# DESIGN AND DEVELOPMENT OF PORTABLE VACUUM FORMING MACHINE

A Final Year Project Report

Presented to

**SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING**

Department of Mechanical Engineering

NUST

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In Partial Fulfillment
of the Requirements for the Degree of
Bachelor of Mechanical Engineering

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by

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20th June, 2021

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# ABSTRACT

This project aims at developing a portable vacuum forming machine for local industry and providing them an inexpensive yet reliable vacuum forming machine. Vacuum forming is a type of thermoforming process in which a thermoplastic sheet is heated to its pliable forming temperature and forced against a mold and shaped by creating a vacuum to force it. This machine is ideal for rapid prototyping in an industry that makes variety of customized products without consuming enormous number of resources.

Our machine is capable of manufacturing products of 2ft by 2ft forming area with moving platen assembly and pivoted heater design, which are controlled using pneumatic actuators. The Machine has been designed to make use of standard market available materials and manufacturing capabilities with defined tolerance.

Currently, there is not a single manufacturer of these machines in Pakistan. Although some companies have made vacuum forming machines available in the international market, but these are very expensive and have high import costs. Our goal is to start manufacturing of these machines locally to provide cost-effective solution to local manufacturers and businesses. This project holds a promising future for manufacturing companies with custom design products, as well as small scale manufacturers of packaging materials, along with an untapped potential in the education sector in Pakistan.

# ACKNOWLEDGMENTS

We would like to express our deepest appreciation to our supervisor, Dr. Mian Ashfaq Ali, for his invaluable support throughout the project. And to Mr. Aaras Bhatti, who is pursuing his masters from SMME NUST, whose help and insight was very critical in completion of this project. We are eternally humbled by the steadfast support of our parents. It is due to the values they instilled in us which enabled us to work with a sense of duty, return their trust with our untiring efforts and push the limits to accomplish our goals. Lastly, we would like to acknowledge all the efforts made by NUST in keeping us safe and cooperating with us during this pandemic-hit final year, for providing us with all possible means to help us follow our ambitions and take dignity in serving the people of this beloved country.

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# INTRODUCTION

## Motivation

Vacuum forming is a highly cost efficient and simple thermoforming process to manufacture various products from plastic sheets. It is widely used in product development due to its cost efficiency and easy operation which can make manufacturing of complicated shapes very easy and efficient without costing a lot of money. Design flexibility offered by vacuum forming process makes it very desirable process in product development and this field has huge potential in local manufacturing industry and businesses which relies on the use of such machines on regular basis.

Our motivation for working on this project is that no such machine is commercially available in Pakistan, and it costs huge amount of money to import such machines from manufacturers in China. So, the idea is to start the manufacturing of vacuum forming machines within Pakistan and commercialize our product. We have worked on machine which can manufacture parts and products from 600mm*600mm size plastic sheets. Products manufactured from this machine are neither too small nor too large and allows the design flexibility that a user might be looking for in a vacuum forming machine. Instead of manual operation, pneumatic actuators are used to automate the operations which makes the whole operation very accurate and efficient.

## Problem Statement

In Pakistan, Vacuum forming machines are not manufactured by any company and are not commercially available. The scope of this project is to design and develop a portable vacuum forming machine which is easy to use, allows the user to control the forming temperature and make products from 2ft-by-2ft size plastic sheets. We also worked on the applications of this machine and generated 3D molds to manufacture products using this machine.

## Objectives

Following are the objectives of this project:

- Design of a portable vacuum forming machine for 2ft x 2ft size plastic sheets
- Validation study and stress analysis of the machine parts
- Development and fabrication of the machine
- Applications of the machine in the form of 3D models of the products

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# LITERATURE REVIEW

Vacuum Forming is a thermoforming process. Thermoforming is a manufacturing process which deals with the shaping of thermoplastics. In Thermoforming, a thermoplastic sheet is heated up to a specified forming temperature which makes it pliable, and then, using a pressure difference which causes a force, it is formed into the shape of a mold. There are two types of thermoforming process. Pressure Forming and Vacuum Forming. Pressure Forming is an upgrade over the basic vacuum forming process.

**Vacuum Forming Process**

In Vacuum Forming, a vacuum is used to shape the plastic. The basic steps, using a modern table sized machine, are:

1. The plastic sheet is first clamped and then heated up to the forming temperature. Usually, the heating takes about 40-50 seconds but depending on the thickness and the sheet material, this range can vary.
2. Application of the sheet on to the mold is the second step. It is important to ensure that a perfect seal is obtained between the sheet and the mold, to create a sealed space.
3. As soon as the sheet encounters the mold, the vacuum suction process starts using a vacuum pump. The air is sucked out, leading to a pressure difference which causes the pliable sheet to be formed.

4. Cooling of the sheet is the next step. Mostly, the sheet is allowed to cool at the room temperature for about 30 seconds.
5. The sheet is removed from the machine.
6. Trimming of the sheet to cut the unnecessary parts is the final step. After this, the vacuum formed product is complete.

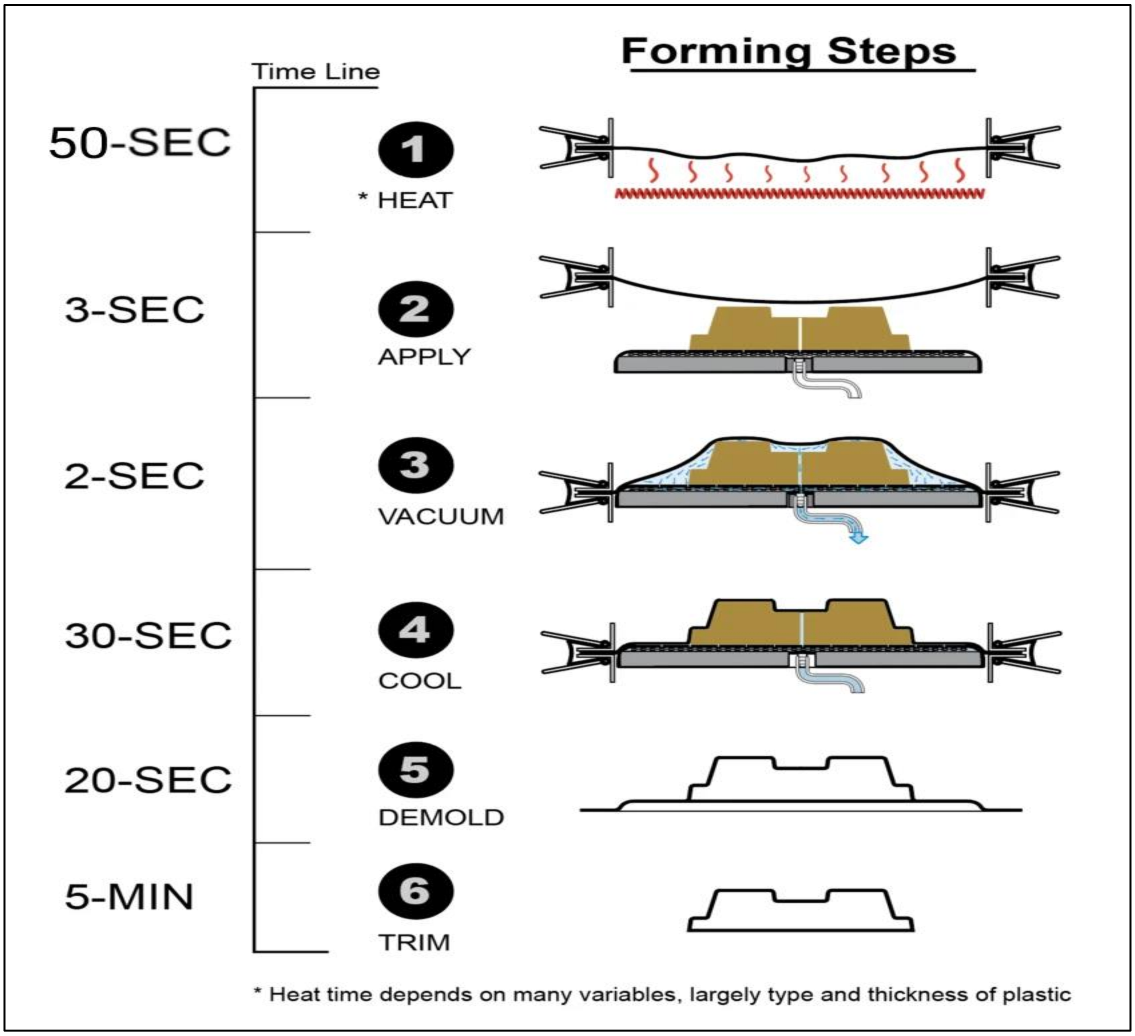



**Figure 1 : Vacuum Forming Steps [1]**

**Materials for Forming**

Some of commonly used thermoplastics are mentioned in the table [2]:

**Table 1 : Common plastics used for thermoforming and their uses**

| Name | Properties and uses |
|---|---|
| Polystyrene (PS) | Polystyrene is a low cost and highly used plastic for thermoforming. It is a brittle material, with low impact strength and poor weather resistance. Most commonly, it is named as general-purpose polystyrene (GPPS) and for higher impact strength, higher impact polystyrene (HIPS) is used. Common uses are in the packaging industry such as disposable plates and cups. |
| Acrylonitrile Butadiene Styrene (ABS) | ABS is an opaque amorphous thermoplastic. The Butadiene part increases impact strength and Styrene improve the formability. The acrylic results in a glossy finish. In thermoforming, it is mostly used in the production of shells and protective housings. |
| Polyvinyl Chloride (PVC) | PVC is a high strength, hard and rigid thermoplastic. It is a self-extinguishing material, which makes it suitable for any applications where flammability is a concern, such as transportation. PVC is used to make trays and some packaging material. |
| Polyethylene Terephthalate (PET) | PET is a crystalline material with a good resistance towards gas, alcohols, and some moisture. Since PET has been approved as a food grade plastic, it is commonly used to make bottles and in the manufacturing of disposables. It is also in high demand due to its recyclability. |

| | |
|---|---|
| High Density Polyethylene (HDPE) | HDPE has good strength and is heat resistant. It is a recyclable plastic, and it is nontoxic. In thermoforming, HDPE is used in marine applications, and products where crack and melt resistance is required. Low density polyethylene is used in flexible packaging of products. |
| Polymethyl methacrylate (PMMA or ACRYLIC) | PMMA is an amorphous thermoplastic, commonly known as Acrylic. It is transparent and has good weatherability. It is an alternate to glass and is used to make signs, windshields, outdoor and indoor lighting equipment etc. |

**Heating Mechanism**

There are basically three mode of heat transfer. Conduction, convection, and radiation. Both conduction and convection take up more time as compared to radiation. Usually both these methods are used in bulk thermoforming setups, but for portable vacuum forming machines, infrared heaters are the most popular ones [3].

For the sheet heating purposes, an infrared heating element with the sheet can be approximately modelled as two parallel plates subject to radiation heat transfer. For this case, it is known that the radiation heat transfer is given by [4]:

$$\dot{q} = \frac{\sigma({T_1}^4 - {T_2}^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$$

Where the $T_1$, $\epsilon_1$ are the heater temperature and emissivity, $T_2$, $\epsilon_2$ are the sheet temperature and emissivity and $\sigma$ is the Stefan-Boltzman constant. Using the above formula, the radiation heat intensity can be calculated, which is usually 45 Watts per square inch. [3].

To calculate the total energy required to heat the sheet up to the forming temperature, the basic heat energy equation is used [4]:

$$Q = mc_p\Delta T$$

Where $m$ is the mass of the material, $c_p$ is the specific heat capacity and $\Delta T$ corresponds to the temperature difference required. The above equation can be modified for plastic sheet thermoforming as:

$$Q = L \times w \times t \times \rho(c_p\Delta T)$$

Where $L$, $w$, $t$, $\rho$ correspond to the sheet length, width, thickness, and density. The above equation can be used for any sheet thickness and type.

Knowing the heater wattage, the ideal time for heating of the sheet can be calculated using the basic definition of Power [4]:

$$t = \frac{Q}{\dot{Q}}$$

Where $\dot{Q}$ is the heater rated wattage.

Since because of the inefficiencies and the view factor involved in radiation, it is very important that a uniform heating is achieved. Due to this, the heating rods must be arranged to compensate the heat loss to the edges. A possible arrangement for attaining uniform heating is [3]:

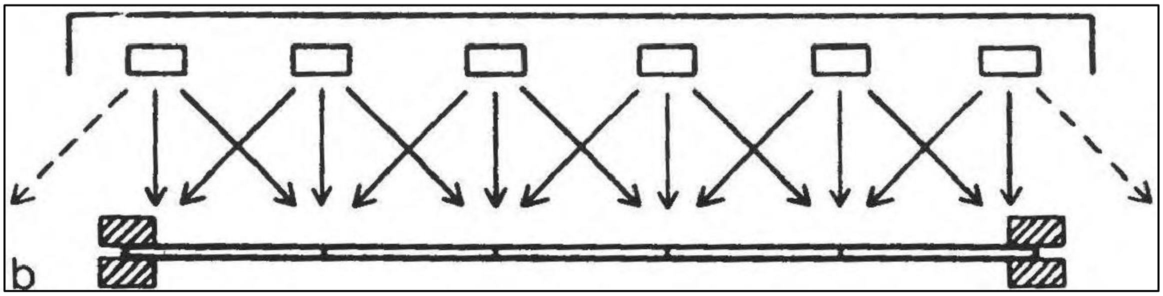



**Figure 2 : Heater configuration**

The forming temperatures differ for each type of plastic, but a reference can be used from literature as [2]:

**Table 2 : Forming Temperatures for different plastics in Degrees Celsius**

| Material | Lower Forming Temp | Normal Forming Temp | Upper Forming |
|---|---|---|---|
| ABS | 126.7 | 148.9 | 182.2 |
| Acrylic | 148.9 | 176.7 | 193.3 |
| Polycarbonate | 168.3 | 190.6 | 204.4 |
| PETE | 121.1 | 148.9 | 165.6 |
| HDPE | 126.7 | 146.1 | 182.2 |
| LDPE | 123.9 | 140.6 | 176.7 |
| PP | 143.3 | 160.0 | 165.6 |
| PS | 126.7 | 148.9 | 182.2 |
| PVC | 104.4 | 137.8 | 154.4 |

**Pneumatics Overview**

The project deals with the selection and assembly of pneumatic cylinders as will be discussed in the next section. A brief overview is provided in this section. The basics of all pneumatic actuators is based on Pascal's law. According to it, a change in pressure at one point in a confined fluid is transmitted through out the fluid.

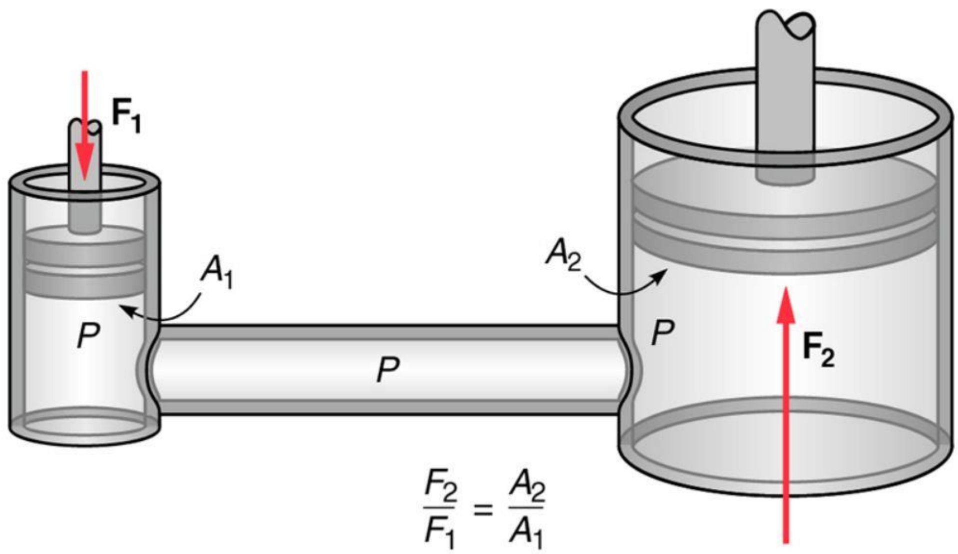



**Figure 3 : Pascal's Law explanation [5]**

An actuator is any component which is responsible for movement and performs a specific action. Pneumatic actuators work on air. Based on the action, there are two types of pneumatic cylinders. Single acting and double acting cylinders. A single acting pneumatic cylinder realizes a stroke only in one direction using compressed air and returns to its original state using a spring. A double acting cylinder consists of compressed air acting on both sides of the piston and the stroke can be realized in both directions depending on the pressure difference.

The forces during each extension and retraction are given by:

$$F_{ext} = P \times \frac{\pi {d_b}^2}{4}$$

$$F_{ret} = P \times \frac{\pi({d_b}^2 - {d_r}^2)}{4}$$

Where $P$ is the supplied gauge pressure, $d_b$ is the full-bore piston diameter and $d_r$ is the rod end diameter. Without going in further detail, the working of a double acting cylinder can be understood by this figure:

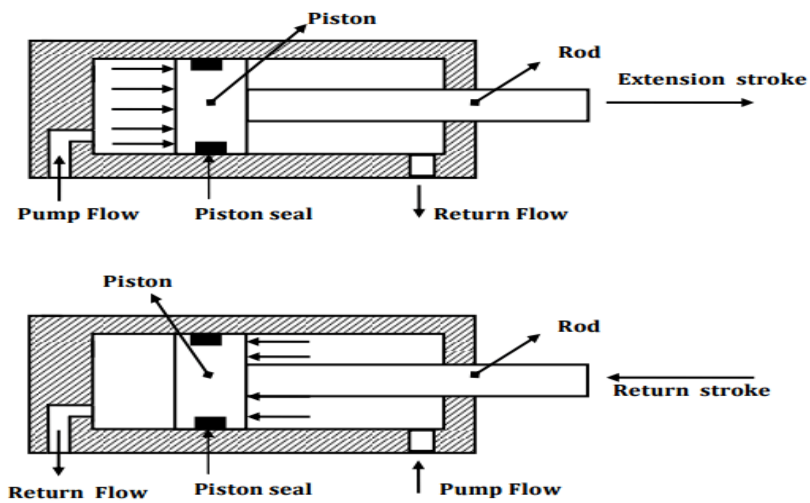



**Figure 4 : Working of Double acting cylinder [6]**

**Market Competition**

Vacuum Forming machines are offered in different sizes and designs. One way to easily categorize all the machines is by size of the forming area. Another way is to compare the actual size of the machines such a floor standing, desktop, large bed sized etc.


Figure 5 : Formech 2440 Large Format [7]

Figure 6 : Mayku FormBox [8]


Figure 7 : Formech 508 Floor Standing Machine [9]

As defined by the objectives of this project in the introduction, the forming area of our machine was pre-defined at 2 ft by 2 ft. This was done because plastic sheets are readily available in this size and most of the consumer products can be manufactured in this forming area.

The design of a floor standing machine can be distinguished based on the position of the heater and the amount of automation. A sliding heater design or an overhead heater can be used.

Figure 8 : Sliding heater design [10]


Figure 9 : Overhead heater design [11]

The primary advantage of a sliding heater design is compactness. With a fixed overhead heater, the height of the total machine increases. However, a balance between both the designs can be obtained using a pivoting heater design as:


**Figure 10 : Pivoting heater design [12]**

**Applications Overview**

There are vast applications of vacuum forming. Some of these are discussed below:

1. Automotive industry – Plastics reduce the weight and the overall cost of any part. Due to this inherent advantage, vacuum formed door panels, bumpers etc. Such parts also provide aesthetics and a cleaner look.
2. Protective housings and covers – Different kind of plastics can be used to provide impact resistance, environmental protection, and fire resistance. Due to ease of manufacturing complex shapes and the short production time, vacuum forming proves to be ideal for such applications. Some common examples include bumper covers for machines, protective packaging for sensitive components etc. [13]
3. Packaging – For designer and unique products, vacuum forming can be used to produce packaging of different kinds. Be it chocolate boxes, food containers,

makeup equipment or medical tools, vacuum formed containers are a perfect use for these. [14]

4. Marketing displays and logos – Using vacuum forming, complex 3d design logos, lightning covers can be easily designed using a 3d printer to make the mold and a vacuum former for actual display. Due to ever changing trends in marketing industry, the short production times provide an invaluable benefit. [15]
5. Rapid prototyping – For any 3d model, a mold using a 3d printer can be used to make a rapid prototype of the product. This can help in visualizing and detailing. [16]
6. Artistic and educational items – 3d topographical maps and artistic products such as face masks, mascots etc. can be developed using vacuum forming. [17]

# DESIGN

Different components of the machine are designed in Solidworks. The dimensions are iterated depending on the requirements, availability, and price. Mostly, the market standard, off the shelf structural components are used to reduce the manufacturing complexities. More focus was on the assembly of parts. Simple designs were followed. The design was divided into different parts, starting from the base frame.

The main components of the machine are:

1. L - Channel
2. Main frame assembly
3. Moving plate assembly
4. H - bar assembly
5. Heater assembly
6. Pneumatic actuators

Different assemblies in 3-D illustration and 2-D drawings of each part are presented below:

**L - Channel**

The basic L type channel was used in the base frame due to its design compatibility, as well as its availability in the market. The L channel provides structural rigidity to form the base frame. The material of the L – channel is Mild Steel. The width and height are of 3 inches and the thickness is $\frac{1}{8}$ inches. The cross section of the channel is shown:

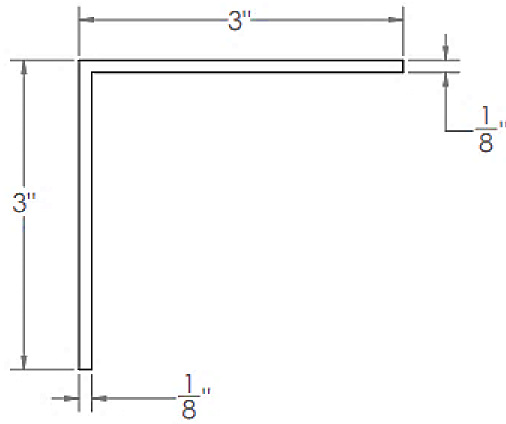



**Figure 11 : L Channel**

**Main frame assembly**

The main frame assembly consists of L – channels as described in the previous section. The thickness and the width of the bars are selected depending on the stress analysis carried out in SOLIDWORKS. The height of the machine is set out using the standard ergonomics, light assembly workbench height range [18]. The bars are cut out in appropriate length and are welded together to make the Frame A, Frame B, Frame C and vertical legs. All the frames and the vertical legs are welded for this final assembly. The dimensions of the frame are also mentioned. The frame C is placed at the distance from top found by the calculation of the actuator placement on it.

The frame B has two pneumatic bases which are C channels. These act as the base for the rear pivot end mountings of the actuators. Both the C channels will be welded to the frame B.

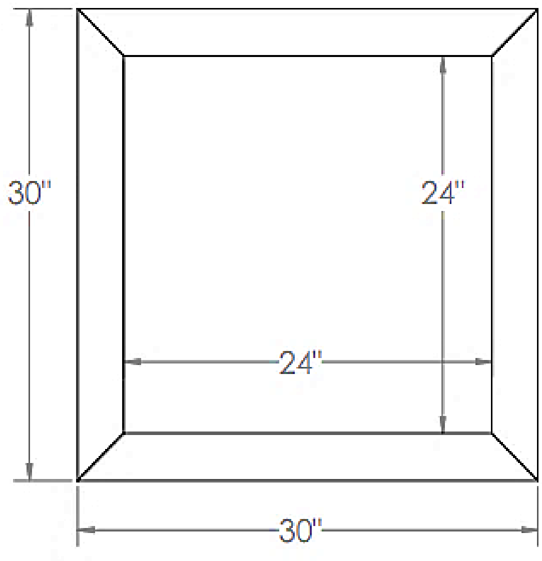



**Figure 12 : Frame A**

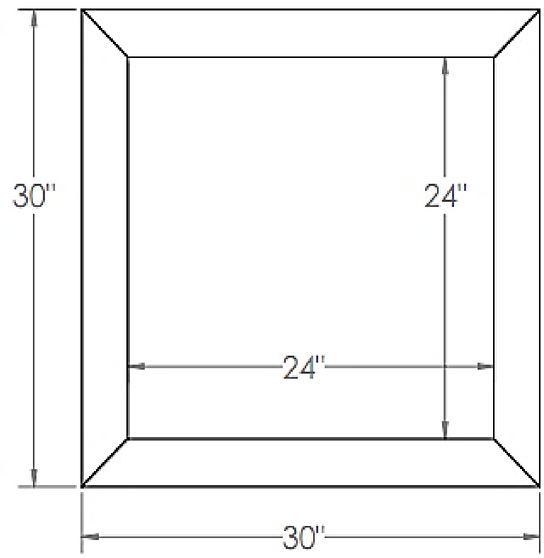



**Figure 13 : Frame B**

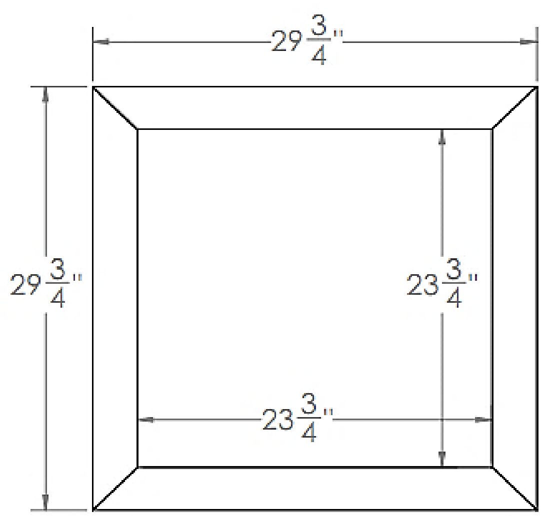



**Figure 14 : Frame C**

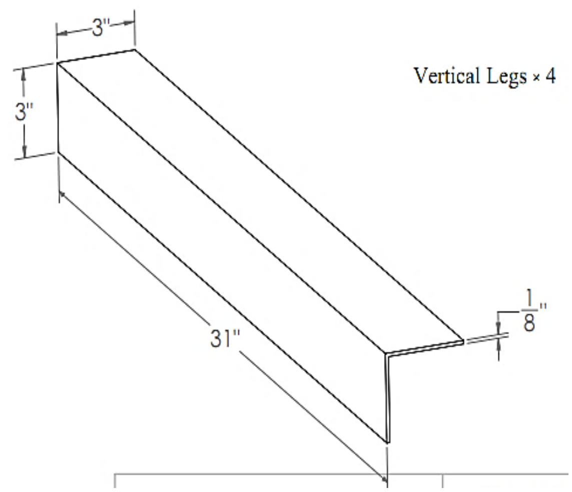



**Figure 15 : Vertical Legs**

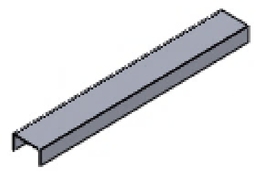


**Figure 16 : C channel for pneumatic base**

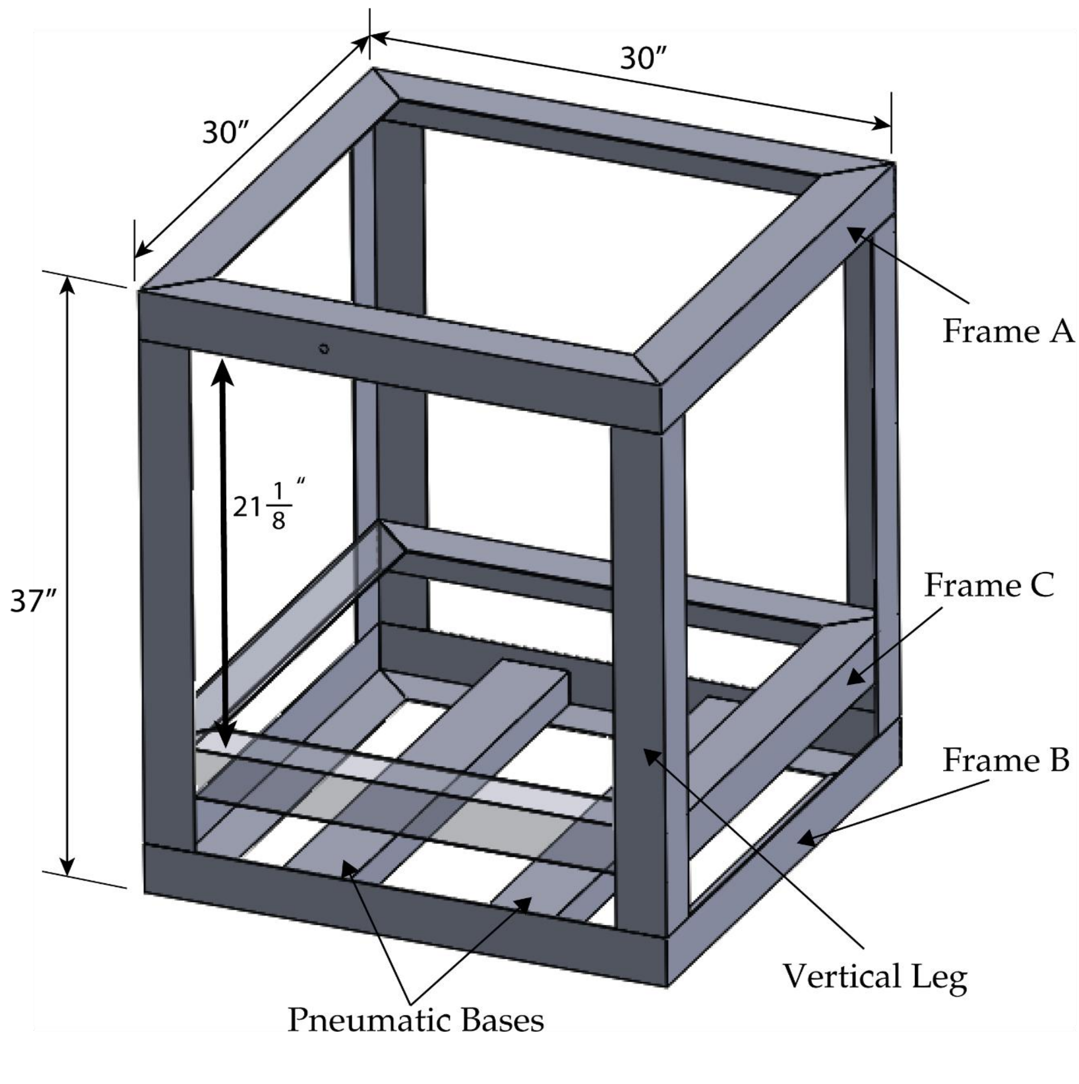



**Figure 17 : Main frame assembly**

**Moving Plate Assembly**

During operation, the mold is placed on the moving plate assembly and its movement is vertically controlled using the pneumatic actuators (50,300). This limit is set out by the stroke of the pneumatic actuators (50,300).

The forming area of the machine is 2 ft by 2 ft. The working area is less than the forming area of the machine, which turns out to be 1 ft 11 in. by 1 ft 11 in. The reduction in the actual forming area is due to the Silicon strip on the moving plate. This is done to ensure an airtight sealing between the H-bar (discussed in next section), the plastic sheet, and the moving plate.

The whole assembly consists of following parts:

- Moving Plate (Platen)
- Moving Plate reinforcement
- 2 Teflon grippers
- 2 U – supports for pneumatic actuators
- Silicon strip
- 2 Holding rods for Teflon grippers

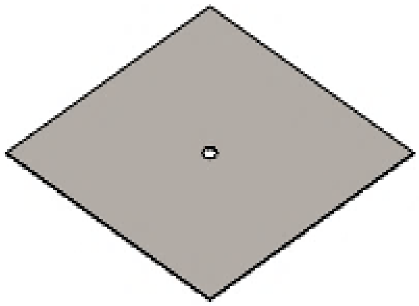


**Figure 18 : Moving plate (Platen)**

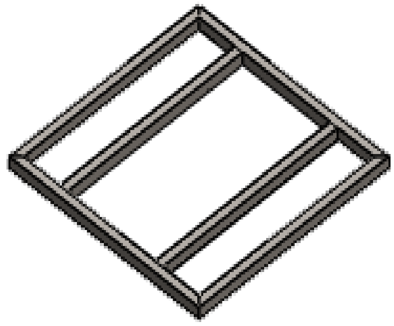


**Figure 19 : Moving plate reinforcement**

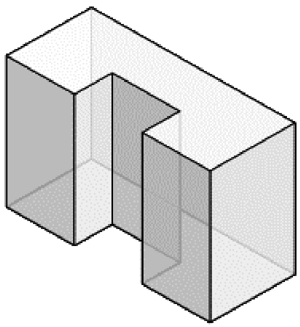


**Figure 20 : Teflon grippers**

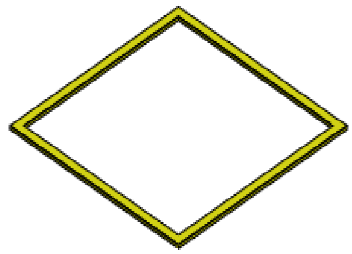


**Figure 21 : Silicon strip**

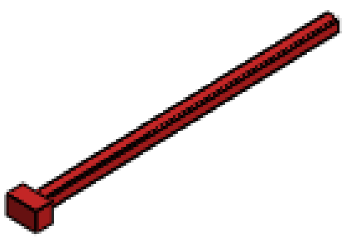


**Figure 22 : Holding rods**

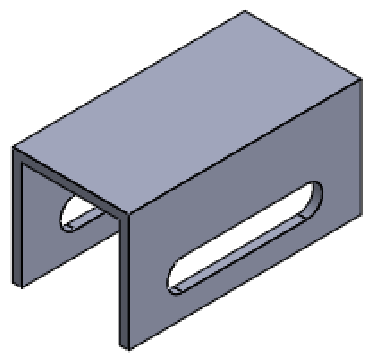


**Figure 23 : U support**

The Moving plate (platen) is welded to the to the Moving plate reinforcement. The reinforcement plate is added to the assembly to support the weight of the mold, and also to fix the U supports for the pneumatic actuators. The U supports are welded to the two main beams of the Moving plate reinforcement. Teflon gripers provide lubrication for the smooth movement of the moving plate. These grippers will be attached using nuts and bolts. The Holding rods will attached to the frame C using nuts and bolts. The dimension of the Moving plate are decided to ensure a close fit between the frame A and platen. The pneumatic actuators (50,300), in the fully extended position, bring the moving plate to the same level (height) as frame A.

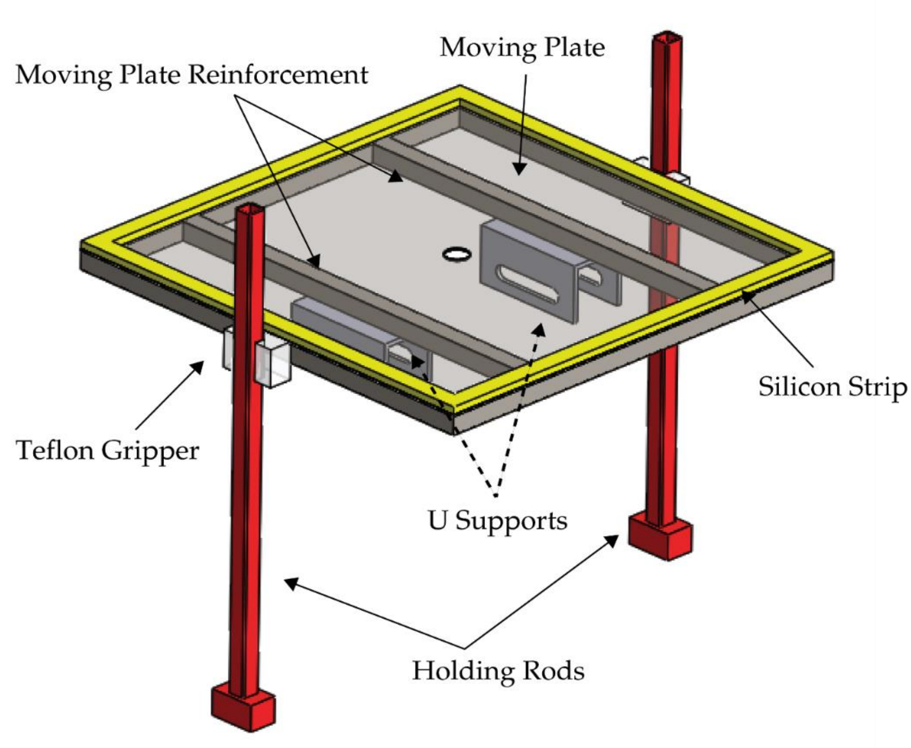



**Figure 24 : Moving Plate Assembly**

**H – bar assembly**

The H-bar assembly consists of :

- Blue plate
- H-bar
- H-bar support mechanism

The Blue plate is placed on the top of the frame to cover the top of the frame. The material of the plate is mild steel, and its gauge is 3mm. The two areas are cut out for the movement of pneumatic actuators (32,400). Two holes are drilled on the back of the plate to hold the springs of the H- bar support mechanism. A silicon strip is also placed on the top of it to make a sealed grip of H – bar against it as explained in the previous section.

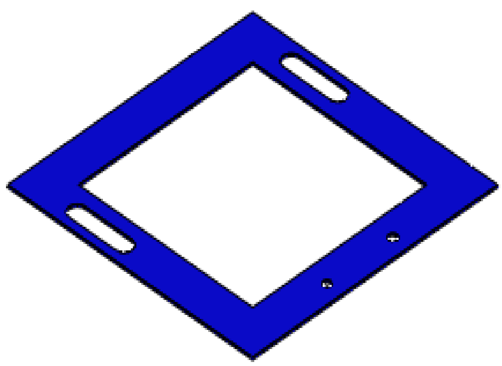


**Figure 25 : Blue plate**

The H – bar support mechanism is used to grip the sheet in position. It is fixed with the help of hinges and spring mechanism fixed on the blue plate. The support mechanism holds the H-bar in position when the actuators are fully stretched. The springs provides tight grip by storing the push of the actuator.

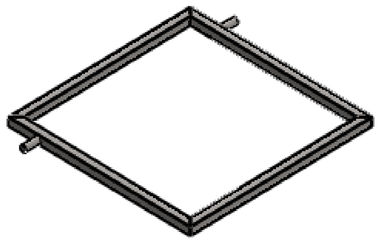


**Figure 26 : H-bar**

**Figure 27 : H-bar spring**

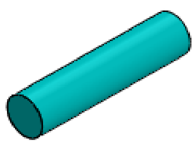


**Figure 28 : H-bar joint**

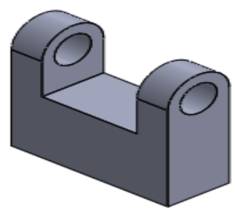


**Figure 29 : H-bar joint 2**

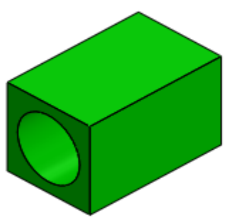


**Figure 30 : H-bar joint 3**

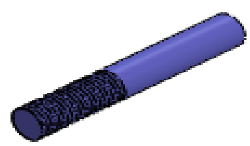


**Figure 31 : H-bar joint bolt**

The H-bar is connected with pneumatic actuators (32,400) for the controlled movement and grip of the H – bar against the silicon strip placed on the moving plate.

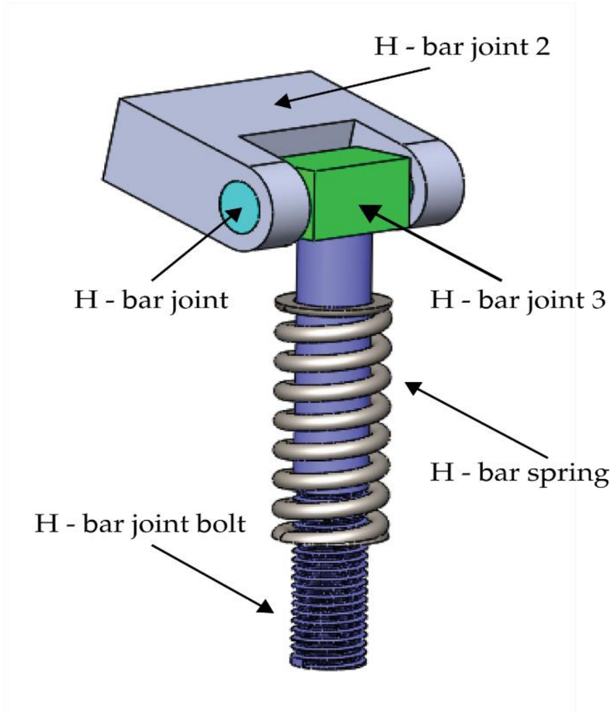



**Figure 32 : H bar support mechanism**

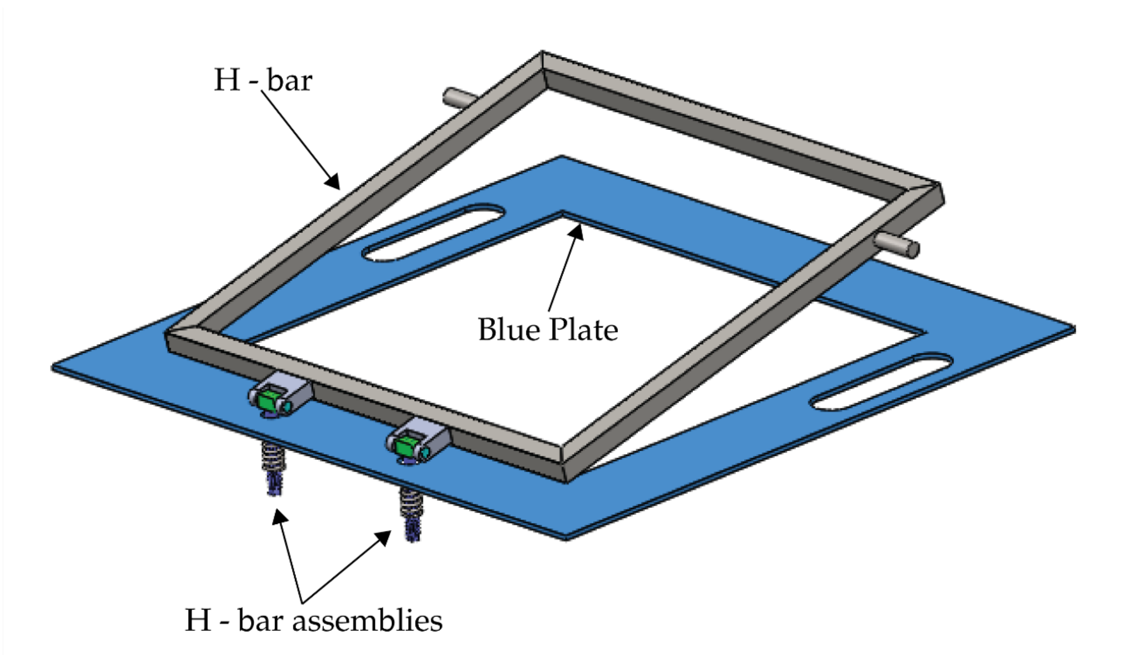



**Figure 33 : H bar assembly**

**Heater assembly**

The heater design calculations are based on the radiation model of two infinite parallel plates as discussed in the literature review. The heater calculations are based on the equation. The complete set of calculations is provided in the following table:

$$\dot{q} = \frac{\sigma({T_1}^4 - {T_2}^4)}{\frac{1}{\epsilon_1} + \frac{1}{\epsilon_2} - 1}$$

**Table 3 : Heater calculations**

| Radiation Heat Transfer Between Sheet & Heater | | | |
|---|---|---|---|
| Heater Temperature | $T_1$ | 300 | °C |
| Sheet Initial Temperature | $T_2$ | 25 | °C |
| emissivity of heater | $\varepsilon_1$ | 0.85 | |
| emissivity of Plastic sheet | $\varepsilon_2$ | 0.85 | |
| Boltzman Constant | $\sigma$ | 5.67E-08 | W/m^2 K^4 |
| Area of Sheet | A | 0.36 | m^2 |
| **Heat Flux** | $\dot{q}$ | **4187** | **W/m^2** |
| **Heater Power** | $\dot{Q}$ | **1507** | **W** |
| Total Heat Energy Required by the Sheet | | | |
| Sheet Initial Temperature | $T_2$ | 25 | °C |
| Forming Temperature | $T_1$ | 150 | °C |
| Thickness of Sheet | d | 0.5 | mm |
| Area of Sheet | A | 0.36 | m^2 |
| Density of Sheet | $\rho$ | 1200 | kg/m^3 |
| Specific Heat of Sheet | $c_p$ | 1920 | J/kg/K |
| **Total Heat Required** | | | |
| $Q = \rho A d * c_p * (T_1\text{-}T_2)$ | $Q$ | **51840** | **J** |
| **Time Required** | $t = \frac{Q}{\dot{Q}}$ | **34** | **sec** |

Based on these calculations, for 0.5 millimeters thick, 2ft by 2ft plastic sheet of ABS, about 1500-watt heater would be adequate. For the practical design, 5 quartz element heaters of about 400-watt each would be used since due to the inefficiencies, we can expect the time required for the heating to be more than 34 seconds.

**Figure 34 : Quartz IR element**

The function of heater assembly is to soften the plastic sheet up to the defined temperature for the sheet. The movement of the sheet is controlled by actuators set of (32,100). These are attached on the opposite sides of the heater box. The heating rods are arranged inside the heating box. The heating box is made of 2mm gauge. It is made electrically insulated. The thermal insulation is also done to prevent it from heating up.

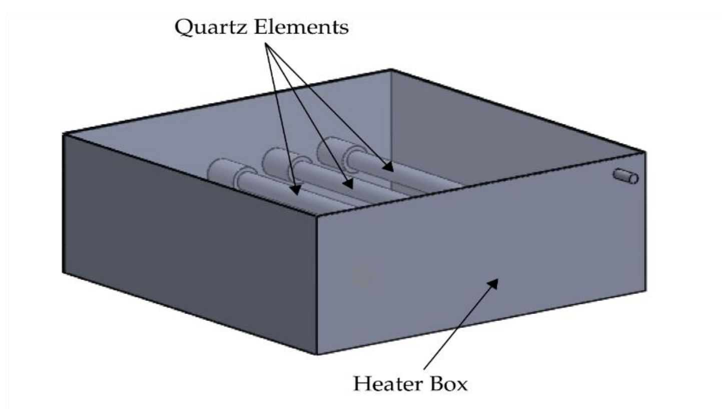



**Figure 35 : Heater assembly**

**Pneumatic actuators:**

All the pneumatic actuators are double acting, single rod and of tie rod construction. The actuator selection was based on the formulae given in the literature review for the extension force. The operating pressure was set to 5 bars as this was based on the available compressor pressure. All the actuators are controlled by 5/2-way solenoid valves, which will in turn be operated using DC supply of 12 volts and switches. The table shows that 32 mm and 50 mm bore actuators were selected and the strokes were chosen based on the main frame height and the extension lengths required for the heater.

**Table 4 : Actuator calculations**

| Bore | Pressure | Force | Mass | x2 |
|---|---|---|---|---|
| mm | bar | N | kg | kg |
| ***32*** | ***5*** | ***402.1*** | ***41.0*** | ***82.0*** |
| 40 | 5 | 628.3 | 64.0 | 128.1 |
| ***50*** | ***5*** | ***981.7*** | ***100.1*** | ***200.2*** |
| 63 | 5 | 1558.6 | 158.9 | 317.8 |
| 80 | 5 | 2513.3 | 256.2 | 512.4 |
| 100 | 5 | 3927.0 | 400.3 | 800.6 |

**Table 5 : Selected strokes**

| Stroke | |
|---|---|
| Heater actuators | 100 mm |
| Moving Plate actuators | 400 mm |
| Base plate actuators | 300 mm |

**Pneumatic actuators (32,100)**

This set of pneumatic actuators is attached with the heater box and main frame. The bore and the stroke of the actuator are designed by the calculation of the movement of the heater assembly, which is based on the geometry and pin location on the heater box and the frame. One of the connections of the actuator is with pin on the heater box. The other is between the ball bearing, rod eye end and the main frame.

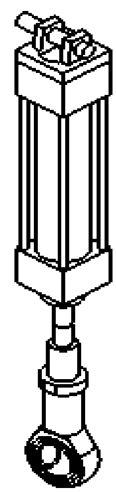


**Figure 36 : Pneumatic cylinder - (32 100)**

**Pneumatic actuators (32,400)**

This set of pneumatic actuators is attached with the Frame C and the H – bar frame. The bore and the stroke of the actuator are designed by the calculation of the movement of the H - bar assembly. One of the connections of the actuator is with pin on the H – bar frame by the ball bearing, rod eye end of the actuator. The other connection is between the rear pivot end and the Frame C.

**Figure 37 : Pneumatic cylinder - (32,400)**

**Pneumatic actuators (50,300)**

This set of pneumatic actuators is attached with the moving plate assembly and the Frame B. The bore and the stroke of the actuator are designed by the calculation of the movement of the moving plate assembly, which is specified by the machine height and force requirements. One of the connections of the actuator is with sleeve through the U – shaped supports by the ball bearing, rod eye end. The other connection is on the pneumatic bases on frame B.

**Figure 38 : Pneumatic cylinder - (50,300)**

All the components of the machine as discussed in the Manufacturing plan are assembled and the Final design of the vacuum forming machine for 2 feet by 2 feet size plastic sheet is shown:

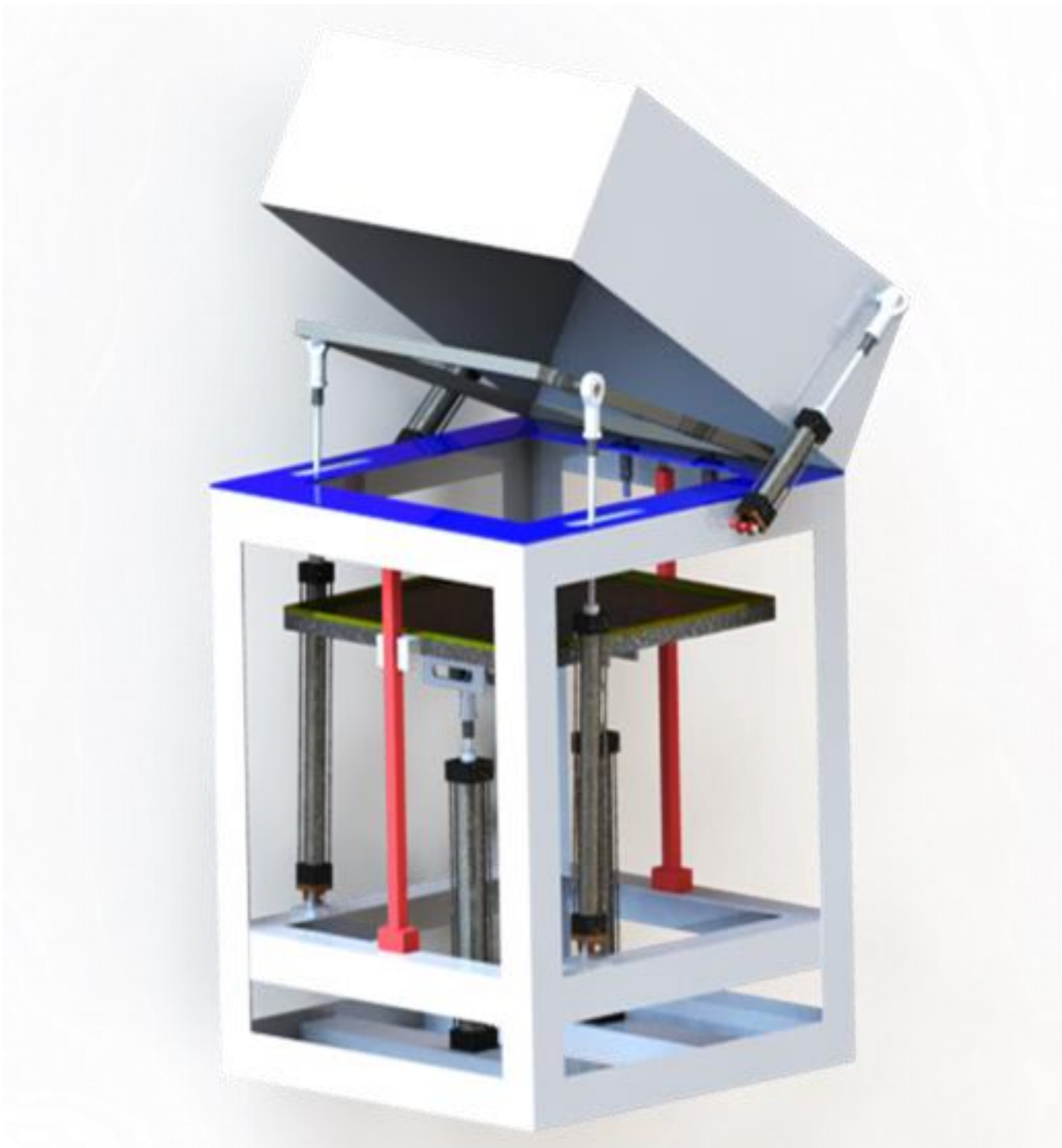


**Figure 39 : Final 3D Design**

# ANALYSIS

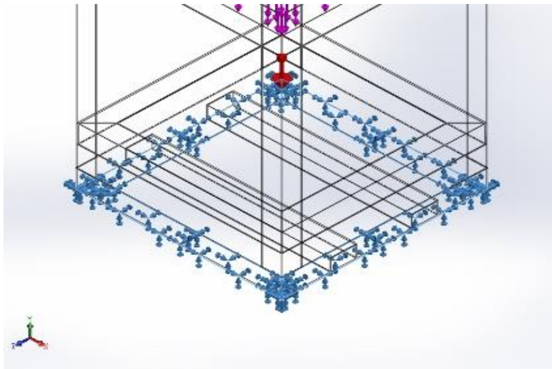
The static analysis of different critical components of the machine is done in Solidworks Simulation. The parameters for the analysis were von misses stress and resultant displacement in each component. The stress, strain and displacement analysis results are plotted and compared with failure criterion of the material to ensure that the structure does not fail under the working load conditions. The analysis of main frame, moving plate assembly and H – bar assembly is done by setting constraints and loading boundary conditions for each component.

**Main Frame**

The vertical legs of the main frame are analyzed by the perpendicular downward load on the frame A. The frame A, frame B and frame C are made rigid in the analysis to calculate stresses just for the vertical components of the structure which are of critical importance. The vertical force is applied in downward direction on the frame A and the whole frame is made fixed on the bottom surface of the frame C.

The steps for the analysis are:

- Static study for the analysis is selected.
- Select the type of the material for the components and the mild steel for all the frames and vertical angles.
- Select the Frame A, Frame B and Frame C and make them rigid.
- Select the bottom surface of the Frame B and make a fix joint.
- Select the top surface of the Frame A and the vertical load of 250 N is applied in downward direction.



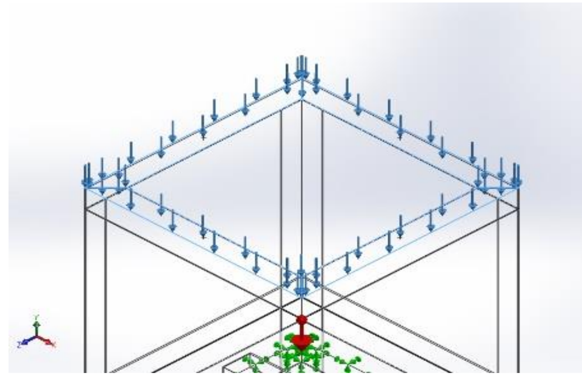


**Figure 40 : Main frame fixation** **Figure 41 : Main frame applied load**

- The material properties along with the mesh information of the frame model is presented below:

**Table 6 : Material properties and Mesh details**

| Material Properties | | Mesh Details | |
|---|---|---|---|
| **Name** | Mild Steel | **Mesh type** | Mixed Mesh |
| **Model type** | Linear Elastic Isotropic | **Mesher Used** | Standard mesh |
| **Default failure criterion** | Max von Mises Stress | **Jacobian points for High quality mesh** | 16 Points |
| **Yield strength** | 4.40422e+08 N/m^2 | **Element Size** | 1.63838 in |
| **Tensile strength** | 3.73826e+08 N/m^2 | **Tolerance** | 0.0819189 in |
| **Elastic modulus** | 2.05e+11 N/m^2 | **Mesh Quality** | High |
| **Poisson's ratio** | 0.29 | **Total Nodes** | 15261 |
| **Mass density** | 7,700 kg/m^3 | **Total Elements** | 7357 |
| **Shear modulus** | 7.9e+10 N/m^2 | | |
| **Thermal expansion coefficient** | 1.3e-05 /Kelvin | | |

**Moving Plate Assembly**

The moving plate and the reinforced frame of the moving plate are analyzed by the vertical downward load on the top surface of the silicon strip and the vertical plate. The

Teflon gripper and the U – shaped connectors are made rigid in the analysis. The vertical force is applied in downward direction on the silicon and moving plate and the whole frame is made fixed by U – shaped connectors and Teflon grippers.

The steps for the analysis are:

- The static study is selected for the analysis.
- Select the type of the material for the components as the silicon for silicon strip and stainless steel for the moving plate sheet.
- Select the U – connectors and Teflon and make them rigid.
- Make the Teflon fixed in the space.
- Select all the faces of the U - connectors and make a fix joint presented by blue portion as shown in the image.
- Select the top surface of the moving plate sheet and the silicon strip and the vertical load of 200 N is applied in downward direction.

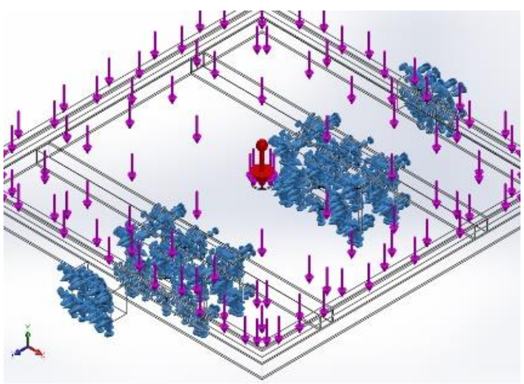


**Figure 42 : Boundary conditions**

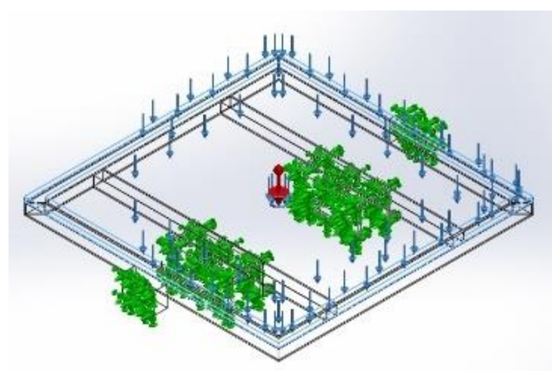


**Figure 43 : Applied loading**

- The material properties along with the definition of connection is shown:

**Table 7 : Material Properties**

| Material Properties | | | |
|---|---|---|---|
| **Name** | **1023 Carbon Steel Sheet (SS)** | **Silicon** | **Nylon 6/10** |
| **Model type** | Linear Elastic Isotropic | Linear Elastic Isotropic | Linear Elastic Isotropic |
| **Yield strength** | 2.82685e+08 N/m^2 | 1.2e+08 N/m^2 | 1.39043e+08 N/m^2 |
| **Tensile strength** | 4.25e+08 N/m^2 | 1.124e+11 N/m^2 | 1.42559e+08 N/m^2 |
| **Elastic modulus** | 2.05e+11 N/m^2 | 0.28 | 8.3e+09 N/m^2 |
| **Poisson's ratio** | 0.29 | 2,330 kg/m^3 | 0.28 |
| **Mass density** | 7,858 kg/m^3 | 4.9e+10 N/m^2 | 1,400 kg/m^3 |
| **Shear modulus** | 8e+10 N/m^2 | | 3.2e+09 N/m^2 |
| **Thermal expansion coefficient** | 1.2e-05 /Kelvin | | 3e-05 /Kelvin |

- The mesh information of the frame model is presented below, and the meshed model is also shown:

**Table 8 : Mesh details**

| | |
|---|---|
| **Total Nodes** | 21178 |
| **Total Elements** | 11086 |
| **Mesh type** | Mixed Mesh |
| **Mesher Used:** | Standard mesh |
| **Jacobian points for High quality mesh** | 16 Points |
| **Element Size** | 26.3371 mm |
| **Tolerance** | 1.31685 mm |
| **Mesh Quality** | High |

## Hold Rod

The side railing/ Hold rod keeps the moving plate in its place during its vertical motion and prevents the side movement in the plane perpendicular to its plane of motion. It is analyzed under surface load condition as the Teflon gripper applies force in this case. It is analyzed by the transverse load on the one surface of the hold rod. The force is applied in transverse direction on the rod and the rod is made fixed on both ends of the rod.

The steps for the analysis are:

- The static study is selected for the analysis.
- Select the type of the material as steel alloy for Hold Rod.
- Select all the faces of the ends of the Hold Rod and make a fix joint presented by blues portion as shown in the image.
- Select the left surface of the Hold Rod and the transverse load of 50N is applied as shown in blue arrows below:

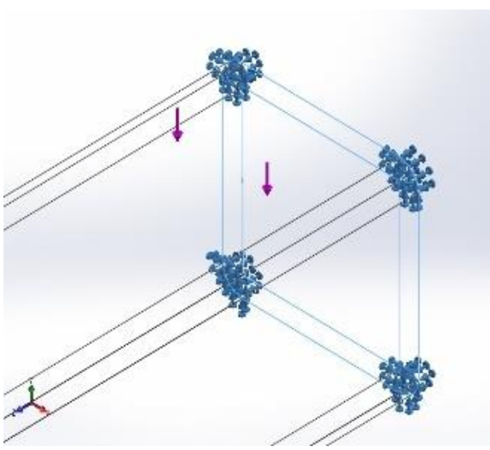


**Figure 44 : Boundary condition**

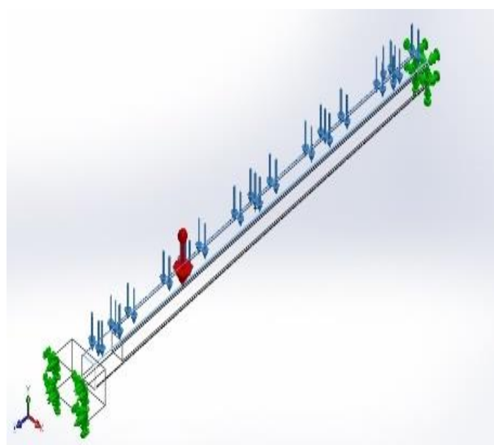


**Figure 45 : Applied load**

- The material properties along with the mesh details is shown in the given table below:

**Table 9 : Material properties and Mesh details**

| **Material Properties** | | **Mesh Details** | |
|---|---|---|---|
| **Name** | Mild Steel | Total Nodes | 18932 |
| **Model type** | Linear Elastic Isotropic | Mesh type | Solid Mesh |
| **Default failure criterion** | Max von Mises Stress | Mesher Used: | Standard mesh |
| **Yield strength** | 4.40422e+08 N/m^2 | Jacobian points for High quality mesh | 16 Points |
| **Tensile strength** | 3.73826e+08 N/m^2 | Element Size | 6.97545 mm |
| **Elastic modulus** | 2.05e+11 N/m^2 | Tolerance | 0.348772 mm |
| **Poisson's ratio** | 0.29 | Mesh Quality | High |
| **Mass density** | 7,700 kg/m^3 | Total Elements | 10015 |
| **Shear modulus** | 7.9e+10 N/m^2 | Maximum Aspect Ratio | 10.834 |
| **Thermal expansion coefficient** | 1.3e-05 /Kelvin | % of elements with Aspect Ratio < 3 | 31.2 |

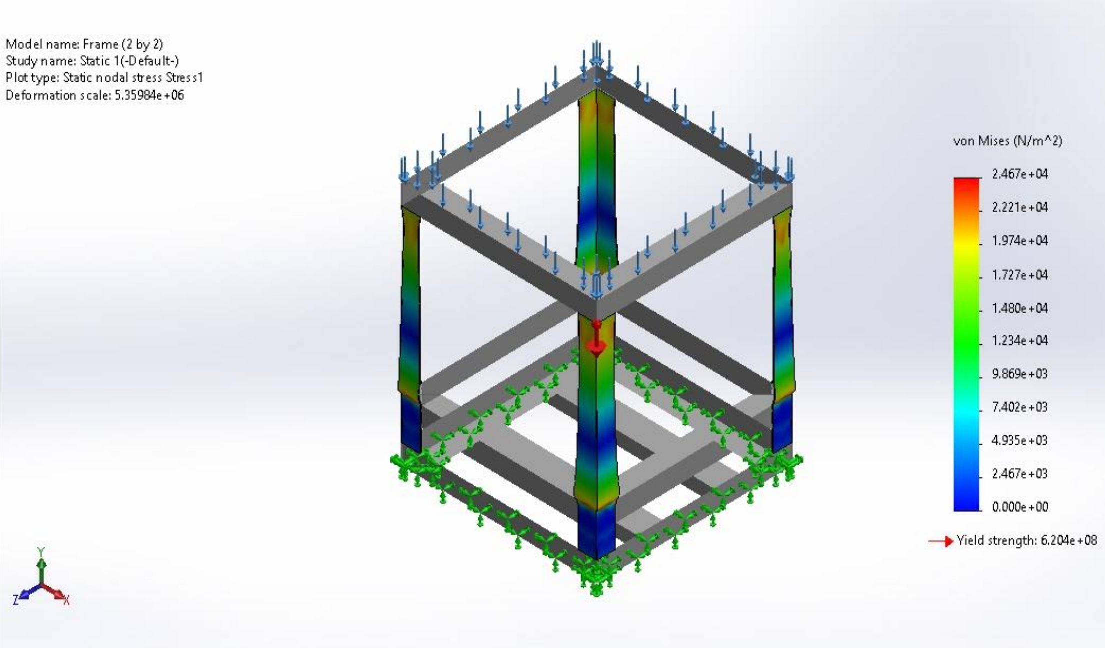
# RESULTS & DISCUSSIONS

All the critical components are analyzed on the defined parameters and the plots of resulting Stress, Strain and displacements for each component are obtained. These computational results have been compared with intrinsic properties of the material to verify the safety of the structure and validate the material and design selection. The regions of the plot represent the values of required parameter.

**Main Frame**

- **Stress**

| Name | Type | Min | Max |
|---|---|---|---|
| Stress | VON: von Mises Stress | 0.000e+00N/m^2<br>Node: 4282 | 2.467e+04N/m^2<br>Node: 1181 |



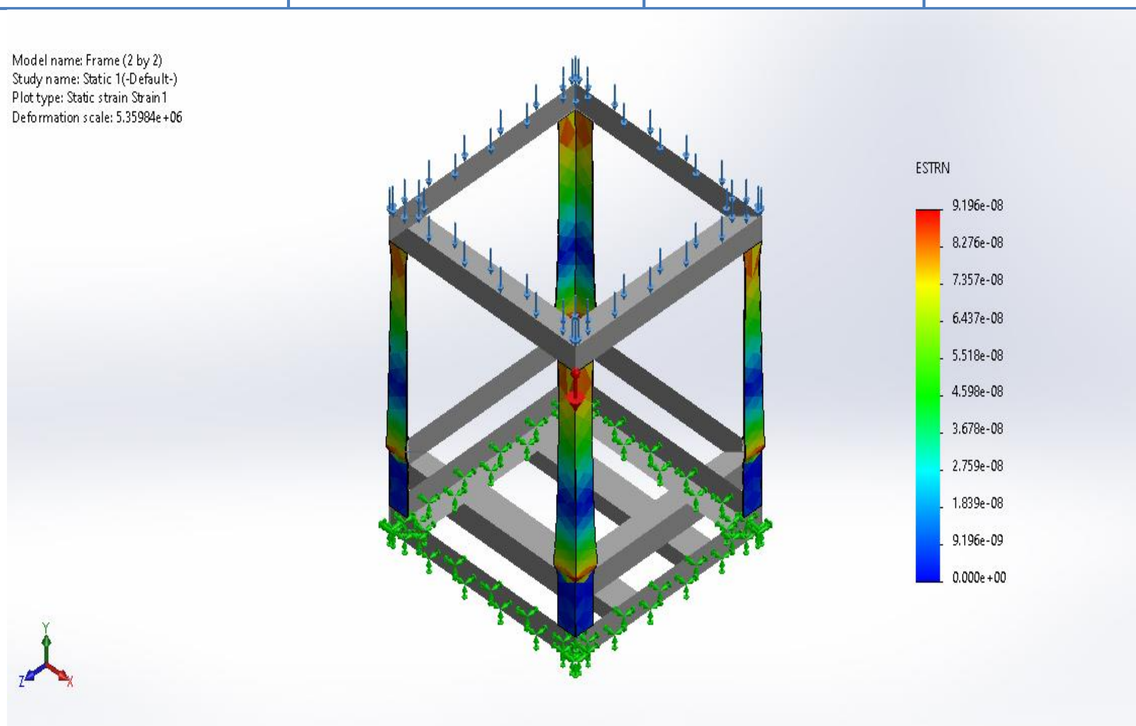

Frame (2 by 2)-Static 1-Stress-Stress1

**Figure 46 : Stress results for Main frame**

The von mises stresses are calculated for the vertical supports. The maximum stress is 24.67 kPa however the yield strength of the alloy steel is 620 MPa. It is in allowable limit of deformation.

- **Strain**

| Name | Type | Min | Max |
|---|---|---|---|
| Strain | ESTRN: Equivalent Strain | 0.000e+00<br>Element: 1882 | 9.196e-08<br>Element: 663 |



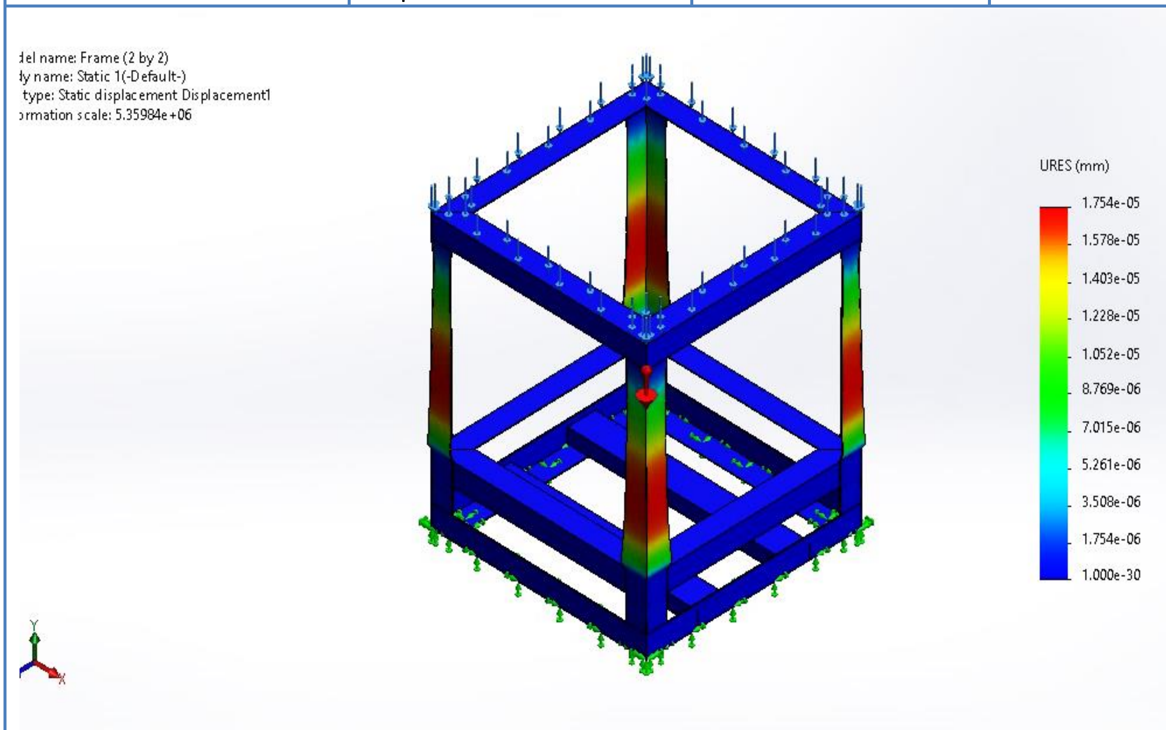

Frame (2 by 2)-Static 1-Strain-Strain1

**Figure 47 : Strain results for Main frame**

The strain in equivalent value is calculated for the vertical supports. The maximum strain value is $9.19 \times 10^{-8}$. And the deformation is scaled to $5.35 \times 10^{+6}$. The value of strain is very negligible.

- **Displacement**

| Name | Type | Min | Max |
|---|---|---|---|
| Displacement | URES: Resultant Displacement | 0.000e+00mm<br>Node: 4282 | 1.754e-05mm<br>Node: 2213 |




Frame (2 by 2)-Static 1-Displacement-Displacement1

**Figure 48 : Displacement results for Main frame**

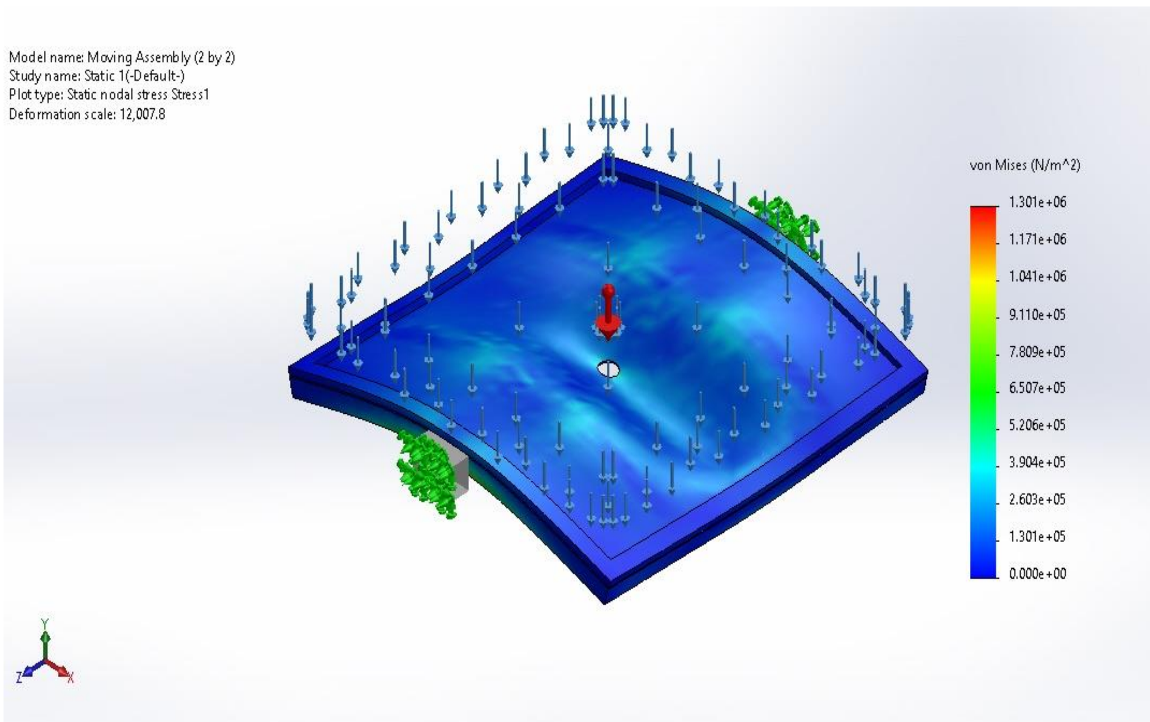
The values of displacement or the deformation are shown for the vertical supports. The maximum value of the deformation is 17.54 $\mu$ m. The value of deformation is negligibly small compared to the total dimensions of the machine frame. Therefore, it can be concluded that the vertical supports and the frame assembly does not fail under the applied load condition.

**Moving Assembly**

The study result of the moving assembly analysis is shown below:

- **Stress**

| Name | Type | Min | Max |
|---|---|---|---|
| Stress | VON: von Mises Stress | 0.000e+00N/m^2 Node: 19275 | 1.301e+06N/m^2 Node: 14378 |



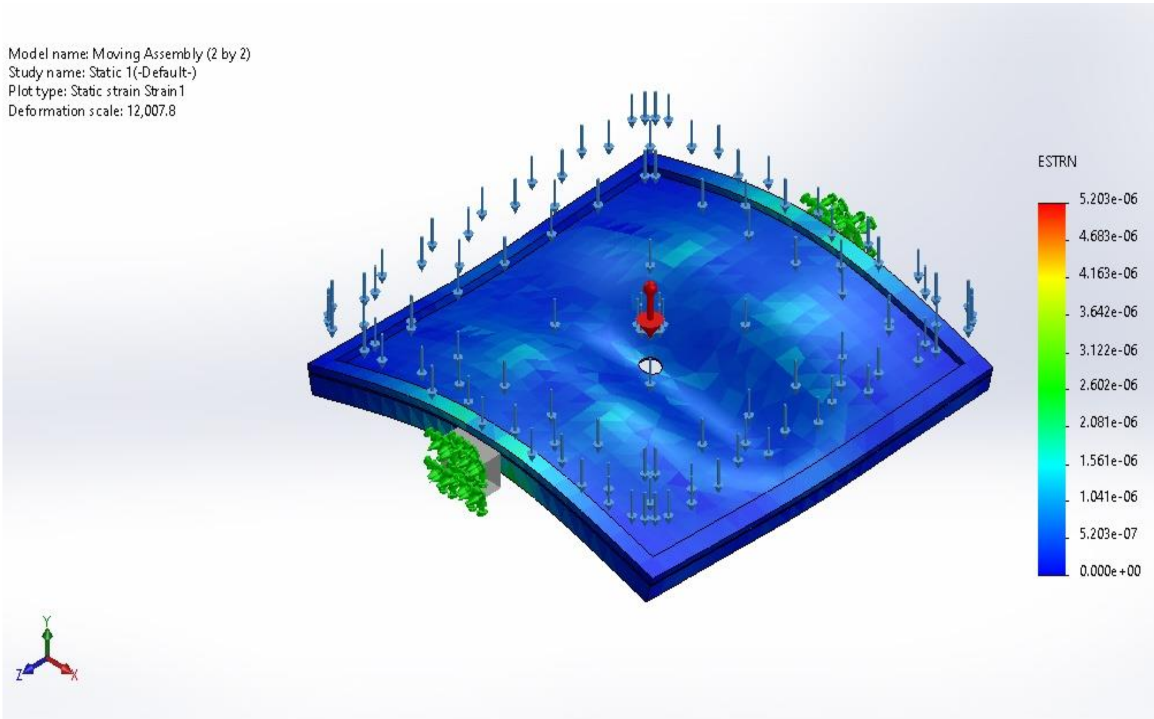

Moving Assembly (2 by 2)-Static 1-Stress-Stress1

**Figure 49 : Stress results for Moving frame**

The values of von mises stresses are calculated for the moving plate and silicon portion. The maximum stress is 1.30 MPa however the yield strength of the Carbon steel is 282 MPa and of silicon is 120 MPa. From the plot of stress, it can be interpreted that the value of stress is in allowable limit of deformation.

- **Strain**

| Name | Type | Min | Max |
|---|---|---|---|
| Strain | ESTRN: Equivalent Strain | 0.000e+00<br>Element: 10135 | 5.203e-06<br>Element: 8435 |



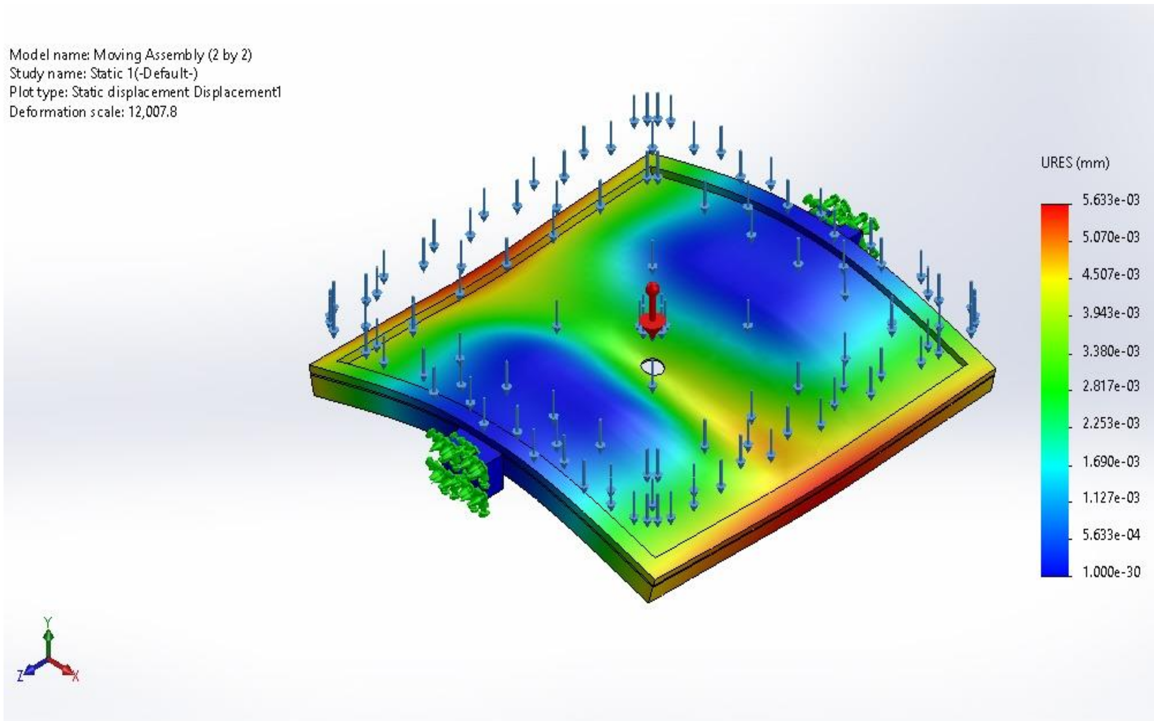

Moving Assembly (2 by 2)-Static 1-Strain-Strain1

**Figure 50 : Strain results for Moving frame**

The strain in equivalent value is calculated for the vertical supports. The maximum strain value is $5.20 \times 10^{-6}$. And the deformation is scaled to 12007.8. The value of strain is very small. From the plot of stress, it can be interpreted that the value of stress is in allowable limit of deformation hence validating the selection of the material and design.

- **Displacement**

| Name | Type | Min | Max |
|---|---|---|---|
| Displacement | URES: Resultant Displacement | 0.000e+00mm Node: 19275 | 5.633e-03mm Node: 10376 |




Moving Assembly (2 by 2)-Static 1-Displacement-Displacement1

**Figure 51 : Displacement results for Moving frame**

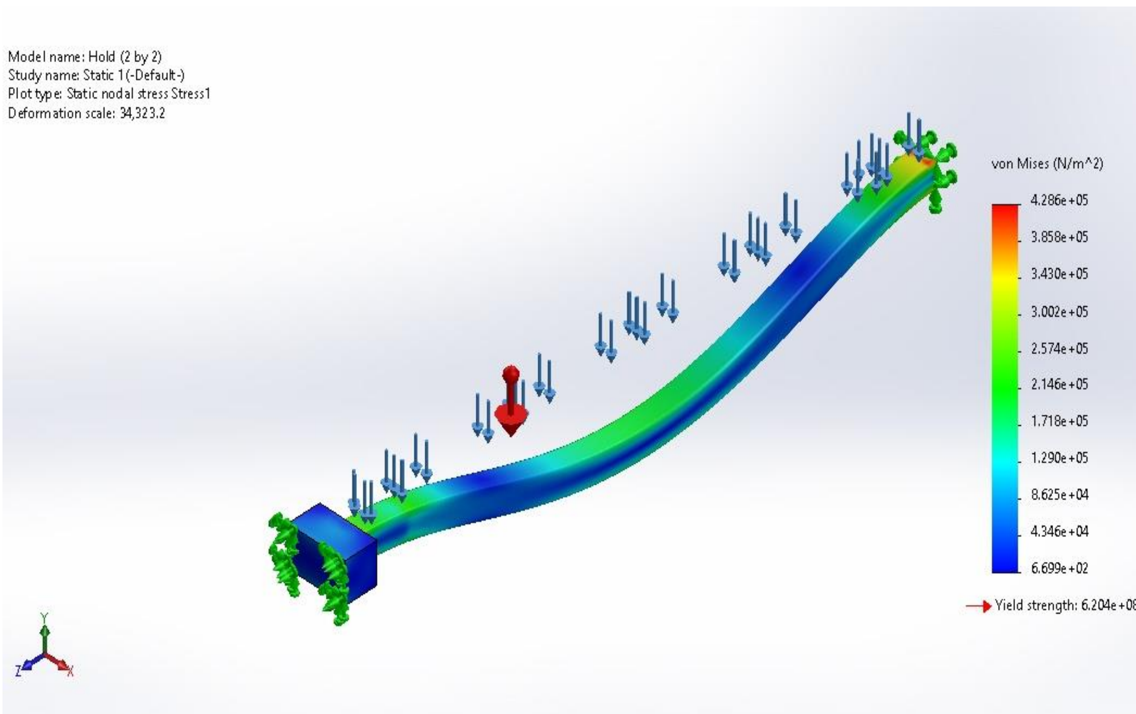
The values of displacement or the deformation are shown for the vertical supports. The maximum value of the deformation is 5.63 $\mu$ m. The value of deformation is negligibly small compared to the dimensions of the moving plate assembly meaning that the vertical supports does not fail under this load condition.

### Holding Rod

The study result of the Holding Rods analysis is shown below:

- **Stress**

| Name | Type | Min | Max |
|---|---|---|---|
| Stress | VON: von Mises Stress | 6.699e+02N/m^2 Node: 15805 | 4.286e+05N/m^2 Node: 818 |



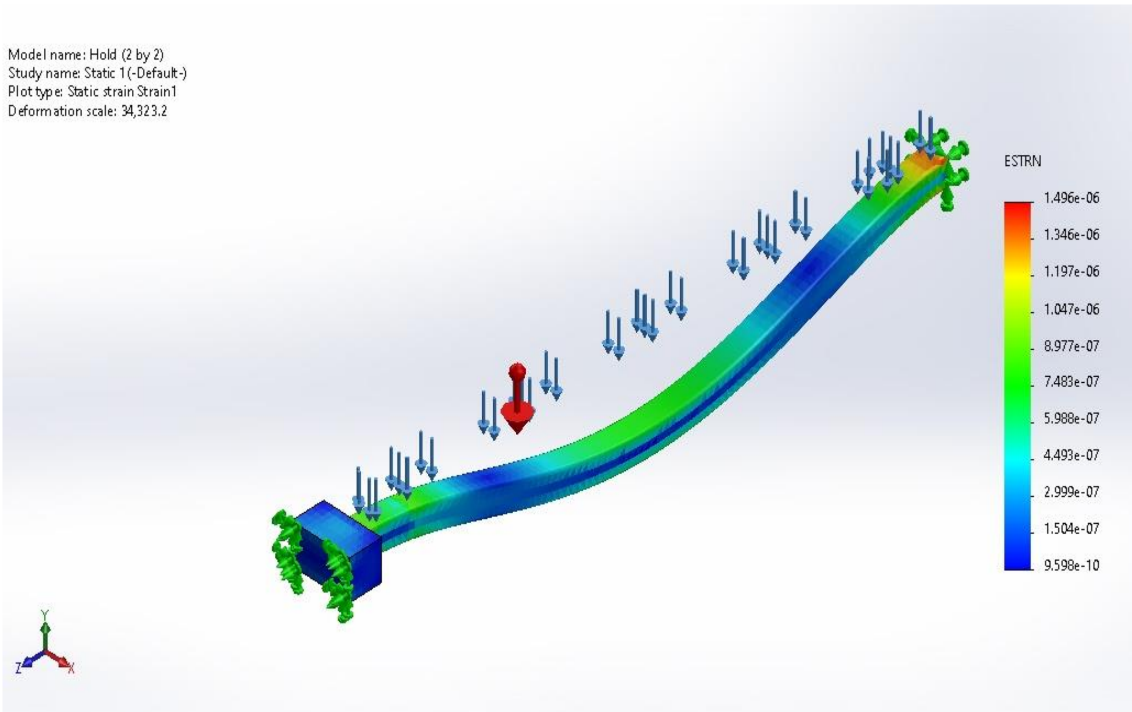

Hold (2 by 2)-Static 1-Stress-Stress1

**Figure 52 : Stress results for Holding rods**

The values of von mises stresses are calculated for the moving plate and silicon portion. The maximum stress is 428 kPa however the yield strength of the Alloy steel is 620 MPa. From the plot of stress, it can be interpreted that the value of stress is in allowable limit of deformation.

- **Strain**

| Name | Type | Min | Max |
|---|---|---|---|
| Strain | ESTRN: Equivalent Strain | 9.598e-10<br>Element: 4878 | 1.496e-06<br>Element: 9423 |



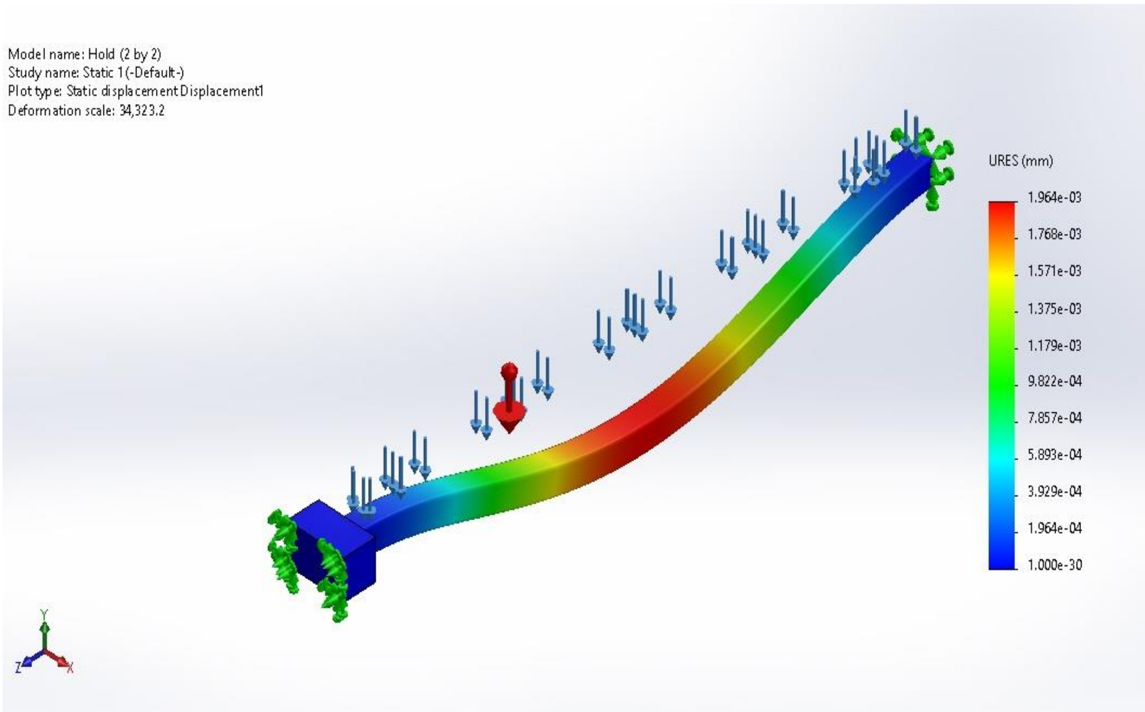

Hold (2 by 2)-Static 1-Strain-Strain1

**Figure 53 : Strain results for Holding results**

The strain in equivalent value is calculated for the vertical supports. The maximum strain value is $1.49 \times 10^{-6}$. And the deformation is scaled to 34323.2. The value of strain is very small. From the plot of stress, it can be interpreted that the value of stress is in allowable limit of deformation meaning that there is no chance of design or material failure.

- **Displacement**

| Name | Type | Min | Max |
|---|---|---|---|
| Displacement | URES: Resultant Displacement | 0.000e+00mm Node: 73 | 1.964e-03mm Node: 11121 |




Hold (2 by 2)-Static 1-Displacement-Displacement1

**Figure 54 : Displacement results for Holding rods**

The values of displacement or the deformation are shown for the vertical supports. The maximum value of the deformation is 1.96 $\mu$ m. The value of deformation is negligibly small compared to the actual dimensions of the rod therefore it can be interpreted from the results that the vertical supports do not fail under this load condition.

# APPLICATIONS

Vacuum forming machine has wide range of applications due to its easy and simple manufacturing process. Products of various sizes, shapes and geometry can be manufactured through it. Here, some applications of the vacuum forming machine and the products made from the machine have been discussed that were part of this project.

### 3D Geographical Terrains

Blender software is used to develop the 3D topographical models of Karakoram Range and K2 peak. The data of the elevation of the terrains from different locations on the earth is captured and presented in the plastic models. These software developed models are easy to be 3D printed to make the molds and these molds can be used to develop the products from plastic sheet. The spread of information presented by the terrain models depends on the available operating area. The models developed are very handy and useful to promote tourism industry in the country and can also be used for educational purposes.

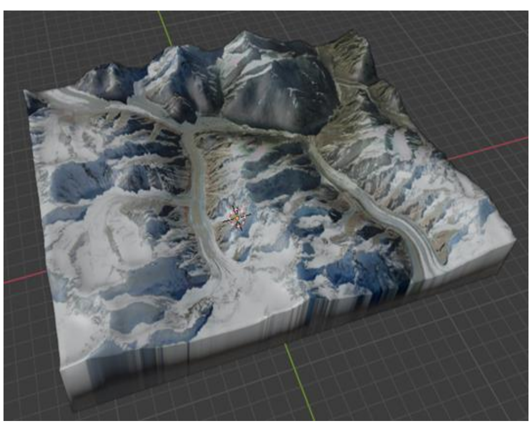


**Figure 55 : Karakoram range**

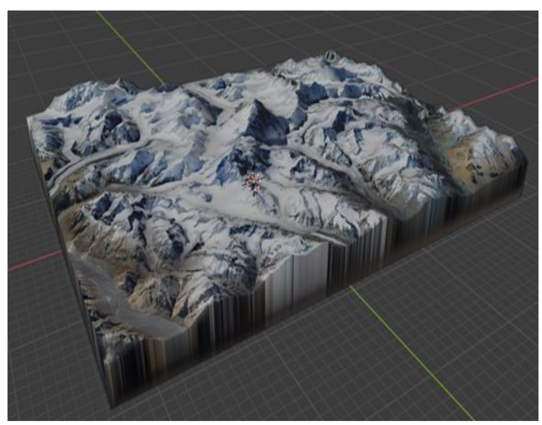


**Figure 56 : K2 peak**

## Packaging Products

The packaging products for equipment of any shape can be developed using vacuum forming machine. The models for the mold are first designed in SOLIDWORKS or any other 3D modeling package. Then the physical mold is developed by either CNC machine or other machining technique depending on the complexity of the mold.

Regarding the application of this machine a packaging product has been developed for a surgical instrument for a Sialkot based company. The 3D models of the mold and other accessories were developed in SOLIDWORKS, and the actual mold was CNC machined on wooden structure. The porosity, air vents and the surface finish of the mold have been considered. The order of 100 packaging parts was completed on the machine.

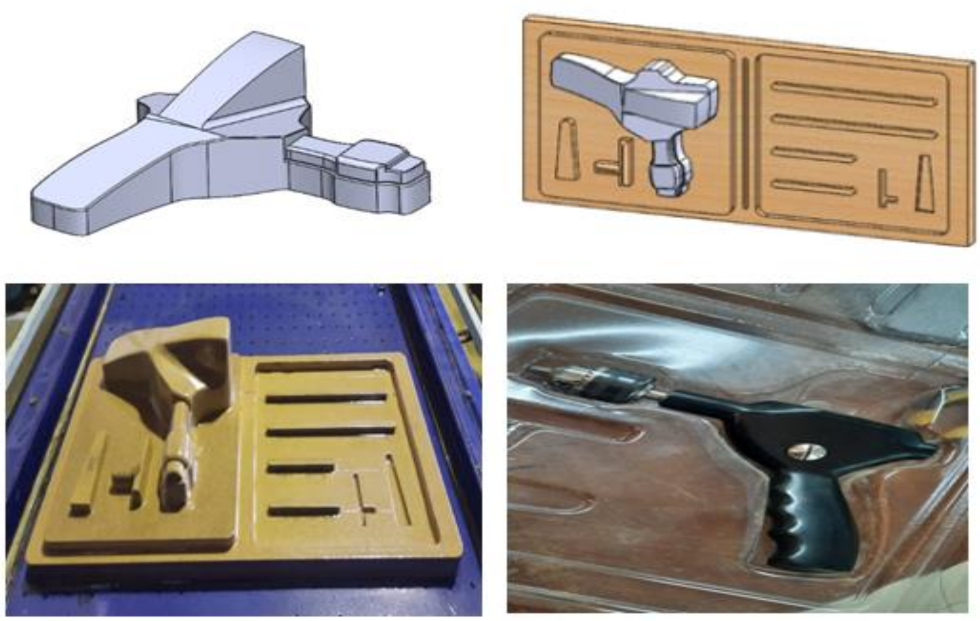


**Figure 57 : Product development stages**

**Advertisement logos**

3D advertisement logos and signs are widely used all over the world which are a part of company's identity. Companies invest a lot of resources in marketing and advertisement of their organization. Vacuum forming provides the capability to make these logos in a cost-effective and simplistic approach. The 3D models are designed in 3D modelling software, the molds of the product are prepared using suitable material like wood and the final product is formed through the vacuum forming process. The use of surface hardening and material strengthening can increase the durability of these products.

The promotional item of bicep for a gym was developed in Blender 3D. The Toyota logo was also made in SOLIDWORKS and later the mold was prepared and formed in the machine to make the final products. Several decoration products can also be developed in the machine which are aesthetically pleasing.

**Figure 58 : 3D Muscle arm**

**Figure 59 : Hyundai logo**

# CONCLUSIONS AND RECOMMENDATIONS

## Conclusions

Following conclusions can be made from this project:

- A complete mechanical design for a vacuum forming machine of 2 by 2 feet size forming area has been made keeping in mind various manufacturing constraints and appearance of the final product delivered.
- Areas of significant importance were carefully designed to ensure the proper working of the machine.
- Uniform and effective vacuum creation is ensured by using sealing silicon strips so that volume between plastic sheet and mold does not leak air due to improper sealing, which will produce a faulty final product.
- Mechanical design of the machine is made keeping in mind the aesthetics and ease of use for the user. That is why the height of the machine is such that a person of average height can easily operate the machine in standing position.
- Material selection has been made to keep the cost of the project as low as possible without compromising the robustness and strength of the machine.
- Machine design has been made to keep it lighter and easy to move from one place to another.
- Instead of manual operation for the movement of mold plate, holding plate and heater, pneumatic actuators have been used to get the components to move with the help of a control system.

- Selection of pneumatic actuators has been made on the basis of the masses of the components that they have to move. Calculations of these forces have been attached in the pneumatic actuators section of design chapter.
- Mechanical design and material selection has been verified by the FEM analysis of the outer structure and high load bearing components which proves the design will not fail under the working conditions of the machine.
- Industry partners were contacted and a mold and packaging material for a local company was developed as part of this project.
- Vacuum forming machines are not manufactured in Pakistan and there is a huge untapped potential in this field which can prove to be very profitable with the right strategy and approach.
- Wide range of applications of Vacuum forming process make this machine very easy to market and in very high demand.

**Recommendations**

- A programmable logic controller (PLC) can be installed to automatically terminate the heating process once the set temperature has been reached.
- LCD touch screen panels can be installed to make the use of the machine very convenient and desirable for the user.
- Considering the wide range of uses, large size vacuum forming machines can also be made for continuous production lines in industries.

- Automatic heat and temperature control modules can be installed which allows the user to select from a list of feasible plastic sheet materials and the rest of the parameters will be automatically selected by the machine without any further input from the user.
- Research on reinforcement of plastic sheets after forming can increase the strength and durability of the products manufactured from vacuum forming process. This will further increase the applications of vacuum forming machines.
- A better approach to prove the mechanical design analysis results would be to manufacture the complete working prototype and test it.
- Vacuum forming machines are not being manufactured in Pakistan and there is a huge opportunity in this field, machines can be manufactured locally. Since most of the imported machines are very expensive and have high import costs, a local manufactured machine would attract a lot of buyers.

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# APPENDIX: DRAWINGS

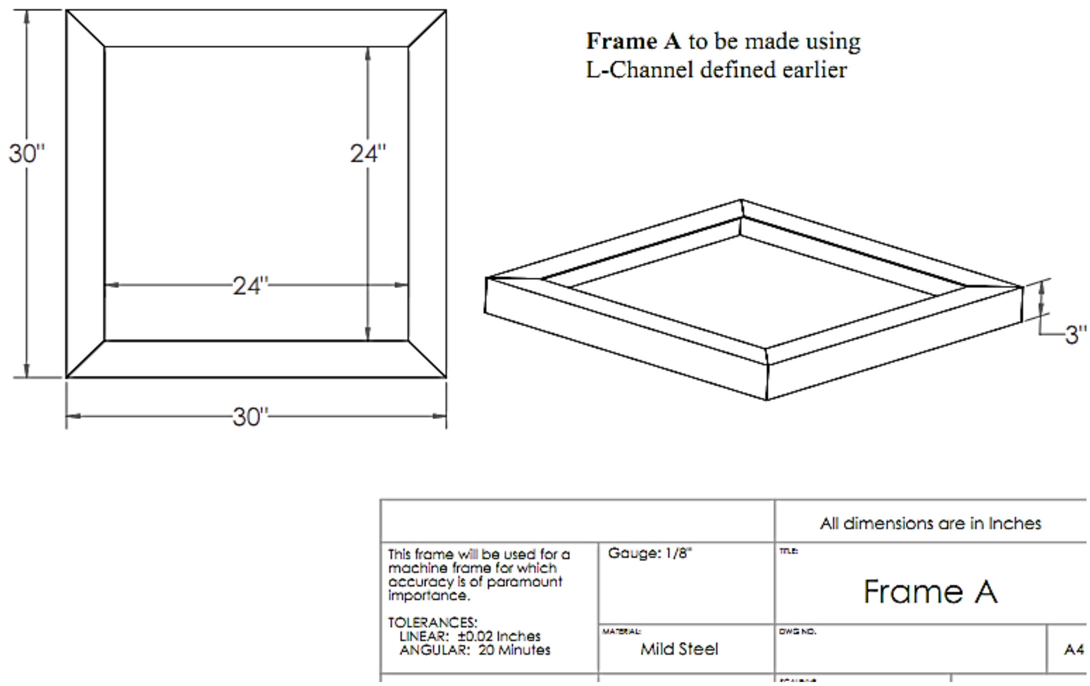


**Figure 60 : Frame A**

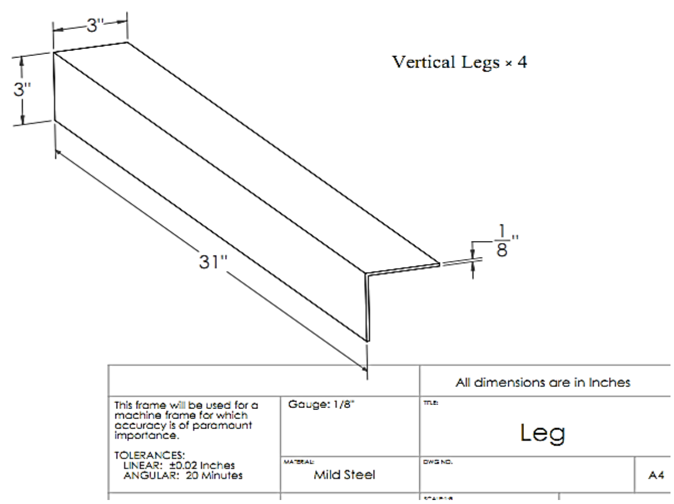


**Figure 61 : Vertical leg**

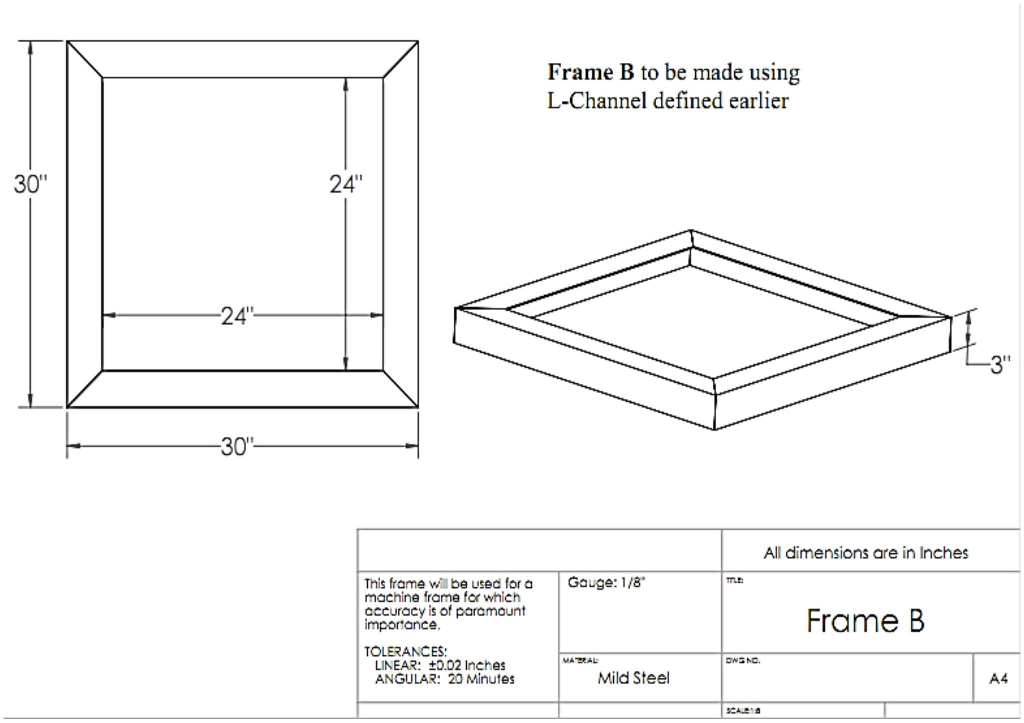


**Figure 62 : Frame B**

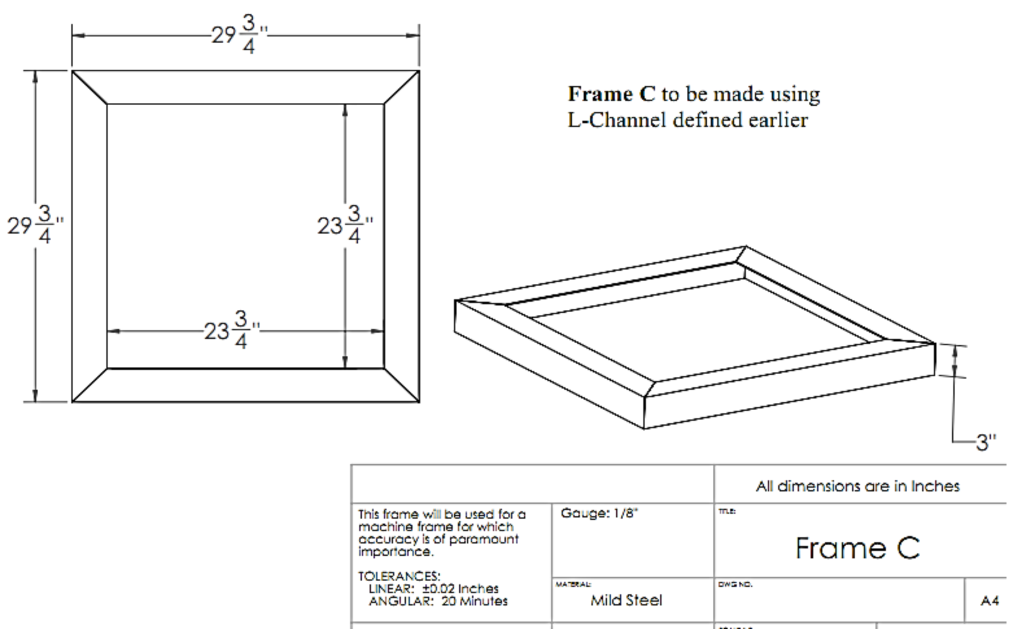


**Figure 63 : Frame C**

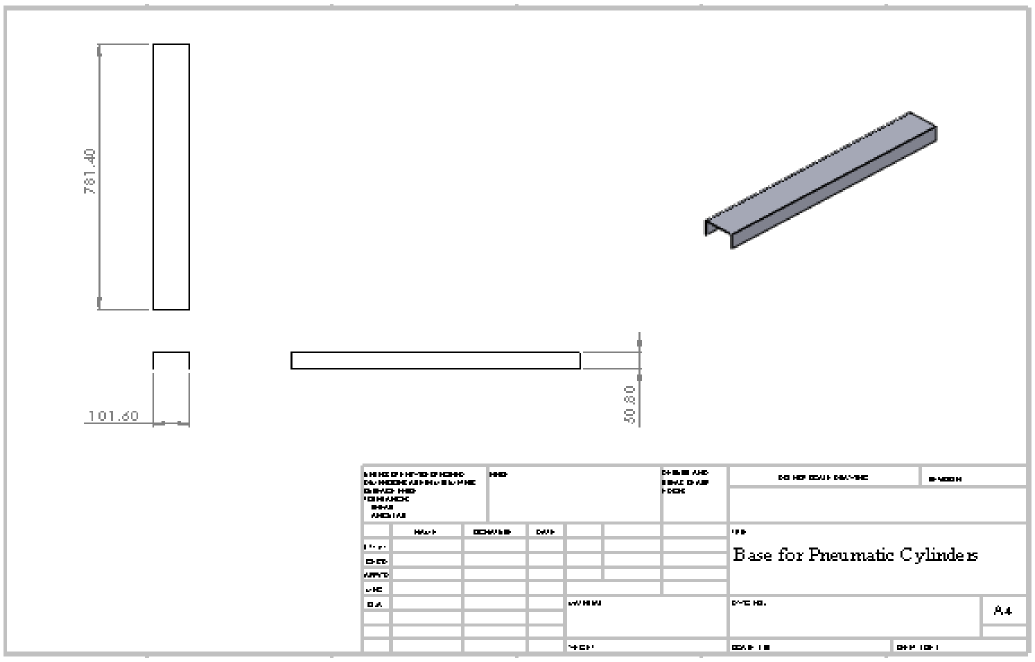


**Figure 64 : Pneumatic base**

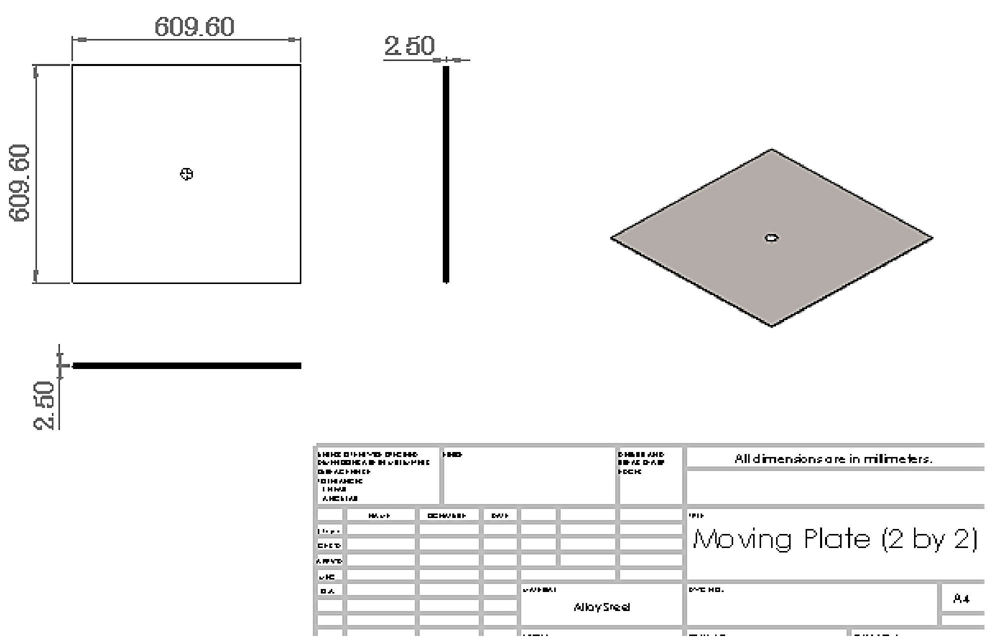


**Figure 65 : Moving plate**

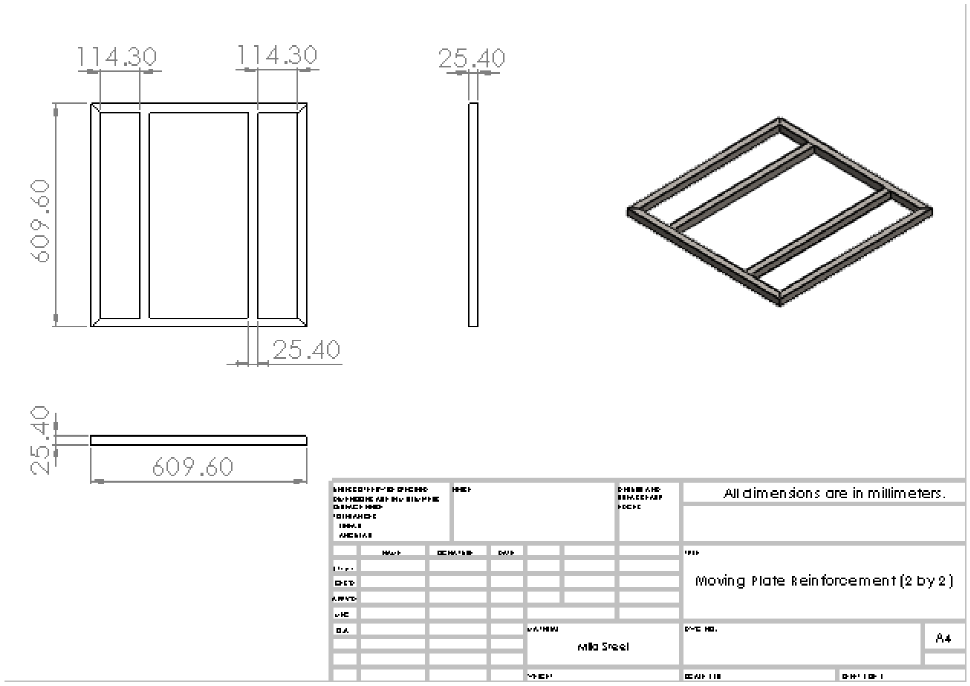


**Figure 66 : Moving bar reinforcement**

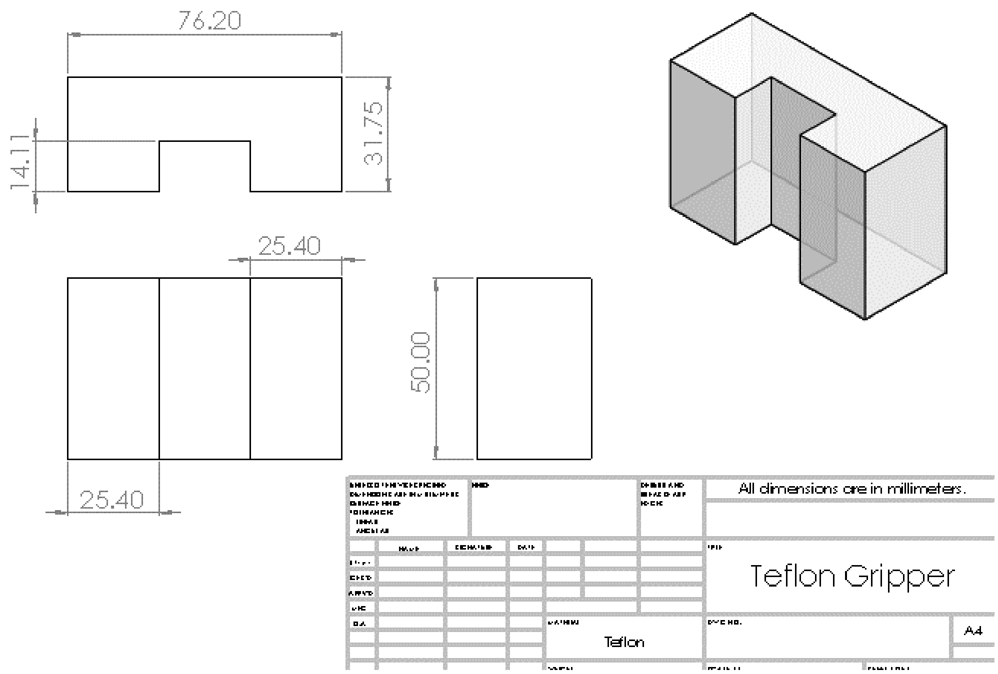


**Figure 67 : Teflon gripper**

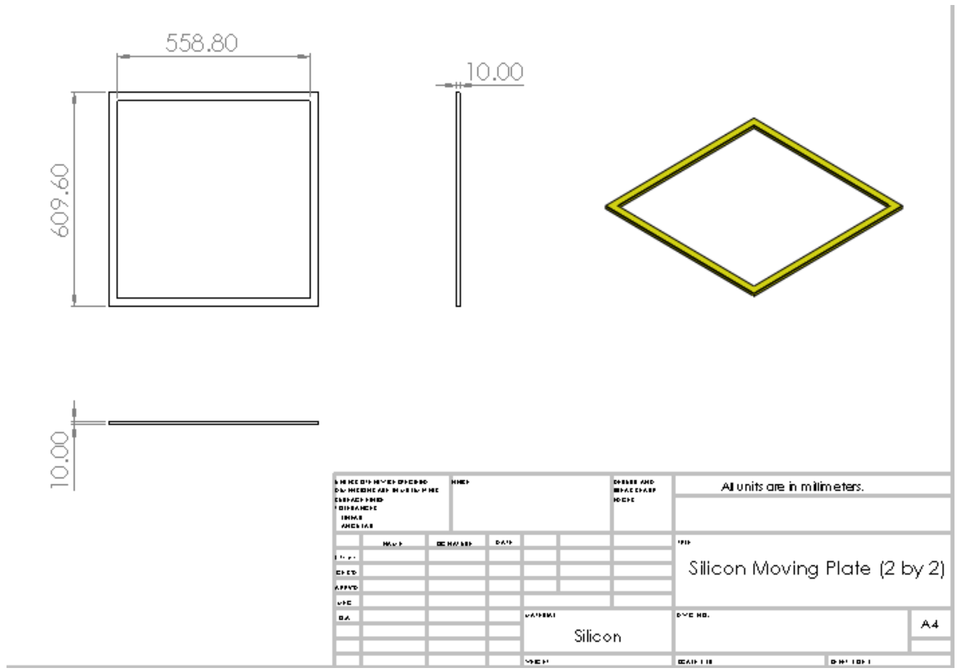


**Figure 68 : Silicon strip**

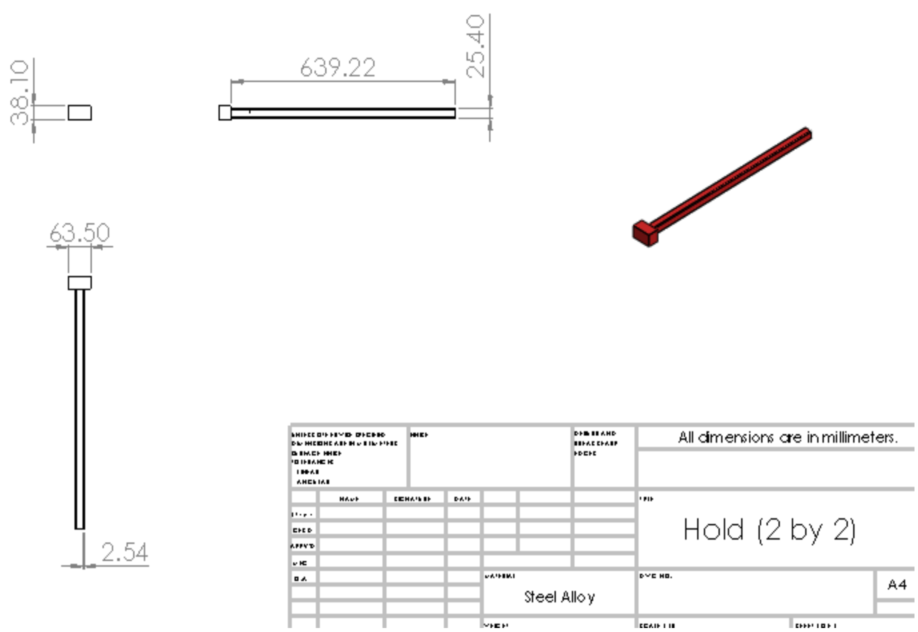


**Figure 69 : Holding rod**

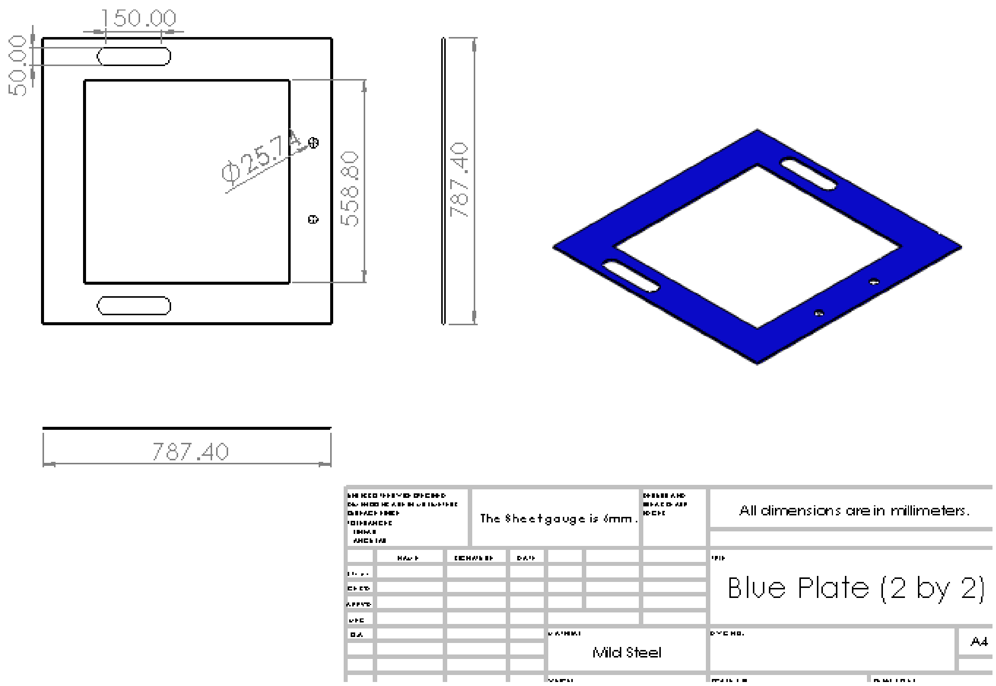


**Figure 70 : Blue plate**

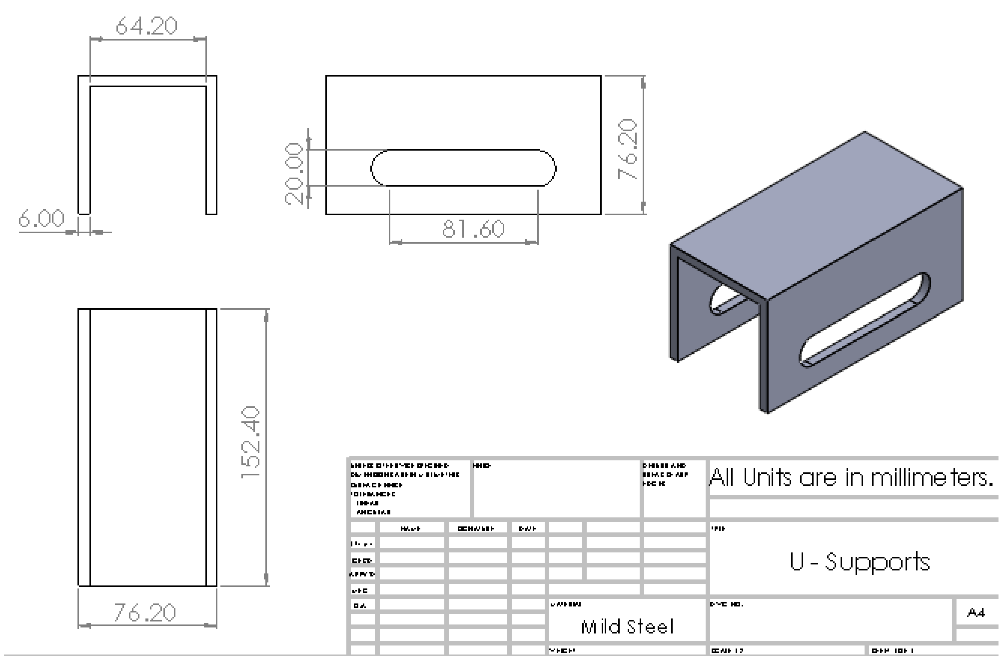


**Figure 71 : U-support**

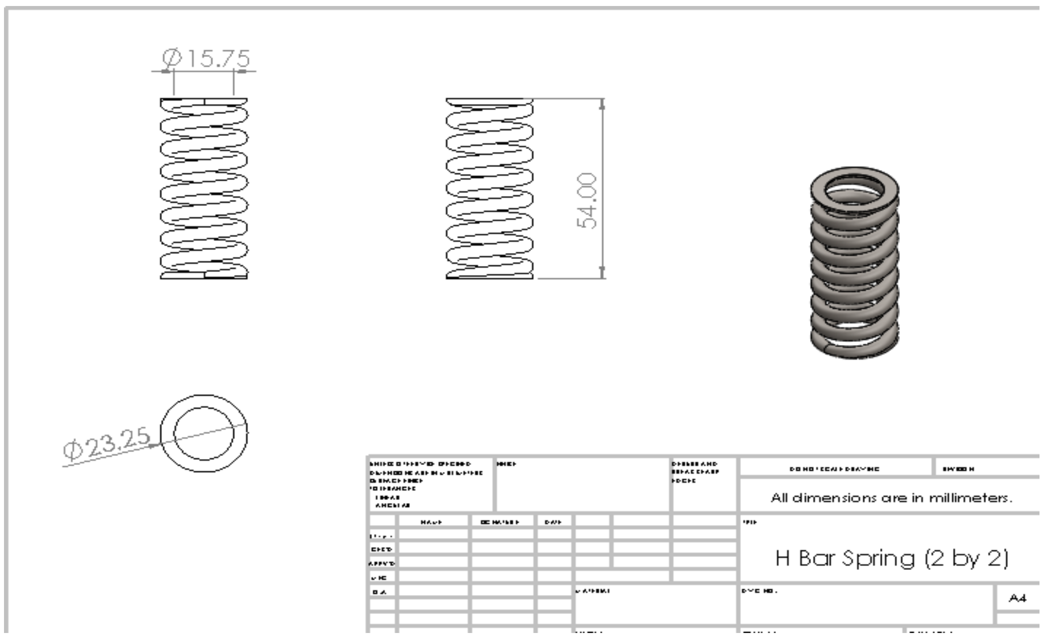


**Figure 72 : H-bar spring**

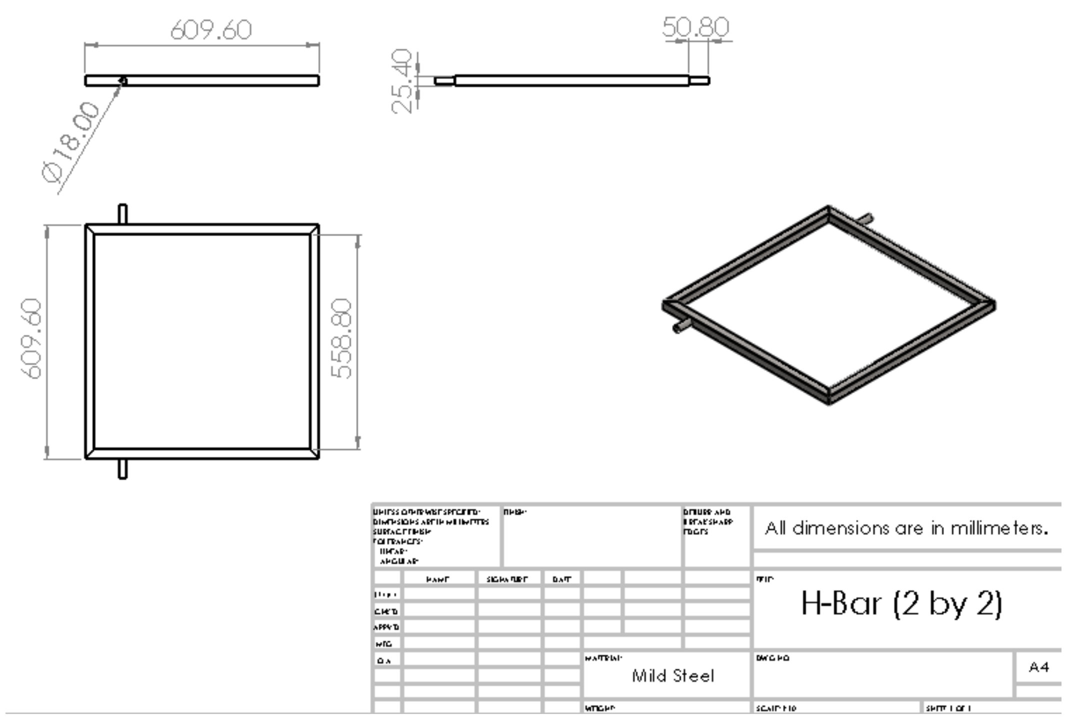


**Figure 73 : H-bar**

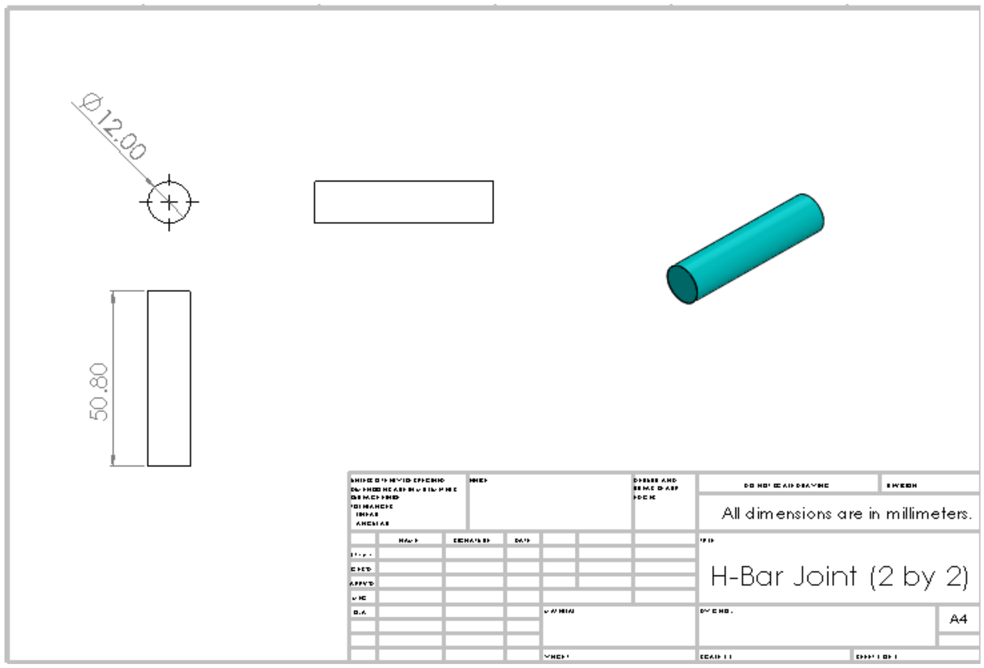


**Figure 74 : H-bar joint**

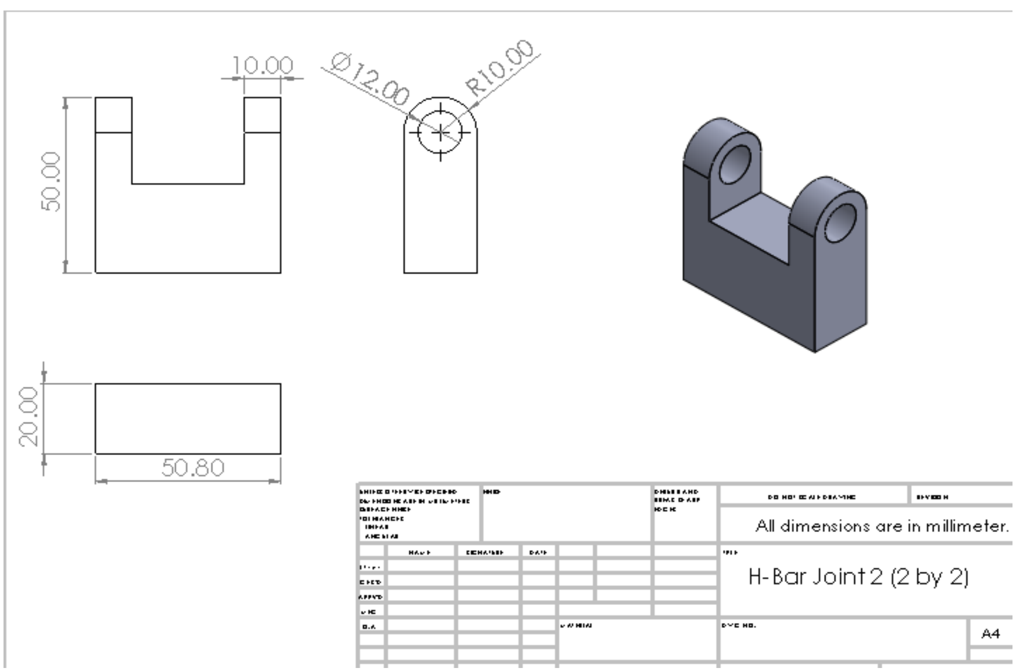


**Figure 75 : H-bar joint 2**

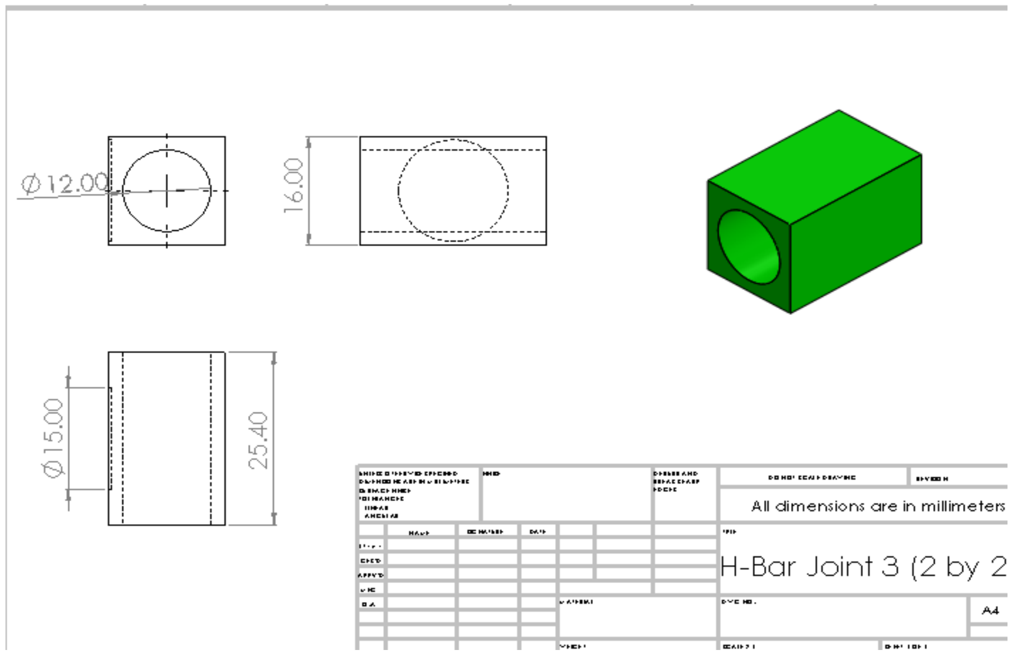


**Figure 76 : H-bar joint 3**

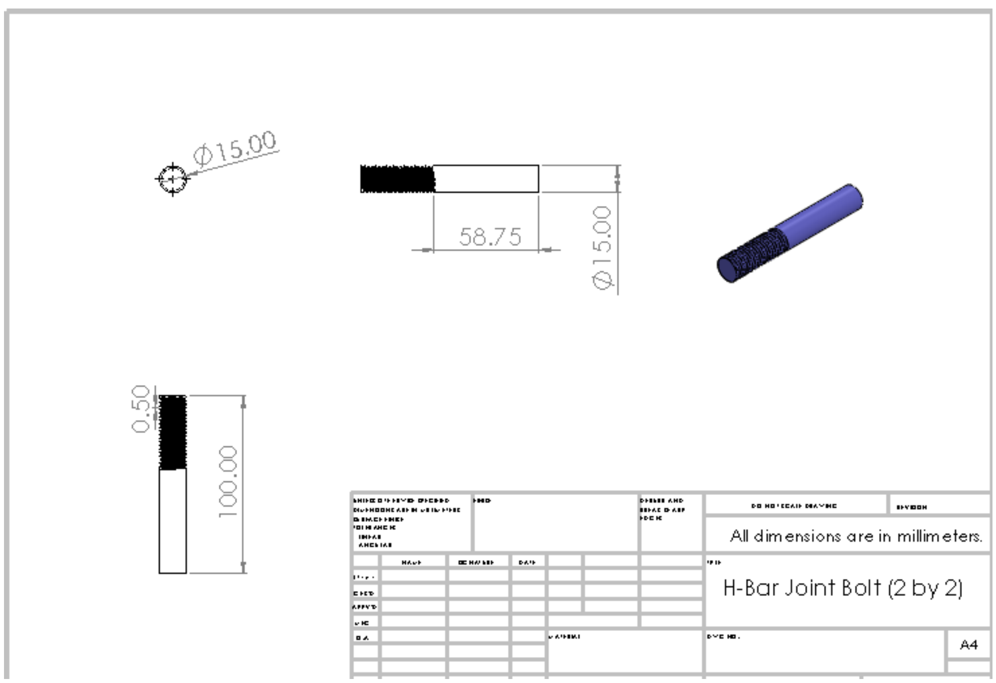


**Figure 77 : H-bar joint bolt**

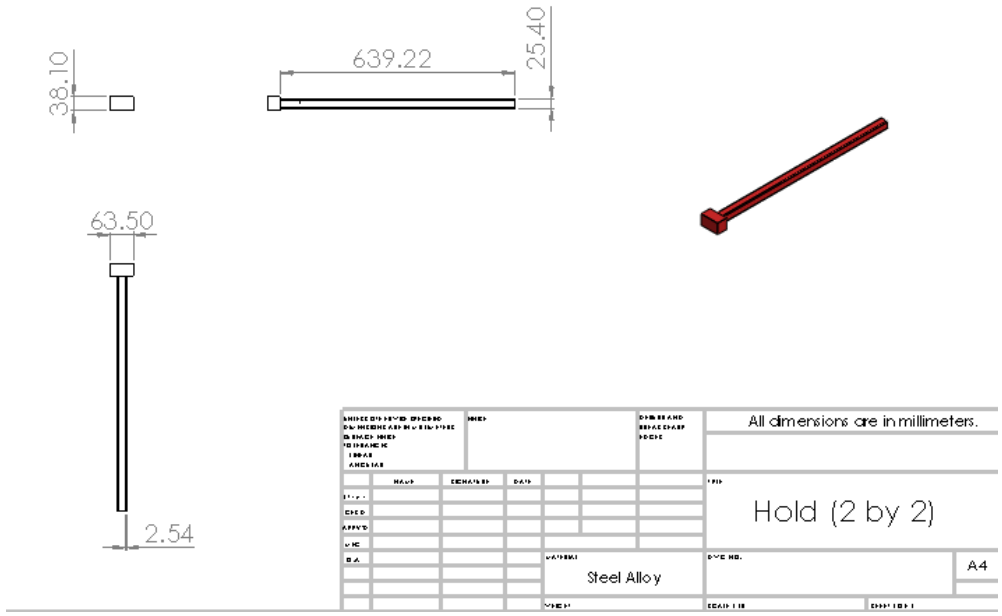


**Figure 78 : Holding rod**