6.1 INTRODUCTION

In the following sections, results of the experimental and numerical analysis for both sheet and tube hydroforming is presented.

6.2 SHEET HYDROFORMING

6.2.1 Conventional Forming

When no fluid pressure is applied, the punch was given a trapezoidal velocity profile as shown in Figure 6.1.

![Figure 6.1 Punch velocity profile - when no fluid pressure is applied]
The variation of drawing load with punch travel for the experimental analysis and FEA for sheet hydroforming without the application of fluid pressure are shown in Figures 6.2 and 6.3. The experimental result for the material thickness of 1.5 mm shows that the material failure occurs at a forming depth of 20 mm. From the numerical analysis it was determined that the initial failure would occur around the center of the sheet at a depth of 18.9 mm. For the material thickness of 0.5 mm, the experimental result shows that the failure occurs at a depth of 18 mm and from FEA it is determined as 17.6 mm which is given in Figure 6.3. This represents a difference of 2.5 - 5.5% between the experimental and the numerical results, which for all practical purposes is acceptable.

![Figure 6.2](image)

**Figure 6.2** Conventional forming – drawing load Vs punch travel

\[D_o=130 \text{ mm}; t_o=1.5 \text{ mm}; d_o=50 \text{ mm}\]
6.2.2 Constant Fluid Pressure Applied to One Side of Sheet

In the experimental procedure, the punch was first brought down until it touched the top of the sheet and then stopped. Then, the fluid pressure was raised to the desired value and kept constant at that level before the punch was allowed to move down to deform the sheet. To simulate this in the numerical model, the punch was controlled by the displacement profile shown in Figure 6.4.

At the constant pressure level of 100 MPa, the FEA correctly predicted that, before the punch moves, the sheet would fail along its corner radii due to strain localization as shown in Figure 6.5. In the experiments, with a constant fluid pressure, it was found that the sheet sometimes fails along the corner radii [Region (R)], as shown in Figure 6.6, soon after the punch starts deforming the sheet.
Figure 6.4  Punch displacement profile for FEA – with fluid pressure applied to one side of sheet

Figure 6.5  FEA-Failure prediction at the edges for a constant pressure level of 100 MPa
Figure 6.6  Experimental work-Failure with fluid pressure applied to one side of sheet

In hydroforming experiments, with constant fluid pressure maintained throughout the process, a significant increase in the punch depth, before failure, was noticed. FEA also predicts higher punch depth, before failure, when constant pressure is applied to the one side of the sheet. Figure 6.7 shows the experimental and numerical drawing load-travel curves for the case of constant fluid pressure of 100 MPa, up to the failure point. Figure 6.8 shows the drawing load-travel plots, up to the failure point, for several constant fluid pressures for the material thickness of 1.5 mm, while Figure 6.9 shows the similar plots for a thickness of 1 mm obtained using FEA.

Figure 6.7  Drawing load versus punch travel for the 100 MPa constant fluid pressure
Figure 6.8  Numerical results of drawing load versus punch travel for Inconel at constant fluid pressure applied to one side of the sheet

Figure 6.9  Experimental and numerical results of drawing load versus punch travel for Inconel at constant fluid pressure applied to one side of the sheet
It is obvious that compared to conventional forming, the hydroformed sheet reaches significantly deeper punch depths, before it fails. This increase in the punch depth improves with increasing the fluid pressure, up to a maximum value of 100 MPa. Besides the obvious improvement in the punch depth, the pressurized fluid also forces the sheet to conform to the shape of the punch more closely, resulting in a better formed part as shown in Figure 6.10. Figure 6.11 shows that by increasing the fluid pressure higher forming depth can be obtained.

(a) Hydroforming - 100 MPa pressure
Forming depth: 27 mm

(b) Conventional forming - 0 MPa pressure
Forming depth: 20 mm

Figure 6.10  Component shape comparison between hydroforming and conventional forming
6.2.3 Varying Fluid Pressure Applied to One Side of Sheet

In the case of varying fluid pressure, the pressure was applied to the topside of the sheet incrementally. In the numerical simulation, the punch was given a velocity profile, since in the experiments the punch was not stopped during the process of applying the fluid pressure. The fluid pressure profile applied in the numerical analysis was given in Figure 6.12. Figure 6.13 shows the predicted punch force before failure, matching the experimental values very well (2.5% difference).

Figure 6.11 Experimentally and numerically determined upper limit of the optimum fluid pressure-punch stroke path for the sheet hydroforming process
Figure 6.12 Varying fluid pressure profile

Figure 6.13 Drawing load versus punch travel for varying fluid pressure
6.2.4 Fluid Pressure Applied to Work as Blank Holding Force

In this case, the idea was to use the fluid pressure to work as the blank holding force. Since the whole blank is supported by the fluid pressure, the wrinkles could be eliminated not just underneath the blank holder region, but also on the unsupported regions of the sheet. Also, better conformity to punch shape would be attained. Because of the limitations of the existing experimental setup, this method was carried out only numerically and the effect of applying the fluid pressure was investigated to find the suitable pressure profile.

In these simulations, a pressure was applied to one side of the sheet to simulate a pressure controlled blank holding force on the sheet. The use of an appropriate fluid pressure profile benefits in two ways: (i) the pressure acts as an active blank holder that suppresses the compressive force in the sheet as it deforms which delays wrinkling and (ii) the fluid pressure forces the sheet to conform to the shape of the punch by applying work against the unsupported regions and forcing them to the punch profile. Several numerical tests were performed at which a constant pressure was applied to the sheet. The forming depth at which the sheet would start to wrinkle was recorded.

Since the pressure in this case will depend on the initial geometry, especially the area underneath the blank holder, tests were made using the two punch sizes (50 and 100 mm) and with multiple initial round blank diameters. The ratio of the initial blank diameter ($D_0$) to the diameter of the punch ($d_0$) was used as a method to generalize the pressure profile to other experiments. Using this method a pressure profile was extracted for different initial blank size to punch diameter ratios. Figure 6.14 shows the results for three different ratios. It should be noticed that the pressure profile depends on the initial size of the blank and the punch diameter. This is similar with the theoretical lower

**Figure 6.14  Pressure profile for different initial blank to punch diameter ratios**

After acquiring the pressure profiles, the same pressure profile was used in the numerical model to test whether it will prevent the sheet from wrinkling and it was noticed that the wrinkles were ironed out. Figure 6.15 shows the comparison between conventional forming and hydroforming with constant and variable pressure with respect to D₀/d₀ ratio and maximum drawing load. It can be seen that the application of fluid pressure increases the D₀/d₀ ratio considerably.
Figure 6.15 Comparison of $D_o/d_0$ ratio and maximum drawing load

Figure 6.16 shows the effect of applying fluid pressure to one side of the sheet and it is clear that the wrinkles have been ironed out; also, a better forming behavior in the form of better overall shape and final sheet thickness distribution is achieved.

Figure 6.16 Effect of fluid pressure as blanking holding force on wrinkling
6.2.5 Failure Criteria

In sheet-forming operations, the deformation is characterized by biaxial stretching (Hosford and Caddell 1983). Failure in stretching operations normally occurs by the development of a sharp localized neck on the surface. By measuring minor and major strains in a specimen during deformation and plotting them, a Forming Limit Diagram (FLD) can be constructed. In this work, FLD displaying contour plots of the minor and major strains were used to determine the locations and the punch height at which the sheet metal would fail due to tearing. The FLD displaying contour plots of the minor and major strains developing in the hydroforming process is shown in Figure 6.17. From this figure it is seen that applying the fluid pressure causes a drastic change in the strain distribution of the formed part as compared with the case of conventional forming without the assistance of the fluid pressure. Also it should be noticed that in the case of hydroforming the strains are well below the failure limit, while in the case of conventional forming the strains are closer to failure limit.

(a) Conventional forming  
(b) Hydroforming

Figure 6.17 Forming limit diagram
In the case of conventional forming, it is noticed that the strains in the sheet are in the biaxial tension region, while applying the fluid pressure to the sheet during the forming process moved the strains in the sheet to the uniaxial (left) region. This redistribution of strains caused a deeper drawing of the sheet without rupturing it, as compared to the case of forming without fluid pressure where the sheet was in the biaxial tension condition.

6.2.6 Effect of Process Parameters on the Forming Performance

The main goal is to develop a method to analyze the effects of the forming parameters on the quality of the part and determine the most significant forming parameter affecting the hydroformability. Experimental analysis and Taguchi method were used to study the effect of forming parameters yielding a part with uniform wall thickness. Experiments were carried out on Inconel 625 by varying the process parameters such as chamber internal pressure and drawing ratio. To design an orthogonal experimental array in order to study the effect of each forming parameter Taguchi method was used. The results obtained from this work are useful for forming quality parts with uniform wall thickness.

First, the quality characteristics and the forming parameters were selected, and the appropriate orthogonal array is constructed. Experimental investigation was performed based on the arrangement of the orthogonal array and the results were then transformed into the Taguchi signal-to-noise (S/N) ratios. Statistical analysis of variance (ANOVA) was performed to find out the effect of process parameters on thinning of sheet metal.

6.2.6.1 Design of experiments

Geometry parameters, material parameters and process parameters are the three categories of parameters influencing hydroformability. Table 6.1 shows the forming parameters selected for study and their levels.
Table 6.1  Forming parameters selected for study and their levels

<table>
<thead>
<tr>
<th>Forming parameters</th>
<th>Notation</th>
<th>Level 1</th>
<th>Level 2</th>
<th>Level 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank diameter (mm)</td>
<td>X</td>
<td>70</td>
<td>100</td>
<td>130</td>
</tr>
<tr>
<td>Thickness of the sheet (mm)</td>
<td>Y</td>
<td>0.5</td>
<td>1.0</td>
<td>1.5</td>
</tr>
<tr>
<td>Internal pressure (MPa)</td>
<td>Z</td>
<td>80</td>
<td>95</td>
<td>115</td>
</tr>
</tbody>
</table>

Based on Taguchi method, the experimental layout of an $L_9$ orthogonal array (Table 6.2) was selected considering the three parameters and three levels of each parameter. Although there are many different proposed criteria for predicting fracture in metal forming processes, the commonly used thinning ratio criteria were used as a measure of forming quality. The successfully formed cups were sectioned at 90° and thickness was measured at several points along the cup wall from the top of the cup to center of the cup bottom. For a successful deep drawing process, the maximum value of thinning should not be beyond 20%.

Table 6.2  Taguchi’s $L_9$ orthogonal array (three parameters/three levels)

<table>
<thead>
<tr>
<th>Trial No</th>
<th>Forming parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
</tr>
</tbody>
</table>
6.2.6.2 S/N analysis

In the Taguchi method, the S/N ratio is defined as,

\[ S/N = -10 \log (\text{Mean square deviation for the quality characteristic}) \]  

(6.1)

Generally there are three categories of quality characteristic in the analysis of the S/N ratio, i.e. the-lower-the-better, the higher-the-better, and the-nominal-the-better. Thinning ratio is the quality characteristic with the objective “the-lower-the-better”. The Mean Square Deviation (MSD) for the lower-the-better quality characteristic is defined by

\[ \text{MSD} = \frac{1}{n} \sum_{i=1}^{n} y_i^2 \]  

(6.2)

where “\(y_i\)” is the value of the-lower-the better quality characteristic and “\(n\)” is the number of tests for a trial condition. Regardless of the category of the quality characteristic, a greater S/N ratio corresponds to better quality characteristics. After conducting experiments and applying S/N analysis, the results of the thinning ratio and its S/N ratio in the 9 trial conditions are shown in Table 6.3. The average S/N ratio of the thinning ratio for each parameter at levels 1 to 3 are shown in Table 6.4 and plotted in Figure 6.18.

<table>
<thead>
<tr>
<th>Trial No</th>
<th>Thinning ratio</th>
<th>S/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.271</td>
<td>9.982</td>
</tr>
<tr>
<td>2</td>
<td>0.456</td>
<td>5.914</td>
</tr>
<tr>
<td>3</td>
<td>0.415</td>
<td>6.454</td>
</tr>
<tr>
<td>4</td>
<td>0.386</td>
<td>7.238</td>
</tr>
<tr>
<td>5</td>
<td>0.522</td>
<td>4.548</td>
</tr>
<tr>
<td>6</td>
<td>0.327</td>
<td>8.430</td>
</tr>
<tr>
<td>7</td>
<td>0.435</td>
<td>6.243</td>
</tr>
<tr>
<td>8</td>
<td>0.323</td>
<td>8.864</td>
</tr>
<tr>
<td>9</td>
<td>0.447</td>
<td>6.026</td>
</tr>
</tbody>
</table>
Table 6.4  Forming parameters and average S/N ratio

<table>
<thead>
<tr>
<th>Forming parameters</th>
<th>Notation</th>
<th>Average S/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Level 1</td>
</tr>
<tr>
<td>Blank diameter (mm)</td>
<td>X</td>
<td>7.66</td>
</tr>
<tr>
<td>Thickness of the sheet (mm)</td>
<td>Y</td>
<td>7.45</td>
</tr>
<tr>
<td>Internal pressure (MPa)</td>
<td>Z</td>
<td>9.45</td>
</tr>
</tbody>
</table>

Figure 6.18  Effect of forming parameters on the thinning ratio

6.2.6.3  Analysis of variance (ANOVA)

ANOVA was carried out to find the effect of forming parameters quantitatively. By comparing variances, ANOVA tests for significant differences between the parameters.

The overall average S/N ratio is given by
\[
\frac{S}{N} = \frac{1}{m} \sum_{i=1}^{m} (S/N)_i 
\]  

where “m” is the number of tests in the orthogonal array and \((S/N)_i\) is the S/N ratio of the \(i^{th}\) test. The sum of the squares due to the variation from the overall average S/N ratio is

\[
SS = \sum_{i=1}^{m} [(S/N)_i - \overline{S/N}]^2 
\]  

The sum of the squares due to the variation from the average S/N ratio for the \(i^{th}\) factor is

\[
SS_i = \sum_{t=1}^{t} T_t \times [(S/N)_{it} - \overline{S/N}]^2 
\]  

where “t” is the number of the factor levels, “\(T_t\)” is the number of the tests of the \(i^{th}\) factor at the \(t^{th}\) level. \((S/N)_{it}\) is the average S/N ratio of the quality characteristic for the \(i^{th}\) factor at the \(t^{th}\) level. The percentage contribution of the \(i^{th}\) factor is defined as

\[
P_i(\%) = \left( \frac{SS_i}{SS} \right) \times 100 
\]  

The result of ANOVA for thinning ratio is shown in Table 6.5 and Figure 6.19. It is concluded that the internal pressure is the most significant forming parameter affecting the thinning ratio. The effect of thickness of the sheet is relatively small compared to that of internal pressure in sheet hydroforming.
Table 6.5 ANOVA for thinning ratio

<table>
<thead>
<tr>
<th>Forming parameters</th>
<th>DOF</th>
<th>Sum of squares</th>
<th>Percentage contribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blank diameter (mm)</td>
<td>1</td>
<td>0.189</td>
<td>0.40</td>
</tr>
<tr>
<td>Thickness of the sheet (mm)</td>
<td>2</td>
<td>0.145</td>
<td>0.37</td>
</tr>
<tr>
<td>Internal pressure (MPa)</td>
<td>2</td>
<td>16.424</td>
<td>36.43</td>
</tr>
<tr>
<td>Error</td>
<td></td>
<td>18.651</td>
<td></td>
</tr>
</tbody>
</table>

Figure 6.19 Percentage contribution of forming parameters on the thinning ratio

6.2.6.4 DOE results

After eliminating the insignificant forming parameter, the analyses of the S/N ratio are conducted again with the two significant parameters, i.e., internal pressure and blank diameter. The same three levels of the internal pressure and blank diameter as shown in Table 6.1 are chosen. A Taguchi L₉ orthogonal array is selected for two factors with three levels, as shown in Table 6.6.
Table 6.6 Taguchi’s $L_9$ orthogonal array (two parameters/three levels)

<table>
<thead>
<tr>
<th>Trail No</th>
<th>Internal pressure ($K'$)</th>
<th>Blank diameter ($L'$)</th>
<th>$K' \times L'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>5</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>6</td>
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<td>3</td>
<td>1</td>
</tr>
<tr>
<td>7</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>9</td>
<td>3</td>
<td>3</td>
<td>2</td>
</tr>
</tbody>
</table>

The $L_9$ orthogonal array is a full factorial array in which all of the possible combinations of factor levels are tested. The last two columns in Table 6.6 represent the interaction of the two factors. Table 6.7 shows the results of the thinning ratio and S/N ratio in the nine trial conditions. The use of the Taguchi S/N ratio assists in discriminating better quality characteristics and the objective in this study is to maximize the S/N ratio of the thinning ratio.

Regression analysis is performed on the data in Table 6.7 to get the relationship of the S/N ratio of the thinning ratio with the forming parameters. The regression equation of the S/N ratio of the thinning ratio $[(S/N)_{TR}]$ is given in equation (6.7).

$$(S/N)_{TR} = 17.48 - 0.09K' + 0.006L' - 0.00015K'L'$$  \quad (6.7)
From the equation also it is understood that the significant parameter affecting thinning ratio is internal pressure.

**Table 6.7  Thinning ratio and its S/N ratio (two parameters/three levels)**

<table>
<thead>
<tr>
<th>Trail No</th>
<th>Internal pressure (K’)</th>
<th>Blank diameter (L’)</th>
<th>K’ × L’</th>
<th>Thinning ratio</th>
<th>S/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>80</td>
<td>70</td>
<td>5600</td>
<td>0.264</td>
<td>9.978</td>
</tr>
<tr>
<td>2</td>
<td>80</td>
<td>100</td>
<td>8000</td>
<td>0.312</td>
<td>8.886</td>
</tr>
<tr>
<td>3</td>
<td>80</td>
<td>130</td>
<td>10400</td>
<td>0.297</td>
<td>9.675</td>
</tr>
<tr>
<td>4</td>
<td>95</td>
<td>70</td>
<td>7125</td>
<td>0.430</td>
<td>8.123</td>
</tr>
<tr>
<td>5</td>
<td>95</td>
<td>100</td>
<td>9500</td>
<td>0.456</td>
<td>7.890</td>
</tr>
<tr>
<td>6</td>
<td>95</td>
<td>130</td>
<td>12350</td>
<td>0.463</td>
<td>7.457</td>
</tr>
<tr>
<td>7</td>
<td>115</td>
<td>70</td>
<td>8050</td>
<td>0.488</td>
<td>6.421</td>
</tr>
<tr>
<td>8</td>
<td>115</td>
<td>100</td>
<td>11500</td>
<td>0.498</td>
<td>6.092</td>
</tr>
<tr>
<td>9</td>
<td>115</td>
<td>130</td>
<td>14950</td>
<td>0.512</td>
<td>5.934</td>
</tr>
</tbody>
</table>

**6.3  TUBE HYDROFORMING**

Typical tube hydroforming operations are made possible by a controlled application of internal pressure and axial feed of tube material from the tube ends. In addition to the use of internal pressure and axial feed, hydroforming of T-shapes requires an application of a counter punch to support the protrusion (branch) while it is being formed. Thus, the protrusion can be formed with more uniform thickness distribution.
Successful T-shape hydroforming depends on the loading paths applied (pressure Vs time and axial feed Vs time curves), geometry of the T-shapes (length of T-shape), initial geometry of the tube (wall thickness), as well as the interface friction conditions. In this work, the main process parameters selected for the analysis are the following: (i) axial feed (ii) initial tube length (iii) internal pressure and (iv) counter punch force. All these parameters were tried out and “optimized” through iterative FEA simulations.

6.3.1 Axial Feeding

To estimate the axial feed necessary to form a T-shape with a desired protrusion height \((h)\) (Figure 6.20) the concept of volume constancy was applied. The original tube wall thickness was assumed to remain unchanged. The material volume at the protrusion section of the T-shape was converted to obtain the necessary axial feed. The tube initial outside diameter was 50.8 mm, tube initial thickness was 1.50 mm and the final T-shape lengths on the left and the right were varied. The volume of material formed into the protrusion area was calculated. Each half of the protrusion was assumed to have been contributed from the axial feed applied on corresponding side of the protrusion. The relationship approximated between necessary axial feeds to the protrusion height \((h)\) indicated that the left axial feed as well as the right axial feeds should be “\(h\)”. Once the axial feeds have been estimated, the initial tube length could be calculated by adding the approximated axial feeds to the designed T-shape lengths. This axial feed calculated was just an initial estimate, the necessary axial feed also depends on the length of the T-shape, tube material, and interface friction conditions.
6.3.2 Internal Pressure Limits

The pressure necessary to start yielding of the tubular preform \( (P_i)_y \) is the minimum pressure required to initiate deformation in the hydroforming process. An equation to approximate this yielding pressure was derived based on a simple axisymmetric expansion of a tube with fixed ends. Although the calculated yielding pressure is accurate only for a simple tube expansion with fixed ends, it was proved to be a good initial guess for hydroforming of more complex parts (i.e. T-shapes) with axial feed applied:

\[
(P_i)_y = (\sigma_y) \left[2t_0/(D_0 - t_0)\right]
\]  

(6.8)

where “\( \sigma_y \)” is the yield strength of the tube material, “\( t_0 \)” the initial tube thickness and “\( D_0 \)” the outside tube diameter. In this work, yielding pressure was estimated as 25 MPa.
Bursting pressure \((P_i)_b\) is the maximum pressure that expands the tube without bursting. Equation (6.9) was used to estimate the bursting pressure for a T-shape hydroforming in which no counter punch is applied. It is based on a balanced biaxial bulging of sheet metal (Jirathearanat et al 2000).

\[
(P_i)_b = (\sigma_u) \left[4t_0/(D_p - t_0)\right]
\]  

(6.9)

where “\(\sigma_u\)” is the ultimate tensile strength of tube material and “\(D_p\)” the protrusion diameter. A maximum bursting pressure of 124 MPa was predicted for the T-shape hydroforming in which no counter punch is applied.

Calibrating pressure \((P_i)_{max}\) is the internal pressure level required to form a tube wall into small die corners. The calibrating pressure was estimated by using equation (6.10) (Koc and Altan 1998).

\[
(P_i)_{max} = \left[2\sqrt{3}\right] (\sigma_t) \left[\ln\left(r_b/(r_b - t_0)\right)\right]
\]  

(6.10)

where “\(\sigma_t\)” is the flow stress of the tube material, “\(r_b\)” the die corner radius and “\(t_0\)” the initial tube wall thickness. With all the estimated pressure limits an initial pressure curve for the hydroforming of the corresponding T-shape can be constructed using linear lines connecting these pressure limits (Figure 6.21). The bursting pressure is expected to be larger than that of calculated by the equation when a counter punch is applied. The “optimal” pressure curve was determined through iterative FEA simulations (Altan et al 2001).
6.3.3 Counter Punch Force

The counter punch force profile was estimated through FEA simulations since there is no simple formula available to determine the approximate counter punch forces. In FEA simulation, the displacement curve (Figure 6.22) governing the counter punch movement is modified until the designed T-shape protrusion can be formed. Then, the necessary counter punch force can be obtained from the contact force between the counter punch and the tube protrusion interface.

Figure 6.22 Counter punch displacement curve for FEA simulation
6.3.4  FEA Simulation

FEA simulations were conducted to investigate hydroforming of T-shapes using a counter punch. The main defects encountered in hydroformed tubular parts are wrinkles and bursting, which was predicted using FEA. The protrusion tip of the T-shape would burst prematurely if excessive pressure is applied. A counter punch should be used to support the growing protrusion. This results in hydrostatic stress state in the area, thus improving the formability.

The hydroforming process could be divided into three main stages: (a) free forming (b) expansion against a counter punch and (c) calibration. The counter punch was positioned in the die just above the die corner radius such that it would not pinch the growing protrusion in the early hydroforming stage. After the protrusion has come in contact with the counter punch, the counter punch will slide slowly upwards as it is supporting the growing protrusion and come to a stop during the calibration stage. The estimated process parameters (internal pressure and axial feeds) were refined through these simulations.

There are two methods for the internal pressure loading: the linear and the bilinear methods. In this work, the internal pressure loading rate was accelerated to a maximum in order to reduce the computing time, without affecting the results of the tube hydroforming process. At the beginning of the tube hydroforming process, the tubular blank is placed at the cavity of lower die, as a following step the split dies are closed in order to avoid movements of the tubular blank. As a further action, the tubular blank is filled with the fluid medium and internal pressure loading is applied. Then the axial punches are displaced in such way to promote the buckling of the tubular blank. This buckling action depends on the pressure transmitted by the pressurised fluid medium. After the punches reaches the programmed maximum stroke, the
internal pressure at the fluid medium into the tubular blank at the die cavity is increased, resulting in an expansion of tube diameter, in a suitable way that promotes the changes of the tube shape and dimension until it assumes the shape and dimensions of the die cavity. This step is called calibration process. Thus, it could be possible to suggest a tube hydroforming process window where a suitable combination of thrust force and internal pressure is applied to obtain tube hydroforming parts without wrinkles or fractures.

The wrinkles that arise during the buckling process of the tubular blank can be harmful or even useful one. Lang et al (2004) classified the wrinkles produced at the buckling step in such way and they are regarded as related to punched stroke and initial internal pressure. The wrinkle will be regarded as useful one if it is possible to remove them completely during the calibration step of the tube hydroforming process. On the other hand, the harmful wrinkles can not be removed. The determination of the pressure range that results in good wrinkles allied to the punch stroke control could be determined through FEM simulations, and this is described in the following section.

6.3.4.1 FEA results

The internal pressure setting up as well as the axial feed stroke during the tube hydroforming process was carried out based on the previous work of Lang et al (2004). The applied values for the punch stroke are 75, 80 and 85 mm and internal pressures are 30, 40, 65, 80, 110, 115 and 120 MPa respectively. The punch strokes of both ends were the same and Figure 6.23 shows the loading path of internal pressure.
The part of the hydroforming process in which the tube expands without tool contact is called free forming. The simulation results for the free forming analysis are given in Figures 6.24 and 6.25.

From the simulation results it can be said that the deformation had taken place only in the bulging region and forming limit diagram indicates loose material zone in the major areas of tubular blank. Additional investigation of stress distribution in the T-section suggested that to obtain a uniform distribution along the tube, major axial feed needs to be provided after the material in the forming zone yields. In tube hydroforming processes, providing sufficient amount of axial force to feed required material into the forming zone is a key issue. In other words, the material needs to be fed into the die cavity in a manner that ensures a uniform thickness distribution while keeping the induced stress lower than the ultimate stress. Internal pressure also plays a crucial role in tube deformation and material flow and conformance of the tube to the die geometry.
Figure 6.24 FEA results for free forming simulation (Pressure=115 MPa)
FEA simulations are done with axial feed to determine the optimum combination of parameters in the second stage. Figures 6.26 to 6.29 show the FEA results for the internal pressures 110, 115 and 120 MPa respectively for punch stokes of 75, 80 and 85 mm. The simulation results and wall thickness distribution analysis are discussed in the following section.
Figure 6.26  FEA results for - Internal pressure 80 MPa and axial feed 75 mm
Figure 6.27  FEA results for - Internal pressure 110 MPa and axial feed 80 mm
Figure 6.28  FEA results for - Internal pressure 120 MPa and axial feed 85 mm
Figure 6.29 FEA results – T-shape protrusion at various internal pressure and axial feed combinations (Deformed shape as a displacement plot)
6.3.4.2 Discussion

The simulations on T-shape protrusion suggest that to achieve a successful final part, the majority of the axial feed should occur after the tube material yields. The tube should initially expand due to the internal pressure and then further material needs to be supplied into the forming zone by means of axial feed. Thus, the material can flow more easily and a higher bulge can be achieved when small increments of stress can generate larger strains. However, at higher pressures, if sufficient axial feed is not provided, thinning is bound to occur which leads to failure. Nevertheless, if higher internal pressure is applied with suitable axial feed, failure can be avoided.

Also, employing larger axial feeds provides an opportunity to meet the minimum thickness deviation and achieve the desired final shape. FE simulations showed that the maximum effective stress is induced at the die corner and the efficient way of making a T-shape protrusion is to allow the tube to bulge freely in the early stages of the process. Major axial feed needs to be provided subsequently to force the material into the forming region. It should be noted that in all simulations the maximum effective stress as well as maximum thinning occurred at the center of the T-shape protrusion.

In the later stages of the simulation, the internal pressure was increased to 120 MPa to flatten the wrinkles inherited from the pre-forming stage and the punch stroke was fixed. Here, the concepts of useful wrinkles and harmful wrinkles can be drawn out depending on whether the wrinkles formed in the pre-forming stage can be flattened in the calibration stage. If the wrinkles formed in the pre-forming stage can be flattened and no fracture occurs in the calibration stage, the wrinkles are called useful wrinkles, otherwise, they are called harmful wrinkles.
6.3.4.3 Wall thickness distributions

The wall thickness distributions of the formed tubes are shown in Figure 6.30. Based on the wall thickness distribution, the formed part can be divided into three zones: The first one is the tube end area, the second is the transferring area and the third zone is the main expansion area, which is shown in Figure 6.30(b). After the calibration stage, the average wall thickness when the punch stroke is set at 75 mm is smaller than when the punch stroke is 80 mm. In main expansion area, the differences of the average wall thickness between the free forming stage and the calibration stage decrease when the internal pressure is increased.

Figure 6.30 shows that if the internal pressure is higher, the wall thickness in the first zone is thicker. And at the same time, following the increase of punch stroke, the wall thickness in the first zone also gets thicker. This is mainly because the frictional force between the tubular blank and the die becomes higher by the increases of internal pressure and the punch stroke.

The thinning ratio is defined as,

\[
\text{Thinning ratio (\%)} = \left(\frac{t_o - t_1}{t_o}\right) \times 100
\]  

(6.11)

where, is ‘\(t_o\)’ the original thickness of the tube and ‘\(t_1\)’ is the critical thickness of the hydroformed tube. The bulge ratio is defined as,

\[
\text{Bulge ratio (\%)} = \left(\frac{r_1}{r_o}\right) \times 100
\]  

(6.12)

where, is ‘\(r_1\)’ the maximum radius of the hydroformed tube and ‘\(r_o\)’ is the original radius of the tube. For the internal pressure of 120 MPa, Figure 6.31 shows the relationship between bulge ratio and thinning ratio for various punch strokes. It can be inferred that the increase in punch stroke results in higher bulge ratio. Also Figure 6.32 shows that, the increase in punch stroke
results in the reduction of tube length. This reduction in tube length causes increase in the bulge ratio.

Figure 6.30  The wall thickness distribution
Figure 6.31  Thinning ratio Vs Bulge ratio for different punch strokes

Figure 6.32  Bulge ratio Vs % reduction in tube length

(a) Comparison  (b) Measurement of bulge ratio and tube length

The Forming Limit Diagram (FLD) displaying contour plots of the minor and major strains developed in the tube hydroforming process is shown in Figure 6.33. It is noticed that the strains are well below the failure limit.
From the above discussions, for the purpose of forming a tube with large expanding area, it is very important to get a suitable combination of punch stroke and internal pressure. For the forming of T-shape protrusion, according to the above discussion, the optimal process window is shown in Figure 6.34. And in the free forming stage, the most possible area is when the punch stroke is between 75 and 80 mm and the internal pressure is between 110 and 120 MPa. To obtain a part with more uniform wall thickness, an internal pressure between 115 and 120 MPa is preferred. It is also found that the wall thickness distribution in the free forming stage is sensitive to the change of process parameters. Several tube hydroforming experiments have been conducted using the available tooling. The process parameters estimated and refined through the FEA simulations were used to hydroform the T-shape protrusion. The results are discussed in the following section.
6.3.5 Experimental Results

Figure 6.35 shows the optimal path applied in the hydroforming experiments. With these loading paths, the simulation results predicted a sound T-shape. The internal pressure curve, shown in Figure 6.35(a), consists of two main stages, i.e., forming stage (including free expansion and expansion against the counter punch) and calibrating stage. During the forming stage, the pressure went up from 0 to 120 MPa, the left and right axial feeds were 80 mm, respectively (refer Figure 6.35(b)). The real axial punch displacement curves exceeded the axial feeds of 80 mm due to some additional axial punch displacement for tube sealing at the beginning of the process.
During the calibrating stage, there were no axial feeds as can be seen from Figure 6.35(b). The axial feeds were not applied during the calibrating stage because the calibrating pressure was usually very high, so that the tube–die interface friction force becomes too large for the tube material to be fed in. Figure 6.35(c and d) shows the counter punch force curve and the displacement of the counter punch, which determines the protrusion height of the T-shape.

Based on the results obtained from FEA simulation, punch strokes of 80 mm and the internal pressure of 120 MPa were used during the experiments. Figure 6.36 shows the experimentally formed parts and
Figure 6.37 shows the thinning ratio from simulation and experiment. The results from experiment are proven to be very similar to those from simulation and the results indicated that the simulation predicts metal flow in the T-shapes accurately.

(a) Formed parts  (b) Part with wrinkling (no counter punch used)  (c) Fractured parts (higher pressure)

Figure 6.36  Experimentally formed parts

Figure 6.37  Thinning ratio between simulation and experiment
As shown in Figure 6.38 the deformed geometry of the tube obtained by FEA is in good agreement with the experiment. Figure 6.39 shows the comparison of results obtained from FEA and experimental work with respect to bulge ratio Vs percentage reduction in tube length when the internal pressure is 120 MPa. It is indicated that the results obtained from simulation are in good agreement with the experiments.

Figure 6.38 Tube deformed geometry: Experimental Vs FEA simulation
Figure 6.39  Bulge ratio Vs % reduction in tube length: Experimental Vs FEA simulation

6.3.5.1  Effect of tube length on bulge ratio

Hydroforming experiments of T-shapes without the use of counter punch were conducted to investigate the effect of tube lengths on forming of the protrusion height. Tubes with different initial lengths on the two sides of T-protrusion (left and right side) were hydroformed using the same axial feeds. Based on the experimental results, S/N analysis and ANOVA analysis are performed with an objective to maximize the bulge ratio. In this work, length of the tube and outer radius of the tube are selected as the parameters with three levels. Table 6.8 shows the experimental results of the bulge ratio and its S/N ratio.
Table 6.8  Bulge ratio and S/N ratio

<table>
<thead>
<tr>
<th>Trail No</th>
<th>Outer radius of the tube (X')</th>
<th>Length of the tube (Y')</th>
<th>(X') × (Y')</th>
<th>Bulge ratio</th>
<th>S/N ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25.4</td>
<td>140</td>
<td>3556</td>
<td>2.50</td>
<td>5.242</td>
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<tr>
<td>2</td>
<td>25.4</td>
<td>130</td>
<td>3302</td>
<td>2.65</td>
<td>5.640</td>
</tr>
<tr>
<td>3</td>
<td>25.4</td>
<td>120</td>
<td>3048</td>
<td>2.75</td>
<td>5.915</td>
</tr>
<tr>
<td>4</td>
<td>30</td>
<td>140</td>
<td>4200</td>
<td>2.33</td>
<td>4.986</td>
</tr>
<tr>
<td>5</td>
<td>30</td>
<td>130</td>
<td>3900</td>
<td>2.37</td>
<td>5.096</td>
</tr>
<tr>
<td>6</td>
<td>30</td>
<td>120</td>
<td>3600</td>
<td>2.45</td>
<td>5.156</td>
</tr>
<tr>
<td>7</td>
<td>31</td>
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<td>4340</td>
<td>2.24</td>
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</tr>
<tr>
<td>8</td>
<td>31</td>
<td>130</td>
<td>4030</td>
<td>2.26</td>
<td>4.756</td>
</tr>
<tr>
<td>9</td>
<td>31</td>
<td>120</td>
<td>3720</td>
<td>2.27</td>
<td>4.887</td>
</tr>
</tbody>
</table>

Regression analysis is performed on the data in Table 6.8 and the regression equation of the S/N ratio of the bulge ratio \([(S/N)_{BR}]\) is given in equation (6.13).

\[(S/N)_{BR} = 26.51 - 0.66X' - 0.13Y' - 0.004X'Y'\] \hspace{1cm} (6.13)

Based on a variance analysis, it is clear that the initial tube lengths affect the obtainable protrusion heights in hydroforming T-shapes and it is evident that a reduction of tube length results in more material flow into the zone that resulted in higher protrusion height.

Figure 6.40 shows the comparison between the bulge height and material feeding with respect to the time. The consistency of the two profiles indicates that the material from axial feeding is used for the bulge height
development and the tube wall thickness variation is simultaneously minimized.

![Figure 6.40 Comparison between axial feed and bulge height](image)

Figure 6.40 Comparison between axial feed and bulge height