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NUMERICAL INVESTIGATION OF HIGH AND LOW PRESSURE TUBE HYDROFORMING

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ABSTRACT: Hydroforming is one option to reduce vehicle weight while increasing component stiffness and rigidity. This typically involves using a fluid to form a component with high internal pressure. Tube hydroforming has gained increasing interest in the automotive and aerospace industries because of its many advantages such as part consolidation, good quality of the formed part etc. The main advantage is that the uniform pressure can be transferred to whole part at the same time. In low pressure hydroforming, the internal pressure is significantly and the hydroformed section length of line stays almost the same as the circumference of the blank tube. This paper details the comparison between high and low pressure hydroforming. It is shown that the internal pressure and holding force required for low pressure hydroforming process is much less than that of high pressure. Also stress and thickness distribution are more uniform and the process is highly suitable for the forming of advanced high strength steels.

KEYWORDS: Hydroforming, low pressure, high pressure.

1 INTRODUCTION

One of the key areas of research at present is to reduce the mass of vehicles for improved fuel consumption. Hydroforming is a metal forming process that is now widely used as it can achieve weight reduction of about 30% compared to conventionally manufactured components [Lucke, Hartl and Abbey (2001)]. At the same time automakers are increasingly exploring the potential to use advanced high strength steels as they can also provide weight reduction without any reduction in other performance characteristics such as crash and durability.

The tube hydroforming process can be categorised into three pressurization systems 1) Low pressure hydroforming (P<83MPa) 2) Multipressure hydroforming (P = 69 to 173MPa) and 3) High Pressure hydroforming (P = 83 to 414MPa) [Singh (2003)]. Most research to date has focussed on high pressure hydroforming particularly to improve the quality of product. For example local thinning and wrinkling can be prevented by oscillating the internal pressure in the pulsating hydroforming. Because of oscillations of internal pressure, a uniform expansion in the bulging region was obtained, and thus the formability was improved by preventing the local thinning [Mori, Maeno and Maki (2007)]. Asnafi and Skogsgardh (2000) proposed stroke controlled hydroforming. Jain and Wang (2005) developed a dual-pressure tube hydroforming process in which the plastic instability is delayed and the ductility of the metal is increased. Smith, Ganeshmurthy and Alladi (2003) presented tube hydroforming with double-sided high-pressure (DSHP) boundary condition which increased formability relative to that observed for the traditional single-sided high-pressure (SSHP).

In comparison the research carried in low pressure hydroforming is limited and there is still insufficient knowledge to design the process. However, one of the attractions of this process is that it requires much lower pressures and it is of note that the high pressures above were for simple low carbon structural steels. For the advanced high strength steels the stresses required to deform the metal are much higher and hence the pressure requirements are further increased.

In this paper, a comparison between low and high pressure tube hydroforming was carried out for the same final component. A ramp pressure curve was applied during the high pressure process, which allows to linearly varying to the desired pressure

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with respect to time until the tube was completely formed and constant pressure was applied for low pressure, which remains constant at desired pressure throughout the process.

2 MATERIAL AND METHODOLOGY

2.1 MATERIAL

The steel investigated in this study is a commercial TRIP 780 grade. The true stress strain curve used for the numerical analysis in section 2.2.3 is shown in Figure 1 while the mechanical properties are shown in Table 1.

Figure 1: True stress-strain curve TRIP 780

Table 1: Mechanical properties of TRIP 780

<table>
<thead>
<tr>
<th>Designation</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
<th>Elongation, %</th>
<th>K (MPa)</th>
<th>n</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRIP 780 grade</td>
<td>550</td>
<td>1120</td>
<td>26</td>
<td>1205</td>
<td>0.220</td>
</tr>
</tbody>
</table>

2.2 METHODOLOGY

In this study the high pressure tube hydroforming (HPTH) and the low pressure tube hydroforming (LPTH) process were numerically investigated and compared. This included the analysis of the filling conditions and the determination and comparison of the pressure and die closing forces for both processes when forming the same part geometry. Additionally the stress and thickness distribution within the part wall was analysed for both processes.

2.2.1 High Pressure Tube Hydroforming (HPTH)

The most commonly used tube hydroforming set up is shown in Figure 2. The lower die is generally fixed with the tube placed in it, while the upper die moves down and closes the tool gap. The tube is then filled with an incompressible fluid and pressurized to form the tube into the desired shape. During this process the tube needs to be stretched to fill the die corners. In this study a square corner die was used. To allow for a reproducible comparison between the high and the low pressure hydroforming process, the same part geometry was used for both processes (Figure 4, with dimension).

Figure 2: Start of High Pressure Tube Hydroforming (HPTH)

2.2.2 Low Pressure Tube Hydroforming (LPTH)

In LPTH the desired shape is obtained using lower fluid pressures than in HPTH. The tube is located between the upper and lower die and pressurized. While the lower die is fixed the upper die moves down and forces the tube into the required shape.

In low pressure hydroforming, the hydroformed section length of line stays approximately the same as the circumference of the undeformed tube. Thus the perimeter of outer un-deformed tube must be same as that of the inner perimeter of the die. So by perimeter equivalence (equation 1), the calculated diameter of the un-deformed tube for low pressure hydroforming is 57.12mm. Therefore to obtain the same final part in this study the final formed tube wall thickness after high pressure hydroforming was used as the initial wall thickness of the tube used for low pressure hydroforming.

Figure 3: Preform tube and start of Low Pressure Tube Hydroforming (LPTH)
Perimeter of Final Product = Perimeter of Initial tube for LPTH  

(1)

The LPTH process is illustrated in Figure 3. In the first step the tube is pre-formed to make it fit into the lower die. In the second step the upper die is moved down. The previously explained perimeter calculation showed that the punch has to move a maximum distance of 12.5 mm to force the tube into the desired shape.

2.2.3 Numerical Modelling

In the numerical study the tube was assumed to be a cylinder and variations of wall thickness and material properties were neglected. For the HPTH process a tube with a material thickness of 2 mm and an outside diameter of 50 mm was studied while in the case of LPTH an overall material thickness of 1.75 mm and a tube outside diameter of 57.12mm was used. Power law behaviour (equation 2) based on fitting of the data in Figure 1 with isotropic plasticity was used in the simulations.

\[ \sigma = K \varepsilon^n \]  

(2)

where,

\( \sigma \) = True stress  
\( \varepsilon \) = True strain  
K = Strength coefficient  
n = Strain hardening exponent

The FE code ABAQUS/Explicit 6.5-1 version was used to simulate both high and low pressure hydroforming. The die was considered as a rigid body, while for the tube deformable CPE4R 4-node bilinear plane strain elements were applied. Two layers through the material thickness were used and the maximum element size was chosen to be 1 mm. In the model the interaction between the tube and the tooling was assumed to be frictionless and the internal pressure was applied within the tube continuously with the movement of upper die (during LPTH).

3 RESULTS AND DISCUSSION

3.1 HIGH PRESSURE TUBE HYDROFORMING

The filling of the die corner radius as a function of the internal tube pressure is shown in Figure 5; indicates that a smaller tube corner radius requiring a much higher pressure for filling.

An internal pressure below 50MPa does not lead to plastic deformation of the tube material as indicated by the unchanged tube radius. Above the critical value of 50MPa the tube material is deformed plastically and is forced into the die corner radius. Thereby the tube corner radius decreases with internal pressure, i.e., the material is forced further into the die corner radius with increasing internal pressure.

Figure 5 was then used to determine the process conditions leading to a 12mm tube radius. All comparisons that will be made in the following work between HPTH and LPTH will be related to a tube formed to a tube corner radius of 12mm.

3.2 LOW PRESSURE TUBE HYDROFORMING

In Figure 6 a tube formed without any internal fluid pressure and using the tool set up of Figure 3 is shown. With no internal pressure the tube is not fully formed into the die leaving several regions of non-contact between the tube and the tool as indicated by circles in Figures 6(a) to 6(d).
In Figure 7 the cross section of a tube formed using the LPTH process but this time with an applied internal pressure of 10MPa is shown. Except for a slight imperfection (indicated by the circle) the tube is now fully formed into the desired shape.

Notice that with the LPTH process the same shape as previously formed with the HPTH process can be obtained but with only a fraction of the internal pressure.

In Table 2 the fluid pressures and die holding forces used in both processes are shown together.
with the percentage reduction of internal fluid pressure achieved when using the LPTH instead of HPTH.

**Table 2: Fluid pressure and holding force comparison for both processes**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>High Pressure</th>
<th>Low Pressure</th>
<th>% Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure (MPa)</td>
<td>155</td>
<td>10</td>
<td>93.5</td>
</tr>
<tr>
<td>Holding Force (N)</td>
<td>4000</td>
<td>2300</td>
<td>42.5</td>
</tr>
</tbody>
</table>

### 3.3 STRESS DISTRIBUTION AND FORMING MODES IN HPTH AND LPTH

The thickness and stress distributions determined over the tube perimeter (Figure 8) are shown for both processes in Figures 9 and 10. Because of the different initial material thicknesses used for the tubes formed in the HPTH and the LPTH process, in Figure 10 the thickness distribution is expressed as the relative thickness, which is the ratio of the deformed thickness to the initial tube thickness.

The high tensile stresses introduced into the material during HPTH lead to severe thinning of the material whereby the material thickness is less reduced in the corner regions compared to the straight wall sections (Figure 10).

In contrast to that the change in thickness of the tube wall formed by LPTH is negligible.

To explain the reduced thinning of the tube wall observed in the corner regions the material deformation present in the HPTH process is analysed in more detail in the following part of this study. In Figure 11 the tube corner, cut in two sections, is shown. While the second section is taken out of the middle of the tube corner, the first cut is performed at the beginning of the flat tube section. The material is assumed to be linear elastic. The bending moments and the resulting tensile forces acting on the elements in both sections during high pressure hydroforming are shown in Figure 12.

The elements are stretching and thereby tensile forces are acting on the elements during HPTH. Due to the tensile force, the material is being pulled from both sides. Thus the tube is thinning less at the corners than the other parts. In the case of LPTH, compressive forces are acting at both of the analysed sections (Figure 13). The elements are mostly experiencing bending and compression. For both processes, the forming mode is the same but the stress are opposite in direction and have different magnitudes.
4 CONCLUSION

High and low pressure tube hydroforming was studied for an identical part geometry using Finite Element Analysis (FEA). It was found that the die closing force as well as the internal fluid pressure needed to form the part can be significantly reduced by using the LPHTH instead of the HPTH process. While in the HPTH process severe material thinning was observed, in LPHTH only compressive stresses are introduced in the sheet material resulting negligible changes of the overall material thickness.

5 ACKNOWLEDGEMENT

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6 REFERENCES