CHAPTER 3

Design and Fabrication of Rubber-based Sheet Hydro-forming Setup

3.1 Introduction

Designing a new product goes through an analytical process and relies on a problem-solving approach to improve the quality of life of the end user and his or her interaction with the environment. It is about problem-solving, about visualizing the needs of the user and bringing a solution. A designer need not usually produce the goods or services which immediately satisfy consumer's needs. Rather he produces the prototype which is used as sample for reproducing the particular goods or services as many times as required [47].

In view of above, the prototype of Rubber Based Sheet Hydroforming (RBSH) set up has been developed at lab scale which can be reproducible for commercial use.

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 finalised based on preliminary outputs which leads to prototype model. This model is tested keeping certain design objectives as constraints. The outputs meets 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 RBSH 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 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 RBSH set up is fabricated. The details of fabrication process steps are described in the next section.

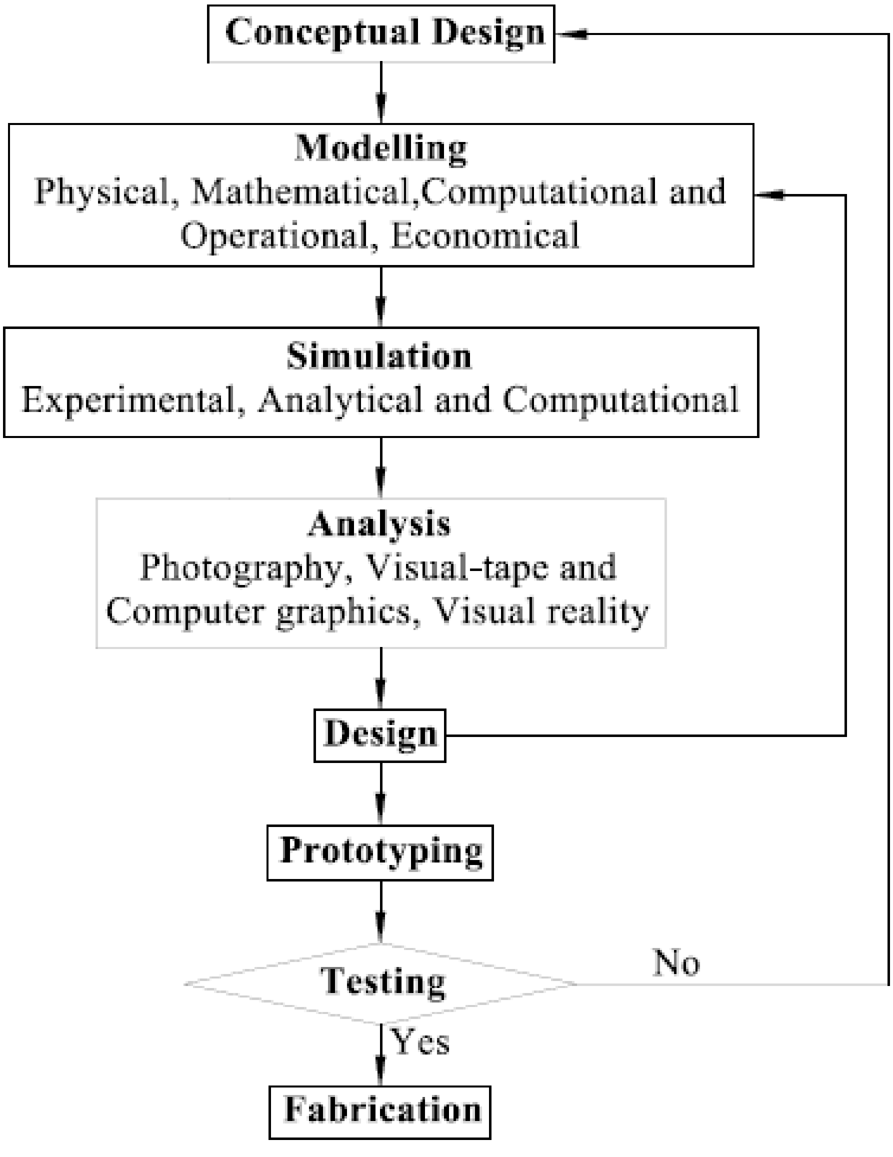


Figure 3.1: Flow Diagram for Product Design

3.2 Essentials factors of product design

The design of rubber based sheet hydroforming set up has been developed considering the following basic factors of product design.

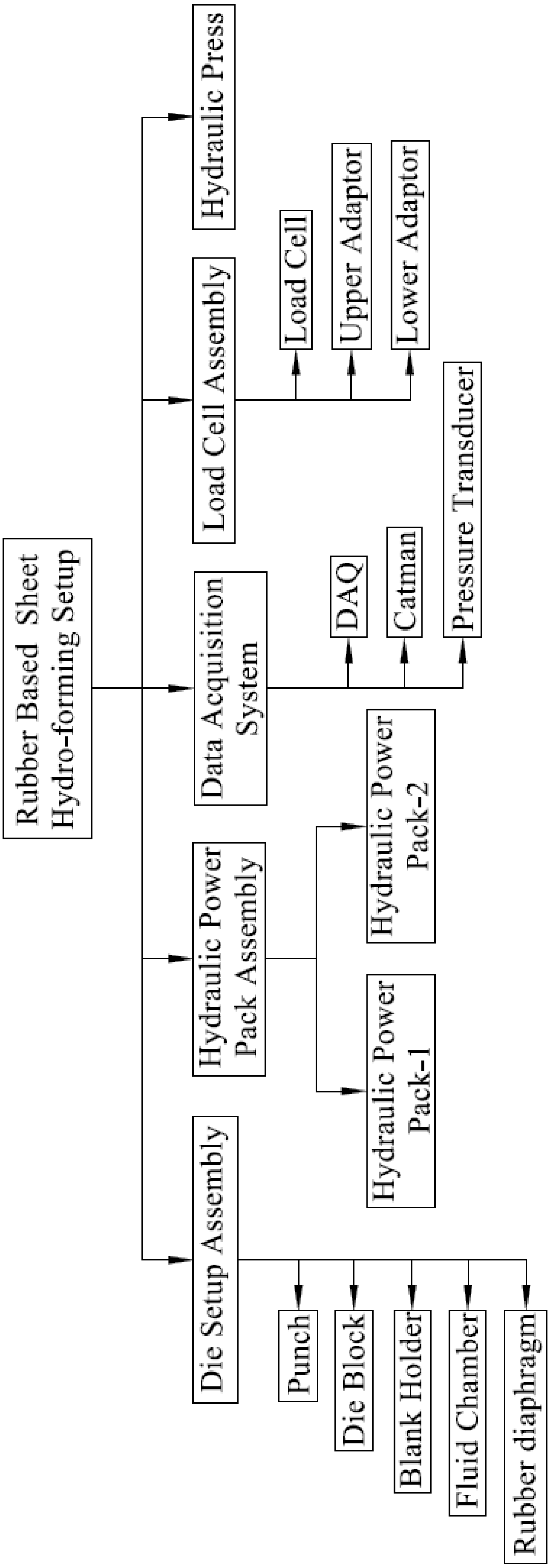


Figure 3.2: Family Tree of RBSH Setup

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 sheet metal components. In addition to that, this set up very much needed for drawing deep conical components which are prone to failure by tearing.

2. Physical Realizability: The study of physical realizability has been carried out by breaking up the RBSH set up into sub-assemblies and components. The family free of RBSH set up is shown in figure 3.2. This set up essentially consists of die set up assembly, load cell assembly, Data acquisition system and Hydraulic power pack assembly. The setup is to be integrated with hydraulic press. The assemblies are further sub-divided into component level. Die setup assembly consists of punch, blank holder, die block, rubber diaphragm and fluid chamber. Similarly load cell assembly consists of load cell, and two adaptors. Data acquisition module, CATMAN software, pressure transducers are the parts of Data acquisition system. Two hydraulic power packs for applying back pressure and fixing cot-off pressure respectively are the parts of hydraulic power pack assembly. Each component was thoroughly studied for availability of material, fabrication feasibility and its integration with data acquisition system. It was concluded that each system can be realised with available resources.

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.

    (a) Feasibility Study : The detailed feasibility study was carried out as explained in physical realizabiltiy section.

    (b) Preliminary Design: It begins with drawing up schematic diagram of RBSH set up as shown in figure 3.4. Die set up assembly comprising punch and die is the nodal point of RBSH process. It is decided to integrate load cell with punch as forming loads transfers to the press through punch or upper die. At this stage, the overall size of dies, blank, fluid chamber, tonnage of press, capacity of load cell etc are designed.

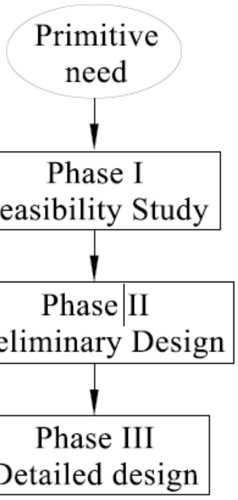


Figure 3.3: Design stages [48]

Pressure transducers are designed to be integrated with fluid chamber which is the part of lower die. Two pressure transducers are selected to monitor inlet and outlet pressures of fluid chamber. As three parameters are to be monitored in each experiment, 3 channels of data acquisition module would suffice. Hence, Data Acquisition Module (DAM) having 16 channels is selected so as to have flexibility of adding more parameters to be monitored, if needed. The software compatible with DAM is selected having liberty to monitor all three parameters in single plot.

(c) 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 Detailed Design of RBSH Test-Setup

The main feature of rubber assisted sheet Hydro-forming is to replace the female die by hydraulic pressure and rubber diaphragm is added. The set-up includes some parts such as punch, blank holder, die block, rubber and die cavity. Generally in sheet Hydro-forming fluid pressure is used either to replace rigid tools or to apply

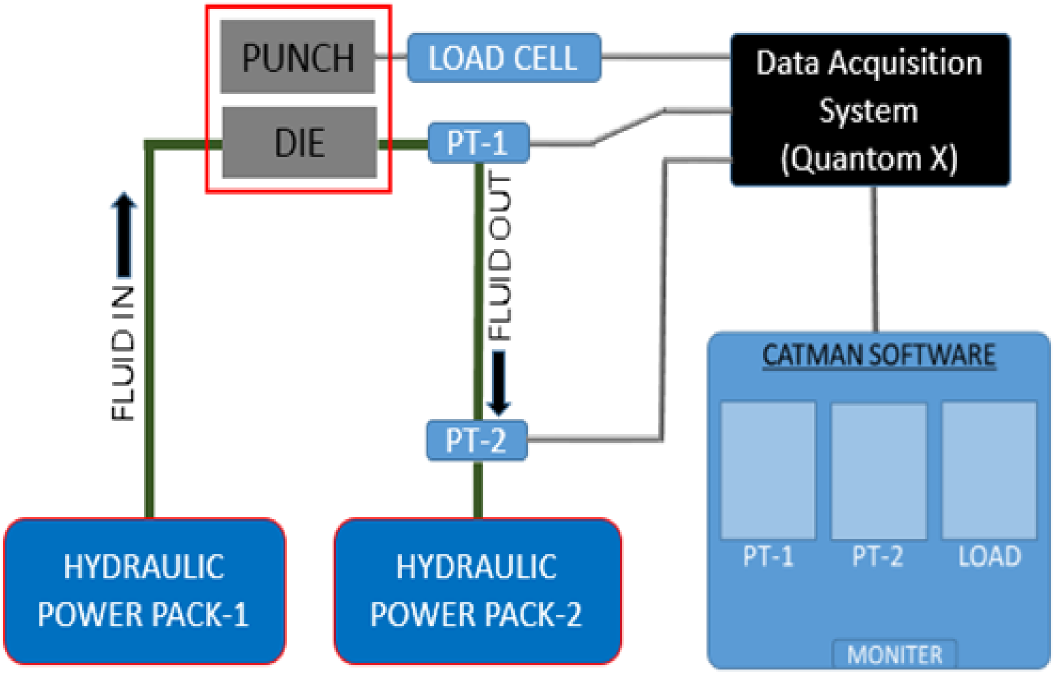


Figure 3.4: Schematic diagram of process in rubber assisted sheet Hydro-forming

counter force on the part to achieve certain benefits [49]. The die cavity which is partly filled with hydraulic fluid is used to apply counter force on the blank. The hydraulic pressure under control would act on a rubber membrane covering the blank. A rigid punch moves down into the fluid chamber and balanced by fluid pressure. The blank is forced to assume the shape of punch under the pressure of the fluid. The compression force from the fluid will act on the pressed area of the formed part and generates hydrostatic state of stress. This introduction of hydraulic 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 formed component. This process is also referred as flexible forming process. Figure 3.4 shows the schematic diagram of process in rubber based sheet hydroforming.

3.3.1 Theoretical Study

Hydro-forming conditions, such as the relationships between the hydraulic pressure, the blank holding force, punch forces and process parameters plays an important role in designing of any Hydro-forming process. It is, however, difficult to determine them properly and they are currently determined by trial and error in the field operations. One of the important parameter while designing the rubber assisted Hydro-forming process is punch force which can be calculated by using following formula

$$F_i = \pi d_i t(UTS)[\frac{D_1}{d_i} - 0.7] \tag{3.1}$$

Where,
F_i = Punch force for required drawing (N/m^2)
d_i = Punch diameter (mm)
D_1 = Blank diameter (mm)
t = Material thickness (mm)

The fluid pressure also plays an important role in design. It is dominant parameter in determining the success or failure of the process. Generally the fluid pressure is controlled by a pump or a valve according to a specific loading curve. Insufficient pressure may cause premature wrinkling, where as excessive pressure may lead to premature tearing. The optimum hydraulic pressure should be determined to solve this problems. The proper fluid pressure path is determined, mostly by trial-and-error experiments, empirical relations and numerical simulations [50]. To determine optimal hydraulic pressure and blank holding force profiles simultaneously, Choi et al.[51] developed an adaptive FE analysis with fuzzy control algorithm. Hyumbo and Dong [52] assumed the pressure path to be proportional to the penetration volume by a punch in hydro mechanical deep drawing process and proposed a linear pressure-BHF load path with the help of trail runs thorough FE simulation. Gelin et al [53] proposed to combine FE simulations and optimization in order to optimize forming pressure versus time.

Many materials can be used in this process, such as low carbon steel, stainless steel, high strength steel, aluminum alloy, magnesium alloy, titanium alloy, etc. All the materials used in conventional stamping can be used in sheet Hydro-forming. Depending on the different means, the liquid pressure in the die cavity is from around from 30 to 150 MPa, but the usage of 200 MPa has also been reported [54, 55, 56]. Tirosh et al [57] found an appropriate relationship for pressure curve versus punch stroke as to maintain the thickness unchanged for Hydro-forming of axisymmetric shapes by using upper bound method. During the study of previous works [58, 59, 60], an interesting fact has been recognized that the shapes of the optimal pressure curve are always monotonically increased with respect to punch stroke. The reason why the shape of the pressure curve is monotonically increasing is attributable to the nature of the hydro-forming process itself, because radii of curvature at the edges of hydro-formed product are always decreasing during the forming stage in order to get a detailed trace of die shape This can be taken as a reference to find out the required pressure for rubber assisted sheet Hydro-forming.

3.3.2 Design considerations for development of test set up

Determination of Forming load, Blank Holding Force & Selection of Load Cell

The experiments are planned with pure copper having sheet thickness of 2mm. The expected forming load can be calculated using equation 3.2

$$F = \pi \times D \times t \times \sigma \tag{3.2}$$

Where F = Forming Load
D = Diameter of Punch (75mm)
t = thickness of blank (2mm)
σ = Yield strength of Material (75 MPa)
Using equation 3.2, F = 3.14 x 75 x 2 x 75 = 35 KN
The maximum blank holding force can be one third of forming load [61]. Using this criteria, the blank holding force has been taken as F/3 = 12kN.

Hence total force acting on punch = 35+12 = 47 KN

Accordingly, the load cell of 50 KN is selected.

Chamber Pressure

In Hydroforming, Blank Holding Force (BHF) is the force required to prevent of separation of die and and blank holder against fluid pressure [62].

Hence,

$$BHF > P \times A_f$$

Where, A_f and P are forming area and pressure respectively.
Using the above equation, the maximum pressure allowed in the chamber

$$P < \frac{BHF}{A_f}$$

$$P < \frac{12 \times 1000 \times 4}{3.14 \times 75 \times 75}$$

$$P < 2.5MPa$$

Hence, hydraulic pressure of 20 bar is meeting the above condition. Also as a thumb rule, the reaction force due to hydraulic pressure is 0.20 to 0.25 of forming load. Hence, the maximum allowed reaction force = 0.25×12= 8.75kN.

Therefore the corresponding hydraulic pressure = (8.75×1000×4)/(3.14×75×75) = 1.9 MPa i.e 19 bar. Hence 20 bar pressure is considered for design of chamber.

Wall thickness of Fluid Chamber

The maximum pressure developed during forming is calculated as 20 bar. The empirical relation for pressure vessel is used to calculate the minimum thickness needed to sustain pressure of 20 bar. The pressure vessel equation is given as Equation 3.3.

$$\sigma = \frac{Pd}{2t} \tag{3.3}$$

Where σ = Yield stress Material
P = Chamber pressure
t = Thickness of fluid chamber
d= Inner diameter of fluid chamber

The present case , P= 20 bar; d = 70mm and σ=200 N/mm ^{2} Substituting these values in equation 3.3 t= 2 * 75/(2*200) = 0.4mm. Hence, the thickness if fluid chamber is taken as 15mm having factor of safety of 40.

3.4 Fabrication of Test Setup

As discussed in previous section, RBSH set up consists of mainly 4 sub assemblies viz die set up assembly, Load cell assembly, data acquisition assembly and hydraulic power pack assembly. Data set up assembly and hydraulic power pack assembly have been selected and integrated as a system. The existing hydraulic press of 20 Tons capacity is used for developing the RBSH set up. The fabrication work has been carried out for die set assembly and load cell assembly. The details of fabrication process is being discussed in this section.

The cross-sectional view of die set up assembly is shown in figure 3.7. This assembly consists of total of 10 items, in which load cell having capacity of 50 KN has been procured and integrated with the help of adapters. The fluid chamber assembly mainly consists of blank holder to arrest wrinkling, die block for ease of bending of blank, rubber diaphragm and fluid chamber to contain pressurised hydraulic fluid. The top side of assembly consists of punch having the desired forming profile, lower adapter to integrate punch with load cell and upper adapter to integrate load cell with press. The fabrication detail of each component is being described in this sub section.

- Upper adaptor: The cross-sectional view of upper adaptor is shown in figure 3.8 and the corresponding fabrication process flow chart is shown in figure 3.5. It is made up of structural steel (Mild steel). As maximum diameter of upper adaptor is ϕ 70mm and length of 70mm, raw material size of ϕ 75 x 75mm length is used for machining. The sequence of operations are rough turning, followed by CNC turning and thread cutting (M22×2). The threads are the integration feature between load cell and press. The slot is also designed for easy tightening and removal of adaptor.
- Lower adaptor: The 2D drawing of lower adaptor is shown in figure 3.9. The

fabrication flow chart is shown in figure 3.5. This adaptor is having overall dimensions of ϕ 70 x 55mm L. Hence raw material size of ϕ 70 x 60 mm L is used for fabrication. The sequence of operations are same as of upper adaptor. In addition to M22 x 2 threads, one additional thread feature of dimensions (M6 x 1) is included in this adaptor to arrest rotation of punch during forming.

- Punch: Three varieties of punches are fabricated to carry out experiments. All punches are designed for base diameter of ϕ 70mm. Figure 3.5 shows the fabrication flow chart of punch. The raw material in this case is ϕ 75 x 7Omm length. The sequence of operations are rough turning, CNC turning and slot milling. The slots is designed to arrest the rotation of the punch. The cross-sectional drawings of punches are shown in figure 3.10.
- Die block: Die block is placed below the blank holder and sheet blank. It is the part of fluid chamber assembly and assists in flow of material during bending of sheet at corners. It is made up of structural steel having overall dimensions of ϕ125 x 8mm L. The height of the die block is kept minimum so that most of the forming takes place in support of rubber diaphragm. The raw material of die block is ϕ130 x 12L as shown in figure 3.11. The sequence of operations are turning followed by drilling. Six holes of ϕ6.5 mm are designed for clamping of die block with blank holder and fluid chamber. An internal step of 2mm is designed to accommodate the sheet blank of thickness 2mm.
- Blank Holder: Blank holder is an essential part of any forming operation. It optimizes the flow of material and resists wrinkling. The design of blank holder is shown in figure 3.12. Blank holder has inner diameter of ϕ75 mm and outer diameter of ϕ 125mm. 6 equispaced holes having ϕ 6.5mm are drilled for clamping of blank holder. The raw material detail and sequence of operations are shown in figure 3.5. Inner diameter of ϕ75 mm is designed as per maximum diameter of punch i.e ϕ70 mm. PCD is fixed at 112mm as per basic design requirement of 1.5 D distance between hole centre and edge of the component.

- Fluid chamber sub-assembly: Fluid chamber sub-assembly consists of base plate and fluid chamber. Base plate is a rectangular plate having overall dimensions of 160mmx 160mm x 12 mm. The flow diagram of operations are presented in figure 3.5. Fluid chamber is the most critical component of die set up assembly. The overall dimensions are ϕ125 x 45mm L. Outer diameter of ϕ 125mm and inner diameter of ϕ75 mm are fixed in the similar manner as explain in blank holder section. The radial groove of ϕ105mm x 15 W is given for clamping of fluid chamber on the press. A through hole of ϕ M12 x 1.75 is designed to mount hydraulic inlet and outlet hoses. 6 Tapped holes of dimensions M6 x 1 (15 deep) are designed to clamp the fluid chamber with die block and blank holder.

Base plate and fluid chamber are joined together by TIG welding. Dye penetration test was carried out to ensure integrity of the joint. The fabrication flow chart is shown in figure 3.6.

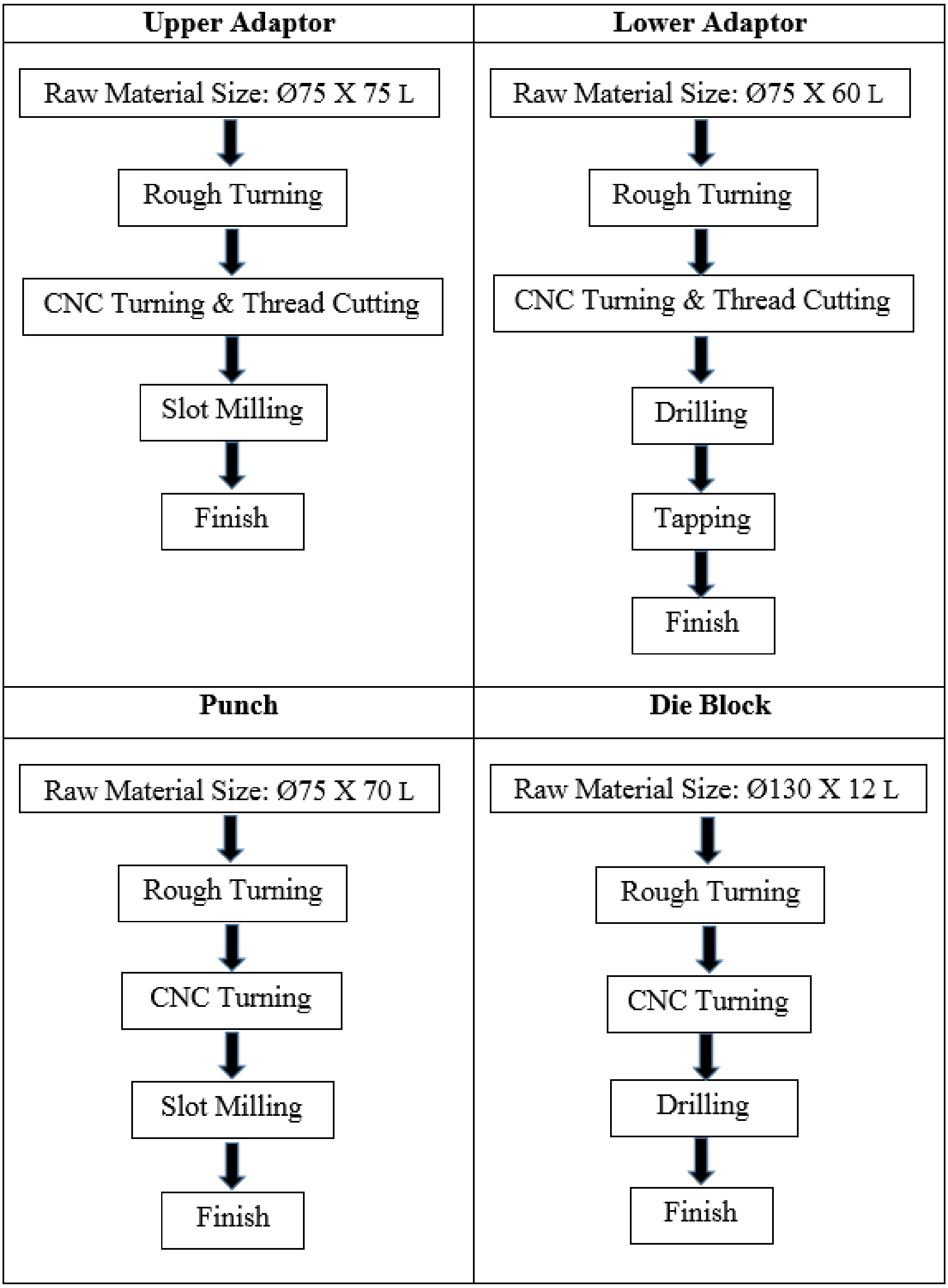


Figure 3.5: Process flow diagram for fabrication of Upper & Lower adapter, Punch and Die Block

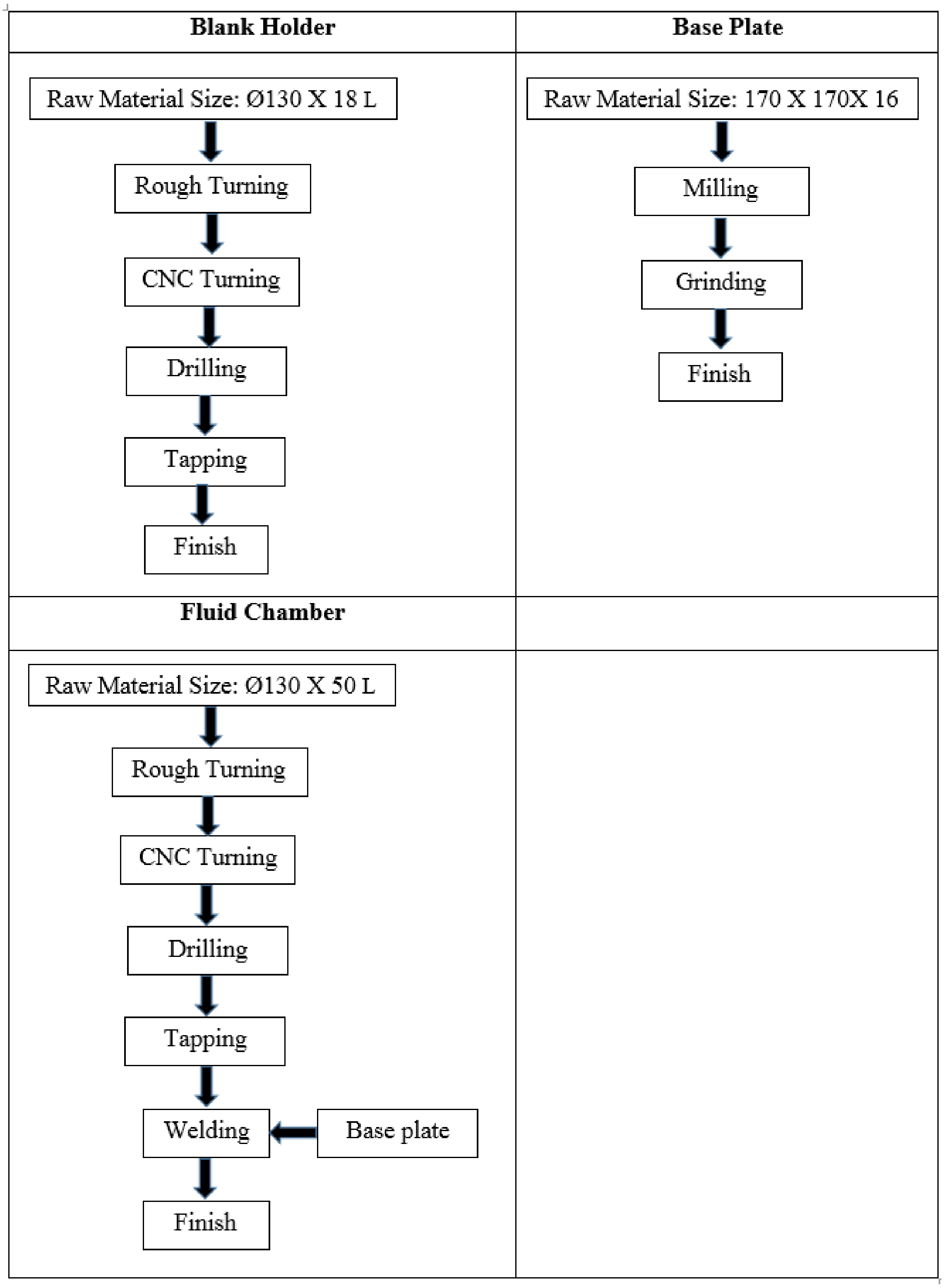
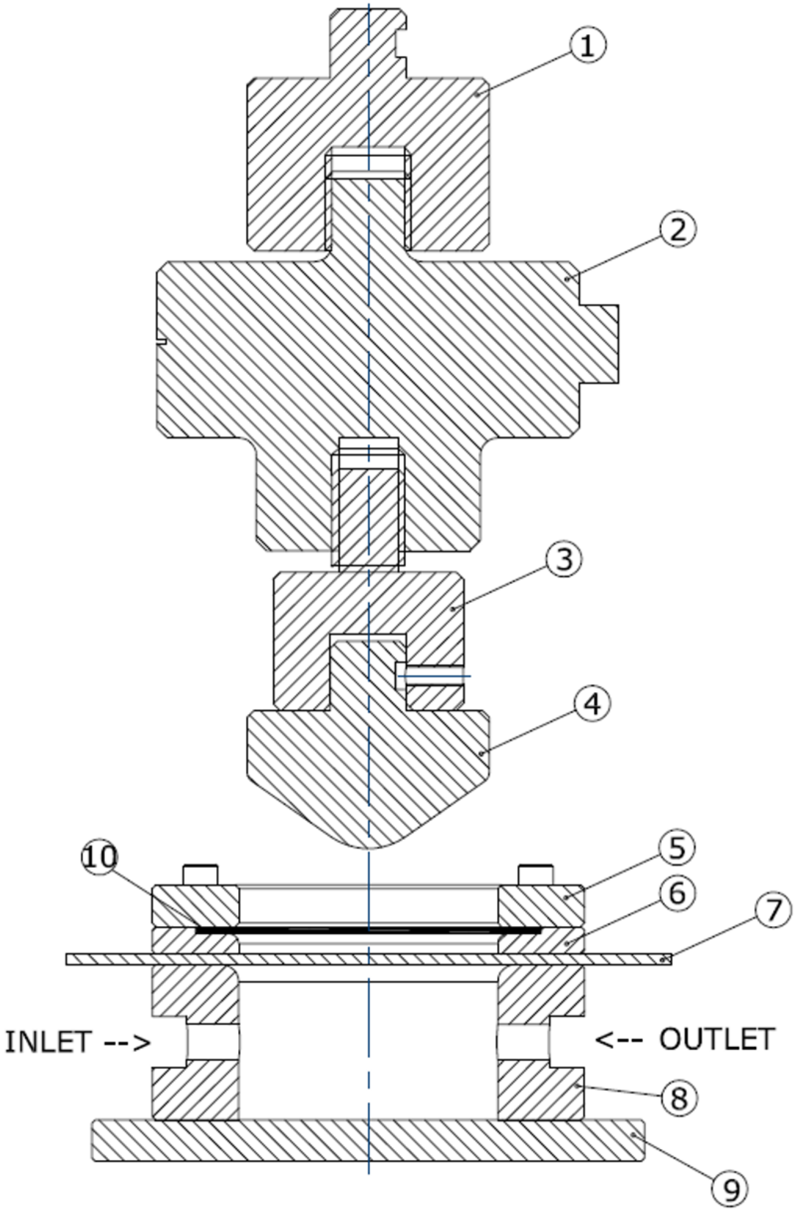


Figure 3.6: Process flow diagram for fabrication of Blank Holder, Base plate and Fluid Chamber



Sl. No.	Nomenclature
1	Upper Adaptor
2	Load Cell
3	Lower Adaptor
4	Punch
5	Blank Holder
6	Die Block
7	Rubber
8	Fluid Chamber
9	Bottom Clamping Plate
10	Blank

Figure 3.7: Die Setup Assembly

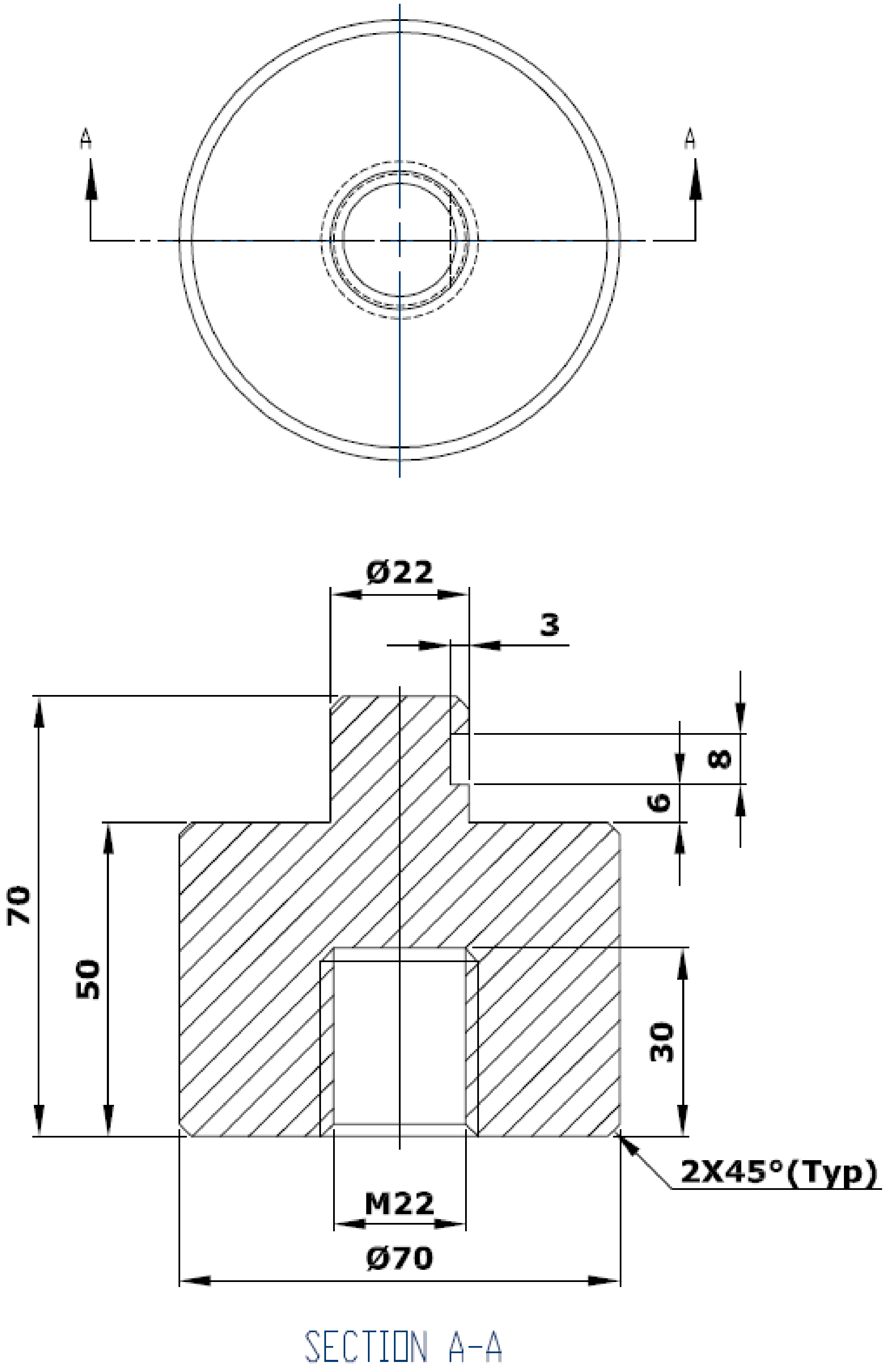


Figure 3.8: Upper Adapter

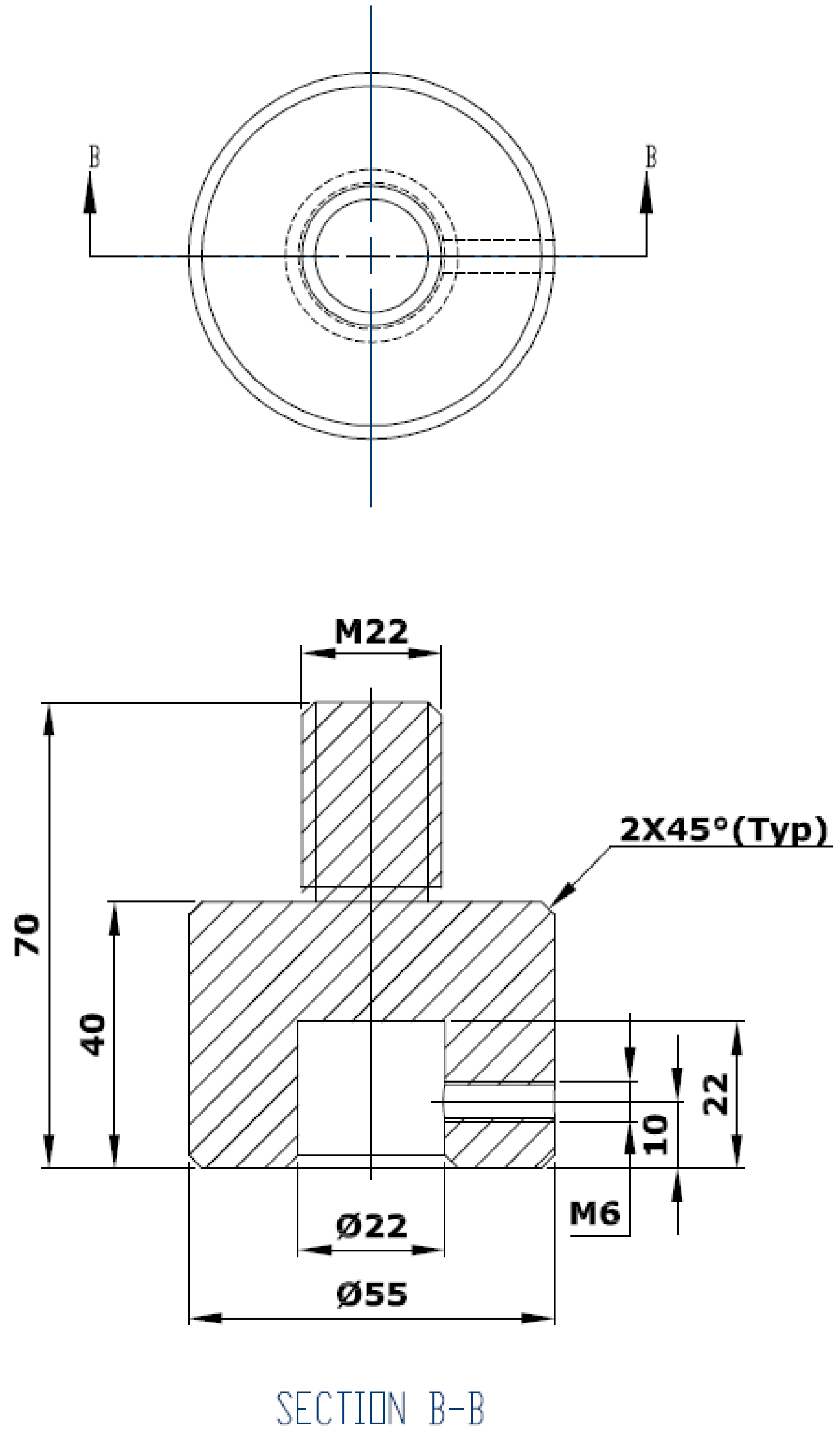
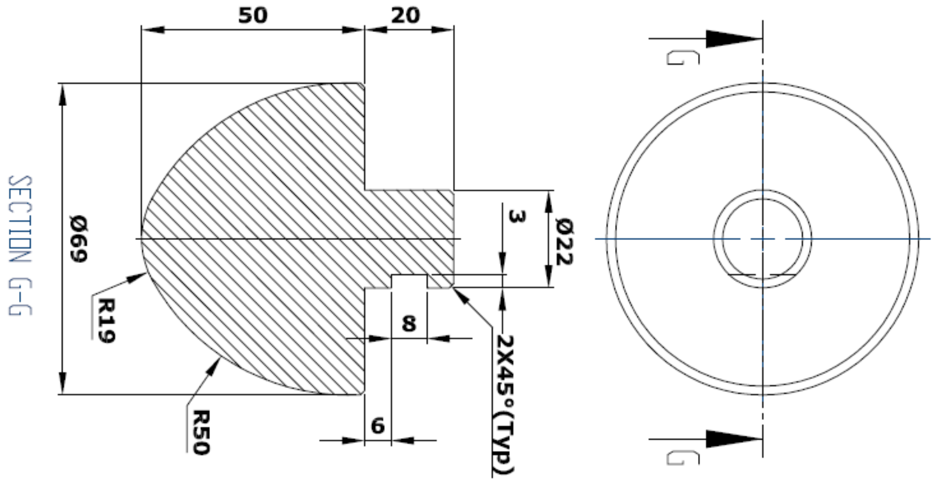
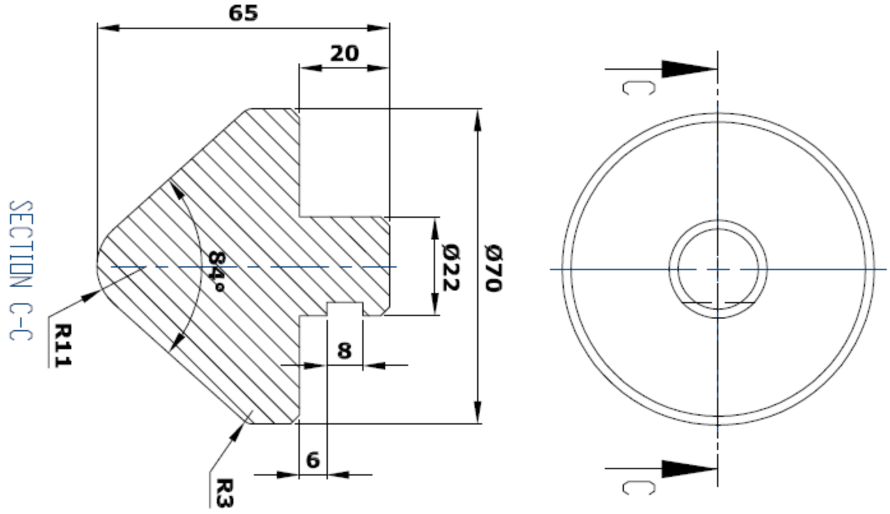


Figure 3.9: Lower Adaptor





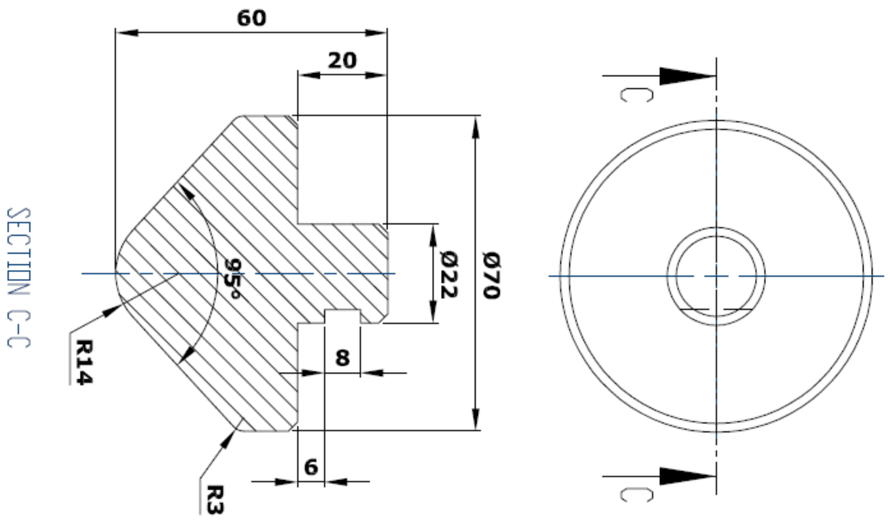


Figure 3.10: Punch

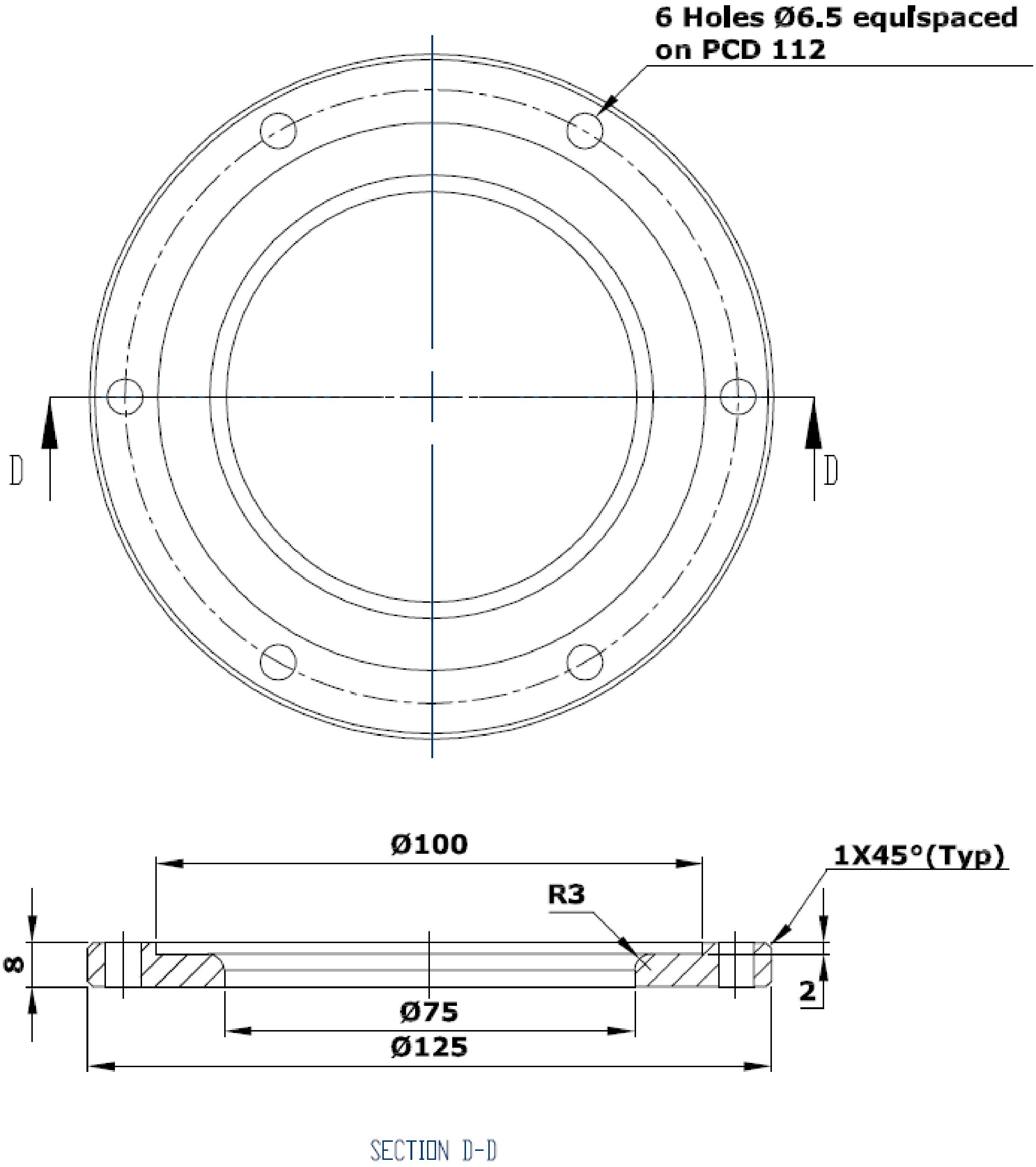


Figure 3.11: Die Block

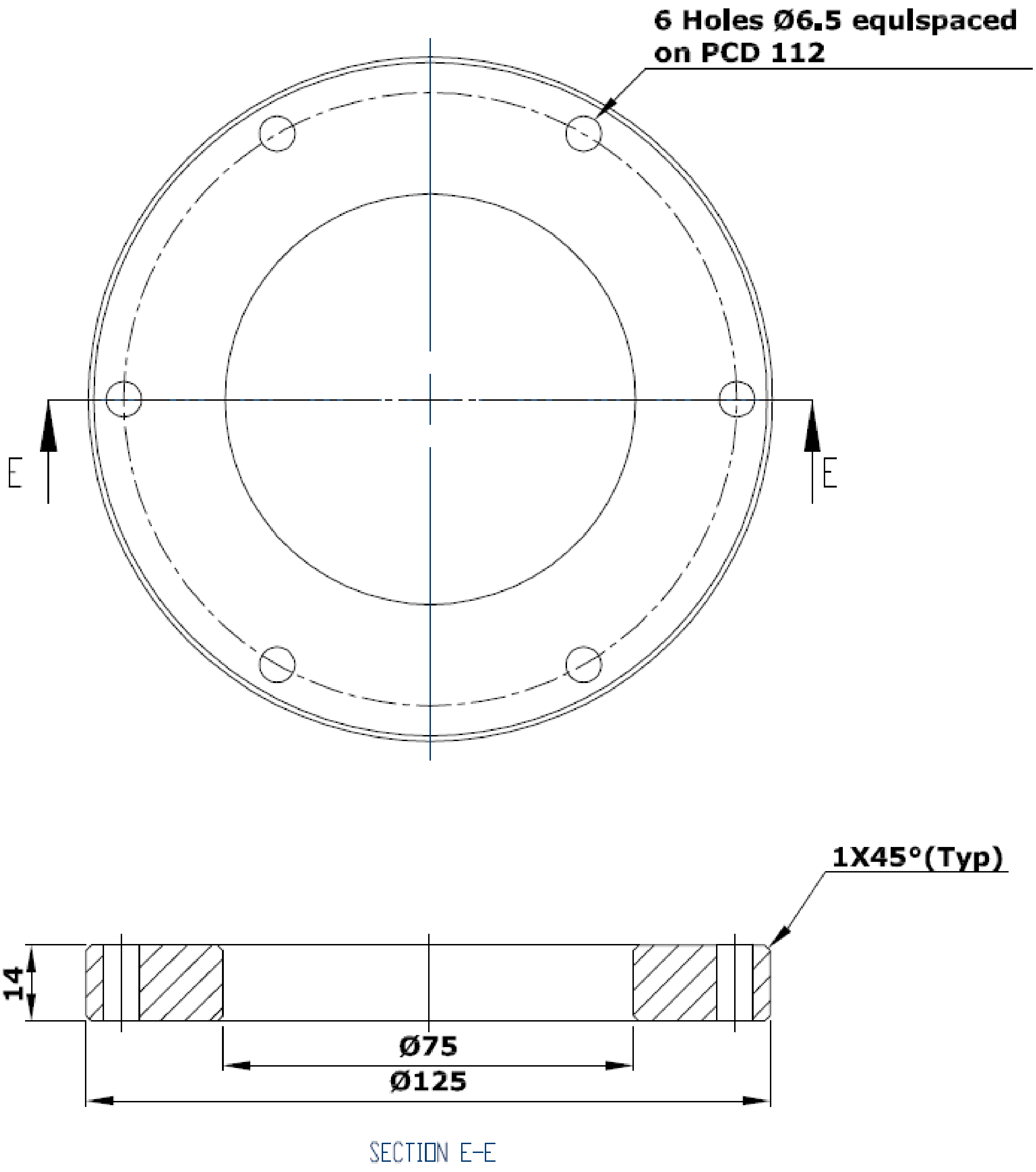


Figure 3.12: Blank Holder

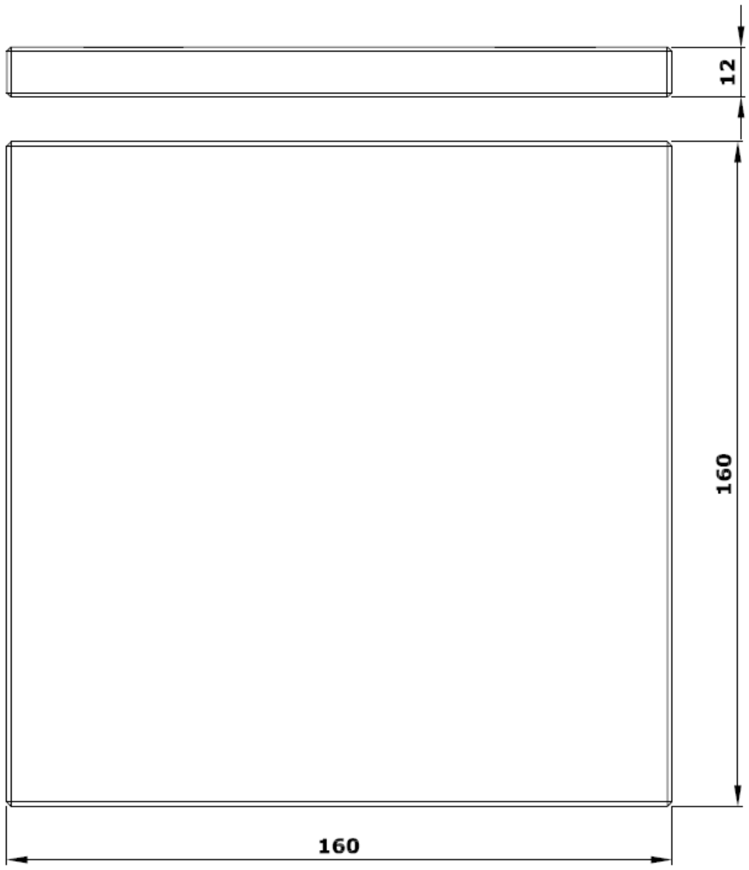


Figure 3.13: Base Plate

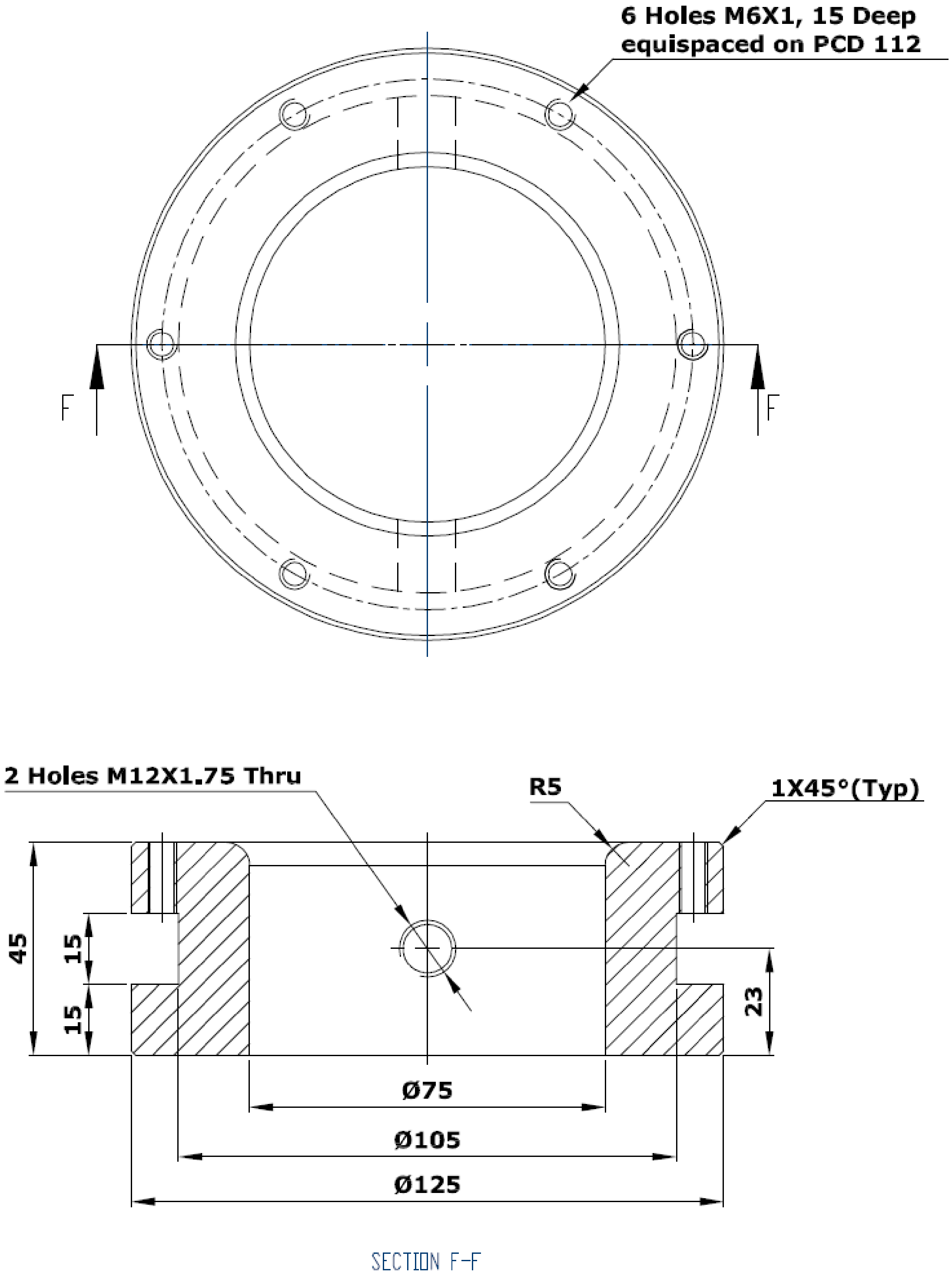


Figure 3.14: Fluid Chamber

3.5 Data Acquisition System

3.5.1 Load Cell

A load cell is a transducer that measures force and output this force as an electrical signal. Most load cells use a strain gauge to detect measurements, but hydraulic and pneumatic load cells are also available. Strain Gauge load cells usually feature four strain gauges in a Wheatstone bridge configuration, which is an electrical circuit that balances two legs of bridge circuit. The force being measured deforms the strain gauges in this type of load cell, and the deformation is measured as change in electrical signal.

A tension/compression load cell is a block that is designed to hold at one point to measure. While tension load cells measure the pulling force, compression load cells measure a pushing force along a signal axis. The strain gauge in a compression/tension load cell is deformed when a load is applied, and this deformation is used to produce the measurement. Compressive/Tension load cells are generally made up of materials that are resistance to rusting and scratches. A hardened cover is often used on the base plate to protect from damage in order to provide precise results. A typical schematic diagram of load cell is shown in figure 3.15.

Specifications[63]

Load Cell Type: Tension/Compression

Load Capacity: 5 Tons

Measurement Principle: Strain gauge

Accuracy: 0.1%

Cable Type: 6 Nos., 5m

Make: HBM

3.5.2 Pressure Transducer

It is an instrument consisting of a pressure sensitive element to determine the actual pressure applied to sensor and some components to convert this information

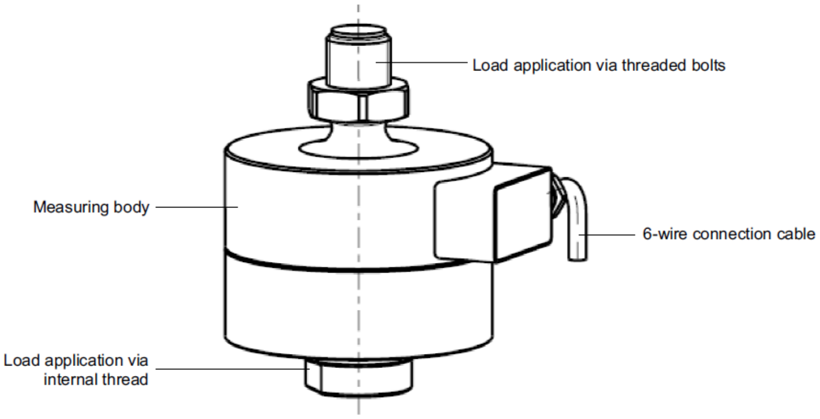


Figure 3.15: Schematic diagram of a typical load cell [63]

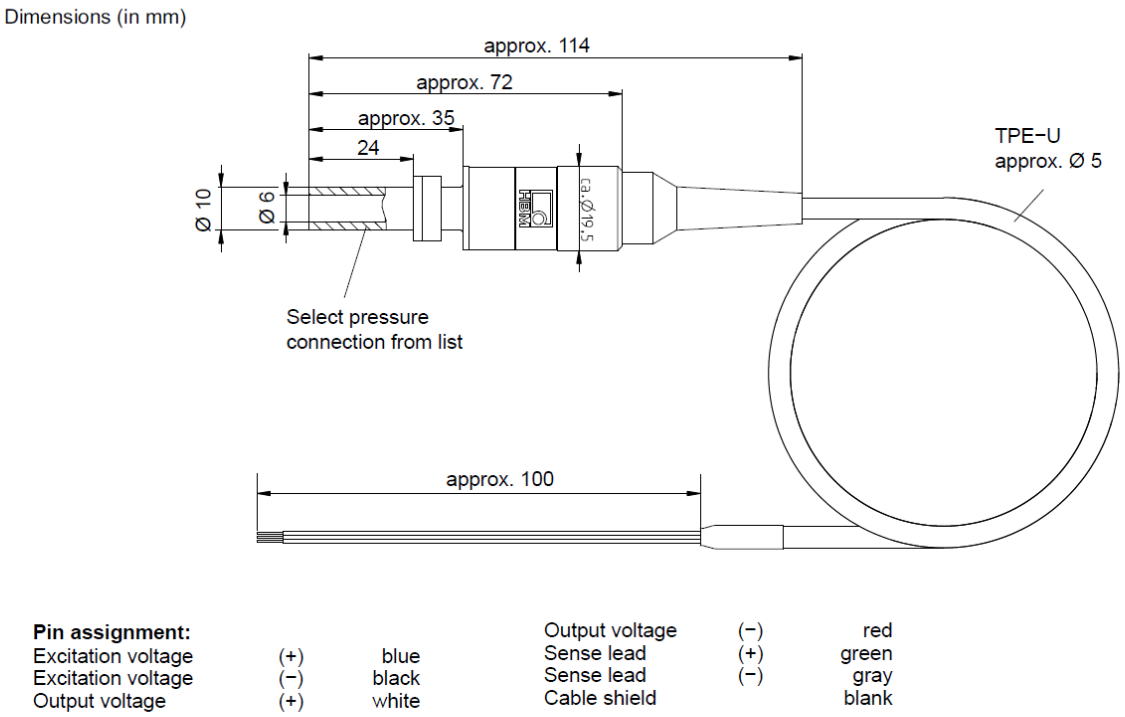
into an output signal. There are variety of different technologies used to provide accurate results.

Strain gauge based pressure sensors use a pressure sensitive element where metal strain gauges are glued. This measuring element can either be a diaphragm or metal foil measuring body. The electrical connection is normally done via Wheatstone bridge which allow for a good amplification of the signal and precise the constant measuring results.

Capacitive pressure sensors use a pressure cavity and diaphragm to produce a variable capacitor. The diaphragm is deformed when pressure is applied and capacitance decreased accordingly. This change in capacity can be measured electrically and is then set in relation to the applied pressure.

Piezo-resistive pressure sensors consist of a diaphragm, mostly made of silicon with integrated strain gauges to detect strain as a result of applied pressure. These strain gauges are typically configured in a Wheatstone bridge circuit to reduce sensitivity and increase the output. Resonant pressure sensors use the change in resonance frequency in a sensing mechanism to measure stress caused by applied pressure. A typical schematic diagram of pressure transducer is shown in figure 3.16.

The P8AP pressure transducer precisely measures liquid and gas pressure up to 500 bar with an accuracy class of 0.3. It is equipped with high grade strain-gauge technology. The P8AP reliably withstands overloads of up to 1.75 times its normal (rated) pressure owning to its robust and corrosion resistance steel measuring body.



Pin assignment:

Excitation voltage	(+)	blue
Excitation voltage	(−)	black
Output voltage	(+)	white
Output voltage	(−)	red
Sense lead	(+)	green
Sense lead	(−)	gray
Cable shield		blank

Figure 3.16: Schematic diagram of Pressure Transducer [64]

The pressure transducer offers temperature stability up to -40^{o}C to +80^{o}C.

Specifications[64]

Pressure Capacity: 200 Bar

Measurement Principle: Strain gauge pressure sensor

Accuracy: 0.3

Cable Type: 6 Nos., 5m

Make: HBM

3.5.3 Data Acquisition Module

A typical data acquisition module is shown in figure 3.17. This data acquisition system/Strain gauge amplifier is necessary whenever strain, forces, displacement, temperature are acquired. The QuantumX MX1615B module is equipped with 16 sensor inputs, arranged in a very compact housing. As a result it offer an unrivaled channel density in a small space. Some important features are as follows,

1. Robust mechanism, which prevents electromagnetic and thermal interference in the measurement results.

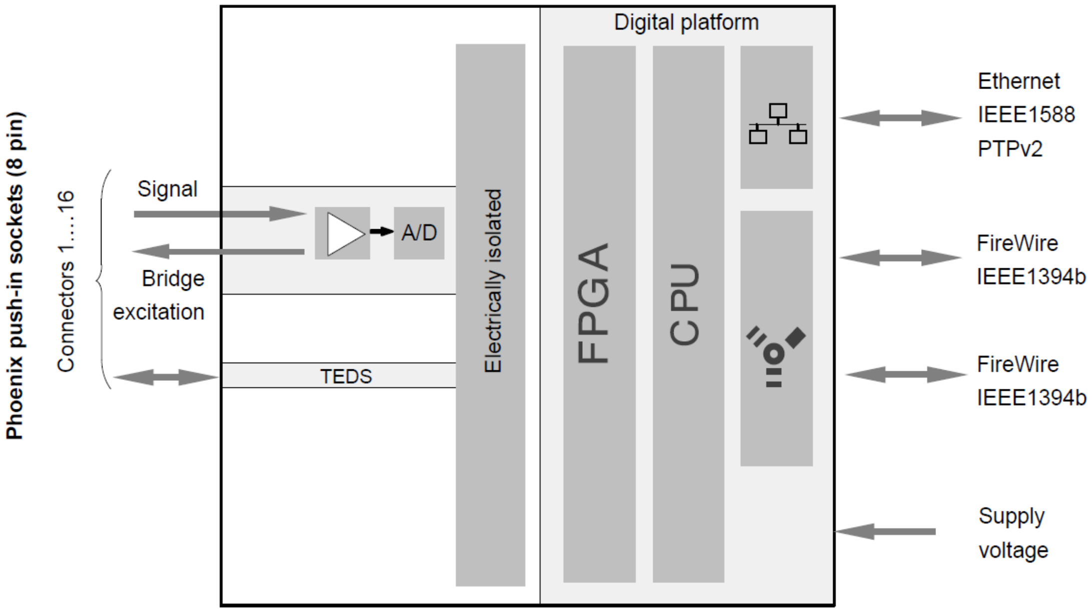


Figure 3.17: Block diagram of Data Acquisition Module [65]

2. Individually configurable measuring rates up to 20kS/s per channel and with high signal bandwidth.
3. Fast instrumentation using push-in plugs
4. Instant calibration of sensors or plausibility check by internal shunt connection.
5. Suitable for a wide range of ambient temperatures(-20^{o}C to +65^{o}C)
6. Instant results with the help of the HBM Catman software for data recording and data analysis.

Specifications[65]

Model: QuantumX MX1615B

Capacity: 35 Ω

Sensor Input: 16 Ports

Make: HBM

3.5.4 Data Acquisition Software

Catman Data acquisition software [66] allows for data visualization, analysis and storage during the measurement and reporting after. Some important features are as follows,

1. Individually visualize and control on multiple pages, screens or in full-screen format.
2. Save data with up to 12 MS/s or 100 MB/s.
3. Record two parallel measurement tasks and statistics log.
4. Use auto sequences to automate work flows and test sequences.
5. Compare data sets, compute and analyze signals.
6. Acquisition, display and analysis of CAN raw data.
7. Multiple format for storage and export available (Catman BIN, Excel, ASCII, MDF, DIAdem, MATLAB, RPC III, UFF58 etc.)

3.6 Experimental Setup and analysis

In this work, an experimental setup has been designed and developed for rubber assisted sheet Hydro-forming of hemispherical cups from copper sheet metals having thickness of 2 mm. This is the most common thickness of sheet materials used in automobile applications. The experimental setup consists of die, blank holder, punch, hydraulic power pack and the data acquisition (DAQ) system as schematically represented in figure 3.18. The experimental Die-punch setup is shown in figure 3.19.A hydraulic power pack as shown in figure 3.18 is used to generate fluid pressure for required blank deformation. 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 DAQ system as shown in figure 3.20. A signal conditioner unit has been used to modify the low voltage signals from the sensors and then sends them to the DAQ system. An electronic DAQ system has been used to record the modified signals from pressure sensor and the load cell. The DAQ system has an analog to digital signal which records and displays on a monitor through Catman software. 3D CAD model of assembly and actual hardware are shown in figure 3.18 to figure 3.21.

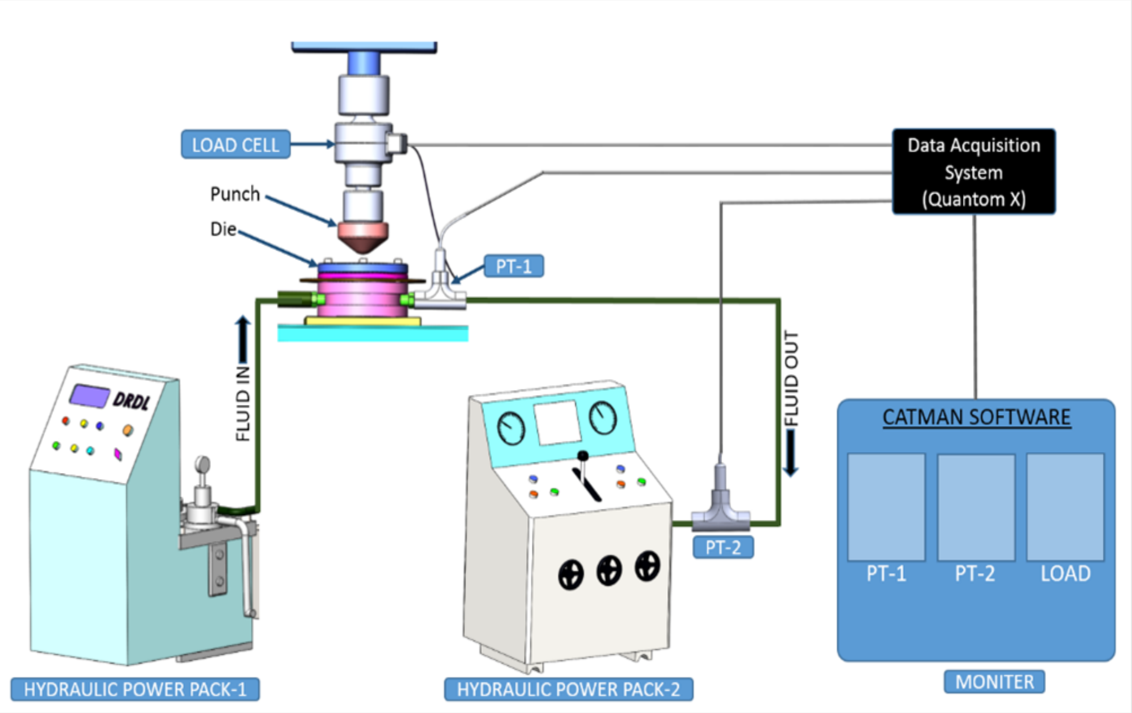


Figure 3.18: Experimental setup in rubber assisted sheet Hydro-forming

3.6.1 Experiment Table and Outcome

The experiment was carried out at various conditions and online variation of input pressure, back pressure and punch force were monitored for each case. In Experiment No. 1 (T1), forming of spherical cup was carried out without back pressure and rubber. The maximum punch force was measured at 40 KN. T2 experiment was carried out with natural rubber and without hydraulic pressure and peak force was measured as 30KN. Similarly total of 16 experiments were carried out in different combinations varying the thick thickness, hydraulic pressure and type of rubber. The real time plot of load, input pressure, rise in chamber pressure and back pressure is shown against each trial. The experiment details are listed in Table 3.1.

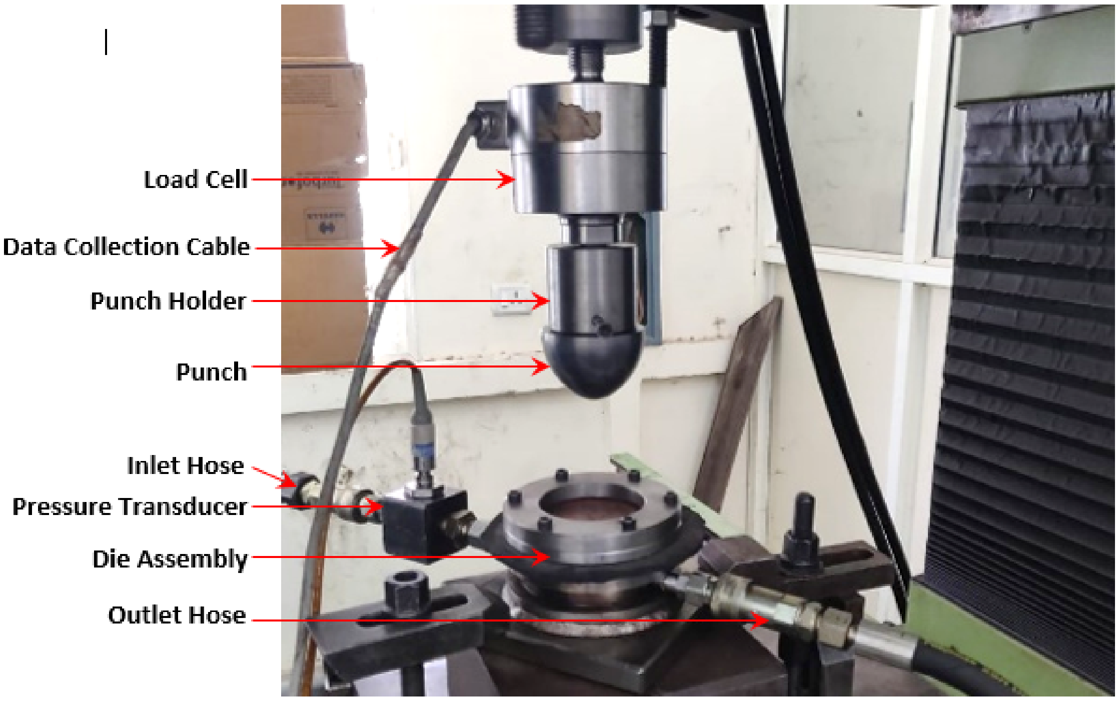


Figure 3.19: Die Punch Set-Up

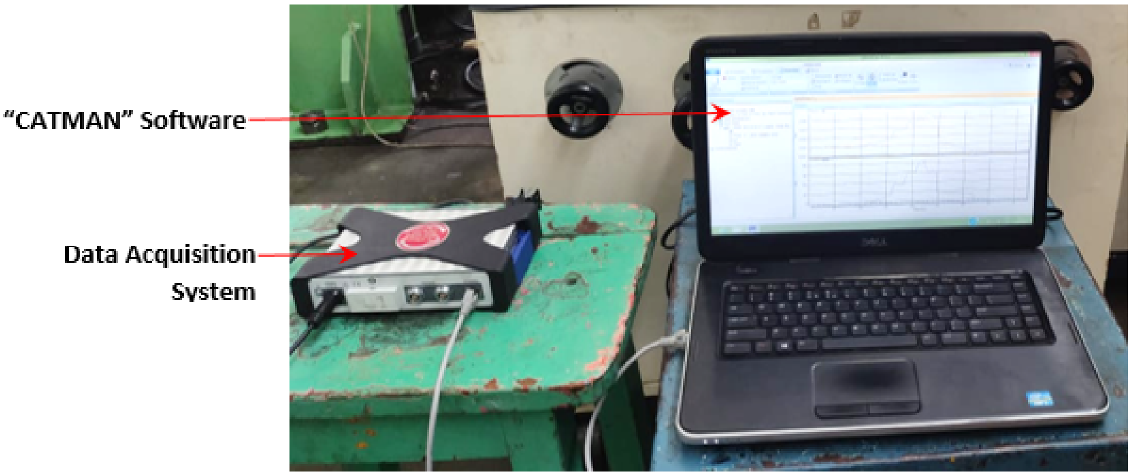


Figure 3.20: Data Acquisition system

Figure 3.21: Rubber assisted sheet Hydro-forming Set Up

Table 3.1: Variation of Load and Hydraulic Pressure

Sl. No.	Material	Rubber Used	Punch Shape	Initial Pressure	Peak Load	Ref. Figure
T1	Pure Copper (2mm)	Nil	Sphere	Nil	42 KN	3.22
T2	Pure Copper (2mm)	Natural	Sphere	Nil	30 KN	3.23
T3	Pure Copper (2mm)	Natural	Sphere	10 Bar	41 KN	3.24
T4	Pure Copper (2mm)	Nil	Conical(95^o)	Nil	28 KN	3.25
T5	Pure Copper (2mm)	Natural	Conical(95^o)	Nil	24 KN	3.26
T6	Pure Copper (2mm)	Natural	Conical(95^o)	10 Bar	28 KN	3.27
T8	Pure Copper (2mm)	Natural	Conical(95^o)	10 Bar	30 KN	3.28
T10	Aluminum (2mm)	Natural	Sphere	10 Bar	50 KN	3.29
T11	Pure Copper (2mm)	Natural	Sphere	10 Bar	41 KN	3.24
T12	Pure Copper (2mm)	Nitrile	Sphere	10 Bar	35 KN	3.30
T14	Pure Copper (0.8mm)	Natural	Conical(85^o)	5 Bar	10KN	3.31
T16	Pure Copper (2mm)	Natural	Conical(85^o)	10 Bar	25KN	3.32

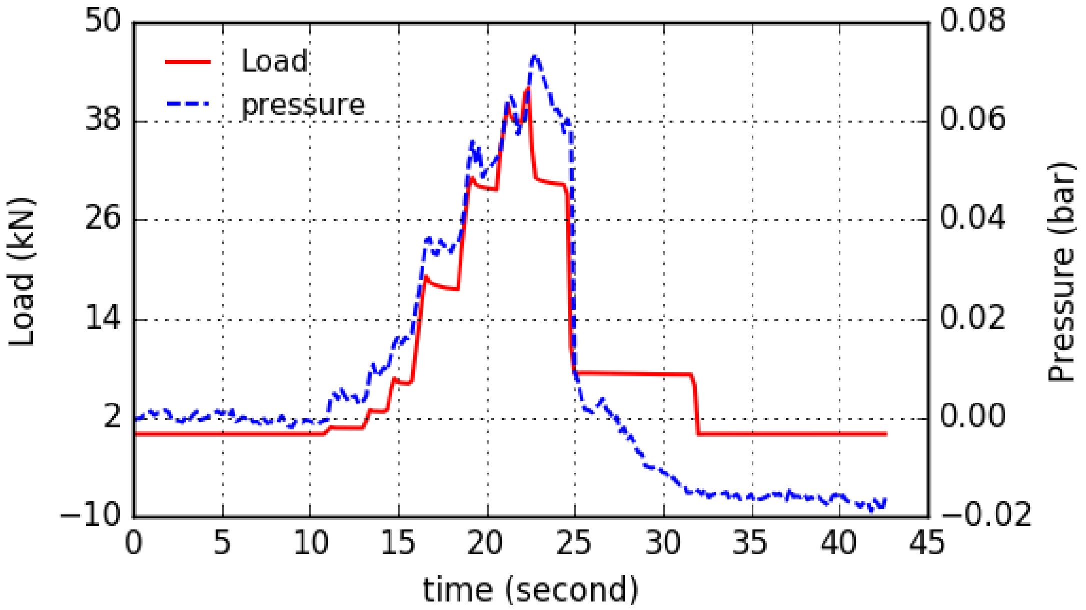


Figure 3.22: Plot showing peak load and pressure rise in chamber (T1)

3.6.2 Experimental Data Analysis

Experiment T1

In first experiment, the forming was carried out without any rubber and hydraulic pressure. The punch was of hemispherical profile and blank is having thickness of 2mm. The peak load observed was 43 KN. The theoretical peak load using formula $F = \pi \times D \times t \times Y$ (yield strength) is calculated as 34KN. Adding blank holding force of F/3 i.e 11 KN, the theoretical forming force is 45 KN. Hence the experimental peak load matches closely with theoretical peak load. The plot of load vs. time is shown in figure 3.22.

Experiment T2

In 2^{nd} experiment, natural rubber diaphragm is added but there was no back pressure. As rubber purely apply hydrostatic pressure all along the profile of hemispherical cup, it further assists in forming of hemispherical cup from the opposite side of punch. Hence the total peak load observed in this case is 30 KN which is less than that of peal load observed in T1. The plot is shown in figure 3.23.

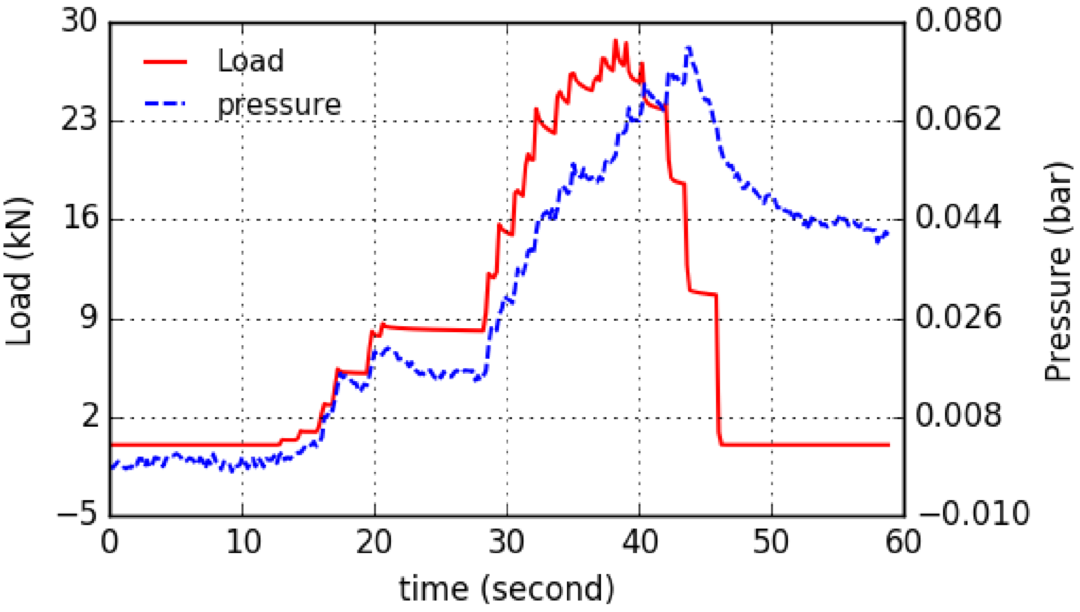


Figure 3.23: Plot showing peak load and pressure rise in chamber (T2)

Experiment T3/ T11

Both trials are identical and has been carried to check the repeatability of the results. In this case, rubber diaphragm has been used and hydraulic pressure of 10bar has been applied. The blank and natural rubber thickness is 2mm and 3mm respectively. Mineral oil is used as hydraulic fluid which is incompressible in nature. Being incompressible fluid, hydraulic fluid resists the punch downward movement and compensate for force relief generated by elastomer rubber. Hence, the measured peak load is 42KN which is almost equals to that measured in T1 case. The rise in chamber pressure is up to 15bar which is directly related to reduction of available volume in the chamber during forming. The combined plot of punch load and chamber pressure is shown in figure 3.24.

Experiment T4/ T5/ T6

In 4th Experiment, conical profile having included angle of 95 deg was drawn having maximum diameter of 70mm same as Hemispherical Cup. Neither rubber nor hydraulic back pressure has been used. The peak load observed was 28KN. In T5 natural rubber diaphragm was added and peak load observed was 24 KN. The reason for lower peak load is explained in the previous subsection. In T6, when

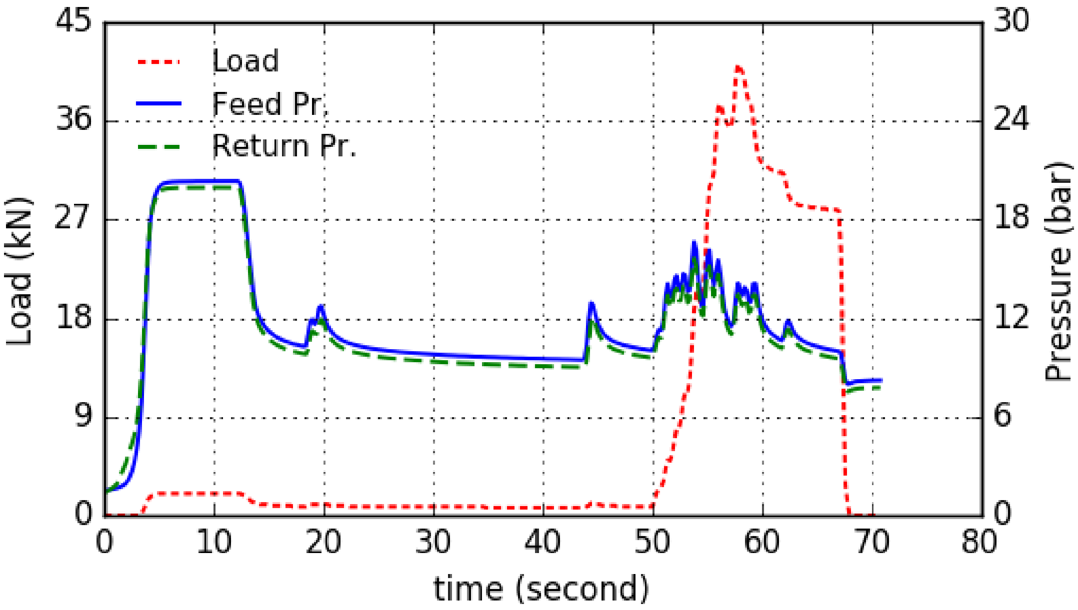


Figure 3.24: Plot showing peak load and pressure rise in chamber (T11)

back pressure was applied, again peak load of 28KN was observed. Hence, there is consistency of variation in peak load under spherical and conical profile forming. Figure 3.25, 3.26 and 3.27 shows the online variation of peak load and back pressure during T4, T5 and T6 experiment respectively.

Experiment T8

T8 experiment is carried out for conical punch having profile of 85 degree cone angle. The hydraulic back pressure was kept at 10 bar. Again in this case natural rubber has been used. The maximum peak load observed in this case is 30 KN which is less than peak load observed during T11 experiment in which spherical punch has been used. The decrease in peak load in T8 is logical as effective forming area in case of cone is less than effective forming area in case of spherical punch.

Experiment T10

In this experiment , pure aluminium has been formed into hemispherical profile. Natural rubber diaphragm is used and back pressure is kept at 10 bar. The peak load observed in this case in 50 KN which can be attributed to the higher tensile strength of Pure Aluminum in compared to pure copper.

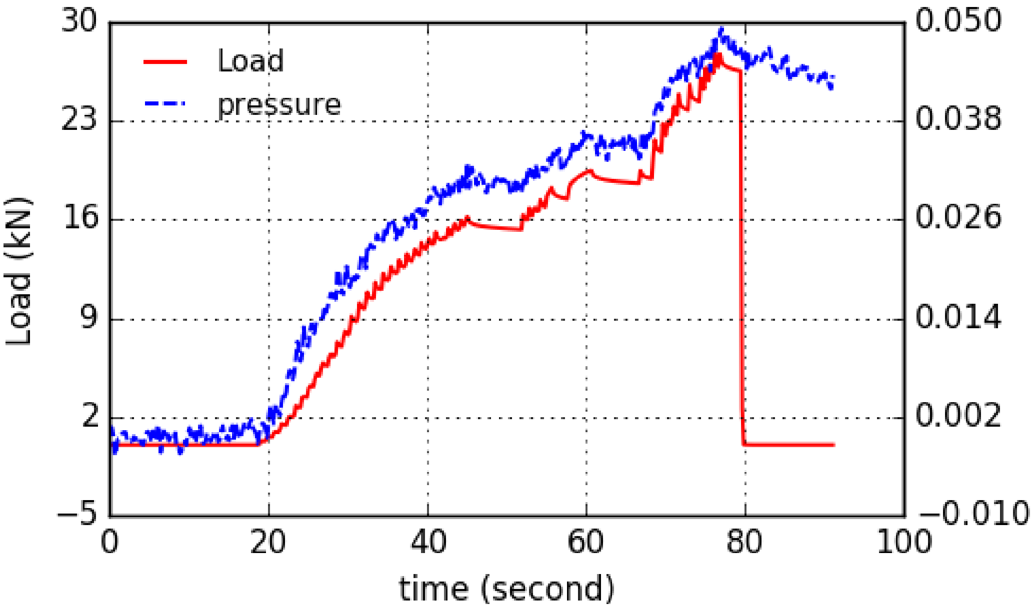


Figure 3.25: Plot showing peak load and pressure rise in chamber (T4)

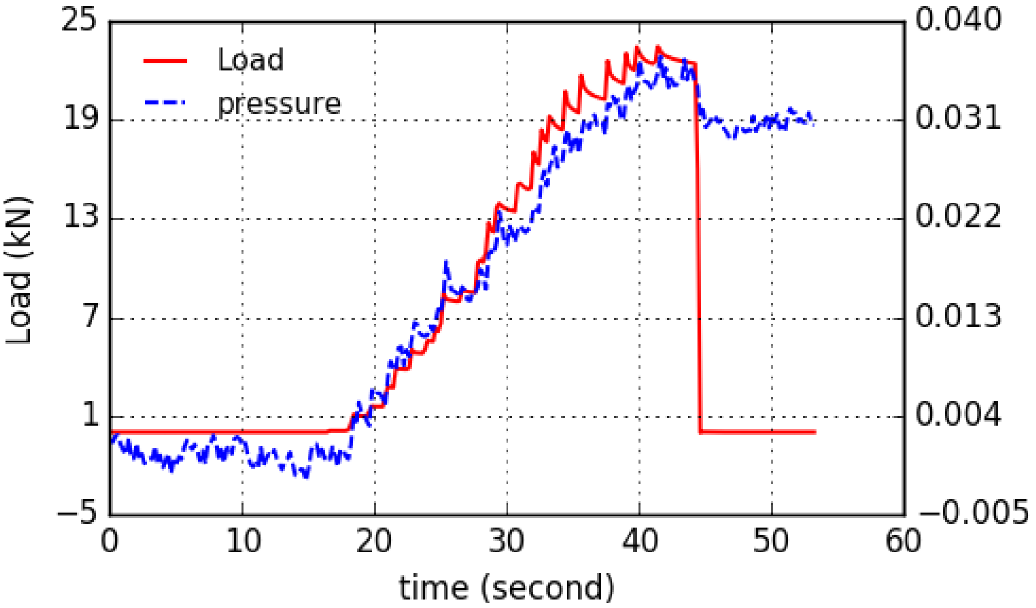


Figure 3.26: Plot showing peak load and pressure rise in chamber (T5)

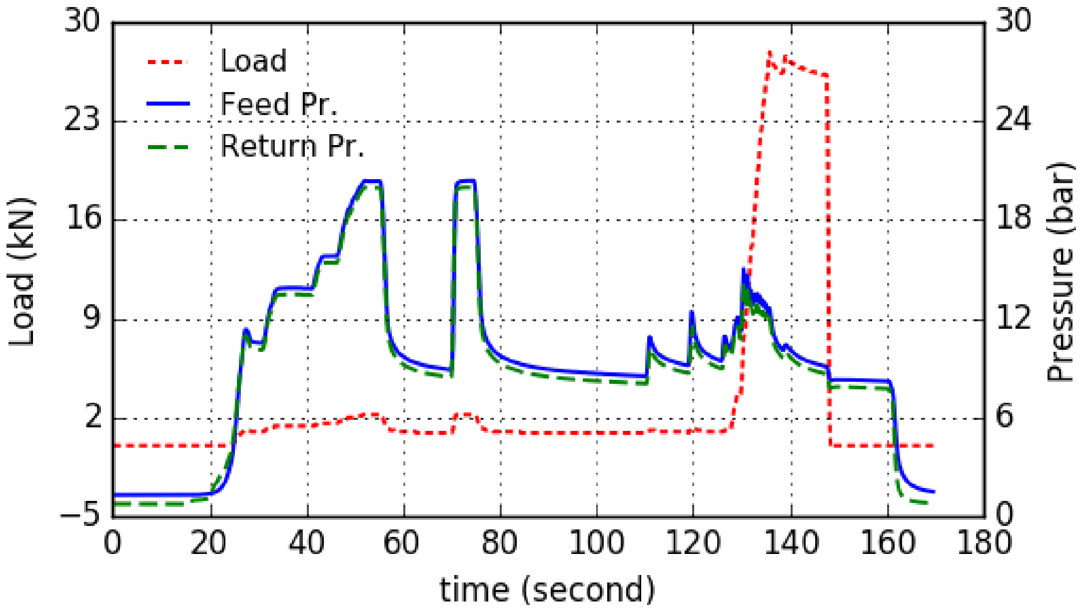


Figure 3.27: Plot showing peak load and pressure rise in chamber (T6)

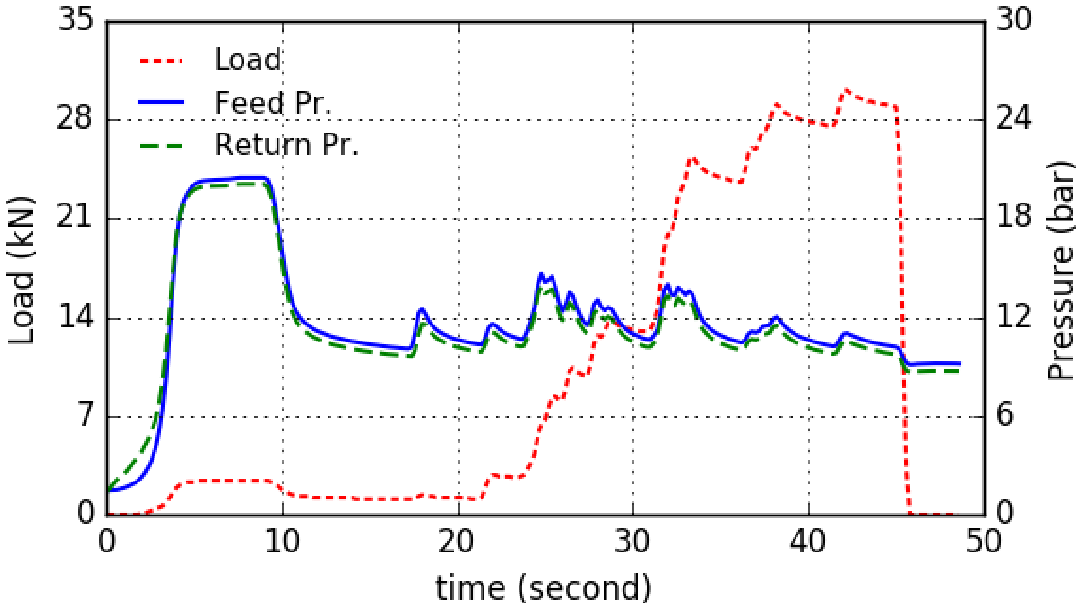


Figure 3.28: Plot showing peak load and pressure rise in chamber (T8)

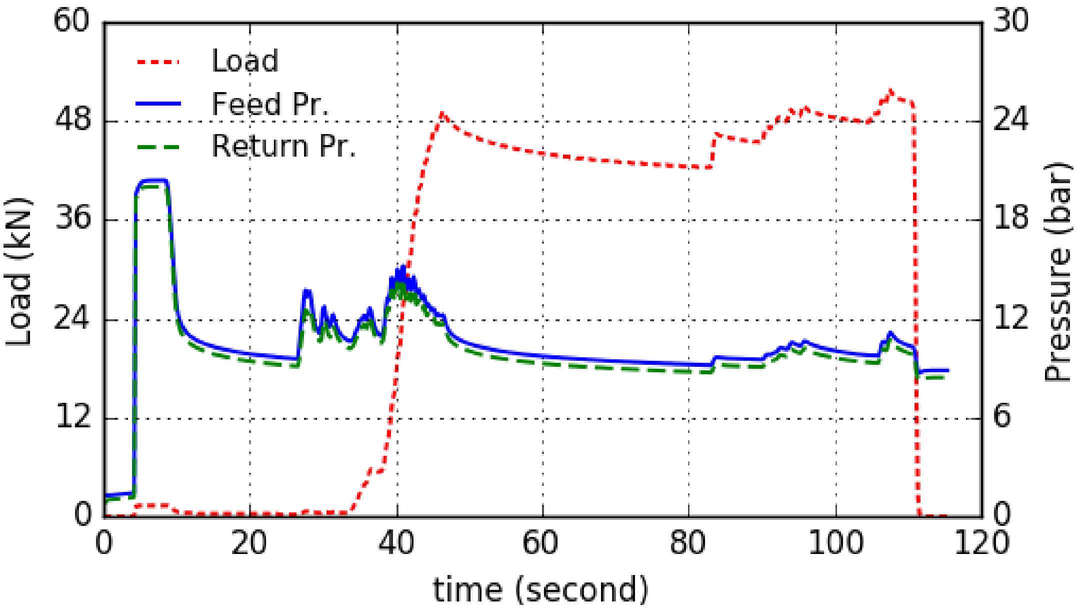


Figure 3.29: Plot showing peak load and pressure rise in chamber (T10)

Experiment T11 and T12

T11 and T12 experiments are almost same, only rubber diaphragm is varied. In T11, natural rubber has been used whereas in T12, nitrile rubber is used. The peak load in T11 case is 41 KN and 36 KN in T12 trial. This variation in peak load can be explained with the help of Young's modulus. The comparative plot of stress vs strain of natural and nitrile rubber indicates that nitrile has lower Young's modulus, hence resistance of nitrile rubber less than natural rubber which resulted into higher peak load in case of Natural rubber. The recorded plot are shown in figure 3.24 and 3.30.

The correlation between theory and observed results indicate that rubber assisted sheet hydroforming set up is very much useful to predict the loads, chamber pressure and back pressure. Further numerical simulation has been carried out to validate this set-up which is presented in chapter 5 .

Experiment T14

In this experiment, 0.8mm thin pure copper sheet is drawn into conical profile having cone angle of 85 degree. As expected the peak load observed in this case

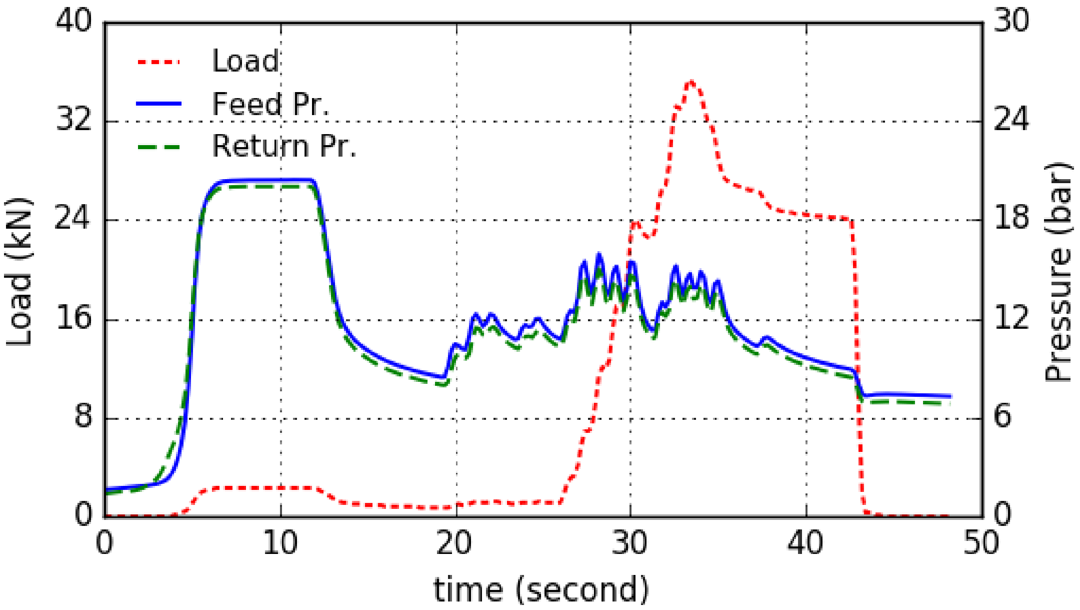


Figure 3.30: Plot showing peak load and pressure rise in chamber (T12)

is only 10 KN which is much less than peak load observed during experiment T10 (blank thickness - 2mm & cone angle 85 degree). Thus the peak load output is completely in the line of expected engineering reasoning.

Experiment T16

In the last experiment, again pure copper blank having thickness of 2mm is used and drawn into conical profile having cone angle of 85 degree. The peak load observed in this case is 25KN which leas between peak load 30 KN observed 30 in T8 (thickness 2 mm , cone angle 95 degree) and peak load 10 KN (thickness 0.8mm, cone angle 85 degree). The less peak load is attributed to the reduced forming area in case of 85 degree cone angle in compared with forming area in case of 95 degree cone forming area.

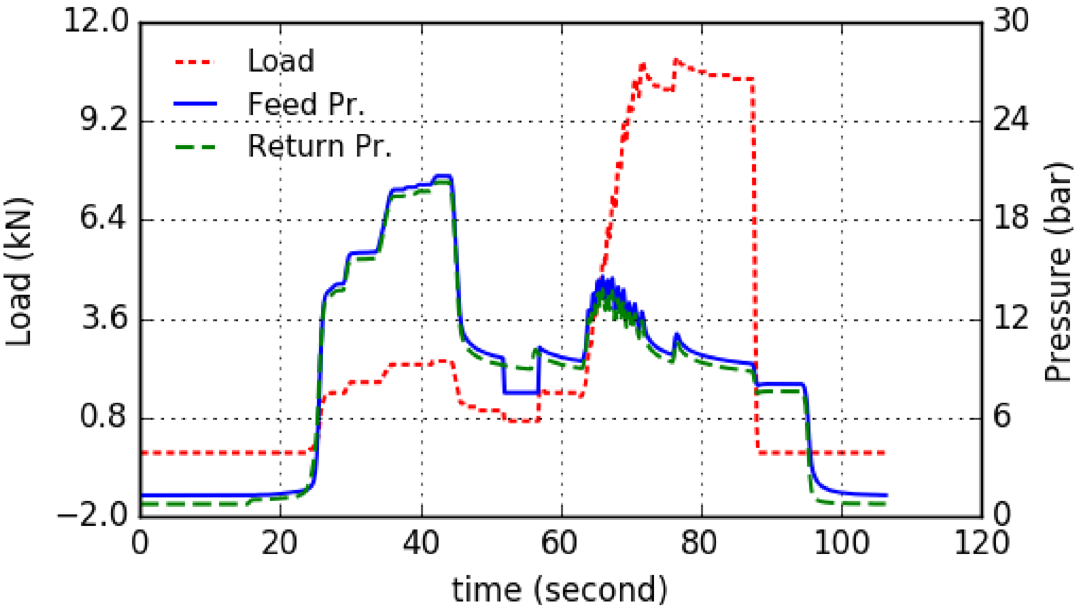


Figure 3.31: Plot showing peak load and pressure rise in chamber (T14)

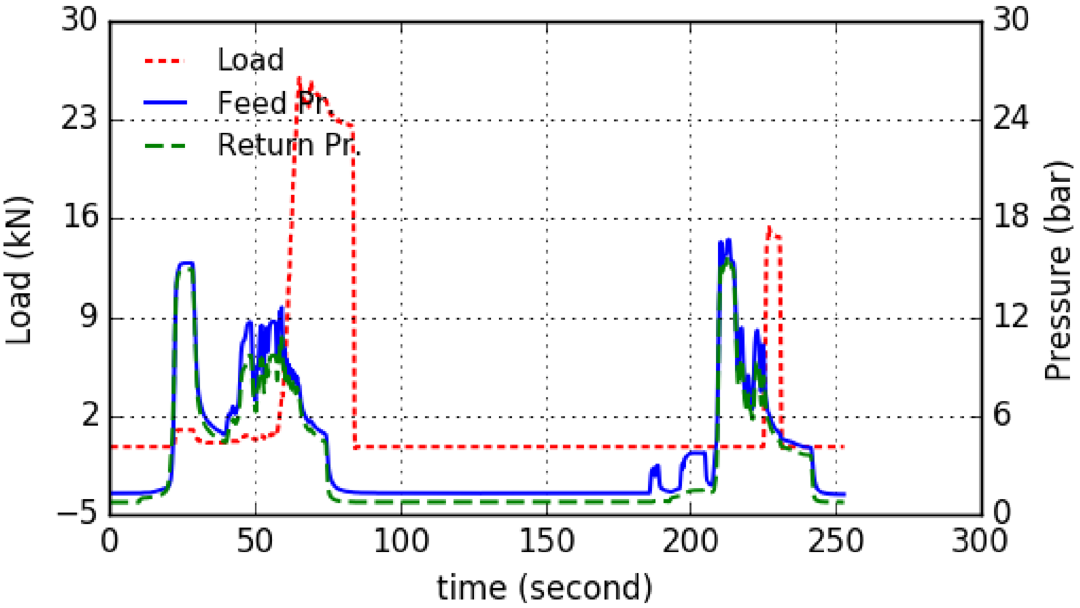


Figure 3.32: Plot showing peak load and pressure rise in chamber (T16)