CHAPTER 3

EXPERIMENTAL PROCEDURE

A detailed account of the experiments and investigations conducted for incremental forming study is presented in this chapter. The experimental procedure was planned keeping in cognizance the work of earlier researchers in the field. It is aimed to develop reliable data, which will be useful during incremental forming of steel sheets. Moreover acquisitions of data pertaining to different parameters during incremental forming are explained in the following experimental procedures.

3.1 MATERIALS USED IN THIS RESEARCH

Low carbon steel alloys IS: 513 CR3 Deep drawing quality steel, IS: 277 galvanized steel, and AISI 304 stainless steel sheets were chosen for incremental forming and the subsequent studies. The alloys were chosen based on the applications to the aerospace and automotive industries.

The alloys were bought as cold rolled sheets of thickness 0.6mm and were cut to the dimensions of Sq. 300 x 300 mm for incremental forming. The base diameter of cone was 75mm and the base size of the pyramid was 75 x 75 mm. The detailed composition of various steel alloys (in weight percentage) used in this study are given below in Table 3.1.
Table 3.1 Material composition of different steel alloys used in this study

<table>
<thead>
<tr>
<th>Material</th>
<th>Percentage (in Weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
</tr>
<tr>
<td>IS: 513 CR3 Deep drawing quality steel</td>
<td>0.10</td>
</tr>
<tr>
<td>IS: 277 galvanized steel</td>
<td>0.15</td>
</tr>
<tr>
<td>AISI 304 stainless steel</td>
<td>0.08</td>
</tr>
</tbody>
</table>

3.2 INCREMENTAL FORMING SETUP

3.2.1 CNC Machine

Incremental forming was carried out in a CNC vertical milling machine developed by Ace Manufacturing Systems Limited (AMS Limited) – India. The specifications of the machine are given in Table 3.2.

Table 3.2 Specifications of CNC Vertical milling machine

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Particulars</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Maximum power</td>
<td>7.5 kW</td>
</tr>
<tr>
<td>2.</td>
<td>Maximum spindle speed</td>
<td>6000 rpm</td>
</tr>
<tr>
<td>3.</td>
<td>Maximum table travel</td>
<td>600 mm in longitudinal direction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>430 mm in headstock travel</td>
</tr>
</tbody>
</table>

The incremental forming machine used for the experiments is shown in the Figure 3.1. During forming, the sheet was firmly fitted on the fixture which was clamped to the bed of CNC vertical milling machine. The specially prepared tool was fitted to the mandrel of the CNC milling machine and moved along the generated tool path to obtain the required final shape.
The experiments were done with various feed rates for different spindle speed and incremental step on constant thickness sheets.

Figure 3.1 (a-b) Incremental forming process in CNC machine

### 3.2.2 Fixture Design

The incremental forming fixture was fabricated using C45 medium carbon steel. Table 3.3 shows the list of materials used in fabrication of fixture.

**Table 3.3 Materials for fixture**

<table>
<thead>
<tr>
<th>Sl. No</th>
<th>Component</th>
<th>Material selected</th>
</tr>
</thead>
</table>
| 1      | Fixture & base plate | C45 steel  
             | Tensile strength $\sigma_t=360$MPa       |
| 2      | Nut & bolts        | C45 steel  
             | Tensile strength $\sigma_t=360$MPa       |
| 3      | Vertical supports  | GI pipes  
             | Young’s modulus $E=2.1\times10^5$N/mm²    |
a) **Frame design**

The fixture frame was designed using the Equations (3.1) to (3.9).

From design Data book (PSG 2008) : For C45 steel

Tensile strength ($\sigma_t$) = 360 N/mm$^2$

Factor of safety (FOS) = 3

Design bending stress

$$\left[ \frac{\sigma_b}{FOS} \right] = \frac{\sigma_t}{3} = \frac{360}{3} = 120 \text{N/mm}^2$$  \hspace{1cm} (3.1)

The Reactions at the support are $R_A = R_B = 5 \times 10^3 \text{N}$

Bending Equation

$$\frac{M_b}{I} = \frac{\sigma}{y}$$  \hspace{1cm} (3.2)

Maximum Bending Moment ($M_b$) for simply supported beam with point load at center is given by

$$M_b = \frac{PL}{4} = \frac{10 \times 10^3 \times 300}{4} = 750 \times 10^3 \text{N-mm}$$  \hspace{1cm} (3.3)

Moment of Inertia ($I$) for a base width ($b$) of 300 mm and thickness ($t$) = 10 mm is calculated by

$$I = \frac{bh^3}{12} = \frac{300 \times 20^3}{12} = 200 \times 10^3 \text{mm}^4$$  \hspace{1cm} (3.4)

The bending stress ($\sigma$) for a deflection ($y$) of 10 mm using the Equation (3.1) is

$$\sigma = \frac{M_b \times y}{I} = \frac{750 \times 10^3 \times 10}{200 \times 10^3} = 37.5 \text{ N/mm}^2 < [\sigma_b] = 120 \text{ N/mm}^2 \text{ (Safe design)}$$
b) Bolt design

The bolts are subjected to direct tensile stress.

\[ \sigma_t = \frac{\text{Load}}{\text{Bolt Stress area}} \text{ N/mm}^2 \]  

(3.5)

Total no of bolts =16

Selecting M12 bolt from data book (PSG 2008) for a pitch 1.75mm and stress area 84.3 mm\(^2\), using the Equation (3.2)

\[ \frac{\text{Load}}{\text{Bolt}} = \frac{\text{Total load}}{\text{No of bolts}} \frac{N}{16} = \frac{10 \times 10^3}{16} = 625 N \]

\[ \sigma_t = \frac{625}{84.3} = 7.41 \text{ N/mm}^2 \]

\[ \sigma_t < \sigma_b = 120 \text{ N/mm}^2 \] (Safe design)

c) Design of Columns

Young’s modulus \( E = 2.060 \times 10^5 \text{ N/mm}^2 \)

Using Euler’s formulae, Load \( (P) = \frac{n \pi^2 EI}{L^2} \),  

(3.7)

where ‘n’ is the slenderness ratio = 1 for both ends hinged and \( L \) is the length of the pipe in mm. The moment of Inertia for a pipe with outer diameter (\( d_o \)) 21 mm and inner diameter (\( d_i \)) 16.5 mm is,

\[ I = \frac{\pi}{64} \left( d_o^4 - d_i^4 \right) = \frac{\pi}{64} \left( 21^4 - 16.5^4 \right) = 5908.2037 \text{ mm}^4 \]  

(3.8)

Length of column \( L = 150 \text{mm}. \)
Substituting the data in the load Equation (3.3),

\[
P = \frac{1 \times \pi^2 \times 2.060 \times 10^5 \times 5908.2037}{150^2} = 533.8754 \times 10^3 \text{ N} \Rightarrow \text{Actual load} = 2.5 \times 10^3 \text{ N}
\]

(3.9)

The Table 3.4 lists the specifications of the fixture. The fixture assembly is shown in Figure 3.2.

**Table 3.4 Specifications of the fixture**

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Particulars</th>
<th>Size</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Frame</td>
<td>300×300×20mm</td>
</tr>
<tr>
<td>2.</td>
<td>Base plate</td>
<td>350×350×20mm</td>
</tr>
<tr>
<td>3.</td>
<td>Column</td>
<td>Inner Diameter 16.5mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Outer Diameter 21mm</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Height 150mm</td>
</tr>
<tr>
<td>4.</td>
<td>Size of the Bolt</td>
<td>M12</td>
</tr>
</tbody>
</table>

(a) 3D Model

(b) Photograph

*Figure 3.2(a-c) (Continued)*
3.2.3 Forming Tool

Two hemispherical shaped forming tools were fabricated with the dimensions as shown in Figure 3.3 by optical profile grinding. The tools were machined from High Speed Steel and Silicon Carbide. The dimensions so chosen were based on several trials.
The tools fabricated with lower diameter than those used in this process produced rough surfaces and also had poor service life. On the other hand higher diameter tools greater than 10 mm those used in this process developed cracks on the sheets. HSS tools were used to form IS: 277 galvanized steel and IS: 513 CR3 deep drawing quality steels. However, on AISI 304 steel, it was noted that the HSS tool developed high heat and rough surfaces to naked eyes. Hence silicon carbide tool was used for forming conical and pyramid shapes on AISI 304 sheets. Synthetic coolant oil was used as the coolant during forming to reduce tool-sheet contact friction. The length to diameter ratio of the tool was fixed on the tool holder as less to withstand the axial load during forming.

### 3.3 PROCESS PARAMETERS

The various input process parameters used during incremental forming of pyramid and conical shapes are given in the Table 3.5.

#### Table 3.5 Experimental input parameters

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Process Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Tool rotational speed</td>
<td>1000, 1500,</td>
</tr>
<tr>
<td></td>
<td>in rpm</td>
<td>2000</td>
</tr>
<tr>
<td>2.</td>
<td>Table feed</td>
<td>1200, 1400,</td>
</tr>
<tr>
<td></td>
<td>in mm/min.</td>
<td>1600</td>
</tr>
<tr>
<td>3.</td>
<td>Step depth</td>
<td>0.4, 0.5,</td>
</tr>
<tr>
<td></td>
<td>in mm</td>
<td>0.6</td>
</tr>
</tbody>
</table>
3.4 RESPONSE PARAMETERS

Forming limit, surface roughness, Vickers microhardness, thickness distribution and microstructure of the formed sheets were characterized. The formability of the incremental forming process on steel sheets was studied based on strain distribution. Out of the various methods to deduce the measure of major and minor strain, this research uses small circles etched on the surface of the sheet.

Strain analysis by grid marking is a useful method, which has been used effectively to solve the problems in metal forming. When sheet metal is formed, its surface is subjected to different stresses. This results into non uniform strains to be developed in the formed part. Thus there will be regions of high strains as well as low strains, which may lead to wrinkling or fracturing of the material. By the grid marking method the areas of high strain can be easily identified.

Initially circles of 5mm diameter were etched on the surface of the sheet. The pattern of etched circles was arrays of contacting circles as shown in Figure 3.4. With small closely spaced circles, it is possible to determine strain gradients accurately.

![Figure 3.4 Schematic sketch of the grind circle](image)

Electrochemically etched circular grids were used in this research. Electrochemical marking method is the most preferred method for applying
grids since it is easy and quick. In this process an electric stencil was placed on the cleaned blank. A felt pad soaked with electrolyte was placed on the top of the blank and an electrode (flat or roller type) was placed above the felt pad. A wooden block was kept above. Leads from a 14 V power source were attached to the electrode and the blank. Current varied between 15 – 200 amperes depending on stencil size and line density. After application of pressure over the electrode, the felt pad squeezed, the electrolyte passed through stencil and came in contact with blank etching the grid pattern electrochemically into the blank. Subsequent to etching the blank was washed with a neutralizing solution. Following incremental forming of the sheets into varying shapes, the etched circles turn into ellipses as shown in figure 3.5. The direction of the strains was indicated by the major and minor axis of the ellipse. The ratio of the major and minor axes of the ellipse to the diameter of the original circle gives the major and minor strain, respectively. Strain was calculated from the following Equations (3.10) and (3.11).

\[
\text{Major strain} = \frac{(\text{major axis length} - \text{original circle dia}) \times 100}{\text{Original circle dia}} \quad (3.10)
\]

\[
\text{Minor strain} = \frac{(\text{minor axis length} - \text{original circle dia}) \times 100}{\text{Original circle dia}} \quad (3.11)
\]

![Figure 3.5 Strain distribution of the circle](image)
Surface roughness was measured using SURFTEST Model: SJ-801, Mitutoyo Japan. After measuring the strain and surface roughness, the specimens were extracted to identify the thickness distribution, microhardness and microstructural characteristics. Specimens were extracted along the lateral face for pyramid shapes and parallel to generator for conical shapes as indicated in Figure 3.6.

![Figure 3.6](image)

(a) (b)

Figure 3.6 (a-b) Cut sectors of the cone and pyramid for thickness measurement

Microhardness measurements were done along the surfaces using Vickers microhardness tester with load of 5N and a dwell period of 15 seconds. The Vickers microhardness measurements were done using Wilson Wolpert Micro Hardness tester, (Make: Germany), with a range of 10g to 2000g. The table size of the dimensions 120 X 120 mm with a resolution from 0.01mm to 25mm and magnification between 100X and 400X.

The macrostructure and microstructure of the specimens were observed using optical and scanning electron microscopes. The specimens for the microstructural observations were also extracted similar to the specimens extracted for microhardness measurements across the formed sheets. The specimens were prepared and then polished using diamond paste. Keller’s reagent and 0.5% hydrofluoric acid were used as etchants. Optical
micrographs were taken by Dewinter optical microscope (Make: India) with magnification ranging from 2X to 1000X.

Scanning electron micrographs were taken with SEM microscope by Hitachi Japan. The microscope has magnification of 5X to 300,000X with a resolution up to 3 nanometers. X ray spectral mapping was also performed with the help of the same microscope.

Figure 3.7  (a-b) Thickness measurements and microstructural zone of the formed sheet
The thickness of the formed specimens was measured using Vernier height gauges (Mitutoyo No. 506-207, Make: Japan) with a range of 0-200 mm (accuracy ±0.03 mm) and micrometer (Mitutoyo with ratchet stop No. 293-250-10, Make: Japan) with a range of 100-125mm (accuracy ±2 μm). The locations used to measure the thickness distribution and observe the microstructural variations are shown in Figure 3.7.

Tensile testing of pre-formed specimens was carried out using a universal testing machine (Make: Avto instruments limited, India) with a maximum tensile force measurement of 50kN and a resolution of 0.01kN. The universal testing machine has an integrated data acquisition system complete with an encoder, an electronic data cell and UTNSRL software to measure tensile strength, compression strength and bending strength and shear loads.

The tensile specimens were prepared according to the American Society for testing of materials standards, ASTM: E8/E8M – 11. The dimensions of the tensile test specimen are shown in figure 3.8. The specimens were loaded in the testing machine at a constant strain rate. True stress and true strain curves were plotted and the behaviour of the sheet materials was studied.

All Dimensions are in mm

Figure 3.8 Tension Test Specimen
Optimization of various monitoring and response parameters used during the incremental forming process, design and analysis was done using the software Design Expert V 9.0.0.7. Response surface methodology technique with Central Composite design was used to analyze problem and model. The response was assumed as a linear function of the independent input variables.

Finite element analysis of the formed specimens was carried out using Abaqus software version 6.10.1. The forming height, thickness distribution and forming time of the formed sheet was established using FEA and was validated with experiments.

3.5 SUMMARY

The various steel sheets used in this research along with their compositions are given. The setup used for incremental forming, the parameters varied and the output parameters monitored are listed. The specifications of the ASTM standards for various steel sheets and testing equipments used in this study are also listed. The techniques used for optimization and finite element analysis are listed in this chapter.