CHAPTER 3

EXPERIMENTAL DESIGN AND FABRICATION

3.1 Introduction

Tube hydroforming (THF) is a relatively complex manufacturing process; the performance of this process depends on various factors (material properties, geometrical factors, and process parameter). This chapter reports on the elliptical tube hydroforming machine die and components development with detailed design and experiments, using the tube hydroforming machine fabricated and assembled in Indian Institute of Technology (Banaras Hindu University), Varanasi in India. The tubes materials, the preparation steps, and the experimental procedures are described. Based on an experimental approach, the influence of material annealing on the hydro formability of aluminium Al6061 T4 tubes was revealed. The Elliptical shape tube hydroforming processes outputs were experimentally examined. From the results, it can be observed that experimental investigations may only give a limited understanding of the process. Therefore, the application of numerical simulation of the tube hydroforming process analysis is suggested in this study to avoid the numbers of testing and trails through experiments in order to achieve successful samples with good dimensional accuracy and ultimately tube hydroforming methods reduces the cost and limitations of compiling a cluster of databases of real-world parts.

A typical product design flow chart is presented in figure 3.1. The new product design begins with conceptual design followed by CAD modelling or mathematical modelling. These models are further subjected to analysis using various simulation tools such as FEA, virtual reality and visual inspection. The prototype design is finalized based on preliminary outputs which leads to prototype model. This model is tested keeping certain design objectives as constraints. The outputs meet the design objectives then it is proposed for mass or batch production. In case, design does not meet the stated objective, it is modified and redesigned.

The design of tube hydroforming set up has passed through all the steps as explained in flow chart. The conceptual design was extracted from Verson-Hydroforming process. The conceptual design was converted into a 3D CAD model using solid works modeling software. The components are designed using basic empirical formulae at preliminary stage which are discussed separately in this chapter. Subsequently, FEA simulation was also carried out using Abaqus analysis software to study the effects of various parameters during forming. In the next step, a prototype of tube hydroforming set up is fabricated. The details of the fabrication process steps are described in the next section.

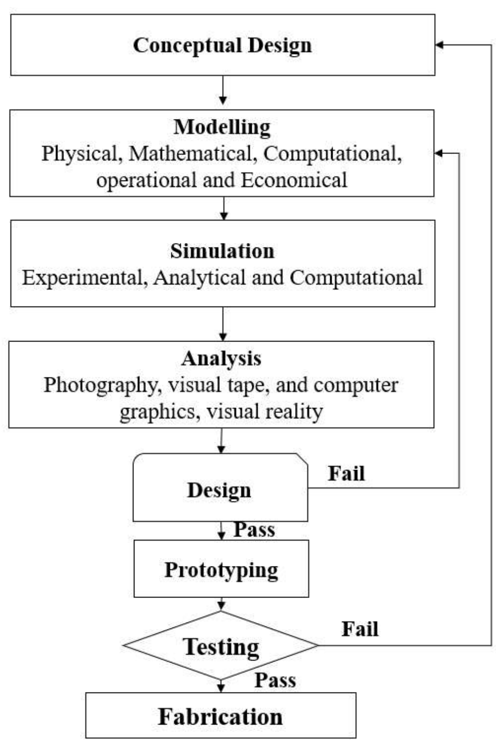


Figure 3.1: Flow Diagram for Product Design

3.2 Essentials factors of product design

The design of elliptical shape tube hydroforming set up has been developed considering the following basic factors of product design.

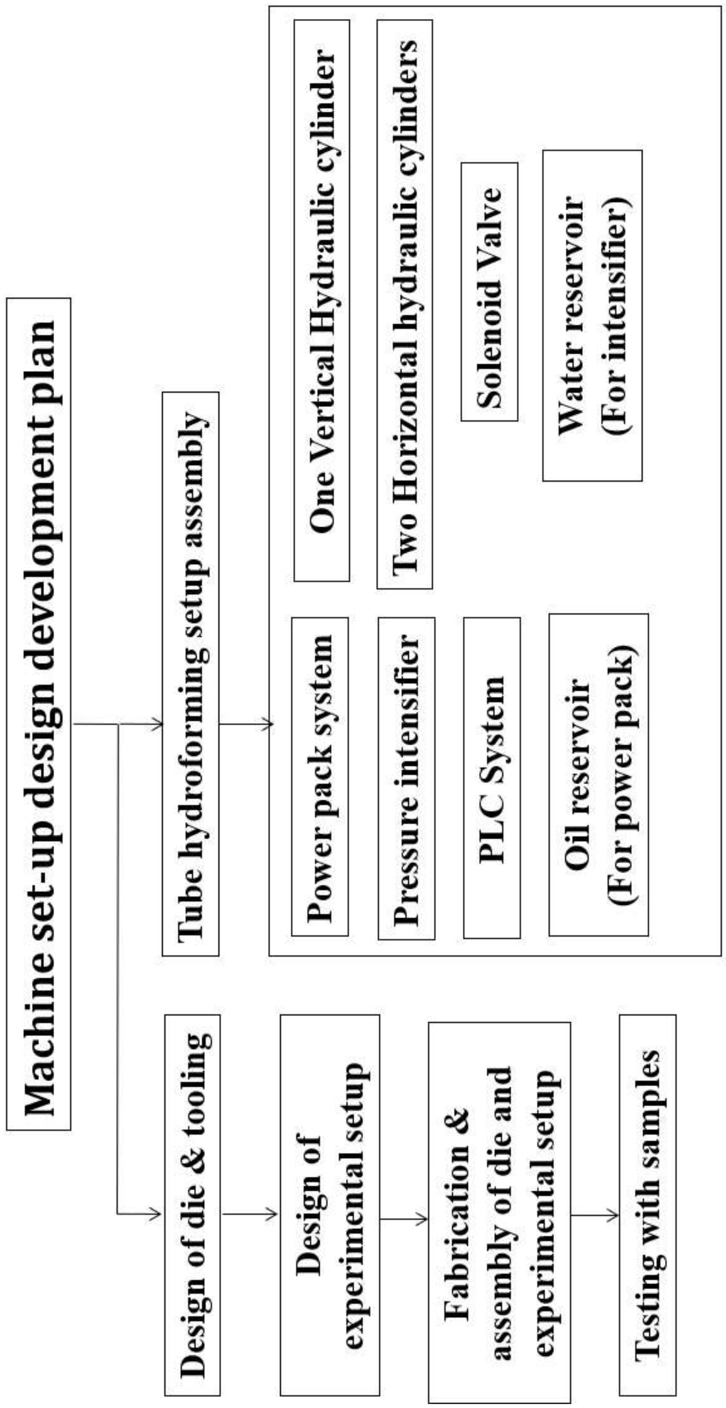


Figure 3.2: Tree outline of tube hydroforming machine assembly design set-up

3.2.1 Need Analysis:

The need analysis part has been explained in the introduction chapter. This kind of set up is very much essential for producing very complex shaped elliptical tube hydroforming set up. In addition to that, this set up very much needed for drawing the die of elliptical cavity components which are prone to failure by tearing.

3.2.2 Physical Realizability:

The study of physical realizability has been carried out by breaking up the tube hydroforming setup into sub-assemblies and components. The tree of tube hydroforming set up is shown in figure 3.2. This set up essentially consists of die set up assembly, PLC system to monitor Hydraulic power pack assembly, flow rate, internal pressure supply inside tube. The assemblies are further sub-divided into component level. It consists of a hydraulic power pack, pressure intensifier, oil reservoir, water reservoir, one horizontal and two axial cylinders for sealing of tube samples. The capacity of hydraulic power packs for applying axial end sealing and vertical die closing force is 10 KW fixing holding pressure are the parts of hydraulic power pack assembly. Each component was thoroughly studied for availability of material, fabrication feasibility. It was concluded that each system can be realised with available resources.

3.2.3 Design stages:

Design is progression from abstract to the concrete. This gives a chronologically horizontal structure to a design project. The three phases of design proposed by Asimow [48] are presented in the figure 3.3.

3.2.4 Feasibility Study:

The detailed feasibility study was carried out as explained in physical realizability section.

(a) Preliminary Design: It begins with drawing up schematic diagram of tube hydroforming set up as shown in figure 3.4. Die set up assembly comprising end sealing ram and die is the nodal point of process. It is decided to integrate pressure gauge connected with output valve of pressure intensifier as forming loads transfers to the press through upper die. At this stage, the overall size of dies, intensifier, water reservoir, tonnage of press, etc. are designed.

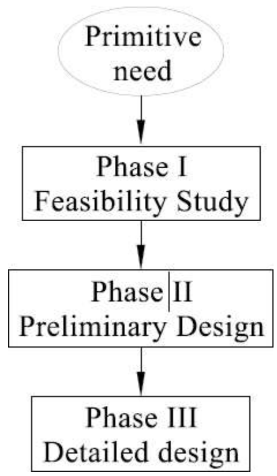


Figure 3.3: Design stages [48]

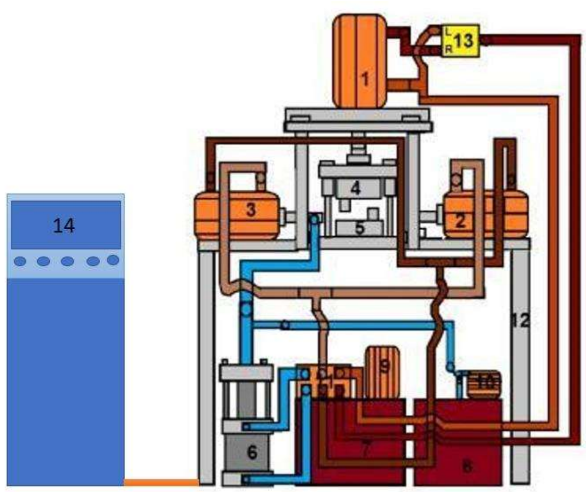
Pressure gauge are designed to be integrated with fluid chamber which is the part of lower die. Two pressure gauge are selected to monitor inlet and outlet pressures of fluid chamber.

3.2.5 Detailed design:

Detailed design involves the designing of each component based on designed parameters. Each feature of the component is designed considering strength, manufacturing aspects and assembly aspects. The design details of assembly and individual components are discussed in section 3.3.

3.3 Design of Tube hydroforming Test-Setup

The main feature of Tube Hydroforming is to replace the complex attachments used in stamping process by internally applied pressure with an additional end sealing enhance the liquid pressure to mould the samples into the desired shapes. The main components of Tube Hydroforming set-up includes Die and Tooling (such as sealing ram, O-rings and die clamping attachments etc.), Hydraulic Power Pack system (includes motor, oil reservoir, solenoid valve arrangements, Pressure gauge etc.), PLC system (includes automatic switching arrangements for internal pressure supply, flow controls switch and monitoring all the hydraulic cylinders connected through power pack system), Pressure intensifier system (includes water reservoir and pump for inlet water supply and high pressure outlet water delivery). This introduction of high internal pressure leads to more uniform strain distribution which improves the formability of the material. It also increases the limiting drawing ratio and decreases the variation of thickness of the formed component. Figure 3.4 shows the schematic diagram of the process in Tube hydroforming.



1. **Vertical Cylinder**
2. **Right Horizontal Cylinder**
3. **Left Horizontal Cylinder**
4. **Upper Half Die**
5. **Lower Half Die**
6. **Intensifier**
7. **Hydraulic Power Pack**
8. **Water Tank**
9. **Motor for oil supply to Intensifier and to all Cylinders**
10. **Motor for water supply to Intensifier**
11. **Hose Pipe connection to power pack**
12. **Structure Supporting THF Machine**
13. **Split Check Valve**
14. **PLC System**

Figure 3.4: Schematic diagram of tube hydroforming setup

3.4 Theoretical Study

Tube Hydroforming conditions, such as the relationships between the liquid internal pressure, hydraulic pressure required for die holding force, punch forces and process parameters play an important role in designing any Hydro-forming process. It is, however, difficult to determine them properly and they are currently determined by trial and error in field operations. One of the important parameters while designing the Tube Hydroforming process is the force which can be calculated by using the following formulae.

During THF process, only a limited length of tube can be pushed into the die cavity. There are some relations between maximum compressive force (F_a); frictional force (F_f); the coefficient of friction between the tube and die surface (μ) and the length of the tube (L). These equations could be obtained by the followings relations

$$\mathbf{F_a = \pi(D - t_i) t_i \sigma_u} \qquad \textbf{Equation 3.1}$$

Where: D is the tube diameter; t_i is the initial wall thickness; σu the ultimate tensile strength of material. The frictional force (F_f); from internal feed pressure could be obtained by the followings

$$\mathbf{F_f = \pi(D - 2t_i) L \mu P_a} \qquad \textbf{Equation 3.2}$$

Where: P_a is the internal pressure. By manipulating these equations, the value for tube length (L) would be

$$\boldsymbol{L = t_i \sigma_u (1 - \tfrac{t_i}{D})(1 - 2\tfrac{t_i}{D}) \mu P_a} \qquad \textbf{Equation 3.3}$$

During the axial feeding stage, the internal pressure for round sections is approximated by the following equation

$$\mathbf{P_a = 2t_i(0.85\sigma_u)/(D - 2t_i)} \qquad \textbf{Equation 3.4}$$

For large D/t_i ratios, ($D-2t_i$) approximates to D; and approximates to 1; so Eqs. (3) and (4) can be simplified to the below relation)

$$\mathbf{L=D/1.7\mu} \qquad \textbf{Equation 3.5}$$

The amount of feed is approximated by equating the material volume of the hydroformed component to the material volume of the tubular blank. Also, component material volume (V_c), and the axial feed length (F) can be calculated as follows

$$\mathbf{V_c=\pi D t_i L} \qquad \textbf{Equation 3.6}$$

$$\mathbf{F=L-C} \qquad \textbf{Equation 3.7}$$

Path diagram of pressure loading is estimated by relating three different parameters which are; yield pressure (P_{Yield}); bursting pressure ($P_{Bursting}$) and calibration pressure ($P_{Calibration}$). These parameters are shown by the followings relations

$$\boldsymbol{P_{Yield} = \sigma_y\left(\frac{2t_i}{D-t_i}\right)} \qquad \textbf{Equation 3.8}$$

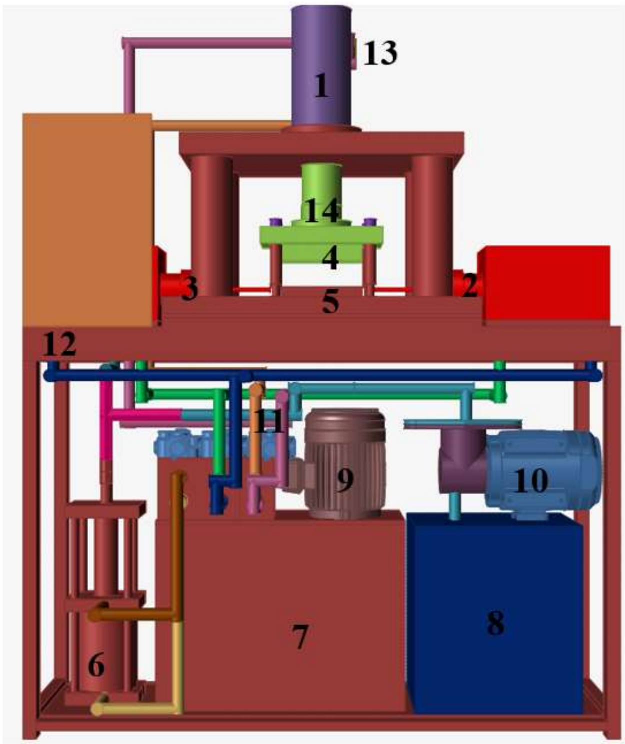
$$\boldsymbol{P_{Bursting} = \sigma_u\left(\frac{4t_i}{D_p-t_i}\right)} \qquad \textbf{Equation 3.9}$$

$$\boldsymbol{P_{Calibration} = \frac{2}{\sqrt{3}}\sigma_f ln\left(\frac{r_b}{r_b-t}\right)} \qquad \textbf{Equation 3.10}$$

As Aue-U-Lan *et al.* (2004) showed in the above relations, σ_y is the yield strength, r_b is the smallest die corner radius, σ_f is the flow stress of the material and D_p is the protrusion diameter. According to the presented theoretical method, the values of the below table was obtained for determining of significant parameters in forming of tubes by THF process.

3.5 Fabrication of Test Setup

As discussed in previous section, Tube Hydroforming set up consists of mainly 4 sub-assemblies viz die set up assembly, Power Pack assembly, Die and tooling assembly, Pressure intensifier and Data acquisition systems. Die assembly, intensifier assembly and hydraulic power pack assembly have been selected and integrated as a system. The tube hydroforming sub-assemblies is shown in figure 3.5.



1.Upper Vertical Cylinder
2. Right Horizontal Cylinder
3. Left Horizontal Cylinder
4. Upper Half Die
5. Lower Half Die
6. Intensifier
7. Power Pack
8. Water Tank
9.Motor for Oil supply to Intensifier and all cylinders
10. Pump for water supply to intensifier
11.Hose pipe connection to power pack
12. Structures supportingTHF machine components
13. Pilot check valve
14. Upper die fixture.

Figure 3.5: Tube hydroforming assembly set-up

The existing hydraulic press of 100 Tons capacity is used for developing the Tube hydroforming set up. The fabrication work has been carried out for die set assembly and measuring instruments assembly. The details of fabrication process is being discussed in this section.

The Isometric view of Lower die assembly is shown in figure 3.6.

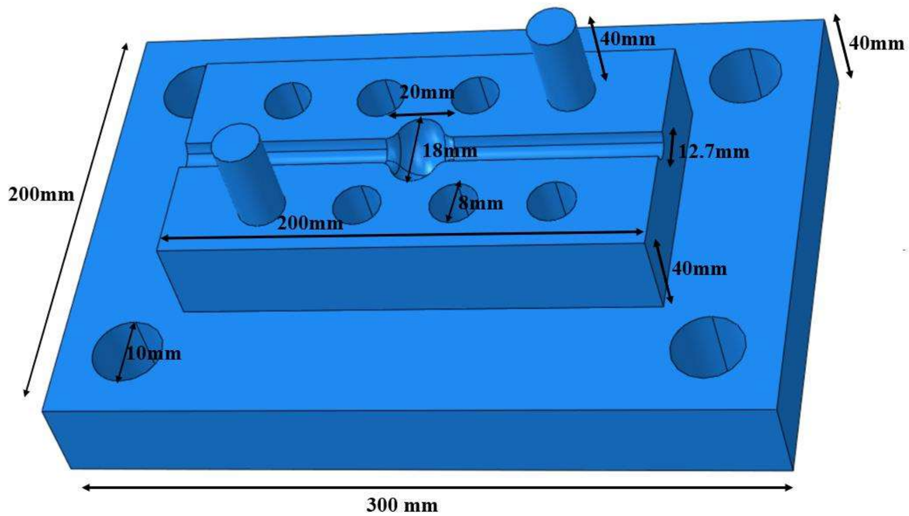


Figure 3.6: Lower die assembly isometric view

This assembly consists of mainly hydraulic power pack system consisting of one vertical cylinder using for closing of upper die, two axial cylinders using for sealing purpose, upper and lower half die in which tube is placed. The guiding pillar is provided at the bottom die. upper die is attached with the fixture tool which is attached with the shafts of the vertical cylinder. Upper fixture makes the die rigid during tube hydroforming operation. The fabrication detail of each component is being described in this sub section.

Hydraulic Power Pack: Hydraulic power units (sometimes referred to as a hydraulic power pack) is a self-contained system that generally includes a motor, a fluid reservoir, and a pump. It works to apply the hydraulic pressure needed to drive motors, cylinders, and other complementary parts of a given hydraulic system. The details of the components consisting of the hydraulic power pack are shown in figure 3.7 and oil reservoir shown in figure 3.8. Its fabrication flow chart is shown in figure 3.13.

Figure 3.7: Hydraulic power pack main components

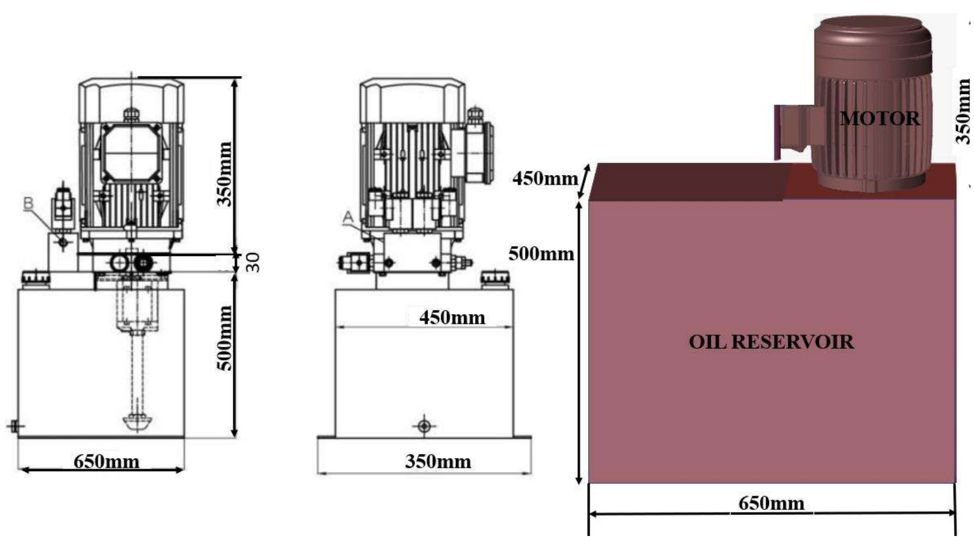


Figure 3.8: Hydraulic reservoir front, side and isometric view

Upper Vertical Cylinder: The cross-sectional view of upper cylinder is shown in figure 3.9 and the corresponding fabrication process flow chart is shown in figure 3.12. It is made up of structural steel (Mild steel). As maximum diameter of upper vertical cylinder piston is φ 80 mm and length of stroke 150 mm, raw material size of φ 85 x 155 mm length is used for machining. The sequence of operations are rough turning, followed by CNC turning and thread cutting (M28×1.5). The threads are the integration feature between load cell and press. The slot is also designed for easy tightening and removal of piston.

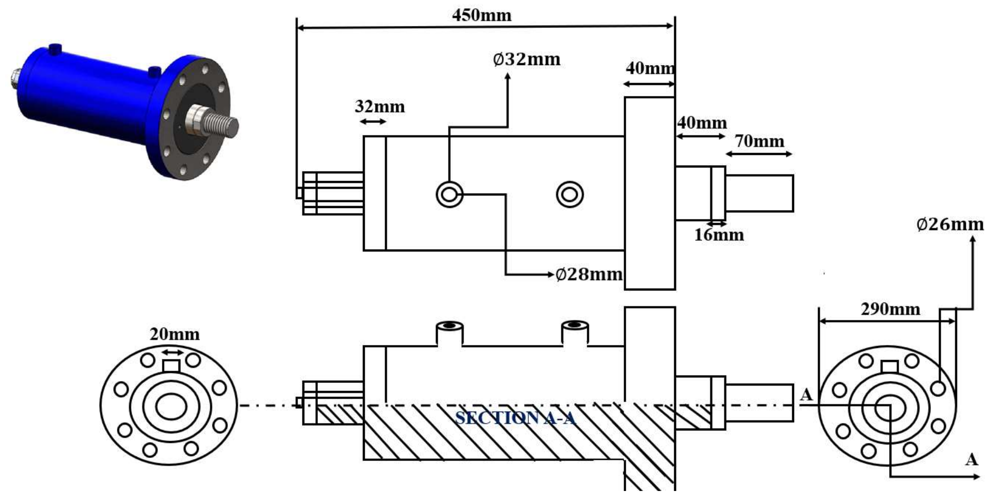


Figure 3.9: Upper hydraulic cylinders top, front, side and isometric view

Axial Horizontal Cylinder: The 2D drawing of axial cylinders is similar to upper cylinder as shown in figure 3.9. The fabrication flow chart is shown in figure 3.12. is having overall dimensions of piston is φ 60 x 150 mm L. Hence raw material size of φ 65 x 155 mm L is used for fabrication. The sequence of operations are same as of upper vertical cylinder. In addition to M28 x 1.5 threads, one additional thread feature of dimensions (M6 x 1) is included in this cylinder to arrest rotation of ram during sealing.

Pressure Intensifier System: It is fabricated to intensify the water pressure. The dimension of the intensifier is 180 x180 mm square plate having 80mm and 120mm diameter two cylinders are attached. The length of the 120mm diameter cylinder is 250mm and 80mm cylinder is 200mm. the plate thickness is 40mm. Figure 3.13 shows the fabrication flow chart of the Intensifier. The raw material, in this case, is φ 185 x

185 x 650 mm in dimensions. The sequence of operations is rough turning, CNC turning, and slot milling. The cross-sectional drawings of intensifier are shown in figure 3.10 and sectional view in figure 3.11.

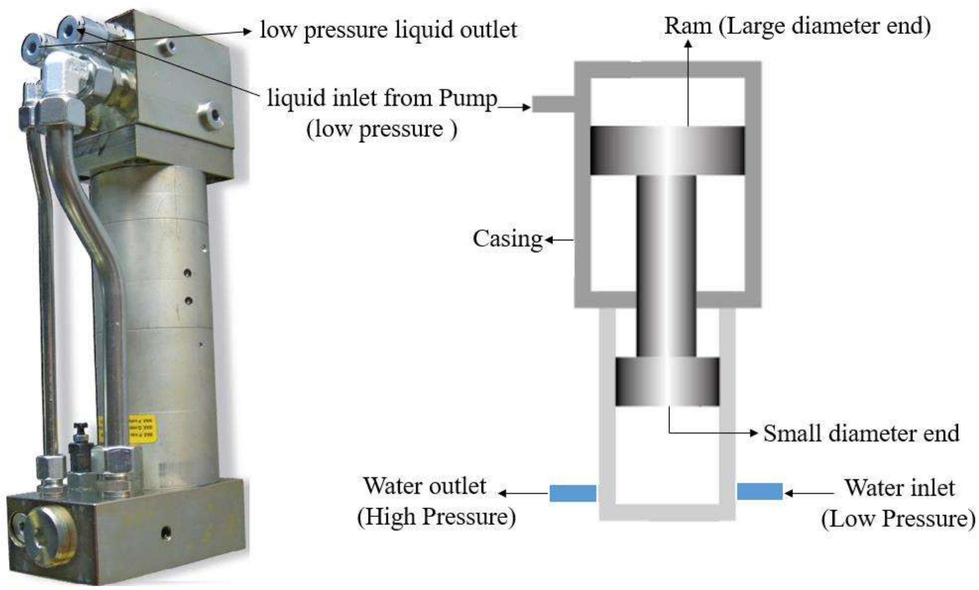


Figure 3.10: Layout of pressure intensifier with basic flow mechanism

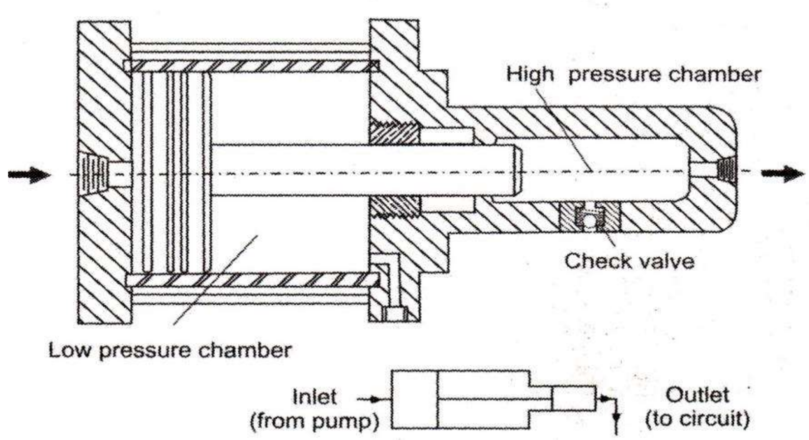


Figure 3.11: Pressure intensifier drawing sectional view

Upper half die attached with Vertical cylinders: Die block is placed below the fixture attached with vertical cylinder. It is the main part of the tube hydroforming assembly and assists in flow of material during liquid pressure action. It is made up of rectangular structural steel having overall dimensions of 300 x 200mm L. The height of the die block is kept 40mm. The raw material of die block is 305 x 205 mm L as shown in figure 3.15. The sequence of operations is turning followed by drilling. Six holes of φ8 mm are designed for clamping and aligning of the upper half die block with the lower half and also align with the two axial sealing cylinders. An internal slot for stopping of 10.7 mm is designed to seal and lock the rams attached to both axial cylinders.

Lower half die: It is same and half portion of the upper die. The only difference is that it has female slots for guiding tools as provided in the upper die. The design of the lower half die is shown in figure 3.14. The lower die has rectangular in shape having a dimension of 300 x 200 mm. 6 equal spaced holes having φ 8 mm are drilled for clamping of lower die with vertical. The raw material detail and sequence of operations are shown in figure 3.12.

Fluid chamber sub-assembly: Fluid chamber sub-assembly consists of the base plate and fluid chamber. The Cuboidal Box reservoir is having overall dimensions of 600 mm x 500 mm x 450 mm having 12 mm thickness. The flow diagram of operations are presented in figure 3.13. Fluid chamber is the most critical component of die set up assembly. Length of 600 mm and width of 450 mm are fixed. All the 3 cylinders and one intensifier are connected to Powerpack fluid reservoir assembly system. A through hole of φ M12 x 1.75 is designed to mount hydraulic inlet and outlet hoses pipes connections. Six hose pipes of 100MPa holding capacity are designed to connect the fluid chamber with die block, all cylinders and intensifier. All plates of the fluid chamber are joined together by TIG welding. A dye penetration test was carried out to ensure the integrity of the joint. The fabrication flow chart is shown in figure 3.13.

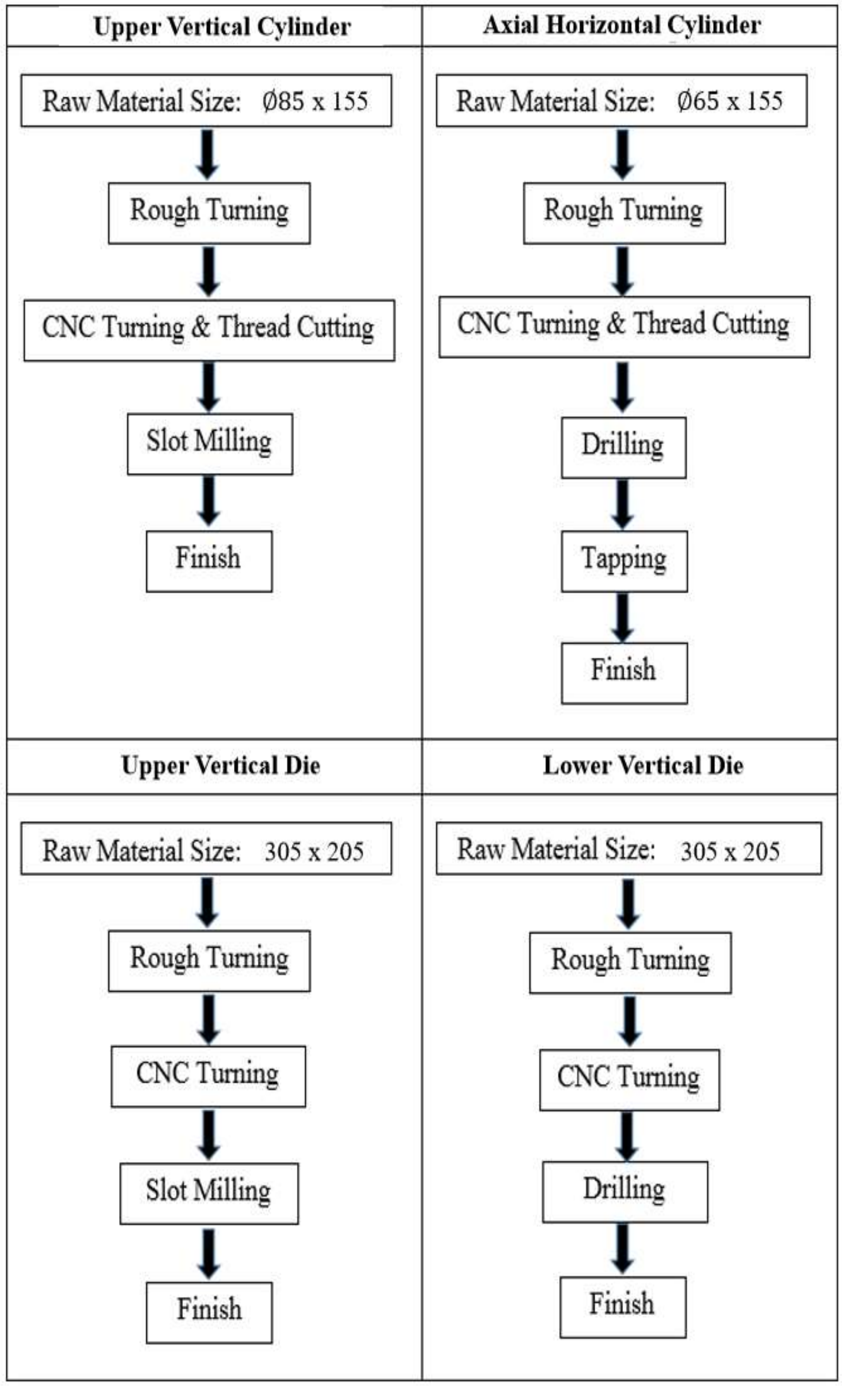


Figure 3.12: Stages follow to fabricate upper cylinder, axial cylinder, upper vertical die and lower vertical die

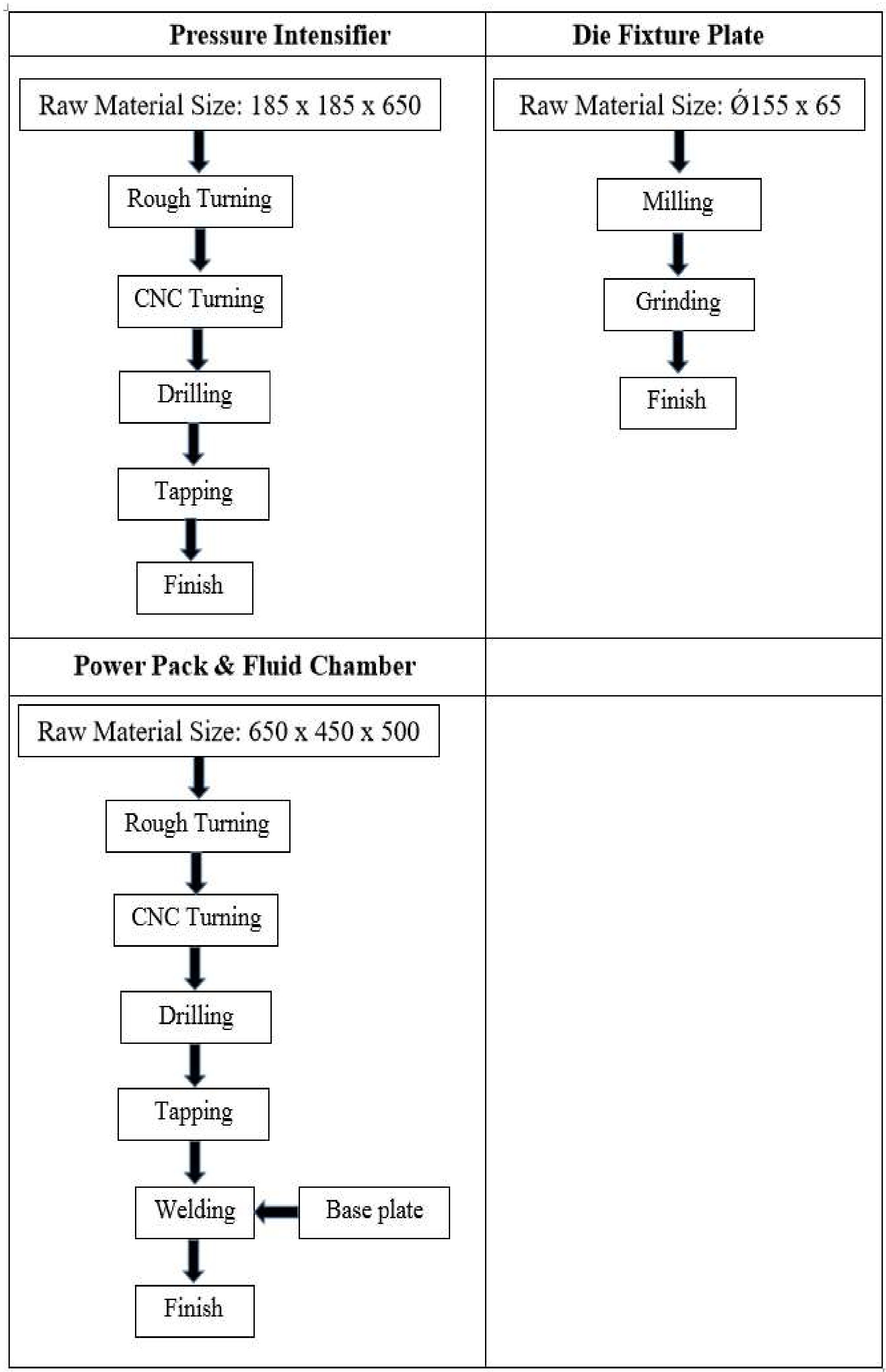


Figure 3.13: Stages follow to fabricate pressure intensifier, die fixture plate and Power pack containing fluid chamber

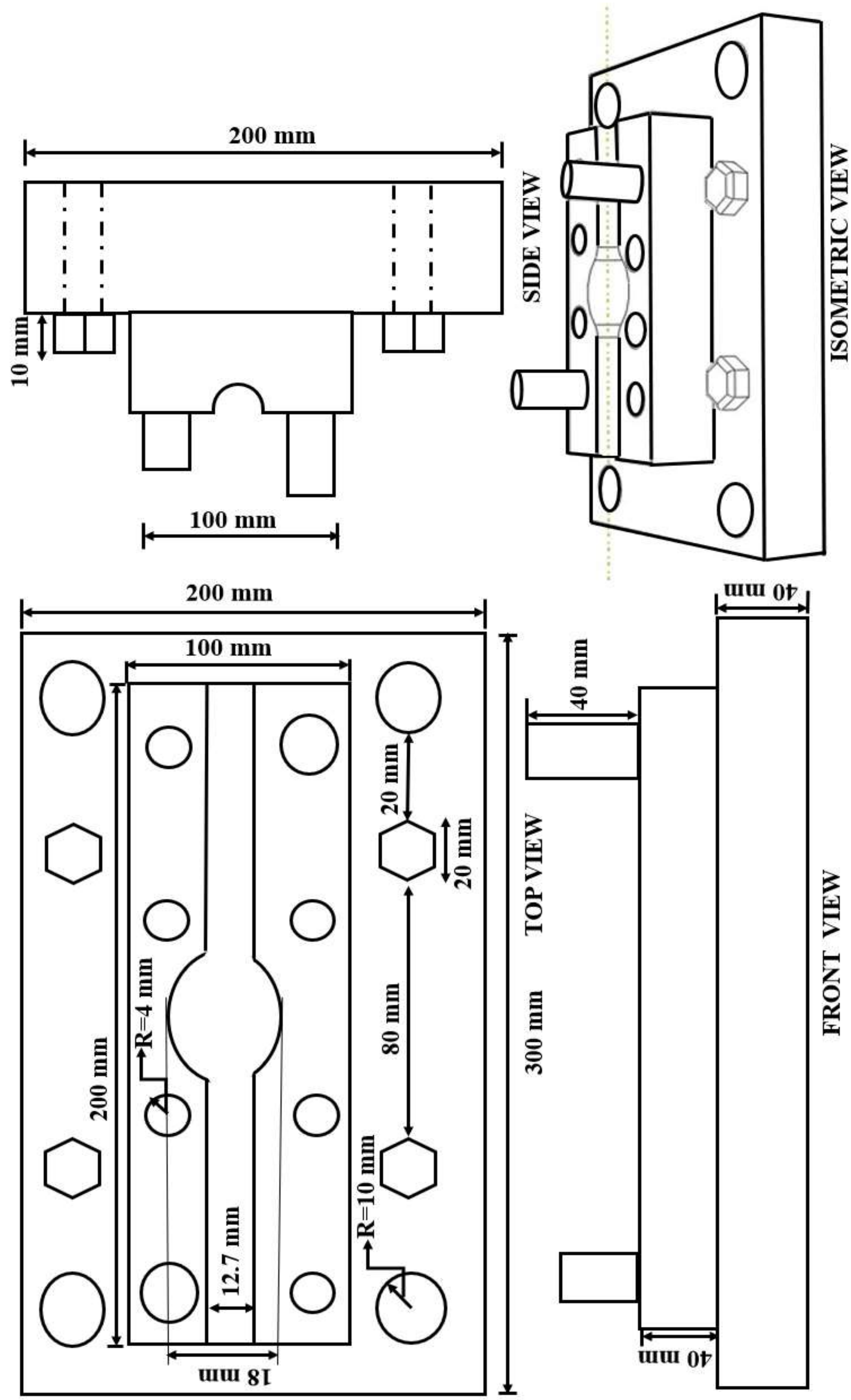


Figure 3.14: Drawing detail of lower die assembly

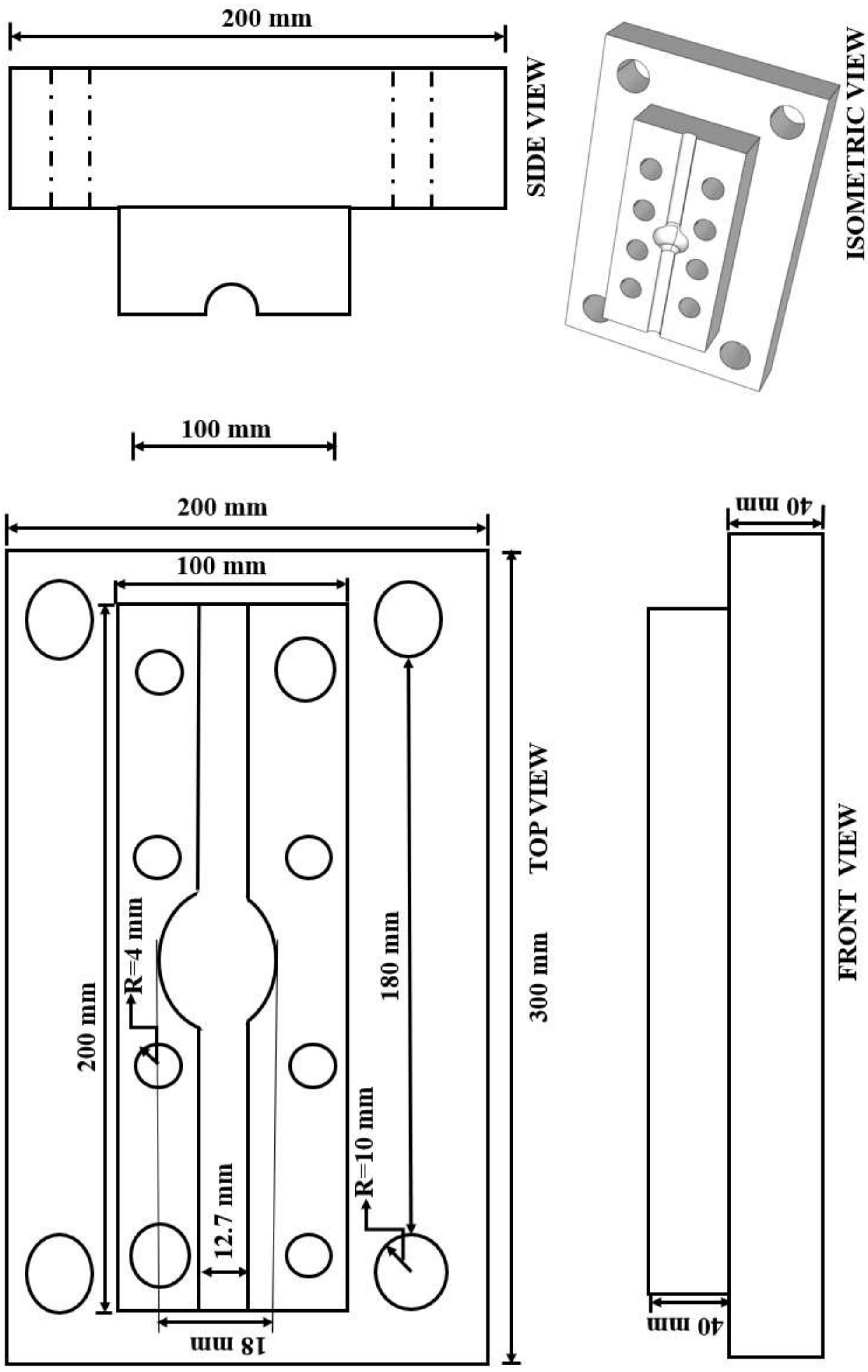


Figure 3.15: Drawing detail of upper die assembly

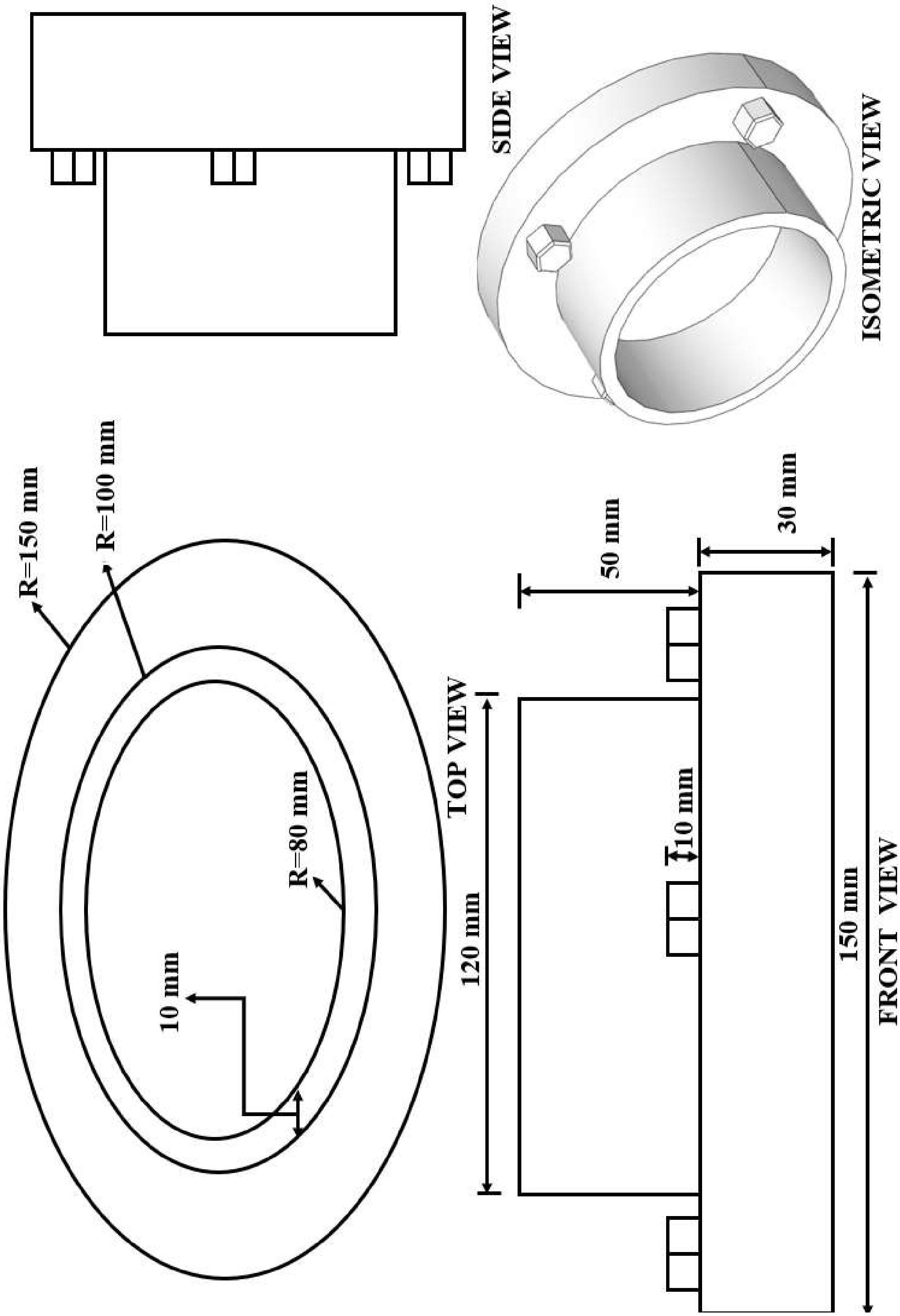


Figure 3.16: Drawing detail of upper die fixture

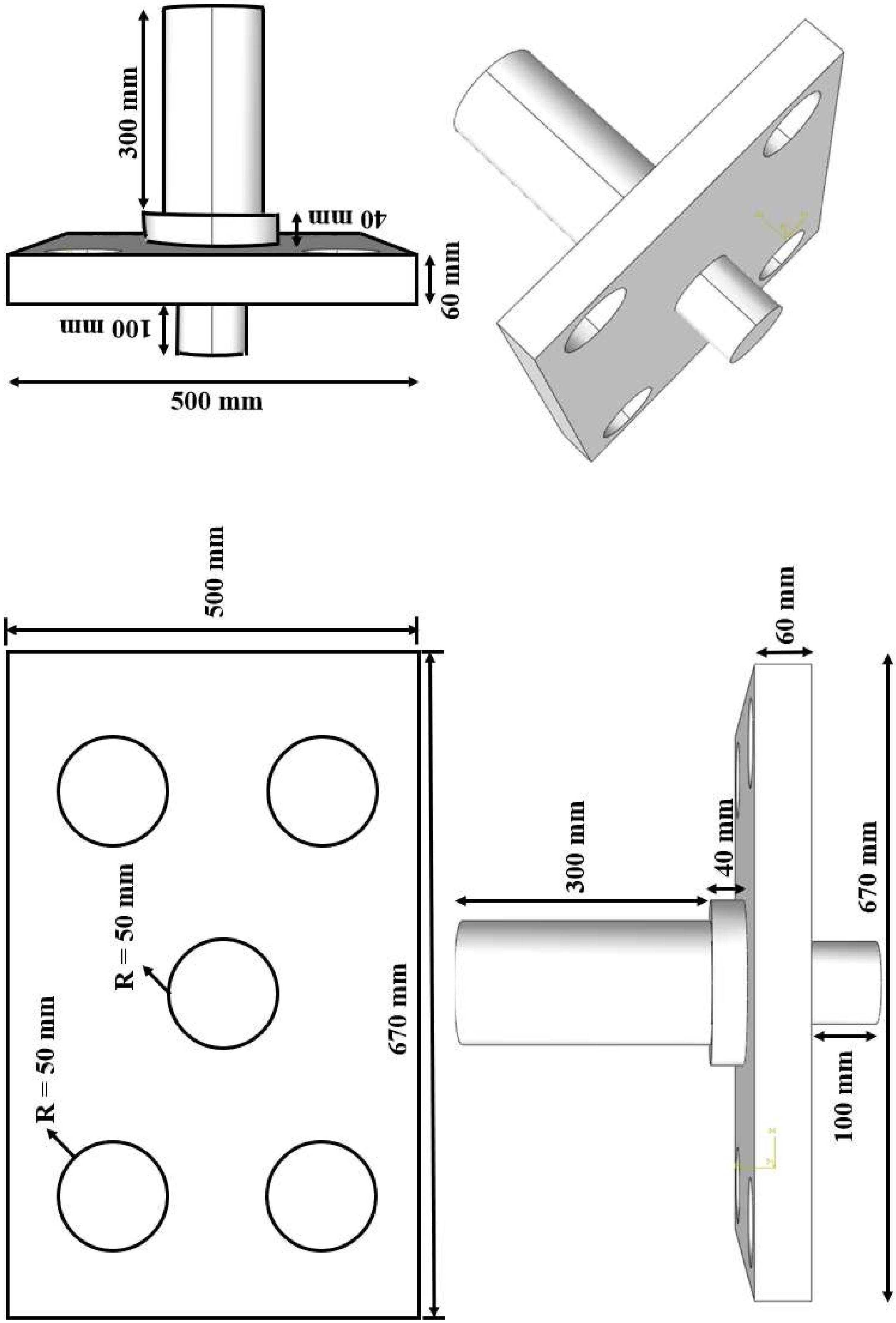


Figure 3.17: Drawing detail of assembly of upper cylinder with supporting plate

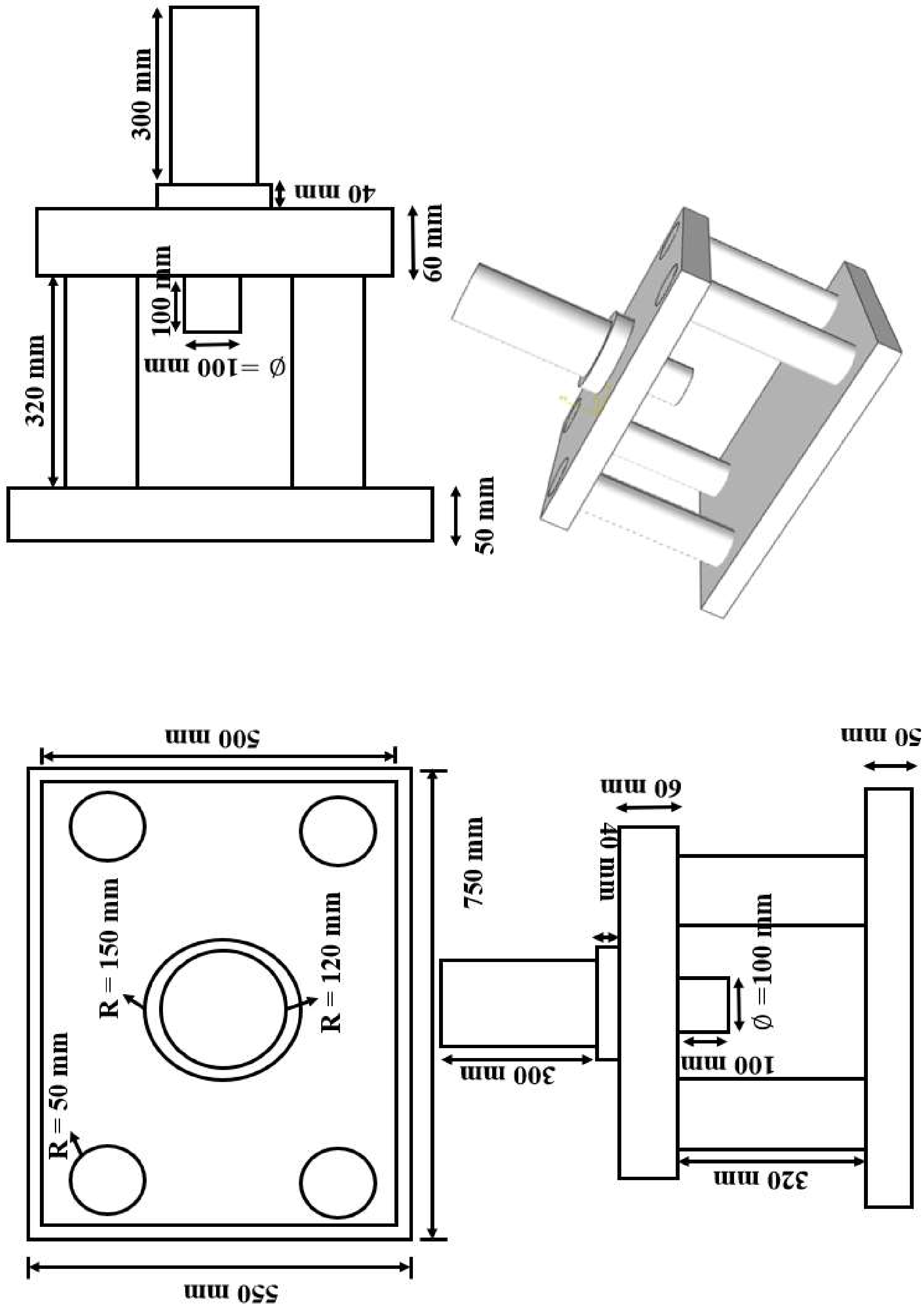


Figure 3.18: Drawing detail of assembly of upper cylinder with top and bottom supporting plate connected to pillars

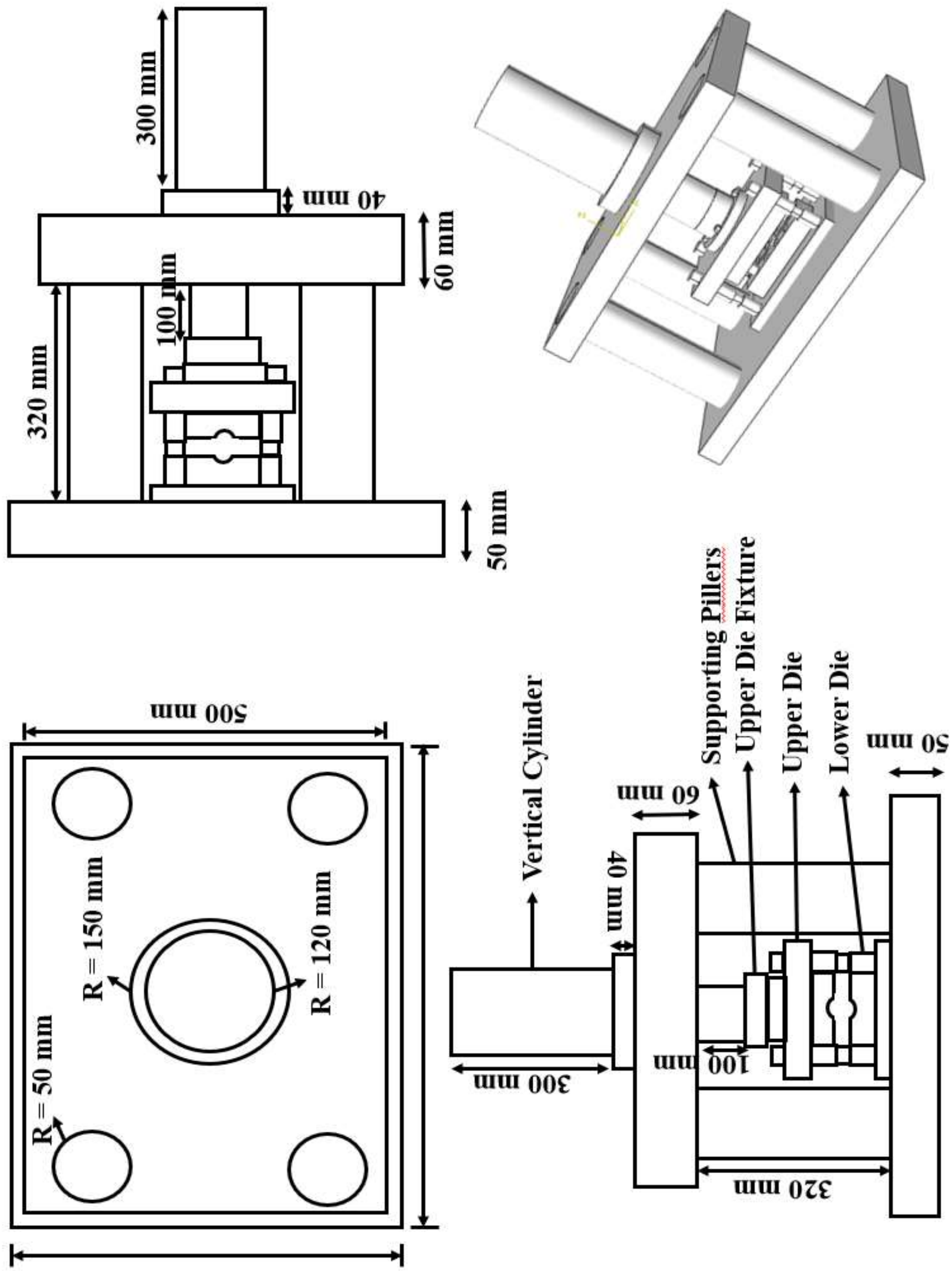


Figure 3.19: Drawing detail of assembly of upper cylinder with top, bottom supporting plate and die assembly connected to pillars

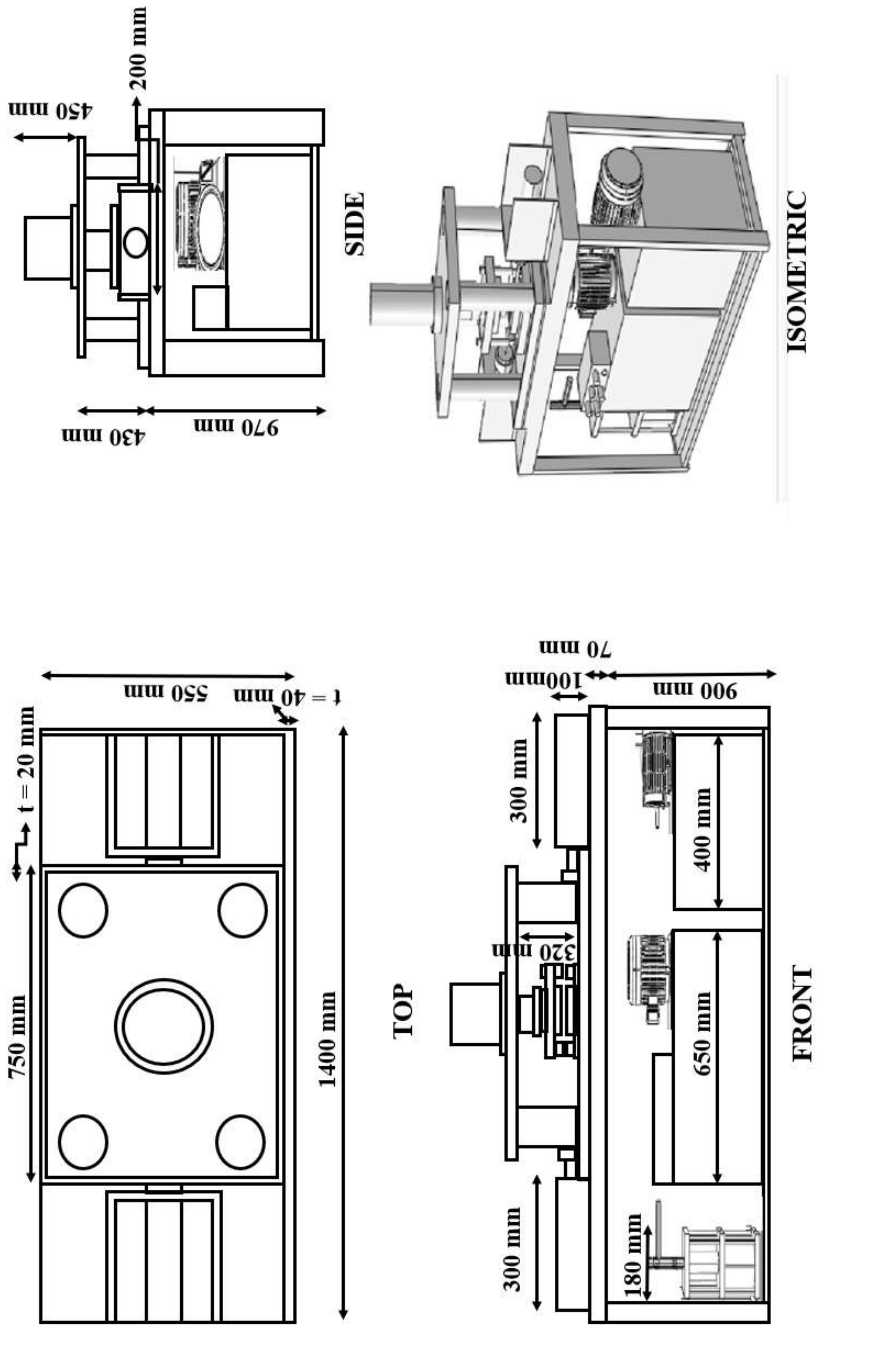


Figure 3.20: Complete Tube hydroforming assembly set-up orthographic design

3.6 Experimental setup and analysis

In this work, an experimental setup has been designed and developed for tube hydro-forming of elliptical shape Al 6061 tube metals having thickness of 1 mm. This is the most common Aluminium 6061 alloy of tube material used in automobile applications such as intake manifold, cylinder heads, transmission housings, cylinder block and suspension arms and contribute to the further improvement in fuel economy and maneuverability of automobiles. The experimental setup consists of die/tooling, sealing punch, hydraulic power pack, pressure intensifier and the data recording system as schematically represented in figure 3.21. The experimental Die/tooling is shown in figure 3.23. A hydraulic power pack as shown in figure 3.7 is used to generate fluid pressure for required pressure for tube deformation. H P - Servo-68 oil has been used as the fluid in the power pack. Programmable logic control (PLC) has been used to execute a pressure path. The power pack is also equipped with the flow control valve to vary the flow rate of the fluid. A load cell has been attached to the main ram of press. It senses the blank holding force exerted by the main ram of the press and generates electric signals for Data recording system as shown in figure 3.21. A signal conditioner unit has been used to modify the low voltage signals from the sensors and then sends them to the data recording system. An electronic Data recording system has been used to record the modified signals from pressure sensor and the load cell. The Data recording system has an analog to digital signal which records and displays on a monitor. Figure 3.16 show the drawing detail of upper die fixture, figure 3.17 show the drawing detail of assembly of upper cylinder with supporting plate, figure 3.18 show the drawing detail of assembly of upper cylinder with top and bottom supporting plate connected to four number of pillars, figure 3.19 represent the drawing detail of assembly of upper cylinder with top, bottom supporting plate and die assembly connected to pillars and figure 3.20 represents the complete tube hydroforming assembly set-up design. 3D CAD model of assembly and actual tube hydroforming machine are shown in figure 3.14 to figure 3.24.

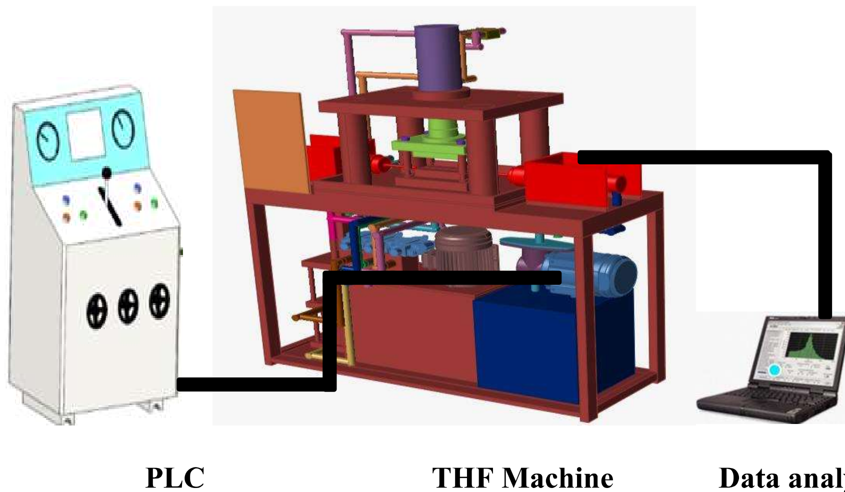


Figure 3.21: Experimental setup in tube hydro-forming process

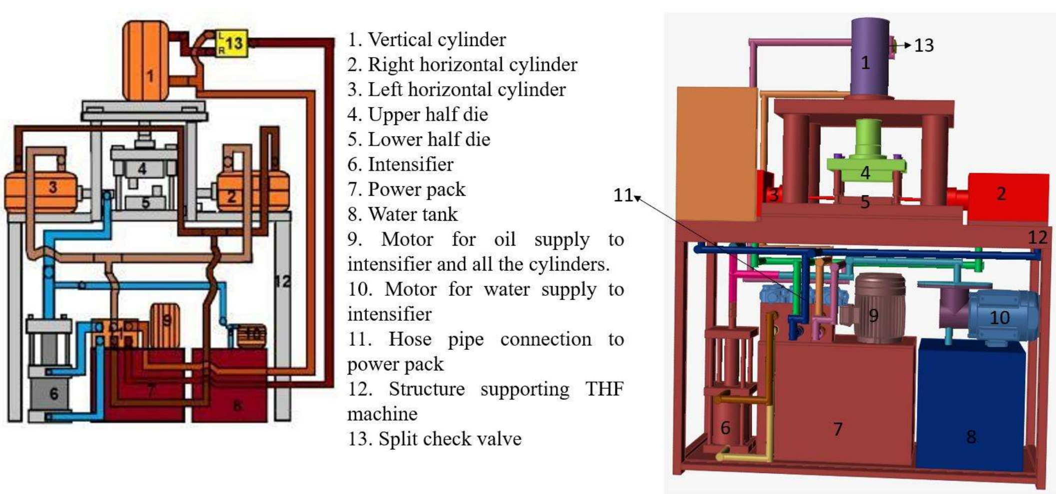


Figure 3.22: Tube Hydroforming machine hose pipe connections arrangements

3.7 Experimental Results and Data

The experiment was carried out at various conditions and online variation of input internal pressure geometrical parameters such as bulge height, corner radius and thickness distribution were monitored for each case. In Experiment No. 1 (S1), forming of elliptical sample carried out at 30MPa internal pressure. Similarly, S2, S3, S4 and S5 experiment was carried out with 40, 50 60 and 70MPa internal pressure respectively. Total of 15 experiments were carried out in 5 different combinations of internal pressure and records thickness, bulge height and corner height in each internal pressure range. The real time plot of input internal pressure vs bulge height growth, thickness distribution and corner radius are shown against each trial.

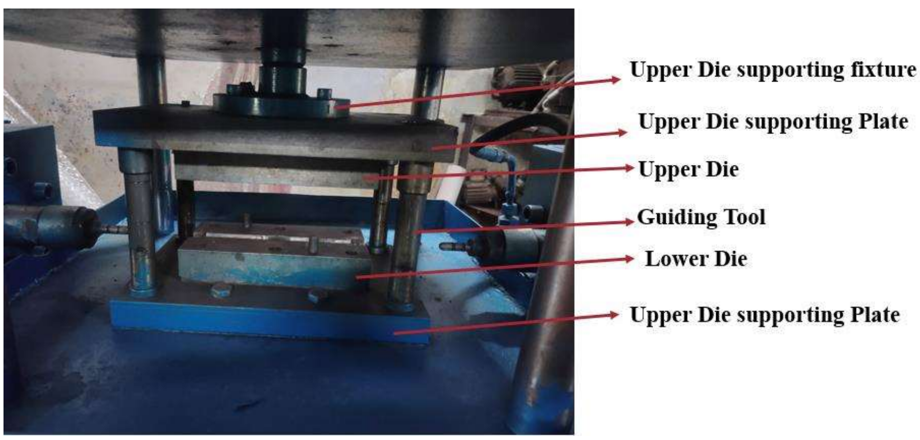


Figure 3.23: Complete die and tooling assembly

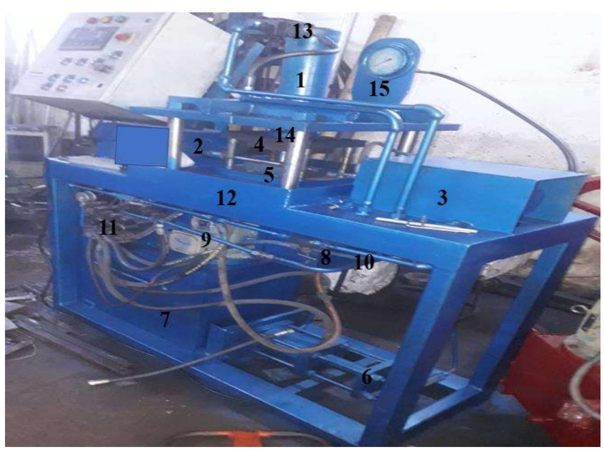


Figure 3.24: Fabricated tube hydroforming machine assembly set-up

1. Upper vertical cylinder
2. Right horizontal cylinder
3. Left horizontal cylinder
4. Upper half die
5. Lower half die
6. Intensifier
7. Power pack
8. Water tank
9. Motor for Oil supply to Intensifier and all cylinders
10. Pump for water supply to intensifier
11. Hose pipe connection to power pack
12. Structures supporting machine components
13. Pilot check valve
14. Upper die supporting fixture
15. Pressure Gauge to measure pressure and force
16. Programmable Logic Controller (PLC) system

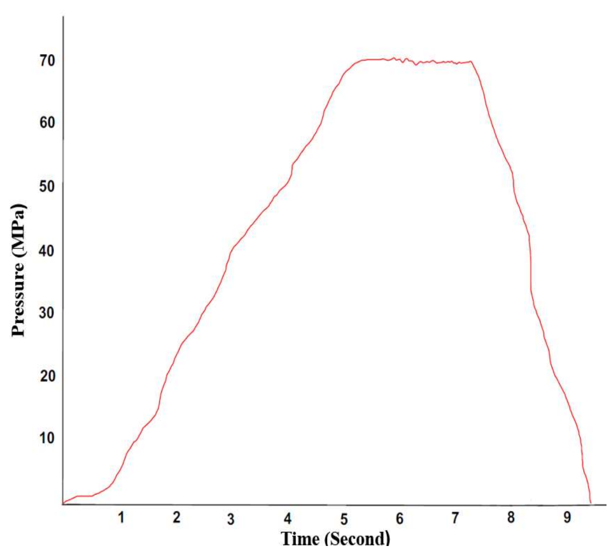


Figure 3.25: Actual Internal Pressure versus time plot.

The pressure rises gradually with the expenses of time. The S.I unit of Pressure is Pascal however its unit representation in different country is varying. Here is the list of table of different pressure unit used in various major country.

Table 3.1 Unit of Pressure used in different country and its conversion

Unit	**Units/ Symbol**	**Corresponds to**	**Country region**
Pascal	Pa	1 bar = 10^5 Pa	-
Bar	bar	1 bar = 1 bar	Western Europe
Kilopascal	kPa	1 bar = 100 kPa	Australia
Megapascal	MPa	1 bar = 0.1 MPa	China
Pound per square inch (psi)	Psi	1 bar = 14.5 psi	North America
Kilogram per square centimeter	Kg/cm^2 or Kgf/cm^2	1 bar = 1.02 kg/cm^2	India, Korea
Inch of mercury column	In Hg	1 bar = 29.53 in Hg	North America

Pressure is not linear due to machine external disturbance and vibration. The pressure rises at the rate of 12.5 MPa per sec. Maximum Capacity of the intensifier is 100 MPa (14503.8 psi) but required tube hydroformed shape obtained at 70MPa (10152.6 psi). The flow control valve auto set at 70MPa so that it cannot further rises after reaching 70MPa internal pressure. The fabricated tube hydroforming machine operates in auto and manual mode. It is set to hold for 2 second at 70MPa internal pressure in order to ensure proper filling of tube sample material inside die cavity. After 7 second pressure releases gradually and in the next couple of second brings to ambient pressure. The numerical analysis is also carried out in order to compare the experimental obtained data with the simulation.