to be applied for long times, which demands a lot of energy.

Hot Forming (HF):

At the opposite, the Hot Forming process, which consists in deforming a few millimeters thick sheet metal using a punch, can be used to produce deformed parts in much shorter times and/or at lower temperatures. It can be related to hot deep drawing in many ways. Indeed, as in hot deep drawing, the sheet metal is forced to adopt the shape of a matrix by the vertical pressure of a punch. However, the temperature is raised beyond the range of standard drawing, between the third and the half of the absolute melting temperature. Furthermore, the HF method is isothermal. That means the tools are heated continuously at the same temperature as the work piece, which is usually not the case in hot deep drawing. In contrast to deep drawing, there are generally no blank holders in the Hot Forming process. This lack of position constraints prevents the blank sheet from stretching, which maintains an almost constant thickness throughout the part.

The main advantage of Hot Forming is a short cycle time (a few minutes) related to higher strain rates than in the case of SPF. However, the complexity of achievable geometries is very limited, with rather small strains due to the low ductility of the material under such temperatures and strain rates.

Hybrid Process (HF+SPF):

Today, increasing production rates requires to produce complex parts with short cycle times. That is why a process combining HF and SPF is being considered. This process is thus divided into two separate steps. The fast performing, comparable to HF, is performed by the movement of a punch, without a matrix but with blank holders. It is immediately followed by the second step of blow forming like in superplastic forming [1] (Figure 1).

Figure 1: Representation of the hybrid process.

The hybrid process allows combining the advantages of HF and SPF processes. Indeed, the preforming step significantly reduces the total cycle time compared to gas forming only, while the SPF completion allows achieving more complex parts than HF.

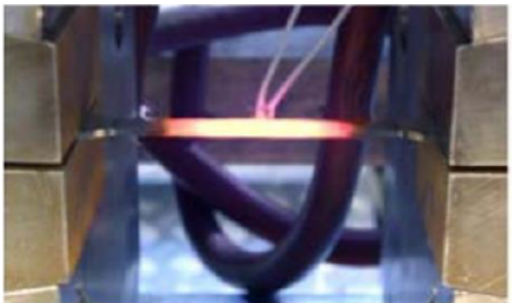
The few reported studies on the hybrid process [2, 3] have demonstrated the ability to produce successfully parts of aluminum and titanium alloys, at temperatures lower than those usually used in SPF. In addition, these parts were all formed with a significantly reduced cycle time compared to SPF. Forming cycles, which typically last between 60 and 120 minutes in SPF, were achieved within reduced time cycle. Our aim is here to characterize the influence of the fast HF preforming on the SPF step, with a more systematic investigation of the associated metallurgical aspects.

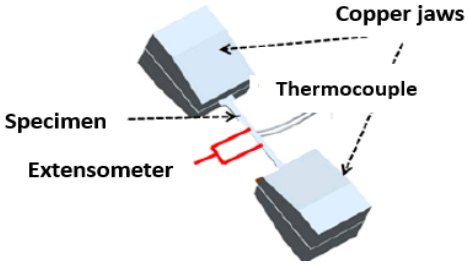
2. Material modelling:

Testing:

Hot-forming conditions:

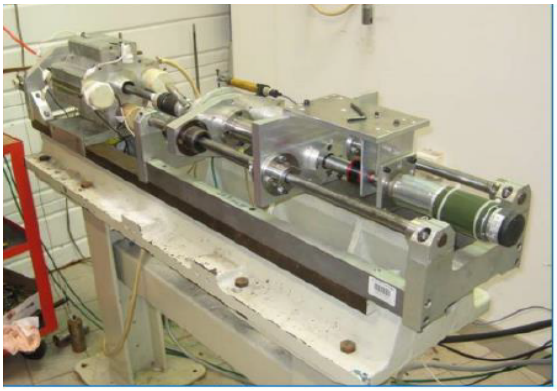
The tension tests have been performed in Arts et Métiers ParisTech, using A GLEEBLE. The specimen is heated to the test temperature with a heating speed of 10 ° C/s, followed by a stable phase of one minute to obtain a nearly homogeneous temperature in the central zone of the specimen (Figure 2). It is then deformed until it broke. Finally, a cooling of the specimen was done with a speed of about 50 ° C/s). The specimen is attached through 2 copper jaws (Figure 2). A type K thermocouple is welded to the center of the specimen to control the temperature in its center. An extensometer is mounted at the most heated zone to follow the movement and to control the rate of deformation there.





Super Plastic forming conditions:

The tension tests were carried out at Arts & Metiers ParisTech laboratory using a horizontal tensile test machine (figure 3) equipped with a tube furnace (four halogen lamps), an argon flow, a K-type thermocouple welded in the center of the specimen, a displacement sensor and a force sensor (1000 N).



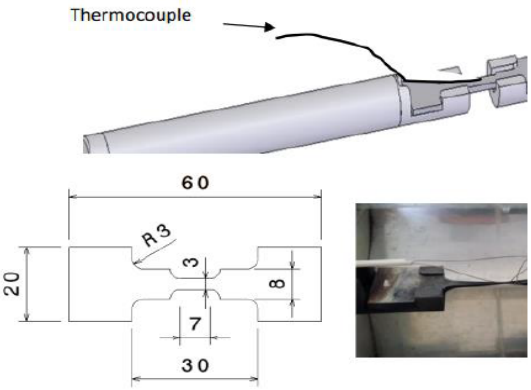


Figure 3: Hot tension machine used for SPF tests

Identification of behavior law:

In order to be able to simulate the mixed HF / SPF forming in a single step, it was necessary to identify a behavior law that covered the entire HF + SPF domains; it is called “the unified law”.

Principle of identification:

The law chosen is that of Norton-Hoff (N-H):

$$\sigma = k\dot{\varepsilon}^m \varepsilon^n \quad \text{(Eq. 1)}$$

The equivalent law in ABAQUS \ Implicit is the CREEP law whose expression is as follows [4]:

$$\dot{\bar{\varepsilon}}^{cr} = \left(A\tilde{q}^n[(m+1)\bar{\varepsilon}^{cr}]^m\right)^{\frac{1}{m+1}} \quad \text{(Eq. 2)}$$

Where $\dot{\bar{\varepsilon}}^{cr}$ is the uniaxial equivalent creep strain rate, $\tilde{q}$ is the uniaxial equivalent deviatoric stress and $\bar{\varepsilon}^{cr}$ is the equivalent creep strain.

A, n and m are the material parameters. The reverse method was used for parameters identification.

Figure 4 shows the comparison between experimental and analytical curves for the different strain rates and for the two steps (HF + SPF). Generally, the analytical identification of the parameters presents a satisfactory level of confidence with respect to the experiment.

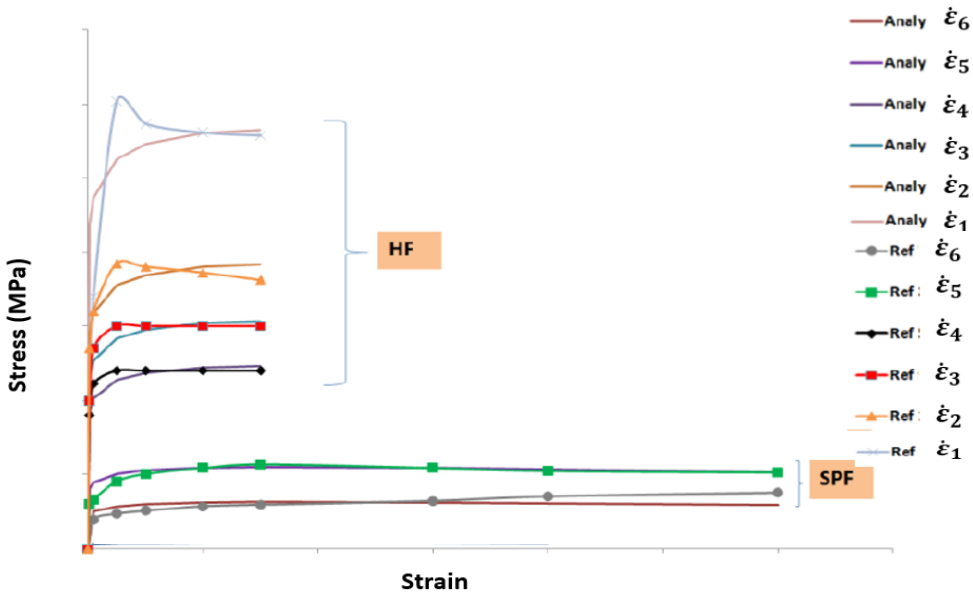


Figure 4: Comparison between experimental and analytical curves (with $\dot{\varepsilon}_1 > \dot{\varepsilon}_2 > \dot{\varepsilon}_3 > \dot{\varepsilon}_4 > \dot{\varepsilon}_5 > \dot{\varepsilon}_6$)

For high strain rates, we find a peak of stress on the experimental curves at about 10% of strain. This phenomenon is linked to microstructural changes at the grain level. The difference between the analytical model and the experimental test is maximal for the highest strain rate of $\dot{\varepsilon}_1$.

3. Process simulation:

Numerical simulation conditions:

For confidential reasons, the tooling used for the results validation is not shown in this study. The die, the punch and the blank holder are considered as rigid bodies. The blank is modeled as a deformable body with using quadratic shell elements. The chosen element size is 10 mm. This value has been optimized after several calculations taking into account the calculation time and the accuracy of the results.

For HF phase, the clamping is applied by blank holder and the stamping is carried out by punch displacement. For the SPF phase, the optimized pressure law is presented by the graph in the figure 5.

The friction coefficient is 0,15.

The model is composed of three main steps:

- Step 1: apply a clamping force;
- Step 2: perform the HF phase with applying the displacement of the punch;
- Step 3: block the movement of the punch;

  apply embedding of the nodes at the gasket level;

  apply the pressure cycle to perform the SPF phase.

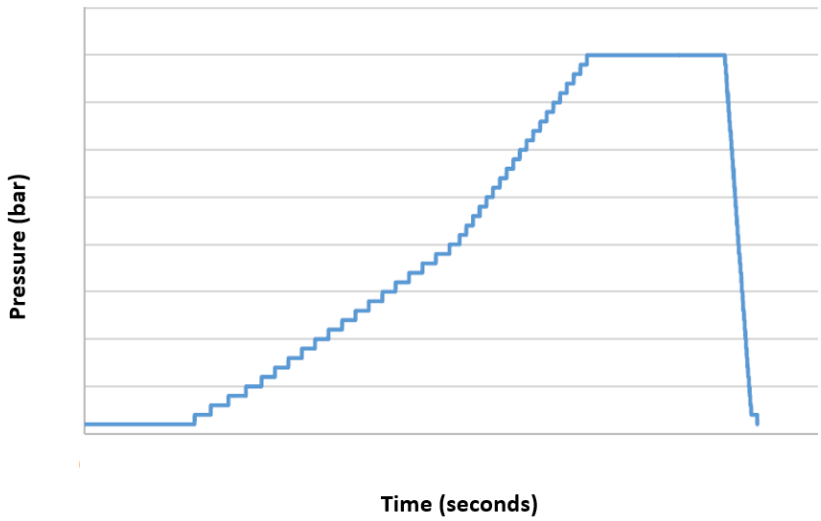


Figure 5: Shape of the optimized pressure law for SPF phase

Results:

Thickness distribution:

The measurement of the thickness at different points of the part indicates that the thinning is very homogeneous throughout the useful part zone with an average value of 10%.

Figure 6 shows the numerical prediction of the thickness at the end of the HF phase. A thinning of 10% can be seen. At the end of the SPF phase (figure 7), the thinning reaches its maximum with a local value of 21% at the corners of the part whose material is strongly deformed. On the rest of the useful area of the part, the overall maximum thinning is about 16%.

These numerical predictions have been verified experimentally through several tests and it has been found that the maximum overall difference is about 5%. This has been considered satisfactory for industrial application.

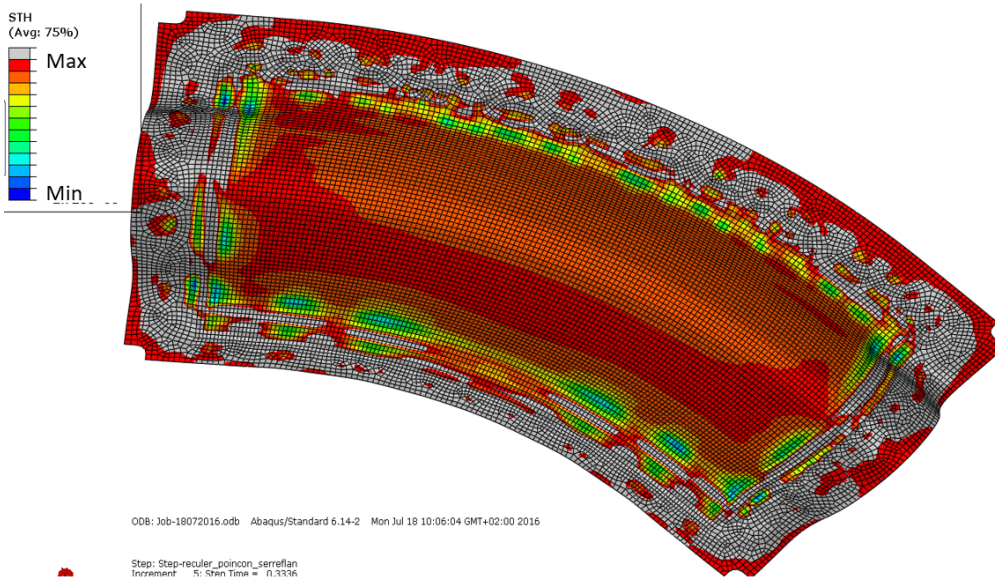


Figure 6: Thickness distribution at the end of the HF phase

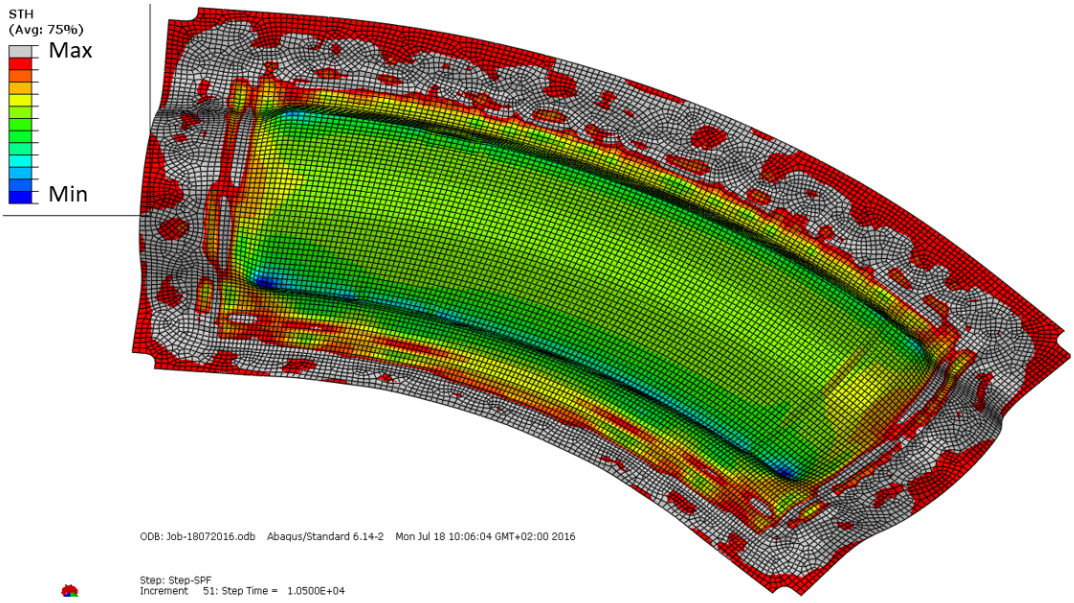


Figure 7: Thickness distribution at the end of the SPF phase

4. Conclusion:

In order to study the possibility to produce parts with a new hybrid process based on hot forming and superplastic forming, we have developed a numerical model which consists of simulating the sequence of two processes (HF and SPF) in the same computation. Based on unified behavior law identified at a same temperature and a strain rates range that combines between the two steps, our results could be summarized as follows:

- This numerical development allowed us to optimize tool geometry as well as the shape of the blank,
- The major thinning has been noticed in the HF phase,
- The SPF phase was used to calibrate the final shape of the part,
- The hybrid process allows to obtain a reduced cycle time and a homogenous thickness distribution in the useful zone of the part,
- The numerical predictions have a good level of confidence to simulate the industrial applications targeted in the project.

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[4] Abaqus user's manual (6.14).