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EXPERIMENTAL AND NUMERICAL INVESTIGATION OF LOW PRESSURE TUBE HYDROFORMING ON 409 STAINLESS STEEL

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ABSTRACT
Tube hydroforming has been widely used to produce automotive structural components due to the superior properties of the hydroformed parts in terms of their light weight and structural rigidity. Compared to the traditional manufacturing process for a closed-section member including stamping and followed by welding, tube-hydroforming leads to cost savings due to reduced tooling and material handling. However, the high pressure pumps and high tonnage press required in hydroforming, lead to increased capital investment reducing the cost benefits. This study explores low pressure tube hydroforming which reduces the internal fluid pressure and die closing force required to produce the hydroformed part. The experimental and numerical analysis was for low pressure hydroformed stainless steel tubes. Die filling conditions and thickness distributions are measured and critically analysed.

Keywords: Hydroforming, low pressure, buckling

1. INTRODUCTION
The requirements for reduced vehicle weight while maintaining crash and other performance characteristics is requiring the auto industries to adopt new high strength steels and improve the metal forming processes. Compared with conventional sheet metal forming process, hydroforming or hydraulic forming is one process to meet the challenges of developing complex, lighter weight components from high strength materials [1,2]. Hydroforming uses the fluid pressure to deform the material. Within, tube hydroforming of tubular blanks has been successfully developed to manufacture of the components for automotive vehicles [3], where this is also called a soft-punch forming technology [4]. With the advancements in computer controls and high-pressure hydraulic systems, this process has become a viable method for mass production, especially with the use of internal pressures of up to 6000 bar [5].

In contrast to many advantages, hydroforming has the main drawbacks that it generally requires high capacity mechanical presses and high pressurization systems. On the basis of internal fluid pressure required to form the part the Tube and Pipe Fabricators Association categorise hydroforming into three processes which are: 1) Low pressure hydroforming \( (P < 83 \text{ MPa}) \) 2) Multi-pressure hydroforming \( (P = 69 \text{ to } 173 \text{ MPa}) \) and 3) High Pressure hydroforming \( (P = 83 \text{ to } 414 \text{ MPa}) \) [6]. In Low pressure hydroforming the hydroformed section length of line stays almost the same as the circumference of the blank tube. During multi-pressure hydroforming the tube is pre-formed and then expanded to the desired shape by pressurizing the fluid. Higher pressures allow the hydroformed section length of line to be expanded up to the limit allowed by the material’s ductility [6]. At present most work focuses on the high pressure form due to its ability to produce more complex shapes.

Various investigations have been performed to reduce the pressure required to form the part from tubular blanks. The concept of sequenced forming pressure is proposed to reduce the thickness variation of the product and the forming pressure [7]. The maximum internal pressure and maximum
die closing force needed in the low pressure hydroforming processes combined with preforming and hydroforming are only about 5% and 7%, respectively, of those in the expansion test [8, 9]. The plastic flow pattern, thickness distribution of the tube and forming pressure requirement have been studied during high pressure; however the experimental study of metal deformation and the potential for buckling during low pressure hydroforming require additional studies. Also the pressure requirement to avoid the buckling and its effect on the stress and thickness distribution during crushing process is still unknown.

In this paper low pressure hydroforming was performed on 409 stainless steel. It is found that it reduces the internal fluid pressure and die closing force for producing the hydroformed part without buckling. Experimental and numerical analysis is performed for the stainless steel tubes during low pressure hydroforming. Die filling condition and thickness distributions are measured and critically analysed.

2. MATERIAL AND METHODOLOGY

2.1 Methodology

In this study the low pressure hydroforming process was investigated experimentally and by Finite Element Analysis (FEA) for two different internal tube pressures, 0 MPa and 10 MPa. This included the analysis of the filling conditions and the determination of the pressure and die closing forces necessary to form the desired square part geometry. Additionally the thickness distribution over the part perimeter and the final part profile were analysed.

2.2 Material

409 stainless steel was studied; the measured thickness and the chemical composition, as given by the supplier, are shown in Table 1.

2.2.1 Tensile Test

Tensile tests were performed as recommended in Australian standard AS 1391-1991 on specimens (Figure 1 and Table 2) that were cut from the tube samples along the longitudinal and circumferential directions and flattened on 50 ton (498 kN) hydraulic straightening press. A non-contact extensometer with a test range of 25±5 mm was used. The tests were performed in a 30 kN MTS. All specimens were marked by two white dots that were situated 25 mm apart from each other on the flat gauge section. Using a video camera system the displacement of the dots during testing was measured giving the force displacement curve. All experiments were performed using a strain rate of 0.08/min.

Table 1. Measured thickness and chemical composition of 409 stainless steel

<table>
<thead>
<tr>
<th>Designation</th>
<th>Thickness (mm)</th>
<th>Chemical Composition (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>409SS</td>
<td>0.8</td>
<td>C: 0.08, Si: 0.6, Mn: 2.0, P: 0.04, S: 0.03, Cr: 19.8</td>
</tr>
</tbody>
</table>

Figure 1. Standard tensile test specimen (AS 1391-1991)

Table 2. Standard tensile test specimen dimensions (AS 1391-1991)

<table>
<thead>
<tr>
<th>Section</th>
<th>Dimension (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge Length, Lg</td>
<td>50.0±1.0</td>
</tr>
<tr>
<td>Length of narrow parallel-sided portion, Lp</td>
<td>60.0</td>
</tr>
<tr>
<td>Initial distance between grips, l</td>
<td>63.0</td>
</tr>
<tr>
<td>Overall Length, Lo</td>
<td>200</td>
</tr>
<tr>
<td>Width, W</td>
<td>20.0</td>
</tr>
<tr>
<td>Width of narrow parallel-sided portion, Wp</td>
<td>12.5±0.6</td>
</tr>
<tr>
<td>Thickness, h</td>
<td>Material thickness</td>
</tr>
<tr>
<td>Radius, r</td>
<td>12</td>
</tr>
</tbody>
</table>

2.2.2 Low Pressure Tube Hydroforming

The hydroformed part profile investigated in this study is shown in Figure 2.
In low pressure hydroforming, the outer circular perimeter of the initial tube needs to be equal to the perimeter of the 2D section perpendicular to the thickness of the final part. Thus the perimeter of the outer undeformed tube must be same as the inner perimeter of the die. The outer diameter and thickness of the tube used in this study was 50.90 mm and 0.8 mm, respectively. The tube ends were welded onto steel plugs which were used to connect one end of the tube to a hydraulic hose and a pressure gauge which were further attached to a hydraulic ram and a cylinder (Figure 3). The other end of the tube was connected to a relief valve which allowed a constant pressure (10 MPa) inside the tube during the forming process.

For 0 MPa, i.e., without using an internal fluid pressure the tube was formed without the end plugs and the hydraulic connection.

The experimental set-up of the low pressure tube hydroforming is shown in Figure 4. The tube was pressurized and placed between the lower and the upper die. While the lower die was fixed, the upper die moved down and formed the tube into the desired shape. According to the perimeter equivalence (equation 1) the down stroke of the upper die that was needed to obtain the shape shown in Figure 2 was 14 mm.

Perimeter of Final product = Perimeter of initial tube outer diameter

2.2.3 Microscopic Thickness and Profile Co-ordinate Measurement

For both test conditions a slice was cut from the formed tube and the thickness distribution measured over the perimeter. For this, marks were indented along the specimen edge at a pre-defined distance of 1 mm using a Vickers’s hardness tester. This enabled the exact recording of the distances between the particular measurement locations (Figure 5a). Using an optical microscope, images of different parts of the specimen were taken. Thereby, generally at least three indentation points were present in every picture (Figure 5b). Using Image Tool (version 3) software [10], the thickness of the specimen at each measurement location was determined.
Thick-ness measurement method applied to the part; \( S_a \) indented tube strip; \( S_b \) microscopic picture of indented tube strip

To determine the final shape of the deformed tube, the outer profile of the tube slice was tracked on graph paper (line distance: 1mm) (Figure 6) and the co-ordinates measured. These were than used to plot the final profile in Microsoft Excel.

\[
\sigma = K e^n
\]

Where: \( \sigma \) - true stress, \( e \) - true strain, \( K \) - strength coefficient, \( n \) - strain hardening exponent

The dies were considered to be rigid bodies while the tube was defined to be deformable (Figure 7) using CPE4R 4-node bilinear plane strain quadrilateral elements. The approximate element size was 0.5mm with a curvature control of 0.1. Two element layers through the material thickness were used and without and with friction conditions were assumed between the tooling and the tube surfaces. Internal pressure and the upper die travel were applied simultaneously. Constant internal pressure curves were used for low pressure tube hydroforming throughout the process. Because of the symmetry of the formed tube, the thickness distribution over the perimeter was only measured for half of the tube, as shown in Figure 8.
3. RESULTS AND DISCUSSION

3.1 Tensile Tests

The true experimental stress-strain curve determined in the tensile test and the fitted power law (equation 2) are shown in Figure 9. The stress-strain curve determined for the longitudinal direction was used, as both longitudinal and circumferential curves were coincident (i.e. isotropic material). Flattening may have had a small effect on the early plastic flow behaviour, but this was not considered to be an important factor as the model also has some deviations with the early stress-strain behaviour. The mechanical properties of the tested material are summarized in Table 3.

3.2 Experimental results

The experimental die closing forces determined for both the un-pressurized and pressurized hydroforming tests are shown in Figure 10. Without the application of an internal tube pressure the required die closing force was 37.5 kN, while with 10 MPa internal tube pressure, a maximum force of 191 kN was needed to form the tube. For both cases the force was linear up to an overall die displacement of 12.5 mm and than suddenly increased as the tube was forced into the die corner radii.

Table 3. Mechanical properties of HSLA, DP and TRIP steels

<table>
<thead>
<tr>
<th>Designation</th>
<th>Mechanical Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>HSLA</td>
<td>240</td>
</tr>
<tr>
<td>DP</td>
<td>520</td>
</tr>
<tr>
<td>TRIP</td>
<td>900</td>
</tr>
</tbody>
</table>

It becomes clear in Figure 9 that the fitted power law does not give a good representation of the near yield behaviour. This is, because a tensile region above 10% strain was used to determine the hardening exponent.

Figure 9. True stress-strain curve from tensile test with fitted power law for 409 stainless steel

Figure 10. Die closing force for 0 MPa and 10MPa

The tube formed without an internal pressure showed buckling on the top and bottom surfaces, with higher buckling observed at the top of the tube compared to the bottom part (Figure 11 and 12). In contrast, the tube formed under pressurized conditions was perfectly formed into the desired shape (Figure 11 and 12). This indicates that an internal pressure of 10 MPa is...
sufficient to prevent buckling during forming for the given material type and geometry analysed in this study.

For both forming conditions the thickness was uniform throughout the part and stayed constant (Figure 13). This indicates that the material was not stretched during deformation but only straightened and bent.

3.3 Numerical results
The closing forces determined using the FEA are in good agreement with the experimental results (Figure 14). In Figure 15, 16 and 17 the numerically predicted final part profiles are compared to the experimental results. Even though for the case of the un-pressurized tube forming the FEA results indicate the risk of buckling in the top and the bottom part of the tube, they show an opposite trend compared to the experimental results. While in the experiments the formed tube showed higher buckling in the top and less in the bottom, the FEA results predict higher material folding in the bottom and less in the top (Figure 15), this is due to the assumption of frictionless dies. With friction between the dies and the tube ($\mu = 0.05$, predicted from best fitted FEA die closing force compared to experiments), the FEA part profile gives good correlation with the experiment (Figure 16). It seems that buckling is affected by the friction condition.

In contrast to that the numerical shape predictions achieved for the pressurized tube forming case are in good agreement with the experimental results (Figure 17).
For both forming conditions the numerically predicted thickness distributions are in good agreement with the experimental results (Figure 18).

4. CONCLUSION
The low pressure tube hydroforming was experimentally and numerically analysed for 0 MPa and 10 MPa internal tube pressures. It was found that a minimum internal tube pressure of 10 MPa was required to form the tube into the desired shape while no internal pressure resulted in buckling of the top and the bottom surface of the formed part.

The FEA predictions of the final shape, the die closing force and the thickness distribution showed good agreement with the experimental results for the pressurized forming process. In contrast to that a weaker prediction of the formed part shape was achieved in frictionless dies, with friction at the die surface for the un-pressurized forming case gave a better prediction, which implies that buckling is affected by friction.

It was found that in low pressure tube hydroforming the material thickness stays uniform over the tube perimeter, as no material stretching is involved in the forming process.

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LIST OF REFERENCES


