ASSESSMENT OF PROCESS MODELING TOOLS FOR TUBE HYDROFORMING USING ABAQUS SOFTWARE: FINITE ELEMENT MODELING AND FAILURE MODES ANALYSIS.

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ABSTRACT

A modeling and simulation methodology based on ABAQUS software is presented for a multistage tube hydroforming (THF) process. Using adequate loading paths and appropriate numerical parameters, it is possible to avoid potential failures that are prone to occur under uncontrolled process. Two examples are considered. First, the failure mechanisms during the initial bulge forming are analysed and useful wrinkles in main deformation areas are used to obtain a good part. Then the simulation of a multistage THF process integrating both a rotary draw bending and a hydroforming stages is performed for assessing the process parameters and numerical difficulties encountered in modeling of a real component.

KEY WORDS: Bending process, Tube hydroforming process, deformation, failure mechanisms, aluminum tubes, wrinkles.

1. INTRODUCTION

Tube hydroforming (in short THF) describes a metal forming process whereby tubular blanks are deformed into complex shapes within a die cavity using simultaneously hydraulic internal pressure and axial compressive forces. Compared to the conventional stamping, or deep drawing processes, the tube hydroforming process is still a relatively new forming method in terms of large scale production and thus with a limited knowledge base about the process and associated tool design. The process still struggles with long cycle times and expensive equipments, [3]. These drawbacks have made its acceptance in the forming industry lag behind. However, tube hydroforming is a unique forming method since during deformation due to inner pressure; it is possible to feed material axially by cylinders at the tube ends. If necessary, counter punches can even be used to control the tube expansion [2]. Research is thus being performed continuously on the subject and improvements in process control, tooling and lubrication together with advances in simulations, contribute to a more general acceptance and utilisation in industrial production, see Hartl [2].

The main advantages of THF over the conventional stamping processes are weight and cost reduction, better structural integrity, increased strength and reduction in part numbers [2,3]. It is even possible to tailor the properties of the hydroformed tube by varying its initial cross section and wall thickness. Tubes with variable cross-sections can be hydroformed in two ways: closed die tube expansion, or tube crushing [5,12, 13]. In closed die expansion, the tube is formed between two die halves through the use of internal fluid pressure. In tube crushing, die closure is utilized to assist deformation like in corner filling. During the deformation, part of the section is in contact with the die. If the material/die interface were frictionless, the strain would be uniformly distributed all over the section and a section with a constant thickness would be formed. However, friction at the material/die interface restricts the flow of material in contact with the die and causes non-uniform distribution of strain. It causes a variation in the thickness of the formed tube along the cross-section with the smallest thickness at the corners. Thus the frictional behavior at the material–die interface is crucial in tube hydroforming.

However, one of the major tasks in setting up a THF process is to avoid failure by finding an appropriate balance between material feeding and internal pressure, so as a part is successfully formed without any defects and with a minimum waste of materials. An inappropriate combination of internal pressure and axial feeding can lead to occurrence of defects such as buckling, bursting and wrinkling during the tube hydroforming process. Dohmann et al. [12] pointed out that wrinkles are unavoidable in the intake region of the expansion tool, but can be eliminated by increasing the internal pressure in the calibration stage.
Moreover, in the case of long expansion tools, wrinkles can be also formed in the center of the workpiece as a result of excessively axial feeding, but can be avoided by controlling the forming process carefully.

Since experimental tests and physical prototyping are rather expensive, numerical simulation is now used to predict defects during the hydroforming process and the adjustment of loading paths is required to smooth the forming process [4,15]. However for a selected set of materials, lubrication conditions, part geometry and tooling design, the success of forming a hydroformed part without any defects and with the required thickness specifications, strongly depends on the selection of an appropriate loading path. And finding the convenient control of the evolution of these loadings is still the main difficulty in many hydroforming processes [2] because this depends on the material behaviour, tube geometry and tool-part interface. A systematic study of the influence of loading conditions on the mechanics of tube hydroforming, as well as failure by occurrence of localized necking, has not been undertaken[6,16]. However, it is important to address this issue because it would enable better design of dies and other associated tools.

In this paper, we study the tube hydroforming process, under the combined action of an axial end feed and injected fluid pressure that plastically deform the tube and force it to conform to the shape of the die (Fig. 1). The challenge is to be able to perform the entire operation without a defect that can cause the rejection of the part. In a first example, we study the hydroforming process of a uniaxial tubular part which does not require additional operations i.e. pre-forming and calibration are performed within the same dies. By various combinations of process parameters, several pre-form shapes leading to different product qualities can be obtained and different failure modes can be observed. We apply the principle of maximum feeding length and minimum internal pressure, so that the loading path is modified in order to keep the tube within the critical status before wrinkling. In a single step simulation process, the load paths have been determined in such a way that as a wrinkle is about to be formed, the internal pressure has to be increased to avoid it. This method is very difficult in the real-time control process. Following analysis by Xing et al. [4] of the instability of tubular blank under axial stress and the effect of loading path and material properties on hydroforming process, it was verified that not all wrinkles are harmful and that the useful wrinkles can be exploited to avoid the excessive thinning of the tube thickness by bringing more material in the expansion zone and by eliminating the wrinkles during calibration phase [14,15]. In a second example, we consider a more complex THF problem where multistage forming operation and material history have to be taken into account when moving from stage to stage using different toolings. A fully integrated process simulation of a multistage forming process allows to simulate tube fabrication either by sheet metal roll forming combined with welding or by tube extrusion with a welded seam. Then, depending on the tube quality and properties and on its intended application, heat treatment may be necessary before the bending operation, in order to restore the formability required by the current and subsequent forming operations [8,9]. A successful manufacturing by tube hydroforming requires knowledge not only about the process parameters, but also more on materials and their behaviour during the process. In our case, the simulation will allow to better understand the tubular hydroforming process of aluminum alloy (AL 7075-T73) and its failure mechanisms before any tooling try-out.

2. SIMULATION OF THE HYDROFORMING PROCESS

In tube hydroforming, the fluid pressure injected inside the tube deforms it plastically by expansion, and forces the tubular workpiece to conform to die cavity of various cross sections. The axial force applied to the two ends of the tube can be used to compensate for the wall thinning induced by the tube expansion under internal pressure (figure 1). It thus allows the control of the thickness of the tube by maintaining the deformation on a desired level.

Figure 1 - The process of tube hydroforming (1 – Axial Punch, 2- Tube, 3 – Lower Die, 4 – Upper Die)
For specific industrial purposes, several analytical approaches based on plastic instabilities have been developed to provide simple but useful guidelines for product designers and process engineers for the avoidance of failure during hydroforming operation [11,13]. In practical cases, however, the necking criterion based on plastic instability may not predict the forming limit in a wide range of hydroforming processes. Especially, in case of aluminum alloys, the bursting failure is often observed without appearance of clear localized necking or thinning due to the low ductility [6,14]. It means that for aluminum alloys, the fracture occurs prior to the onset of localized necking influenced by the work-hardening characteristic and the normal anisotropy. Therefore, the analytical approaches based on the plastic instability or bifurcation theories are not always applicable for aluminum alloy tubes. The progress of thinning is also often delayed and suppressed by the friction of the tools and the deformation history, and the blank does not fracture immediately after the onset of the localized thinning. In that case it thus better to introduce a ductile fracture criterion and to estimate the occurrence of fracture from the calculated results by means of the finite element simulation. Once validated, this approach will provide a feasible method to satisfy the increasing practical demands for the computer aided formability evaluation system for hydroforming process.

2.1 SIMULATION OF THE TUBE HYDROFORMING WITHOUT PRE-FORMING

In this example, the FE simulations based on geometrical analysis of wrinkling, stress and strain state and thickness variation after wrinkling are used for investigating the control and use of wrinkles in tube hydroforming and the factors affecting the wrinkling behaviour. By noticing that not all wrinkles are defects and that some wrinkles can be used to increase formability, the key issue is then to obtain “useful” wrinkles instead of “dead” wrinkles. It is proposed that accumulation of material in expanding area by formation of wrinkles is an effective method for obtaining preforms.

The formability of the aluminum alloy (AL 7075-T73) is thus explored by considering an isotropic hardening law. In order to detect eventual material failure, the Gurson’s fracture criterion can be used to represent a material in which the relative dilute concentration of void and the relative density is 0.9. As an application example, we choose to study the free bulge test, often considered in literature, and hydroforming within a die. The example from the paper by J. Kim et al [5] was considered and hence all the parts dimensions and the die configurations are shown in the Fig 2. By several numerical tryouts using ABAQUS, we have determined that a feasible loading path for the internal pressure and the axial feeding displacement can be defined by the amplitude diagram of (Fig. 3). The curves on the diagram controls the internal pressure and the axial feed loading history during the forming process.

![Figure 2 - The Dimensions (in mm) and configurations of the die and final bulged parts [ref 5].](image)

A. Single Step Simulation

Five simulations corresponding to different loading paths involving a simultaneous application of internal pressure and axial feed, each associated with a given amplitude program, have been performed. Taking the mid process simulation time as a reference (0.5ms), one can notice that the evolution of wrinkling is different from simulation to simulation. If pressure is increased, the wrinkle radius also
increases. If internal pressure is set at 120 MPa, the tube conforms to the die and there is no wrinkle produced. Due to contact between the die and the blank, we cannot attain the maximum allowable axial displacement (3.76 mm still to go), indicating that less material is fed in the expansion zone; hence tube thinning and possible necking are expected to occur. Wrinkling has been eliminated but necking has become unavoidable.

Figure 3 – Normalized pressure and axial feed amplitudes

As a next step in our preliminary investigation, we wanted to find by numerical trial and errors how we can generate a wrinkled perform that can be successfully formed into the desired shape by a final calibration stage with a minimum internal pressure. In other words, we want to determine the process windows and the different loading paths required to hydroform the part without any defect.

Figure 4: Single step simulation for different loading paths

B. Two loading Step Simulation

Several loading programs have thus been considered, each involving a two steps loading process: (a) a pre-forming stage using maximum allowable axial feed combined with internal pressure varying up to a certain fixed value below that of the press capacity (Stage 1) and (b) a calibration phase with no further
end feed but with increasing internal pressure up to the maximum press capacity (Stage 2). Several trial and error tests were run in order to find an acceptable loading path, and figure 6 shows two such simulations. Defects during the hydroforming process are predicted by numerical simulation and the adjustment of loading paths is presented to smooth the forming process [3,5].

In the performing stage, several pressure levels are combined with the maximum feed to see how many wrinkles are produced in the free expansion zone, which load path produces good or bad wrinkles and which one can lead to bursting. In the first simulation, an estimation of maximum axial feed is calculated and a value of intermediate allowable forming pressure to be provided by the press at the end of feeding pre-forming stage is predefined at a value far below its capacity. In ref [13], this pressure is kept constant during the pre-forming stage while here we vary it from 0 to a predefined value. When wrinkles are produced without burst, a calibration stage is then performed by increasing the internal pressure until the blank conform to the die wall with or without defects. Good wrinkles can be corrected by this expansion while bad wrinkles can lead either to folding back or to dead wrinkles (the application of maximum press capacity cannot flatten them).

As a result of excessive axial compressive loading during the bulging process, wrinkling can occur on the tube wall as illustrated in Fig. 5. If the pressure is low, the preform will present some wrinkles and the problem is to know which of them can be corrected during the calibration stage (beneficial) and which ones result in undesirable part defects (dead wrinkle or folding back). In the calibration step, a radial expansion is produced by increasing the internal pressure up to the maximum allowable by the press or until the tube conforms to the inner surface dies wall. In the shown results only two cases have been selected for discussion.

(i) Preforming with maximum end feed with a target pressure of 40MPa: The first case concerns the pre-forming stage where the maximum axial end feed is applied incrementally while the internal pressure is increased up to a maximum of 40 MPa. It is observed that wrinkling is produced and that a further calibration at 60, 80 or even 100MPa do not correct the wrinkles, indicating that dead wrinkles have been produced in the perform (figure 6).

The question then is, how many wrinkles have been produced? What are the effects of calibration pressure on these wrinkles? In this case, we have to avoid buckling but one could not avoid wrinkling (Fig. 7).
the trial and errors tests simulations, we find the maximal pressure necessary to calibrate all useful wrinkles.

(ii) Preforming with maximum end feed and a target pressure of 60MPa: In order to find a successful load path, we modified the target pressure from 40 to 60MPa. As in the previous tests, the preforming stage is made by incrementally applying the maximum end feed while varying the pressure up to a maximum of \( P = 60\text{MPa} \). The pre-form now presents good wrinkling (small wrinkles are produced), (figure 8). The tube conforms better with the wall of the die but not smoothly, meaning the dead wrinkles are obtained with that calibration pressure. It is observed in this case that a further calibration up to a pressure of 80MPa leads to a part that conforms correctly to the die inner wall surface. The results are better than in preceding simulation (Fig. 9).

Figure 8 – Third simulation (Stage 1: P=60MPa, Stage 2: P=60MPa)

Figure 9 – Fourth simulation (Stage 1: P=60MPa, Stage 2: P=80MPa)
In the process of tube hydroforming, it is not straightforward to find the loading function of coordinated axial feed and radial pressure required to produce a defects free part, because of the many involved unknown parameters that influence the process. For the considered part where we have a pressure dominant process with important end feed, it is believed that producing a pre-form with good wrinkles will lead to a final hydroformed part requiring less press capacity. The generated wrinkles during the performing stage can then be used to feed material in the expansion zone. Once enough material is fed in the free expansion, then a calibration stage requiring less energy (i.e. lower pressure) than in a single forming stage requiring a proper coordination of pressure and end feed can be realized. Hence for such a part we can have two process windows, one with wrinkles and another one without wrinkles. Utilizing wrinkled pre-forms can enlarge the hydroforming process window and this may be appropriate to the low formability materials such as aluminum alloys and low volume production. To reduce the numbers of experimental tests, one must use the numerical simulation to understand the evolution of the deformation during the process.

2.2 SIMULATION OF TUBE HYDROFORMING WITH PRE-FORMING

In this example, we consider a more complex tube hydroforming process, where different forming processes and tooling are required in order to successfully form the required product. In that case, each forming step has to be carefully considered, since pre-forming stage can prevent the completion of the THF process and thus a waste of material if not successfully completed (without enabling defect) with enough remaining material formability for subsequent operations. For complex parts manufacturing by tube hydroforming process, several intermediate operations are required. Besides the manufacture of the tube itself, the most important are tube bending and tube crushing, and recently tube wrinkling. It is thus a necessity to include/understand the connection between the involved process parameters, geometry parameters and behaviour of material and to evaluate the formability of materials in the context of the tube hydroforming process. The example of a multistage forming process considered here is concerned with hydroforming of pre-bent tube. It is provided in order to demonstrate the capability of ABAQUS/CAE in handling such kind of problems for idealized process parameters and material parameters. An integrated process simulation is adopted, thus allowing to take into account the full material history in the multistage forming simulation process.

2.2.1 TUBE BENDING SIMULATION BY COMPRESSION BENDING

For tube bending, a compression tube bending process has been used. This process is very used in industry because of its low cost and accurate and high quality results. The tooling consists of a bend die, clamp die and wiper shoe. The bend die and clamp die wiper are stationary and the wiper shoes pushes the tube along the bending die as it rotates around it (Fig. 10). We start with a straight precut tube to be prebent in a rotary bending machine to fit the hydroforming tool. The tube undergoes significant deformation during the bending and a number of different tools can be used to prevent excessive flattening, wrinkling and thinning of the tube in the bending process. Although the only necessary tools for the bending operation are a bend die, a clamp and a pressure die, very often, a wiper die is included to prevent wrinkling. Besides providing boost to the tube, the pressure die is located so as to prevent the tube from rotating with the die. This operation reduces the thinning of the tube in the bend and can be useful when the bending angle is large or the bending radius is small. However, it also increases the thickening inside the bend. The simulation starts from the points when the wiper shoe starts rotating, thereby drawing the tube around the bend, and terminates when the wiper shoe stops rotating.
The tooling design has been performed in ProEngineer Wildfire and parts were exported in ABAQUS/CAE through IGS file (ref 1). In ABAQUS, all tool types are modelled as «Discrete Rigid» while the tube is modeled as «Deformable». The position and movement of a rigid body is defined by a reference point of the instance created in the Assembly module (Fig. 11).

For tube material definition, two aluminum alloys are considered: AL 7075-T73 and AL3%Mg. For plastic behaviour, stress-strain curves are considered and for the interaction between the tools and the tube, a friction coefficient of 0.15 was used. The tube dimensions (D= 68 mm, L=614 mm) have been calculated so as to compensate for springback and make the tube fit into the hydroforming die (after the bending). The clamp die provides the normal force on the tube to secure it around the bend die, thus drawing the tube around the bend. The pressure of the mandrels was replaced with another step (additional inside pressure). In experimental point of view, the mandrel prevents the walls of the tube from collapsing during the bend.

**Results of bending**

Because of the chosen part, several intermediate forming operations are required before the final shape can be obtained. The bending is the first operation to be carried out on the as-received extruded tubes. Since the minimum allowable formability requirements are sometimes established by the bending operation and not the hydroforming operation, a careful examination of the process limits and parameters has to be made, especially with respect to the evaluation of the thickness distribution in the bent portion of
the tube. During the process, the thickness increases at the intrados (surface of the tube in contact with the die) while it decreases at the extrados (surface of the tube in contact with the wiper shoe). Thus this thickness variation on the circumference of the tube can be an essential ingredient for the next forming stages (crushing and hydroforming). Fig. 12 and Fig. 13 illustrate how the evolution of the thickness is different in every points of the tube during the simulation.

Before moving to the next stages (crushing and hydroforming), it is necessary to evaluate the thickness distribution throughout the deformed portion of the tube (Fig 14). If the thickness is not constant during hydroforming, the tube becomes deformed non-uniformly along the circumference. By evaluating the thickness of the tube, one notice that there is a reduction between 2% - 5% in the upper, lower and extrados of the tube when compared to the initial thickness, and an increase between 8 -10% in the intrados of the tube. The thickness variation in the tube intrados can support the appearance of the wrinkling.

By using two materials having different formability, AL3%Mg and AL 7075-T73, two simulations were made. At the end of the simulations, we have observed that the thickness variation of the tube is different from one material to another, AL3%Mg, which is more ductile than Al 7075-T73, has a slope steeper than the other material (Fig. 15). Therefore, the thickness shift compared to the initial value increases with the formability of material; this implies a different progress of the deformation and damage. If one can know this thickness distribution on the whole tube, one can predict the evolution of the deformation in function of this thickness variation and the loading conditions.
Figure 14 - Variation the thickness at the end of bending simulation on the curved portion of the tube
(Material used: AL7075-T73)

Figure 15 – Evolution of the thickness at the end of the bending simulation for two different materials
(AL 3%Mg and AL7075-T73)
2.2.2 HYDROFORMING SIMULATION

In order to determine the deformation limits of the two materials used (Al 7075 - T73 and AL3%Mg), a hydroforming process simulation of the prebent tube into a complex non symmetrical part is considered, thus with an additional difficulty in die modeling and manufacturing (Fig. 16).

The principal difficulty in manufacturing this part resides in the non uniform die section including both convex, concave rectangular shaped section and T-shaped section. Hence, upon die closure, there will be tube crushing in order to force the tube to conform more closely to the die wall section, and different end section feed are required in order to fill the T-shape. We have already presented the bending operation in section 3.2.1, and we noticed the available thickness distribution for the next operation. The internal pressure that was injected in the tube during the bending has a direct influence on the thickness distribution on the whole tube (Fig. 14). For hydroforming simulation, we can use a bend tube which has a constant thickness or we can use a tube geometry recovered from the bending operation (fig. 17 and fig. 18).

Since finding the desired optimal loading path is still a challenging task because of many involved parameters: multistage forming process, parts and tools geometries and characteristics, material flow and formability issues, desired product performance, an iterative process was used to find an acceptable one.
**Figure 18** - Damage localisation for AL3%Mg (Maximum pressure used 75MPa)

**Figure 19** – Evaluation of the thickness in the upper damage zone for AL7075-T73 and AL3%Mg (Maximum pressure used 120MPa and respectively 75MPa)

**Figure 20** – Evaluation of the thickness in the longitudinal damage zone for AL7075-T73 and AL3%Mg (Maximum pressure used 120MPa and respectively 75MPa)
The thickness variation depends on the material model considered. We tried out, by numerical simulation, the hydro-processing of two different materials: Al 7075, which is strongly work hardening and AL3%Mg, which is more ductile. We have located the necking in both cases and have observed that for the materials which are less hardenable, the physical surface of damage is larger. On the other hand, for hard materials the necking settles on a smaller surface.

CONCLUSION AND PERSPECTIVES

The objective of this paper was to better understand the tubular hydroforming of aluminum alloys and other materials used in aerospace structural components. Based on geometrical analysis of wrinkling, stress and strain state and thickness variation after wrinkling, we first studied the control and use of wrinkles in tube hydroforming, and the factors affecting the wrinkling behavior by FE simulation using ABAQUS.

In a second step, the modeling and simulation of a multistage tube hydroforming process comprising prebending process simulation using a compression bender machine, followed by calibrating and calibration within the same die of complex asymmetrical shape with T-shape protrusion were performed.

A successful tubular hydroforming depends on a reasonable combination of the internal pressure and the axial compression force at the tube ends. Thus, the information on the tubular hydroforming limit, the final wall thickness distribution and the final contact quality between the deformed tube and the tools is necessary for a designer. A trail and error numerical simulation approach was used in order to find the loading path required to successfully complete a hydroforming process without defects, however this is rather time consuming, since several simulations are required while one would rather prefer an automated load path determination within minimum time. However, the used approach provides a feasible method to satisfy the increasing practical demands for a computer-aided formability evaluation system for the hydroforming process. More work is still needed for finding the desired optimal loading path. Moreover, an automated process implementation, we first require a more appropriate constitutive model of the material used and adequate wrinkling and necking/fracture indicators required to control the deformation and the damage of the material. This tool is required in order to predict the deformations and thickness distribution of the tubes and to find the optimal combination of the process parameters that allow to produce a part of given geometry and strength at lower costs and in a minimum amount of time.

REFERENCES