

Development of Process Maps for Tube Hydroforming Process

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ABSTRACT

Tube hydroforming technology has been in existence for more than 30 years; but its use has been mostly limited to simple shapes and low-volume applications [1]. The process involves forming a straight or a pre-bent tube into a die cavity using internal hydraulic pressure, which may be coupled with controlled axial feeding of the tube. Recent advances in forming machines and machine control systems have allowed for the introduction and the implementation of the process to produce several automotive components, which were originally produced by the stamping process. Components such as side rails, engine cradles, space frames, and several others can be economically produced by tube hydroforming. The main benefits obtained from the tube hydroforming technology include weight reduction due to improved part design, part consolidation where a single component replaces an assembly, reduced tooling cost as a result of part consolidation, and improved structural strength and stiffness of the hydroformed component [2]. However, the drawbacks include incomplete knowledge base of the effects of processing parameters on the final product, expensive tooling requirement, and slower cycle times compared with metal stamping.

1. INTRODUCTION

Tube hydroforming is a manufacturing process in which an internal hydraulic pressure is applied to transform either a straight or a pre-bent tubular blank into a structural component with different or varying cross-sectional shapes along its length [1]. High pressure tube hydroforming is the most common form of the tube hydroforming process in which a tubular blank is placed in a closed die and an internal hydraulic pressure forces the tube to conform to the shape of the die cavity. In order to reduce thinning in the tube wall, the tube ends are fed into the die cavity by the use of hydraulic cylinders [2]. Punches may also be mounted in the die to pierce holes in the tube wall during the forming operation. A schematic of the loading scheme is shown in Figure 1 with F_e denoting end feed and P denoting the internal pressure for a tube with radius r , wall thickness t , and tube length, l .

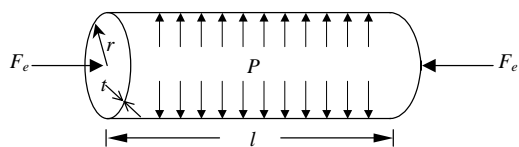


Figure 1. Loading Scheme in High Pressure Tube Hydroforming

The process is being used or is being considered for use to make a wide range of components for both automotive and non-automotive applications. Pressure levels over 50,000 psi are sometimes used to produce industrial size parts; however, most parts are typically produced at pressure levels under 50,000 psi [3]. Automotive parts currently under development or in production include seat frames, engine cradles, rails, exhaust manifolds, and space frame components [4]. Interest in the tube hydroforming process by the automotive industry is due to the possibility of replacing many multi-piece stamped and welded assemblies in body, frame, or chassis components with one-piece hydroformed components. Thus, there is a great potential for not only weight saving, but also for tooling and labor cost saving that may occur due to the elimination of multi-stage stamping and assembly processes through part consolidation. A drawback of the process is the need for expensive tooling (dies and presses) that can provide and sustain the required forming pressures. Thus, numerical simulation is needed in order to reduce the production cost.

The two most likely defect modes in this process include tube bursting and wrinkling. Tube bursting occurs when the tube cannot support the tensile load produced by the internal pressure; once the tube bursts, splitting occurs

near the burst area due to excessive deformation. Tube wrinkling is caused by excessive compressive force generated by end feeding. Either of these two modes of failure results in an unusable product [6].

The objective of this paper is to present a recently developed experiment on tube hydroforming that can be used in metal forming classes to introduce the students to the effect of hydroforming pressure and end feed on the thickness distribution. The experiment will also help in identifying conditions that lead to producing defect free components. Numerical models of the process are also carried out; the experimental findings are compared to numerical modeling results and conclusions are made.

In this experiment, tubes are formed in the laboratory, under different processing conditions, to demonstrate the different modes of failure, and the conditions that can lead to defect free hydroformed parts. Numerical modeling of the tube hydroforming process is conducted using the finite element tool DYNAFORM, and the model is analyzed using the finite element analysis code LS-DYNA. The hydroformed tubes are cut into sections, and thickness measurements are made along these sections. The physical test results are then compared with the numerical results. Students completing this exercise learn to identify the effects of processing parameters on the final product, and are introduced to numerical modeling tools for metal forming.

2. PREREQUISITE KNOWLEDGE

Basic knowledge of finite element analysis and the use of a finite element modeling tool (i.e. DYNAFORM); mechanical properties of materials; strength of materials.

3. EQUIPMENT

The hydroforming press used in this experiment was acquired through funding from the Education Foundation of the Society of Manufacturing Engineers. DYNAFORM is annually provided to the Department as an in-kind gift from Engineering Technology Associates (ETA).

1. Interlaken servo-hydraulic press
2. Hydroforming dies
3. Unitest data acquisition and machine control software
4. Welded stainless 302-L steel tubes: 7.9 to 8.0 inch long, 2.0-inch outer diameter.
5. DYNAFORM and LS-DYNA
6. Micrometer

4. PROCEDURE

The class is divided into two halves and conducts this exercise over two laboratory sessions. In each lab session, half of the students work on the experimental study of tube hydroforming and the other half work on the numerical study. In the lab, the students run different tests in order to determine the conditions under which the tube fails (i.e., bursts or wrinkles) for simple part shapes, using the die shape and size shown in Figure 2.

4.1 Experimental Procedure

1. Observe the safety instructions posted in the lab and make sure to wear safety glasses.
2. Start-up the hydroforming machine control and data acquisition program.
3. For the first tube, set the internal pressure level to 14,000 psi.
4. Set the end feed to 0.3 in for each end.
5. Install the tube in the die with the weld line aligned parallel to the parting line.
6. Turn the hydraulics on to form the part, and once the die opens turn off the hydraulic pump.
7. Remove the part from the machine and label it.
8. Repeat steps 3 to 7 for another tube with the weld line aligned at 45 degrees to the parting line of the die set.
9. Form other tubes using several different combinations of internal pressure and end feed.
10. Plot the results in the pressure vs. end feed for each experiment as shown in Figure 3 and distinguish between the pressure-end feed combinations that led to defect free product, and those that led to defect.
11. Sketch the boundaries identifying the safe production zone and the failure zone as indicated in Figure 3. (Note that the shape of the border lines will be affected by the number of formed tubes, tube material, etc.)

4.2 Numerical Procedure

Depending on the abilities of the students, either they can develop their own finite element model of the process, or they can just change parameters in a pre-developed model. In our case, a pre-developed model was provided to the students. The model was developed using ETA's DYNAFORM, which is a pre processor for developing LS-DYNA input decks. The students were first introduced to DYNAFORM in prior laboratory sessions. Following is the procedure given to the students to conduct the simulation:

1. Import the provided die and tube drawings (in IGES format) into your modeling tool (DYNAFORM).
2. Using a surface mesh, auto-mesh the die using shell elements with maximum element size 0.6 inch and minimum element size of 0.4 inch
3. Define the meshed die as tool in the "Define Tools" menu.
4. Define the tube material properties using piecewise stress-strain data. (Mat. No. 24 in DYNAFORM)
5. Mesh the tube using Belytschko-Tsay shell elements with element size of 0.1 inch.
6. Define the pressurization curve as a linearly increasing pressure up to 14,000 psi.
7. Define the end feed curve for each end as linearly increasing up to 0.3 inches
8. Run the analysis and obtain the thickness distribution in the hydroformed tube.

To introduce the students to metal forming analysis, each group of students is assigned an experimental pressure and end-feed combination that yields a defect free part

(Figure 4), as well as a combination that causes either bursting (Figure 5) or wrinkling (Figure 6) of the tube. Data from all student groups is then compiled and distributed to all groups. The students use the data to develop a two dimensional processing map for bursting and wrinkling and identify the safe forming zone similar to Figure 3.

Each student group cuts then the defect-free tube into sections perpendicular to its axis of rotation (Figure 4) and measures the thickness along the cut line using the micrometer. The numerically predicted thickness distribution at the location of the cut is then obtained from the results of the numerical model. A plot of the experimental results and the numerically predicted results is then generated and the results are compared; a sample plot showing the experimental and numerical thickness distribution, is shown in Figure 7 [5].

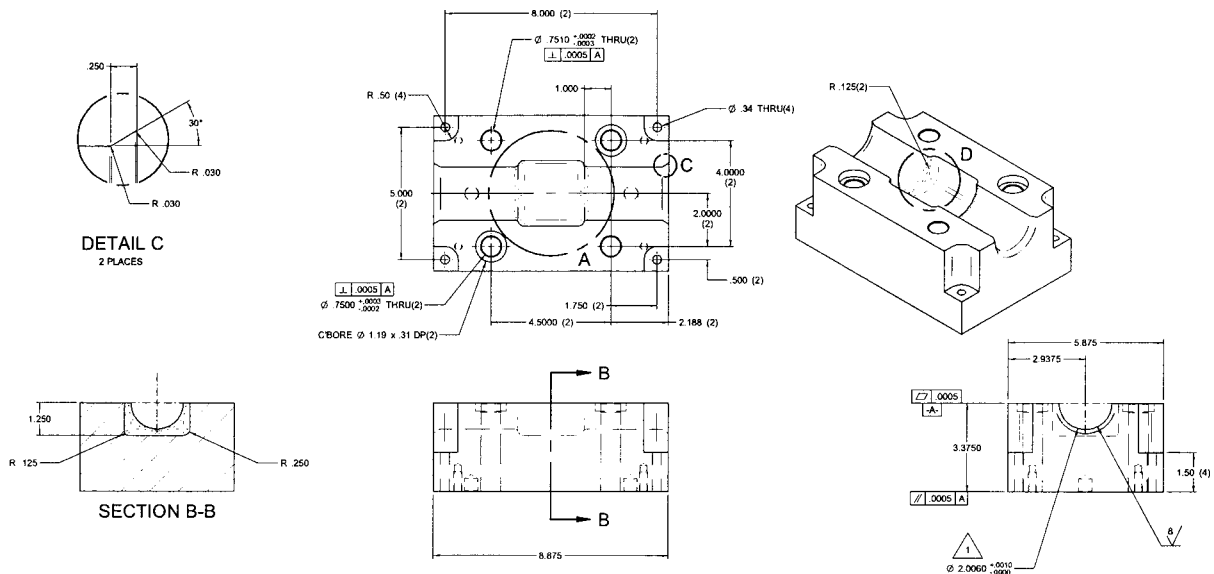


Figure 2. Dimensioned drawing of die used in the experiments

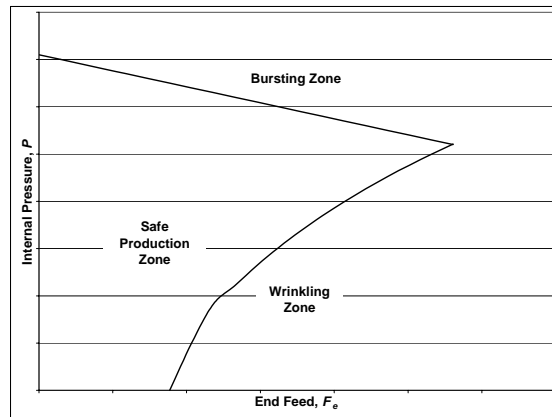


Figure 3. Schematic of a process map for tube hydroforming

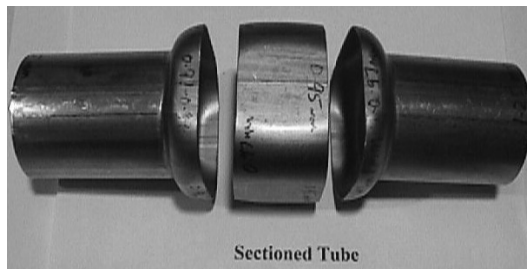


Figure 4. Image of sectioned tube hydroformed without defects

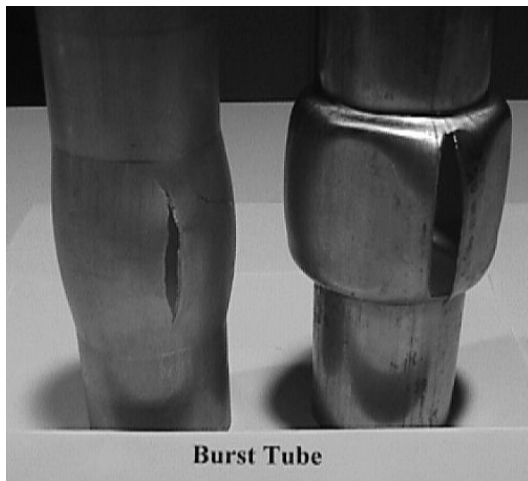


Figure 5. Burst and split tubes due to high levels of internal pressure (seamless Al 6061-T6 tube on the left and welded 304-L stainless steel tube on the right)



Figure 6. Wrinkled tube due to excessive end feed

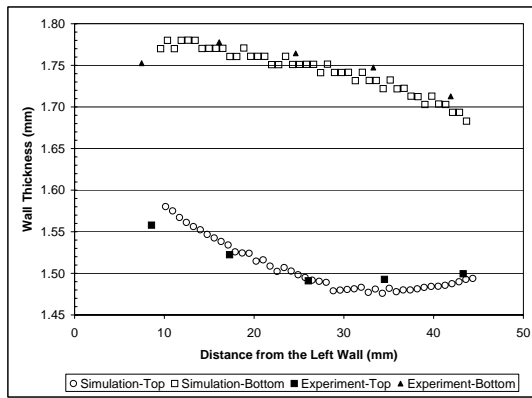


Figure 7. Sample thickness distribution plot showing experimental and numerical results (left wall refers to side of the tube between the 0.125 corner radii shown in Figure 2 section B-B)

5.0 COMMENTS

The tubes are most likely to burst near the weld line due to the physical and metallurgical characteristics of the material near the weld line. Thus by aligning the weld parallel to the parting lines of the die, the weld and the adjacent material experience the least amount of deformation since they contact the die walls at early stages of the hydroforming process. When the weld is aligned at 45 degrees to the parting line of the die, it is located in the zone that experiences the highest level of deformation, thus bursting is likely to occur near the weld.

The tube begins to deform plastically once the internal pressure causes a hoop stress level (σ_h) that is greater than the yield strength of the material according to the relationship shown in equation (1)

$$P = \frac{\sigma_h \cdot t}{r} \quad (1)$$

According to equation (1), the internal pressure is directly proportional to the tube wall thickness and hoop stress, and is inversely proportional to the tube radius. The internal pressure in the tube will increase at the early stages of deformation (due to strain hardening of the tube material), reaching a peak, then decreases as the tube expands further [6]. If the applied pressure exceeds the peak pressure, the tube bursts. Thus, the pressure level at the onset of bursting may be calculated using equation (2)

$$\frac{dP}{dr} = 0 \quad (2)$$

The pressure at the onset on wrinkling is typically related to the axial stress in the tube, which is a function of the effective flexural rigidity of the tube, the effective

modulus of the tube, the tube radius, and the tube wall thickness. The properties of the tube material, such as strength coefficient, strain hardening exponent, elongation to fracture, and anisotropy, will result in different processing maps for different tube materials.

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