CHAPTER 4
EXPERIMENTAL WORK

4.1 INTRODUCTION

In this section, the experimental apparatus for sheet and tube hydroforming is described, followed by discussions on the experimental results obtained using Inconel 625 blanks of thicknesses 0.5 mm, 1 mm and 1.5 mm. Blanks of diameters 70, 100, and 130 mm were used in the tests with circular punch of 50 mm diameter. Last part of this section deals with the results obtained during the study of tube hydroforming.

4.2 EXPERIMENTAL APPARATUS - SHEET HYDROFORMING

The experimental apparatus was built around an in-house designed double action sixty ton hydraulic press, shown in Figure 4.1. The double action refers to the clamping mechanism moving independently of the punch mechanism. This allows for the boundaries of the sheet blank to be clamped while the punch pushes the sheet into the liquid chamber filled with supporting fluid. In the experiments, the blank-holder is fixed to guarantee the blank holding force. When the cylindrical cups are formed, the punch penetrates into the liquid chamber, and the pressure is established. In hydroforming process, when the fluid pressure in the chamber is too high, it causes material flow through the radius of curvature much faster than the allowable ductility limit of the material. This results in premature rupturing of the sheet
material. On the other hand if the fluid pressure is too low, enough stretching force will not be available and hence leads to wrinkling. Hence the pressure has to be maintained in a safe working zone between the ruptures and wrinkling zones to ensure a defect free part. To maintain the fluid pressure - punch travel path in the working zone, material specific wrinkle and rupture governing equations were formulated by Yossifon and Triosh (1977, 1984, 1985, 1985a, 1988). In this present work, the safe working zone via user defined pressure profile was established by interfacing the punch travel by means of Linear Variable Differential Transducer (LVDT) with the Pressure Relief Valve (PRV) of the hydro forming apparatus. This interface was controlled by a Personal Computer (PC) with the help of commercial software LabVIEW (National Instruments 2002).

Figure 4.1 Experimental apparatus used for sheet hydroforming of cylindrical cups
The schematic of the interface is shown in Figure 4.2. The punch travel is trapped by LVDT of range 0 to 350 mm, with a voltage input ranging from 0 to 20V (D.C); chamber pressure is measured by the pressure transducer with a signal input 0 to 24 (D.C), and output signal of 8 to 40 mA; PRV is to control the chamber pressure, with an input signal 24V (DC), and an operating signal which varies from 0 to 15 V (DC); Data Acquisition Card (DAQ) (6025E, 100 pin series) is to transfer the data through a PC. The linear motion of the punch is converted to corresponding voltage signals using the linear scale attached to it. This voltage is given to the LabVIEW program through the analog input channel of the DAQ which is converted into displacement. The pressure to be maintained for that punch displacement should be within the safe working zone. The optimal curve to be maintained in the working zone is traced by varying the pressure in the pressure chamber using PRV in accordance with the punch traverse. Based on the pressure to be maintained the required voltage is given to the PRV through the analog output channel of the DAQ. The arrangement of valves and electronic data acquisition system is shown in Figure 4.3 and the block diagram for the control panel and pressure evaluation are given in Figures 4.4 and 4.5 respectively. A sample snapshot of pressure travel diagram obtained from LabVIEW and the control panel to communicate to DAQ are given in Figures 4.6 and 4.7 respectively.

Figure 4.2 Schematic of punch travel - fluid pressure interface
Figure 4.3 Arrangement of PRV and DAQ
Figure 4.4 Block diagram for control panel used in LabVIEW
Figure 4.6 Sample snapshot of pressure travel diagram obtained from LabVIEW

Figure 4.7 Snapshot of control panel to communicate to DAQ
4.3 TARGETED EXPERIMENTS - SHEET HYDROFORMING

In order to study the effects of fluid pressure on the formability of super alloy sheets during the sheet hydroforming process, both experimental and numerical studies were conducted. The experiments were carried out using Inconel 625 of thicknesses 0.5 mm, 1 mm and 1.5 mm. Round blanks of diameters 70, 100 and 130 mm were used in the tests with circular punch head of 50 mm diameter. Specific tests were carried out in order to establish the objectives mentioned earlier, as follows:

I. Experimental Studies:
   - Conventional forming - without fluid pressure
   - Fluid pressure applied to one surface of the sheet metal - constant pressure and varying fluid pressure

II. Numerical Studies:
   - Studying several important issues related to the reliability of the finite element analysis model that could be used for hydroforming simulation - Material modeling and Geometrical effects
   - Simulating sheet hydroforming process with the commercial explicit dynamic finite element analysis code DEFORM 3D
   - FEA for establishing the optimal pressure curve

In the following section, the experimental works will be described, sample results will be presented and some important issues encountered will be discussed. For comparison, all experimental results will be presented along with “numerical analysis” results in chapter 6.
4.4 EXPERIMENTAL WORK - SHEET HYDROFORMING

The experimental apparatus which has been designed and fabricated mainly consists of a pressure chamber, blank holder, punch and some accessories to employ as a pressure control system. To proceed with the drawing of a cup the pressure chamber should be initially filled with oil. The blank is then placed in the desired position on the upper surface of the chamber and the blank holder is tightened to hold the blank. Then the punch is inserted through the central hole in the blank holder to set down the blank. Figure 4.8 illustrates the experimental test set-up for the process.

![Figure 4.8 Experimental test set-up for sheet hydroforming](image)

Now an initial pressure can be generated by regulating the pressure control valve manually to a desired value which is recorded by a pressure gauge. When the internal pressure exceeds the pre-set value the valve is opened to drive away an amount of oil from the container then the valve is closed again at the pre-set pressure and so on. The internal pressure is
recorded during the process by the pressure gauge which is assembled in the chamber as well as the drawing load is recorded by the force gauge. At the end of the process the blank holder moves up-wards and the oil pressure in the chamber is released. Once the chamber is depressurised, the punch is withdrawn. The cup that has been formed remains in the pressure chamber and it can be taken out. The internal pressure is recorded during the process by the pressure gauge which is assembled in the container as well as the drawing force is recorded by the load cell.

4.4.1 Sheet Metal Properties and Blank Sizes

Inconel 625 material of diameters \(D_0\) 70, 100, and 130 mm and thicknesses \(t_0\) 0.5 mm, 1 mm and 1.5 mm were used in the tests with circular punch head of 50 mm diameter \(d_0\). The physical properties and mechanical properties of Inconel 625 are shown in Tables 4.1 and 4.2 respectively. In the present work several tests were carried out on circular blanks. The formed cylindrical cups are shown in Figure 4.9.

**Table 4.1 Physical properties of Inconel 625**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>8.44 g/cm(^3)</td>
</tr>
<tr>
<td>Melting Range</td>
<td>1290-1350°C</td>
</tr>
<tr>
<td>Permeability</td>
<td>1.0006</td>
</tr>
</tbody>
</table>

**Table 4.2 Mechanical properties of Inconel 625**

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum Tensile Strength</td>
<td>827 MPa</td>
</tr>
<tr>
<td>Minimum Yield Strength</td>
<td>414 MPa</td>
</tr>
<tr>
<td>Minimum Elongation</td>
<td>40%</td>
</tr>
</tbody>
</table>
In the sheet hydroforming process of cylindrical cups, fracture and wrinkling are the failure modes and fluid pressure plays an important role in the process. Wrinkling is usually due to insufficient blank holding force which is commonly obtained in conventional processes. Wrinkling in hydroforming process is considered as a major failure mode unlike in conventional deep drawing where it can be adjusted in the following redrawing process. Figure 4.10(a) shows the photos of wrinkled cups due to insufficient initial pressure. Fracture occurs around the die profile because of very high chamber pressure. Figure 4.10(b) shows the tearing in the cup wall for cylindrical cups.
The chamber pressure as well as the drawing load is plotted against the punch travel for different sheet thicknesses as shown in Figures 4.11 - 4.15. The chamber pressure and drawing load are increased gradually by the progress of the punch and then decreased during the later stages of punch travel. The results from Figures 4.11 - 4.15 shows that, for super alloy, under the condition of the same drawing ratio, the maximum chamber pressure is much higher than that of lower strength material and it is necessary for the chamber pressure to be established quickly at the beginning. Also, the higher the thickness of cups, the higher the pressure required for drawing process. For gradual pressurization, the establishment of chamber pressure is decided by punch speed and liquid viscosity. In the experiments, ordinary hydraulic oil is chosen as the fluid medium, so the changeable parameter is punch speed for the establishment of pressure. In order to obtain friction holding between punch and sheet metal, a speed of 5 mm/s is chosen, which can guarantee the establishment of pressure at the beginning.
Figure 4.11  Chamber pressure versus punch travel ($t_o=0.5$ mm)

Figure 4.12 Chamber pressure versus punch travel ($t_o=1$ mm)
Figure 4.13  Chamber pressure versus punch travel ($t_o=1.5$ mm)

Figure 4.14  Drawing load versus punch travel ($t_o=0.5$ mm)
For a successful sheet hydroforming process, the maximum value of thinning should not be beyond 20%. When drawing ratio reaches 2.6, the thickness distribution is shown in Figures 4.16 and 4.17. Along the cup wall the thickness strain varies from negative values at the most wall height to positive values at the top of the cup. As shown the thickness strain in the wall region is almost uniform which is one of the advantages of the hydroforming process.

Figure 4.15 Drawing load versus punch travel \((t_o=1.5 \text{ mm})\)

Figure 4.16 Distribution of thickness thinning ratio \((t_o=1.5 \text{ mm})\)
The majority of the experimental results and conclusions related to sheet hydroforming is presented in Chapter 6, along with the numerical analysis results.

4.5 EXPERIMENTAL APPARATUS - TUBE HYDROFORMING

The basic system requirements for performing a successful tube hydroforming operation are as follows: (i) electronic control system (ii) oil hydraulic cylinders (iii) pressure medium (iv) tooling (v) sensors for feed control (vi) computer interface for precise parameter input and (vii) dial gauges for indicating the parameters like internal pressure and feed.

The tube hydroforming apparatus used for experiments had the following three major elements along with PC based control system: hydroforming tool, hydraulic press and hydraulic system for internal pressure intensification and axial feeding. The hydroforming tool is dependent on component shape and size. Each component to be hydroformed requires its own tool. The function of the hydraulic press is to open and close the tool.
Once the tool is closed, the halves of the tool must be kept together without any movement in vertical or lateral directions during the pressurization phase of the forming process.

A hydroforming system has oil based hydraulic circuits for the actuation of the axial feed cylinders, internal pressure creation inside the tool set up, movement of the punch and the ram. The hydroforming press used for the experiment and the fluid pressure control unit is shown in Figures 4.18 and 4.19 respectively. The tool for tube hydroforming, a T-Shaped tube, comprising of upper die and a lower die and these dies are made of Oil Hardened Nitriding Steel (OHNS). The two halves are held together by allen-screws as shown in Figure 4.20.
Figure 4.19 Fluid pressure control unit used for tube hydroforming

(a) Upper and Lower die     (b) CAD model

Figure 4.20 Tooling for tube hydroforming
The axial feed cylinders form an important part of the press since the axial feed is given through these actuating cylinders. The feed cylinders tend to actuate the feed rods on both sides, subjecting the feed rods to an imposed displacement. The feed rods slides in to the tool set up provided that a proper oil seal is ensured by the O-ring seals. The axial feed cylinder arrangement is shown in Figure 4.21. A fixture was required to hold the entire tool set up comprising of an upper die, lower die, and the tube. The fixture was mounted to the machine bed and it was held at proper height from the bed surface. This must be properly ensured to avoid the deflection of feed rod that may pose an error related to the offset of the central axis of the tube.

![Figure 4.21 Machine feed rod used for tube hydroforming](image)

The exploded 3D CAD model of the tooling along with fixture and machine feed rod is shown in Figure 4.22. One oil entry path and one oil exit path is designed in the axial feed cylinders, as shown in Figure 4.21. The oil entry path is located at the center of the cross-section of the cylinder. Whereas, the oil exit path is located at the upper part to let the air flow out easily at the beginning of the hydroforming process. A smaller diameter is made at the front end of the axial feed cylinder for oil sealing. The counter punch is just used for applying a force to counterbalance the internal pressure.
4.6 TARGETED EXPERIMENTS - TUBE HYDROFORMING

To know the effects of fluid pressure on the formability of super alloy tubes during the tube hydroforming process, experimental work and numerical analysis using FEM were conducted. A hydroforming machine with two axial feeding cylinders and a counter punch was developed and the following studies were carried out.

I. Experimental Studies:
   - Free forming and calibration process
   - T-shape protrusion forming
II. Numerical Studies:

- Simulating tube hydroforming process, with the commercial finite element code Altair HyperForm
- FEA of T-shape protrusion forming
- Wall thickness distribution analysis

In the following section, a brief description about the experimental work and some important experimental results are discussed.

4.7 EXPERIMENTAL WORK - TUBE HYDROFORMING

The tube blank is positioned into the lower die cavity and then the top die is positioned to avoid the movement of the tube blank. In the next step, the tube is filled with a liquid medium through a feed hole in the feed rod and initial pressure is applied. In the subsequent steps, the feed rods are moved in order to apply a thrust force at the ends of the tube.

Depending on the combined effect of the thrust force feeding and the internal pressure loading synchronization, tube buckling as well as wrinkling may occur. After the punch reaches the desired stroke displacement the internal pressure on the fluid into the tube is increased expanding the tube, in such a way that it takes the form of the die cavity. This operation is called as calibration. In general, there is a process window which shows the combination of thrust feeding force and internal pressure, in order to obtain hydroformed parts without wrinkles or rupture.

The wrinkles produced during the buckling in the tube hydroforming process could be good or bad one. The wrinkle would be a good one if it can be completely removed in the calibration step. One of the
primary objectives of the FEA, which is described in the following section, is to determine the most suitable combination of thrust feed force and initial internal pressure for avoiding wrinkles.

4.7.1 T-Shape Protrusion Forming

A T-shape protrusion forming process of Inconel 625 was conducted and the counter punch was used to control the branch height and to avoid over-thinning or bursting at the corner of the protruded branch. Inconel 625 tubes with initial outer diameter of 50.8 mm and thickness 1.55 mm with a symmetrical open die was used during experiments. Two kinds of loading paths are used to control the axial feeding punches, the counter punch and the internal pressure, as shown in Figures 4.23 and 4.24. From the figures, it is known that at the first stage of forming, the counter punch did not move. After an enough contact area is generated between the counter punch and the branch, the counter punch starts to move backward. In this way, the thickness distribution at the top of the branch can be controlled until the end of the forming process.

In Figure 4.23, the left and right axial feeding punches travel 88 mm forward, the maximum internal pressure reaches 90 MPa, and the counter punch travels 36 mm backward, whereas, in Figure 4.24, the stroke of the axial punches is 81 mm, and the maximum internal pressure is 115 MPa. At the late stage of the pressurization, the internal pressure is increased dramatically to make the corner radius reach 5 mm. The formed products are shown in Figure 4.25.
(a) Internal pressure Vs Time

(b) Axial feeding and counter punch displacement Vs Time

Figure 4.23 Loading path for T-Shape protrusion forming (Axial feeding=88 mm; Chamber pressure=90 MPa)
Figure 4.24 Loading path for T-Shape protrusion forming (Axial feeding=81 mm; Chamber pressure=115 MPa)
Because the axial feeding punches moved more distance, and the internal pressure is less in the first case, wrinkling occurred at the surface of the product as shown in Figure 4.25(a). There are several stops while the counter punch is moving backward, as shown in Figure 4.23. That is probably one of the reasons for the wrinkling occurring at the surface. The appearance of the product for the second case is wrinkling-free with the same branch length. Thus, the loading path of the second case produces sound products without wrinkles.

(a) Axial feeding=88 mm/Chamber pressure=90 MPa

(b) Axial feeding=81 mm/Chamber pressure=115 MPa

Figure 4.25 Products of T-shape protrusion forming
The thickness distribution for both cases is shown in Figure 4.26. It is clear that the thickest part occurs at around the die entrance because the material is accumulated there. The tube at the guiding zone becomes thicker than the initial thickness, because it is subjected a compressive stress and the die and axial punches undergo elastic deformation. The thinnest part is located at the center of the protruded branch. Nevertheless, the thickness ratio is still larger than 0.9.

![Figure 4.26 Thickness distribution of the formed part](image)

**Figure 4.26 Thickness distribution of the formed part**

In Chapter 6, along with the FEA results, majority of the experimental results are discussed to have better understanding about the numerical analysis. The comparisons of the protrusion height of the formed parts with and without counter punch are also discussed in detail in Chapter 6.