Design and Development of Table-Top Vacuum Forming Machine

A Final Year Project Report

Presented to

SCHOOL OF MECHANICAL & MANUFACTURING ENGINEERING

Department of Mechanical Engineering

NUST

ISLAMABAD, PAKISTAN

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

by

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EXAMINATION COMMITTEE

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Titled: "Design and Development of Table-Top Vacuum Forming Machine" be accepted in partial fulfillment of the requirements for the award of BE Mechanical Engineering degree with grade ___

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ABSTRACT

Vacuum forming machines serve critical roles across diverse industries, including advertising, packaging, and medical fields, for crafting intricate 3D signage, packaging components, and orthotic parts. However, their widespread adoption is hindered by their high costs. This report endeavours to address this challenge by conceptualizing and realizing a cost-effective Vacuum Forming Machine capable of moulding ABS, HIPS, and acrylic materials with precision and reliability.

Leveraging reverse engineering techniques and incorporating advanced features such as a efficient vacuum system, sensors, and an intuitive user interface, the machine facilitates the creation of complex 3D parts with consistent accuracy.

Overall, this project seeks to democratize plastic part production, enabling creativity, innovation, and entrepreneurship within budget and space constraints. Through the development of a practical solution for rapid prototyping and small-scale manufacturing, it aims to catalyse innovation across industries and empower individuals to bring their ideas to life.

ACKNOWLEDGMENTS

We begin with heartfelt gratitude to Almighty Allah for bestowing upon us the knowledge, perseverance, and fortitude to successfully undertake and complete this project.

It is with immense pleasure that we extend our sincere appreciation to our supervisor, Dr. Mian Ashfaq Ali, PhD., Associate Professor at the School of Mechanical and Manufacturing Engineering, National University of Sciences and Technology (NUST). His unwavering support, invaluable guidance, and mentorship have been instrumental in steering us through this endeavor.

Lastly, we extend our deepest gratitude to our parents for their boundless love, unwavering prayers, and countless sacrifices made for our education. It is their steadfast support and encouragement that have empowered us to overcome challenges and reach the culmination of this project.

ORIGINALITY REPORT

This project report is a culmination of our original work and research efforts. We affirm that no portion of this project, including but not limited to text, ideas, concepts, methodologies, and findings, has been plagiarized or copied from any other source.

Throughout the development of this project, we have adhered to ethical standards and academic integrity guidelines. All contributions, analyses, interpretations, and conclusions presented in this report are the result of our own independent work and intellectual efforts.

Furthermore, we have appropriately cited and referenced any external sources, including published literature, research studies, and intellectual property, that have informed or influenced our work.

We stand by the originality and authenticity of our project, affirming that the findings and conclusions presented herein have been genuinely and originally produced by us.

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ABBREVIATIONS

ABS	*Acrylonitrile Butadiene Styrene*
PETG/VIVAK	Co-polyester
PP	Polypropylene
PE	Polyethylene
PVC	Polyvinyl Chlorine
HIPS	Polystyrene

CHAPTER 1: INTRODUCTION

Motivation

The expanding interest in rapid prototyping and small-scale production has underscored the necessity for accessible and cost-effective manufacturing solutions. Currently, the market lacks affordable tabletop vacuum forming machines tailored to the needs of designers, entrepreneurs, and educational institutions. This gap inhibits the efficient production of customized plastic components, hindering innovation and product development cycles.

The motivation behind this project is to address these challenges by designing and developing a user-friendly, compact tabletop vacuum forming machine. By creating a device that is both affordable and easy to use, we aim to democratize the production of plastic parts, empowering individuals, and small businesses to realize their design concepts without the barriers posed by expensive industrial equipment.

Through meticulous design and engineering, our goal is to create a machine that not only meets the functional requirements of vacuum forming but also integrates seamlessly into various environments, from design studios to classrooms and small workshops. Key to achieving this goal is the development of an integrated circuit system that ensures precise control and monitoring of the vacuum forming process, enhancing reliability and repeatability.

Throughout the project, we will emphasize optimization, seeking to strike a balance between performance, cost-effectiveness, and user-friendliness. Rigorous prototype testing will validate the machine's functionality and durability, ensuring that it meets the diverse needs of its intended users.

Ultimately, the design and development of this tabletop vacuum forming machine aim to democratize plastic part production, enabling creativity, innovation, and entrepreneurship to flourish within budget and space constraints.

Problem Statement

The absence of **affordable** and space-saving **tabletop** vacuum-forming machines presents a barrier to the rapid prototyping and **small-scale production** requirements of designers and entrepreneurs. Existing manufacturing alternatives tend to be **costly** and space-demanding, thus restricting accessibility. This gap underscores the need for an **accessible, user-friendly** solution that enables individuals, small businesses, and educational institutions to effectively **manufacture custom plastic parts.**

Objectives

Objectives of our FYDP are as follows:

1. Design and 3D Modelling of Vacuum Forming Machine
2. Integrated Circuit Design
3. Fabrication and Integration of all Modules
4. Prototype Testing and Optimization

CHAPTER 2: LITERATURE REVIEW

Plastic forming processes play a crucial role in existing manufacturing, facilitating the creation of diverse products featuring different shapes, sizes, and material characteristics. The selection of a manufacturing method is influenced by factors such as the product's dimensions, shape, material composition, production volume, and cost considerations. Each process comes with its own set of pros and cons, necessitating manufacturers to carefully opt for the one aligning with their specific requirements.

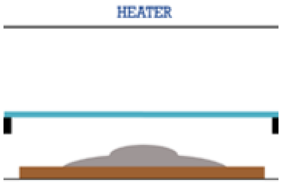
Thermoforming As a Plastic Forming Process:

There are two primary thermoforming techniques: vacuum forming and pressure forming.

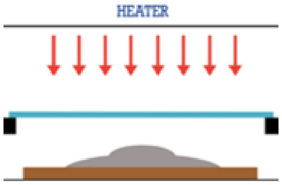
Vacuum forming:

Vacuum forming is the more straightforward and widely used method, employed for producing large and uncomplicated shapes like trays, covers, and packaging. In this procedure, a plastic sheet is secured in a frame, heated to the desired temperature, and then drawn over a mold through vacuum suction. The vacuum pressure compels the heated plastic to adopt the mold's shape, followed by cooling and trimming to obtain the final product.

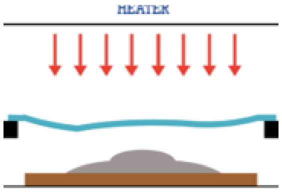
A customised mold is produced that is according to the shape which is required after Vacuum froming.



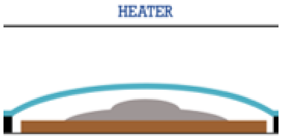
A plastic sheet is then placed above the mold and under a heating system.



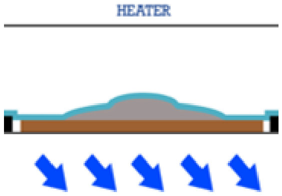
The sheet is then subjected to heating with the help of an oven until it bacomes mouldable and flexible.



Once the plastic sheet is ready the shelf on which the wooden mold is sat on, is moved upwards.



The technician creates a bubble effect to stretch the plastic, this will give it a more consistent finish across the mold.



The vacuum is then switched on, removing all air. This allows the plastic to form to the shape of the mold. The molded part is then cooled.

Vacuum Forming Machine:

The vacuum forming machine is ideal for producing large and simple shapes such as trays, covers, and packaging. It involves clamping a plastic sheet in a frame, heating it, and drawing it over a mold through vacuum suction. The resulting vacuum pressure shapes the plastic to the mold, and after cooling and trimming, the final product is obtained.

Pressure forming:

Pressure forming is a more sophisticated method capable of creating intricate shapes with tighter tolerances. In this process, a plastic sheet is heated and clamped over the mold, and air pressure is applied above the sheet. This pressure compels the sheet to conform to the mold's shape, facilitating the creation of sharper features and tighter tolerances in the end product. Post-forming, the plastic undergoes cooling and trimming.

Currently Available Vacuum Forming Machines:

- Following are the designs which a UK based company **Formech** manufacture:

Formech 508DT
19 x 17’’ 3.2kW

Formech 686
25.5 x 24.5" 8.0kW

Formech 1250/1500
46.5 x 46.5" 25.0kW

- A US-based company **Centro form** manufactures the following portable vacuum forming machine:

EZFORM SV 1217
12 " x 17 " 1.5 k Watts

Types of Vacuum Pumps generally used in the construction of VFM’s:

Rotary Vane Vacuum Pumps:

Rotary vane vacuum pumps are a type of positive displacement pump commonly used in various industrial applications. These pumps consist of a rotor with vanes that rotate inside a cavity. The rotor is eccentrically mounted in the pump's housing. As the rotor turns, the vanes slide in and out of the rotor slots, creating expanding and contracting volumes. This action traps and pumps gas from the inlet to the outlet. Key features of rotary vane vacuum pumps include their ability to achieve relatively high vacuum levels and their compact design. They are efficient for applications requiring a consistent vacuum level and are often utilized in industries such as packaging, woodworking, and material handling. However, they may not be suitable for processes with high vapor loads or when a continuous, oil-free vacuum is essential.

Positive Displacement Vacuum Pumps:

Positive displacement vacuum pumps are a broader category of pumps that includes various types such as rotary vane, rotary piston, diaphragm, and screw pumps. The defining characteristic of positive displacement pumps is their ability to trap and move a fixed amount of gas with each cycle. Positive displacement vacuum pumps operate by periodically expanding and contracting a cavity, which allows gas to be drawn in during expansion and expelled during contraction. These pumps are effective in achieving high vacuum levels and maintaining a consistent vacuum regardless of the process conditions. They find applications in industries like pharmaceuticals, laboratories, and semiconductor manufacturing.

Types of Heaters generally used in the construction of VFM’s:

Hot Air Heating

Hot-air heaters are devices designed to generate and distribute warm air for heating enclosed spaces. They typically operate by passing air over a heating element, which can be an electric coil or a combustion chamber. The heated air is then circulated through the space using fans or blowers. Hot-air heaters are commonly used in residential, commercial, and industrial settings for space heating. They offer a quick and efficient way to raise the ambient temperature and are often employed in portable heaters, HVAC systems, and forced-air heating systems.

Ceramic Heating

Ceramic heaters utilize a ceramic heating element to generate heat. These heaters consist of a ceramic plate or core that heats up when an electric current passes through it. The ceramic material is chosen for its ability to withstand high temperatures and rapid heating cycles. Ceramic heaters are known for their energy efficiency, quick heating response, and even distribution of warmth. They are commonly used in space heaters, heating appliances, and some types of infrared heaters. Ceramic heaters are valued for their durability and safety features, making them a popular choice for various heating applications.

Quartz Heating

Quartz heaters, often referred to as infrared heaters, use quartz tubes or bulbs to produce infrared radiation. These heaters emit heat in the form of infrared rays, which transfer energy directly to objects and people in their path. Quartz heaters are known for their rapid heating capabilities and energy efficiency. They are commonly used in outdoor heating applications, patio heaters, and specific industrial processes that require targeted heating. Quartz heaters are appreciated for their ability to provide warmth without extensively heating the surrounding air, making them a practical choice for focused heating needs.

Different Types of Materials (Plastics) Available

Thermoplastics:

Thermoplastics soften when heated and become malleable, allowing them to be easily formed into different shapes.

Thermoplastics are advantageous in vacuum forming because they can be reheated and reshaped multiple times without significant degradation of their properties. This allows for easier prototyping and modification of designs.

Thermosetting Plastics:

Thermosetting plastics undergo a chemical reaction during curing that irreversibly sets their shape.

In vacuum forming, thermosetting plastics are less commonly used because they cannot be reformed after the initial curing process. If an attempt is made to heat and reshape thermosetting plastic, it will typically degrade or burn rather than becoming malleable.

Hygroscopic Materials:

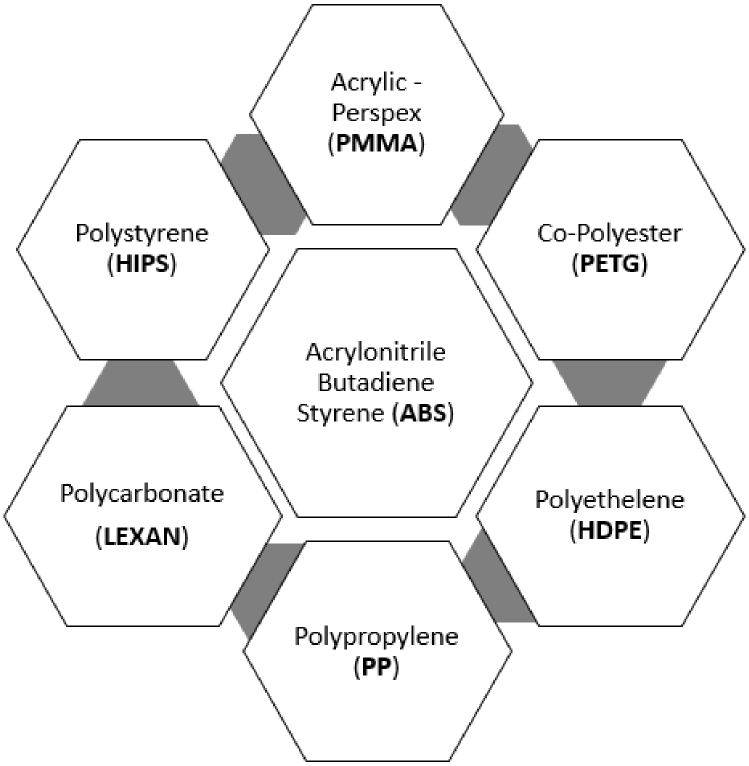
The absorbed moisture may vaporize or expand rapidly when subjected to the high temperatures used to soften the plastic sheet prior to forming. This can lead to bubbles, voids, or surface defects in the formed part.

Hygroscopic materials are substances that readily absorb moisture from the surrounding environment. This moisture absorption can occur from the air, especially in humid conditions.

In summary, while both thermoplastics and thermosetting plastics can be used in vacuum forming, thermoplastics are more commonly preferred due to their ability to be reheated and reshaped multiple times, making them more versatile for prototyping and manufacturing processes. To mitigate these issues, it's often necessary to pre-dry hygroscopic materials before vacuum forming.

Plastic Sheets used in Vacuum Forming Machine:

Suitable materials for use in vacuum forming are conventionally thermoplastics. Parts can be made through following materials using Vacuum Forming Machine:



Vacuum formed plastics mentioned above possess a certain set of characteristics that originate from their atomic structure. There is a wide range of additives that induce specific properties in plastics.

The **properties** that make a plastic **ideal for vacuum forming** are that they should be easy to form with a low forming temperature, show a low level of shrinkage when subjected to cooling and possess a firm thermal and high impact strength.

Optimal Temperature Conditions for Forming Processes

Polymers exhibit a range of forming temperatures determined by factors such as polymer **type and part design**. While generic references often provide upper and lower limits, such as for polystyrene (PS) with a purported 100°F window, practical experience reveals narrower ranges. For instance, PS's glass transition temperature of 210°F and injection molding temperature of 425°F suggest a wide window. However, in practice, the thermoforming window may be as small as 10°F or less, dependent on mold shape.

Similarly, Acrylonitrile Butadiene Styrene (ABS) lists a forming range of 150–205°C. However, actual forming windows may be narrower than expected due to specific molding conditions and part geometry. Understanding the nuances of forming temperature variations is crucial for optimizing thermoforming processes and achieving desired part quality.

Hence, this means that the actual forming temperature for the manufacturing of any part really depends on the particular conditions and this can only be determined by experimentation on that part, and this would be best known by the operator. The forming temperature for each material is provided in the appendix section below.

Considerations on Sheet Thickness in Manufacturing Processes

The thickness of sheet depends on the machine's design, including heating elements, and vacuum power. Tabletop vacuum forming machines are generally designed for smaller-scale projects and may have the capacity to handle thin sheets. For our project we will work with 0.2-1 mm sheet thickness.

Areal Draw Ratio

A draw ratio is the calculation that lets you know what gauge of plastic you need to start with for any given thermoformed part. Thermoforming works by stretching a sheet of plastic over a mold. The more stretching that occurs, the thinner the plastic gets.

Areal Draw Ratio, often given the symbol R, is the ratio of the area of the part being formed to the area of the sheet needed to make the part.

$$R = \frac{A_{part}}{A_{sheet}}$$

Consider a cylinder one unit in diameter by one unit high. The area of the cylinder is (pi + pi/4) = 5pi/4. The area of the sheet used to form the cylinder is pi/4. Therefore, the areal draw ratio, RA, is 5.

The reciprocal of the areal draw ratio is the average reduced thickness of the formed part, being 1/5 = 0.20. In other words, the original sheet thickness has been reduced by 80%, on the average.

Calculating starting material thickness, once you have your draw ratio, you can use it to calculate your minimum starting gauge with,

$$Draw\ Ratio * Desired\ Finished\ Gauge = Minimum\ Starting\ Gauge$$

Applications of Vacuum Forming Machine

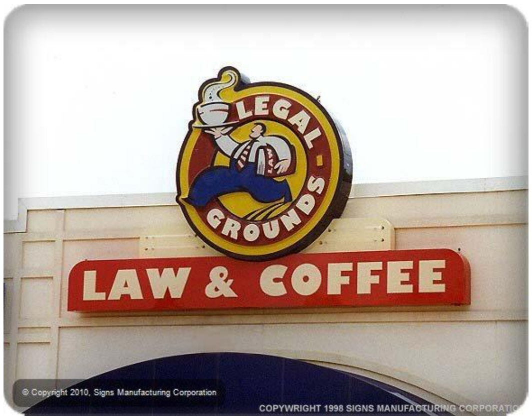
In 3D Signage

Vacuum forming technology finds a significant application in the realm of 3D signage, particularly in the creation of lightweight and cost-effective signboards commonly seen atop shops and establishments.

Traditionally, 3D signage made from materials like metal or wood can be cumbersome and labor-intensive to produce. These materials often require substantial structural support due to their weight, leading to increased labor costs and longer production times.

In contrast, vacuum-formed 3D signs offer a compelling alternative. By utilizing vacuum-formed sheets, these signs can be crafted with lightweight materials, resulting in reduced production costs and easier installation. The inherent strength of vacuum-formed sheets ensures that the signs can withstand external forces and maintain their structural integrity, even in adverse weather conditions.

Furthermore, the versatility of vacuum-formed sheets allows for the creation of intricate designs and shapes, enabling businesses to achieve eye-catching and visually appealing signage.



Overall, the adoption of vacuum-formed technology in the production of 3D signage offers a practical solution that balances cost-effectiveness, durability, and aesthetic appeal. It represents a superior choice compared to traditional materials, providing businesses with signage solutions that are not only visually striking but also robust and weather resistant.

In Medicine

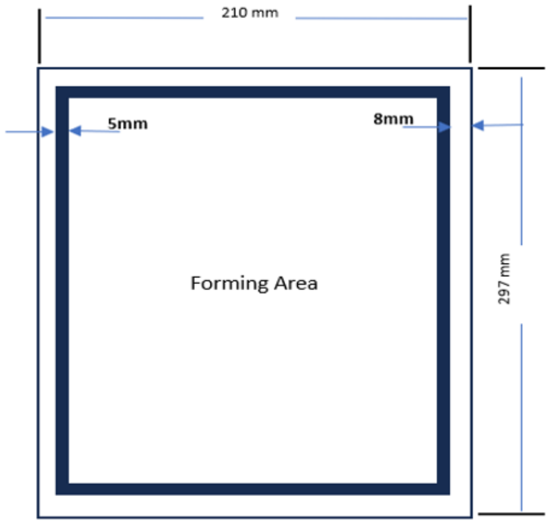
Vacuum forming technology has become an indispensable tool in the field of medicine, offering a versatile and efficient method for manufacturing a wide range of medical devices and components. From wheelchair seat inserts to medical-grade packaging, radiotherapy masks to dental castings, the applications of vacuum forming are diverse and impactful.

The benefits of vacuum forming in healthcare are manifold. It allows for the production of lightweight, customized components that meet stringent medical standards while reducing costs and turnaround times. Moreover, vacuum-formed products offer advantages such as enhanced sterility, ease of disposal, and adaptability to various sizes and shapes.

By leveraging vacuum forming technology, medical device manufacturers can innovate and deliver high-quality products that improve patient care and enhance healthcare outcomes. Whether it's optimizing patient comfort and safety or streamlining medical procedures and equipment design, vacuum forming continues to play a vital role in advancing medical technology and serving the needs of patients and healthcare professionals alike.

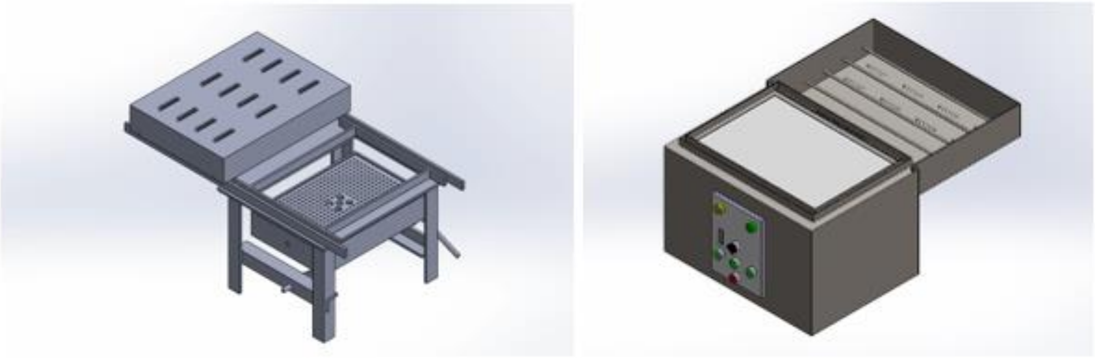
CHAPTER 3: METHODOLOGY

The initial phase of our vacuum forming machine design was driven by the vision of creating a compact tabletop model that offers portability without compromising functionality. Our goal was to tailor it specifically to utilize A4 sheets of plastics for part formation. A pivotal aspect of this design concept involved integrating a grip mechanism that not only securely holds the plastic sheet but also serves as a conduit for vacuum generation.



MACHINE DESIGN

In the quest to transform the machine into a tabletop version, an initial design was crafted. However, recognizing the paramount importance of user-friendliness and functionality, a subsequent redesign ensued. This iteration process aimed to refine and enhance the design, ensuring seamless integration into tabletop environments while prioritizing ease of use and optimal functionality for the end user.



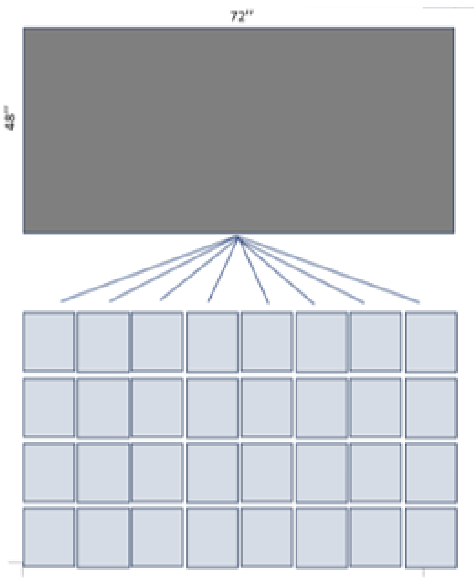
The machine was designed using SolidWorks software, resulting in a design resembling the image depicted.

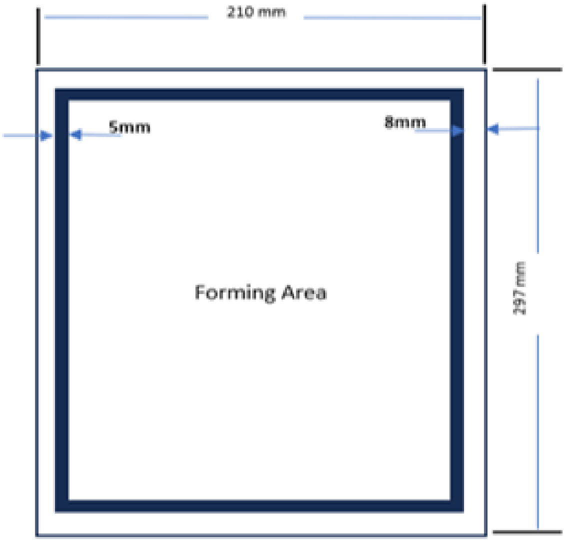
Target Specifications

In the pursuit of designing a highly functional and cost-effective vacuum forming machine, it is essential to establish clear and achievable target specifications. These specifications serve as guiding principles to ensure that the final design meets the specific needs and requirements of the intended users. The following target specifications have been identified to guide the development process:

- Can Thermoform sheets of standard A4 size.
- Tabletop Size of around 300mm*250mm*500mm
- Approx. weight of 10-12 kg

- Heats the plastic sheets to 150-200 degC.
- Cost within 50,000 PKR
- Appropriate structural integrity
- Simple innovative design, Easy to operate.
- Repeatability.

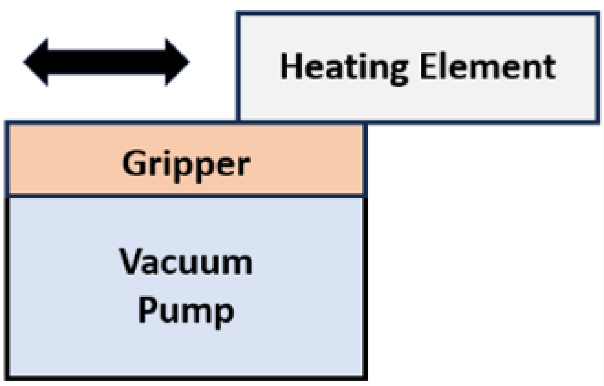


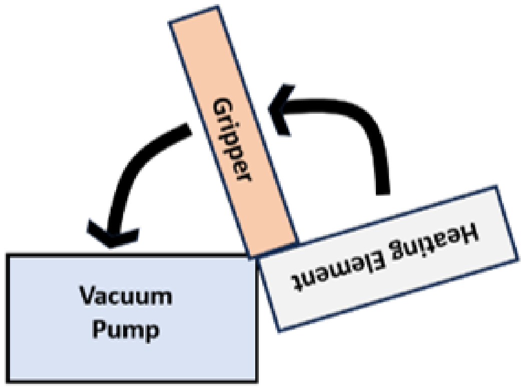


We found that the standard sheets of ABS plastic are of the size 72” by 48” and we can get 32 A4 ABS plastic sheets out of it. 8mm would be left from each side of the sheet and 5mm would be in covered in the grip, the reaming area is called forming area.

Mechanism Considerations

We considered two potential mechanisms for the design. In one concept, the heating element can slide over the working table and gripper, while in the other mechanism, both the gripper and heating element pivot about the same axis. Both of these mechanisms are illustrated in the pictures below.





We considered the pivoted design as it would take less space and cost as it includes fewer components in the assembly.

Materials

The selection of materials is a crucial initial step in the machine design process, as it significantly influences both the functionality and cost-effectiveness of the final product. Several variables were considered in the material selection process, including cost, availability, mechanical properties, and manufacturing considerations.

In our deliberations, we examined various materials such as aluminum, mild steel, and stainless steel. Ultimately, mild steel emerged as the preferred choice for several reasons:

Cost-effectiveness: Mild steel typically offers a lower cost compared to other materials like aluminum or stainless steel, making it economically advantageous for the project.

Mechanical Characteristics: Mild steel possesses sufficient mechanical strength and durability to withstand the operational requirements of the machine. It provides adequate structural integrity while keeping material costs in check.

Availability: Mild steel is widely available, ensuring a consistent supply chain and mitigating any potential delays in the manufacturing timeline.

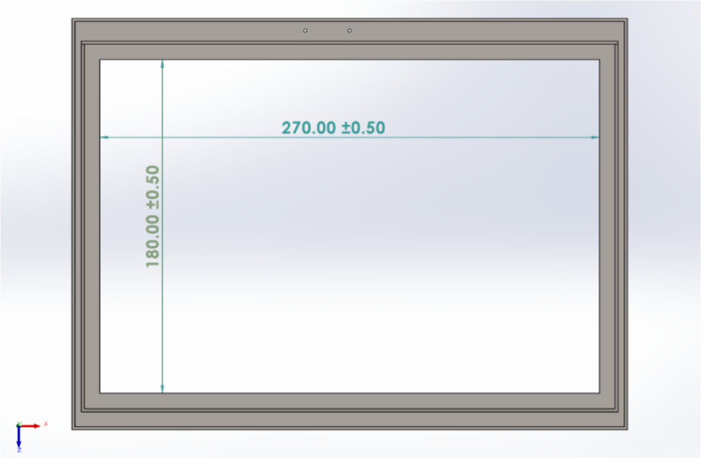
Overall, the selection of mild steel aligns with our goal of developing a cost-effective machine design without compromising on performance or quality.

When evaluating material options, it is essential to assess their machining capacity. A material may be cost-effective, but if it is difficult to machine, it can lead to increased production time and costs.

Parts of the Vacuum Forming Machine

Grippers:

Central to our design philosophy was the development of a grip mechanism that not only securely clamps the plastic sheet but also establishes a seal essential for vacuum formation with the help of the sealing material. By ingeniously incorporating this feature, we aimed to streamline the forming process while optimizing material usage and minimizing wastage.



Working Table:

The working table serves as the platform where the component to be manufactured is positioned. It features a perforation strategically positioned to accommodate seamless attachment of the vacuum pump. facilitating the vacuum formation process.

The working table will incorporate a control panel, offering convenient access to essential functions such as activating or deactivating the vacuum pump and heater. This integrated control system ensures seamless operation, allowing users to regulate the vacuum and heating elements with ease and precision directly from the tabletop workspace.

Calculations of the total weight of the VFM:

The following calculations are computed with the help of MathCAD software. Firstly, the most important forming area is calculated, then total volume of the machine is obtained, after which surface area has been calculated which is then combined with the density gives us total mass of the vacuum forming machine.

$$A4\_Std\_Dim := 297\ mm \cdot 210\ mm$$

$$Area\_of\_A4Sheet := A4\_Std\_Dim = \left(6.237 \cdot 10^{4}\right)\ mm^{2}$$

$$Grip\_Dim := 2 \cdot 5\ mm\ (297-8-8)\ mm + 2 \cdot 5\ mm \cdot (210-8-8)\ mm$$

$$Total\_Grip\_Area := Grip\_Dim = \left(4.75 \cdot 10^{3}\right)\ mm^{2}$$

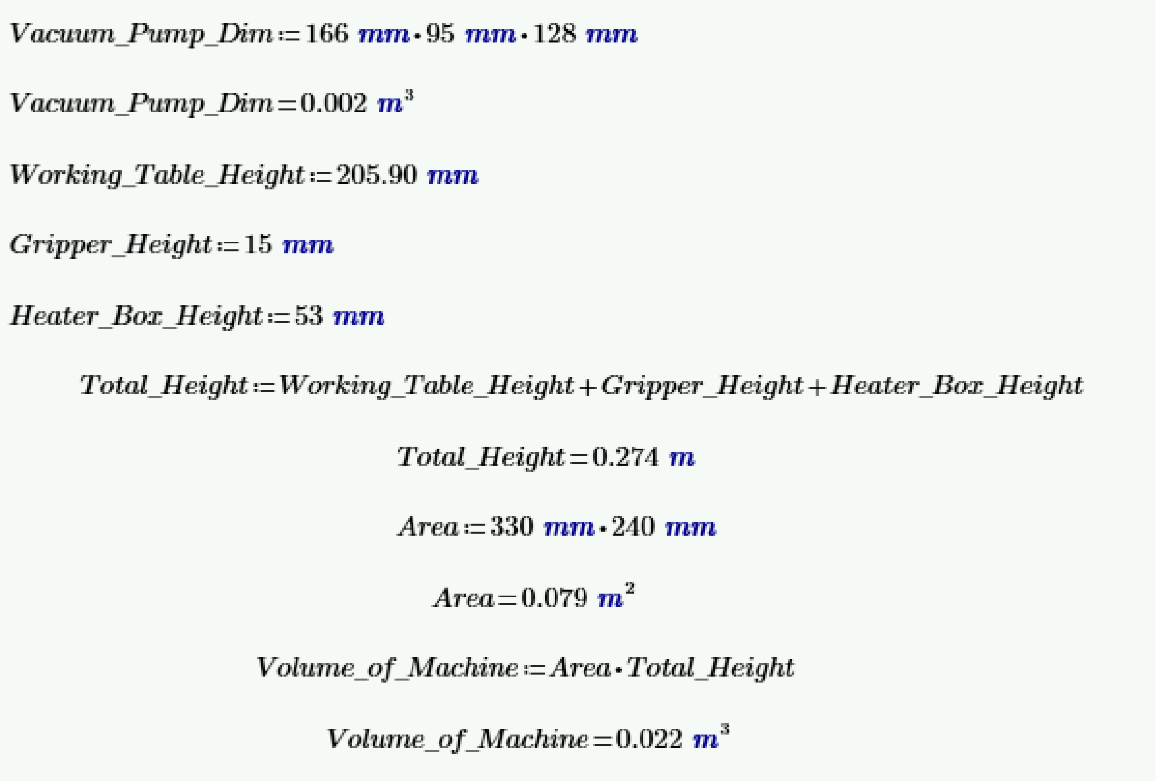
$$Outer\_Dim := 2 \cdot (8\ mm \cdot 210\ mm + 8\ mm \cdot 297\ mm)$$

$$Outer\_Area := Outer\_Dim = \left(8.112 \cdot 10^{3}\right)\ mm^{2}$$

$$Forming\_Area := Area\_of\_A4Sheet - Total\_Grip\_Area - Outer\_Area$$

$$Forming\_Area = \left(4.951 \cdot 10^{4}\right)\ mm^{2}$$

$$Forming\_Area = 0.05\ m^{2}$$



$$Vacuum\_Pump\_Dim := 166\ mm \cdot 95\ mm \cdot 128\ mm$$

$$Vacuum\_Pump\_Dim = 0.002\ m^{3}$$

$$Working\_Table\_Height := 205.90\ mm$$

$$Gripper\_Height := 15\ mm$$

$$Heater\_Box\_Height := 53\ mm$$

$$Total\_Height := Working\_Table\_Height + Gripper\_Height + Heater\_Box\_Height$$

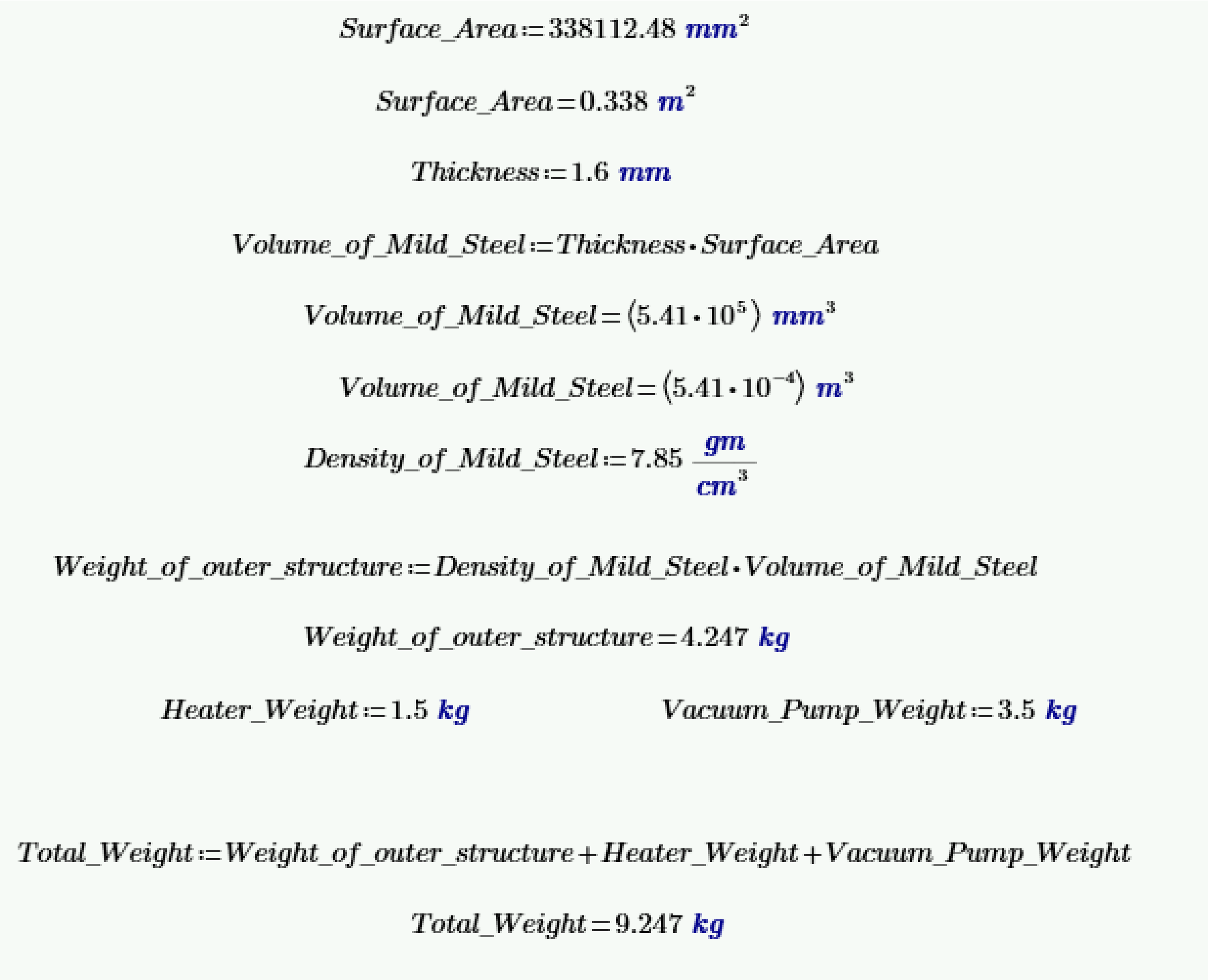
$$Total\_Height = 0.274\ m$$

$$Area := 330\ mm \cdot 240\ mm$$

$$Area = 0.079\ m^{2}$$

$$Volume\_of\_Machine := Area \cdot Total\_Height$$

$$Volume\_of\_Machine = 0.022\ m^{3}$$



$$Surface\_Area := 338112.48\ mm^2$$

$$Surface\_Area = 0.338\ m^2$$

$$Thickness := 1.6\ mm$$

$$Volume\_of\_Mild\_Steel := Thickness \cdot Surface\_Area$$

$$Volume\_of\_Mild\_Steel = \left(5.41 \cdot 10^{5}\right)\ mm^3$$

$$Volume\_of\_Mild\_Steel = \left(5.41 \cdot 10^{-4}\right)\ m^3$$

$$Density\_of\_Mild\_Steel := 7.85\ \frac{gm}{cm^3}$$

$$Weight\_of\_outer\_structure := Density\_of\_Mild\_Steel \cdot Volume\_of\_Mild\_Steel$$

$$Weight\_of\_outer\_structure = 4.247\ kg$$

$$Heater\_Weight := 1.5\ kg \qquad Vacuum\_Pump\_Weight := 3.5\ kg$$

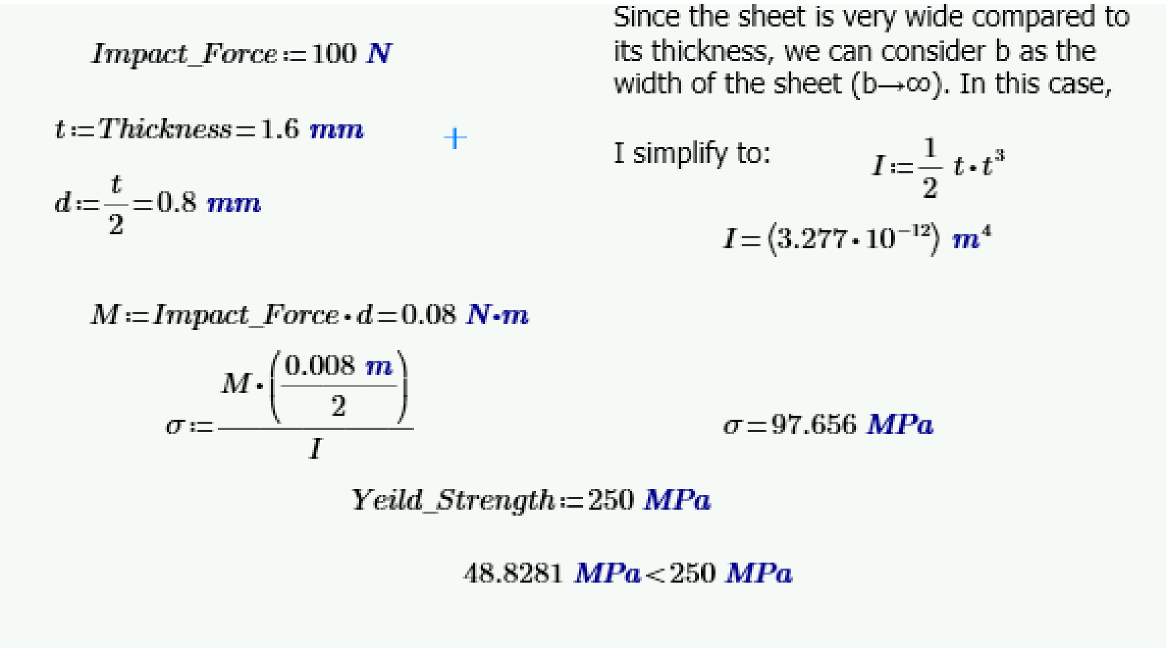
$$Total\_Weight := Weight\_of\_outer\_structure + Heater\_Weight + Vacuum\_Pump\_Weight$$

$$Total\_Weight = 9.247\ kg$$

The resulting weight of the machine comes out as 9.3kg approximate which is well under our requirements.

Stress calculations of the VFM and its structural integrity:

To ensure the structure of our vacuum forming machine doesn't fail, we have calculated the stress acting on the machine due to impact force of 100N. Then, the value of stress is compared with the strength of mild steel to confirm the structural integrity of the VFM.



$Impact\_Force := 100\ N$

Since the sheet is very wide compared to its thickness, we can consider b as the width of the sheet (b→∞). In this case,

$t := Thickness = 1.6\ mm$

I simplify to: $I := \frac{1}{2}\ t \cdot t^{3}$

$d := \frac{t}{2} = 0.8\ mm$

$I = \left(3.277 \cdot 10^{-12}\right)\ m^{4}$

$M := Impact\_Force \cdot d = 0.08\ N \cdot m$

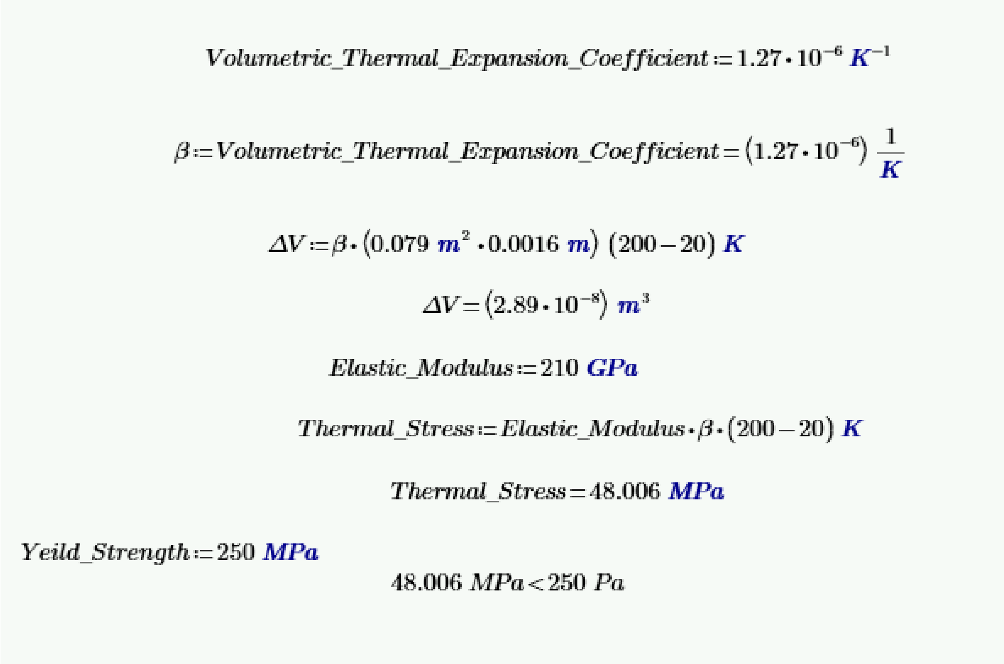
$\sigma := \frac{M \cdot \left(\frac{0.008\ m}{2}\right)}{I}$

$\sigma = 97.656\ MPa$

$Yeild\_Strength := 250\ MPa$

$48.8281\ MPa < 250\ MPa$

Because a VFM has in-built heating mechanism to heat the plastic sheets up to 150 deg Celsius. We have also computed the thermal stresses in the structure generated by the heating source. (quartz heater)



$Volumetric\_Thermal\_Expansion\_Coefficient := 1.27 \cdot 10^{-6}\ K^{-1}$

$\beta := Volumetric\_Thermal\_Expansion\_Coefficient = \left(1.27 \cdot 10^{-6}\right)\ \frac{1}{K}$

$\Delta V := \beta \cdot \left(0.079\ m^{2} \cdot 0.0016\ m\right)\ (200 - 20)\ K$

$\Delta V = \left(2.89 \cdot 10^{-8}\right)\ m^{3}$

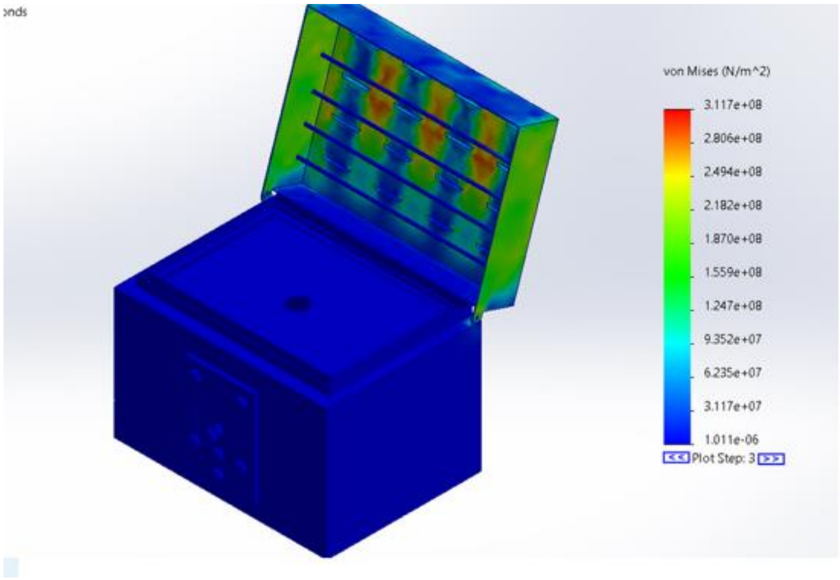
$Elastic\_Modulus := 210\ GPa$

$Thermal\_Stress := Elastic\_Modulus \cdot \beta \cdot (200 - 20)\ K$

$Thermal\_Stress = 48.006\ MPa$

$Yeild\_Strength := 250\ MPa$

$48.006\ MPa < 250\ Pa$



Both the stresses due to impact force and the thermal force are well under the strength of the material of VFM. Ensuring that the structure will not fail.

Standard Operating Procedure

1. Flip the heater to reveal the grippers and working table surface.
2. Lift the upper gripper part and lay an A4 sized plastic sheet over the lower gripper part.
3. Position the upper gripper over the sheet and clamp both gripper parts securely using toggle clamps or latched clamps.
4. Flip the clamped sheet over and position it on top of the heater.
5. Heat the sheet to an adequate forming temperature.

6. Place the pattern of the part on the working table, lay the soft, heated plastic sheet over the pattern.
7. Create vacuum to remove air in between the sheet and working table surface and allowing the sheet to take the shape of the pattern, capturing intricate details.
8. Allow the formed sheet to cool.
9. Remove the formed sheet from the working table.

Fabrication of the machine:

The fabrication process of the table-top vacuum forming machine is completed. Mild Steel makes up the biggest chunk of the material used in making the machine’s frame. Most of the material has been acquired from the market.

The major processes involved in the complete manufacturing and fabrication of the machine are as follows:

- Marking
- Cutting
- Welding
- Laser Cutting
- Gas Cutting
- Grinding
- Bending
- Installation of Heaters
- Installation of Vacuum pump
- Electrical Circuit Construction
- Painting and Finishing

The project's fabrication part is divided into 3 phases.

1st Phase: Manufacturing of Grippers

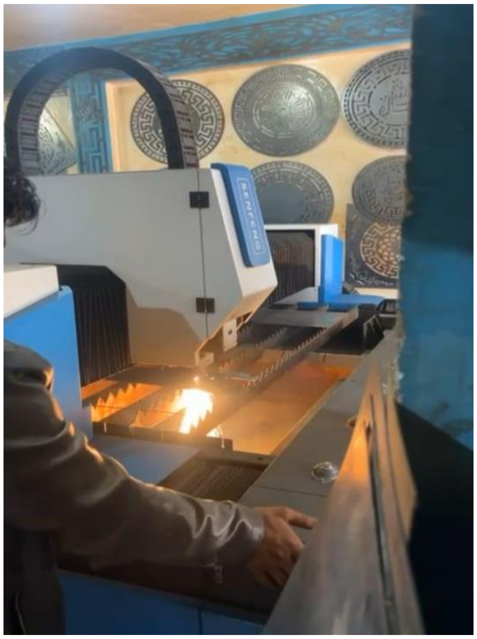
For the manufacturing of gripper, we have used the following processes:

1. Bending
2. Cutting
3. Grinding
4. Welding

After fabrication we tested the grippers to ensure that they function effectively in creating the necessary vacuum. This vacuum is essential for molding the ABS sheet accurately into the desired shape, as per the provided pattern.

Through testing procedures, we aimed to validate the performance of the grippers and guarantee their ability to achieve optimal vacuum levels, ultimately contributing to the successful realization of the vacuum forming machine.

2nd Phase: Manufacturing of Heater Casing and Working Table



For the manufacturing of the heater casing and working table, we have used the following processes:

1. Bending
2. Laser Cutting
3. Gas Cutting

4. Welding
5. Grinding

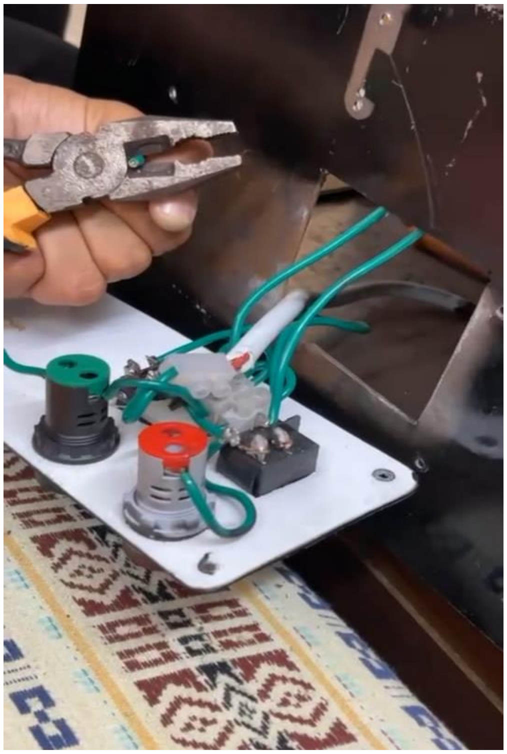
During the phase of manufacturing of the heater casing, it was ensured that the area of the grippers is entirely under the application of heater rods. In total, 3 heater quartz tubes were installed, they were placed equidistant from eachother, ensuring that the sheet is heated evenly, the height of the heater was according to the height of the grippers as when the heater is closed and brought on to the working table, the heater tubes donot collapse with the grippers.

Secondly, the woking table was fabricated entirely by bending a mild steel sheet with the pupose to place the vacuum pump and the electrical wires and circuit board. The Working table has the potential to bear any vibrations from the vacuum pump due to the strenght of the mild steel. It has enough space to accommodate the pump and other accessories with it.

3rd Phase: Installation of components and Finishing

The last job was to install the heater tubes into heater casing and installing the vacuum pump into working table along with the construction of the circuit that supplies electricity to the heater and vacuum by 220V min source. We have used the following processes:

1. Drilling
2. Installation
3. Gas Cutting
4. Finishing
5. Painting

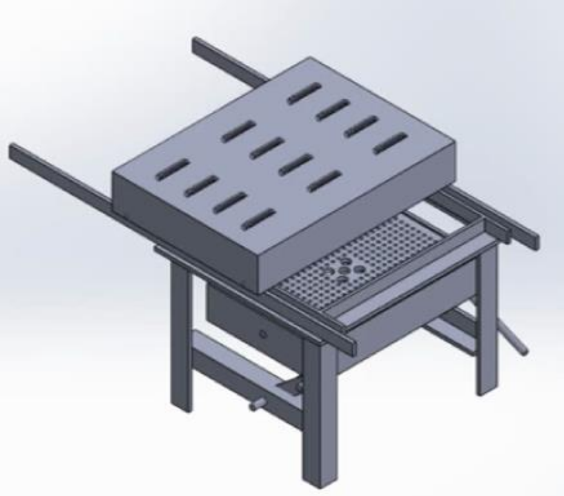


To install the heater tubes, slots were designed with the help of laser cutting to ensure the fixing of the heaters in the heating case. The pump was connected to the hole created in the upper surface of the working table. The electrical buttons, wires and power lights were developed to supply the connection to the heaters and the pump. Lastly, for aesthetics the paint was sprayed to the outer surface of the machine.

CHAPTER 4: RESULTS AND DISCUSSIONS

Several steps were involved to get to the finalized design. Initially, the free sketch designs were made, then some of them were modeled with the help of SolidWorks. The following are the completed designs of the vacuum forming machine.

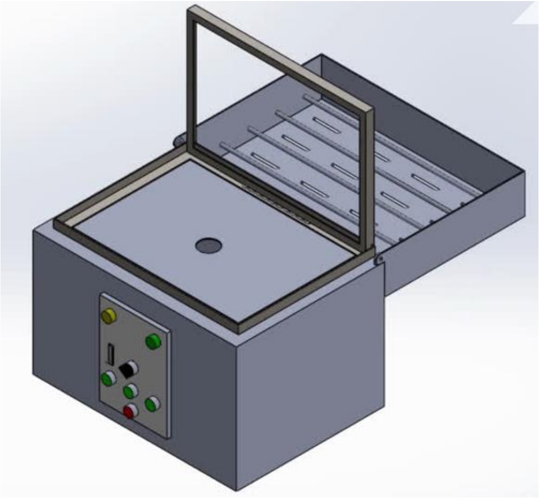
Initial design



Initially the following vacuum forming machine was designed. It has a slider and carriage mechanism to bring heater on to the plastic sheet along with a lifting mechanism to lift the mold and allow the plastic sheet to take the shape of the mold. This model looks quite complex and contains many mechanisms. These mechanisms also add extra weight to the overall total weight of the machine. Thirdly, it will be difficult to package the VFM and transport it from one place to another, creating the lack of compactness.

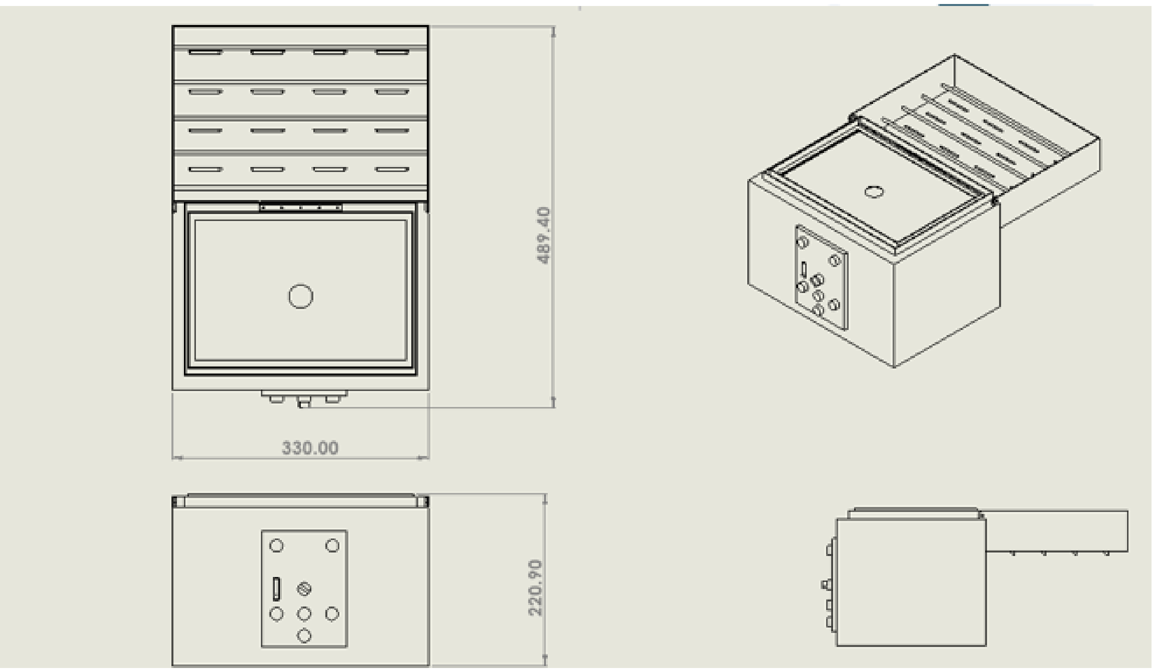
As our goal is to make a table-top vacuum forming machine, we must need a simpler design with less material used and simple mechanisms are incorporated so that we can a more light-weight and compact machine.

Finalized Design:



As we tried new models and designs in the search of a less complex, lightweight and a compact design of table-top vacuum forming machine without compromising on its structural integrity, we came to the following finalized model.

This design of VFM doesn't contain any slider and carriage mechanism nor it has a lifting mechanism. It rather has a simpler hinge mechanism, which enables the gripper and heater to move angularly around and a common axis with the help of hinges. This not only make the vacuum forming machine simpler but also reduces a good amount of weight and because the rotation of both the gripper and heater is around a single axis it also makes the machine more compact.



The vertical and horizontal dimensions of the machine are determined by the forming area which is the area used to make the product. The dimensions also depend on the size of the heater and the installed vacuum pump.

Final selected vacuum pump

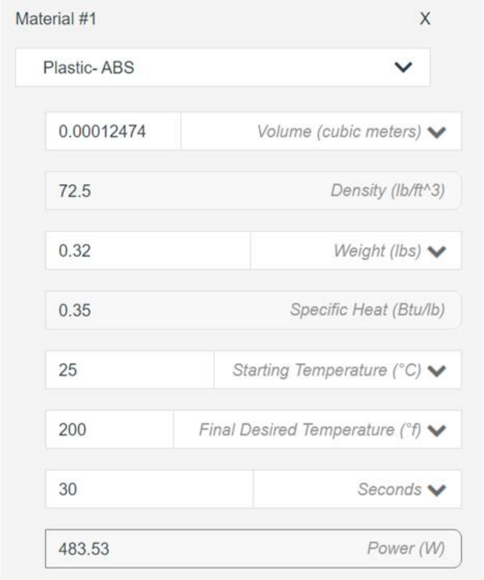
To achieve complete application of the vacuum pressure, and to ensure that the plastic sheet takes every little contour and feature of the mold, we must have a suitable and up to the requirement of vacuum pump. This makes the selection of a vacuum pump quite significant for the development of a reliable and efficient vacuum forming machine. The main parameters of a vacuum pump are ultimate vacuum pressure and discharge size. We also can’t ignore the weight of the vacuum pump because our objective is also to get the minimum weight of the machine.

After calculations and analysis, we have selected a vacuum pump with following specifications:

Specifications	
Type	Piston
Ultimate Vacuum	-83Kpa
Discharge Size	6mm
Installation Size	44 * 77 mm
Maximum Flow	20(60 HZ) / 16(50 HZ) LPM
Voltage	AC 110V / 220V
Power Consumption	85 W
Size	165*95*128 mm^3
Weight	2.1 kg
Price	30 USD

Final selection of Heater

In a vacuum forming machine, the sheets used are commonly of polymer material. Polymer sheets need the temperature in the range of 120-220 degree Celsius. To obtain temperature of the certain range we need to install a corresponding heater keeping in mind that the overall weight doesn't increase too much due to the weight of the heater. We are also required to make sure that heaters are of simple kind so that the overall complexity of the model doesn't get high. For that, calculations were accomplished and hence we understood that quartz tubes will be


Material #1

Plastic- ABS

Volume (cubic meters): 0.00012474

Density (lb/ft^3): 72.5

Weight (lbs): 0.32

Specific Heat (Btu/lb): 0.35

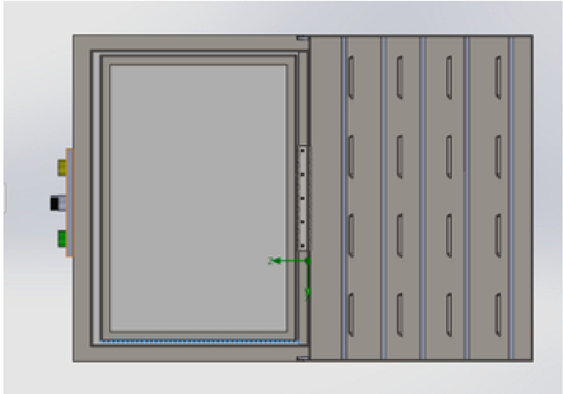
Starting Temperature (°C): 25

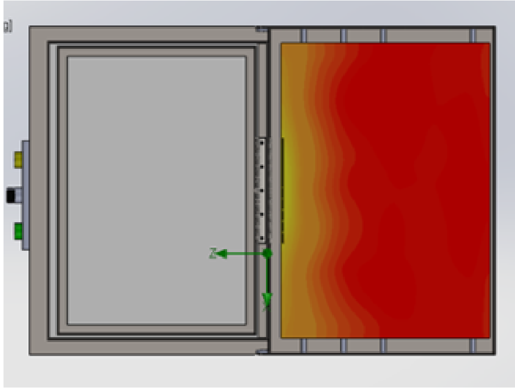
Final Desired Temperature (°f): 200

Seconds: 30

Power (W): 483.53

the best option as they can create temperatures within required range, are light-weight and simple. Following are the parameters which were considered while finalizing the heater.





Parts Produced from Our Vacuum Forming Machine

In the culmination of my final year design project, I successfully engineered a tabletop vacuum forming machine distinguished by two key features. Firstly, it is compact and designed to fit on a tabletop, offering practicality and space efficiency. Secondly, its operation is remarkably straightforward, making it accessible to unskilled operators. With minimal training, even individuals lacking specialized expertise can effectively operate the machine after a single demonstration.

The parts produced by our vacuum forming machine exhibit intricate details and consistently meet our highest standards of quality. Notably, these parts are not only of superior quality but are also cost-effective to produce compared to alternative manufacturing techniques.

Furthermore, the versatility of our vacuum forming process allows us to create parts with complex designs and precise specifications, ensuring that they fulfill the diverse needs of our customers.

In addition, the affordability and efficiency of vacuum forming make it an ideal choice for producing a wide range of components, providing our clients with reliable solutions while optimizing production costs.

As a result, the parts manufactured by our vacuum forming machine stand as a testament to our commitment to excellence, innovation, and cost-efficiency in meeting the demands of our customers.

Vacuum-formed sheets are readily accessible in the market, offering a diverse range of options to suit various needs. These sheets come in different thicknesses and appearances, crafted from a variety of materials.

In the medical industry, where sterility is paramount, specialized vacuum-formed sheets are available to meet these stringent requirements. These sheets are designed to maintain sterile conditions, ensuring the safety and integrity of medical applications.

For signage purposes, where durability is essential for outdoor environments, vacuum-formed sheets with enhanced strength characteristics are available. These sheets are engineered to withstand environmental factors and maintain their structural integrity over time, ensuring longevity and reliability in signage applications.

Furthermore, for food-related applications, such as packaging or container production, vacuum-formed sheets made from Food Grade PET (Polyethylene Terephthalate) are utilized. These sheets are specifically formulated to meet food safety standards, ensuring that containers made from them are safe for storing and packaging food products, thus safeguarding the health of consumers.

Overall, the availability of vacuum-formed sheets in various grades and materials caters to the diverse needs of different industries, ranging from medical to signage to food packaging, offering solutions tailored to specific requirements and standards.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

In response to the identified lack of affordable and compact tabletop vacuum-forming machines hindering rapid prototyping and small-scale production, this project sought to bridge the gap by developing an accessible, user-friendly solution. Through rigorous research, reverse engineering, and meticulous design, a Vacuum Forming Machine capable of processing ABS, high-impact plastic (HIPS), and acrylic materials was successfully engineered.

The manufacturing using of Vacuum Forming Machine can be scaled

Customization: Vacuum forming allows for the creation of custom-shaped components by molding thermoplastic sheets to precise contours. This customization ensures that each part meets specific requirements, whether it's for packaging, signage, or medical devices.

Material Selection: Vacuum forming accommodates a variety of materials with different properties, such as thickness and flexibility. This versatility enables manufacturers to choose materials that best suit the application, ensuring optimal performance and durability.

Ease of Prototyping: Vacuum forming facilitates rapid prototyping, allowing manufacturers to quickly iterate and refine designs based on feedback. This iterative process ensures that the final product meets desired specifications effectively.

Efficiency and Cost-Effectiveness: Vacuum forming is a relatively fast and cost-effective manufacturing process compared to traditional methods. Shorter lead times and reduced production costs make it an attractive option for various industries, from automotive to consumer goods.

There is a lot more to do in terms of research and development in Pakistan. The development of this machine is surely a proof that local development and production of these types of machines can also be done with the resources we have in our country. This will not only create more job opportunities but will also have a great impact on reducing import bills.

In future, this developed technology can be used to create more vacuum forming machines considering local requirements and tailored accordingly. Various types of vacuums forming materials can be studied in terms of this specific technology and machine can be improved with the passage of time. This prototype is the first step for exploring this massive field and product development and machine durability can be improved with time.

REFRENCES

Web link reference:

[1] Extrusions, E. (2016, March 15). *The Principle of Thermoforming - Euro Extrusions*. Euro Extrusions. https://www.euroextrusions.com/the-principle-of-thermoforming/

[2] *Formech | Vacuum Forming Machines | Vacuum Forming Plastic*. (n.d.). https://uk.formech.com/category/desktop

Research paper reference:

[3] Dreuth, H., & Heiden, C. (1999, December). Thermoplastic structuring of thin polymer films. *Sensors and Actuators A: Physical*, *78*(2–3), 198–204. https://doi.org/10.1016/s0924-4247(99)00237-x

[4] Leite, W., Campos Rubio, J., Mata Cabrera, F., Carrasco, A., & Hanafi, I. (2018, February 2). Vacuum Thermoforming Process: An Approach to Modeling and Optimization Using Artificial Neural Networks. *Polymers*, *10*(2), 143. https://doi.org/10.3390/polym10020143.

[5] Birton, B. A., & Gergely, A. (2021, October 1). Design and Implementation of a Vacuum Forming Machine. *Acta Materialia Transylvanica*, *4*(2), 75–78. https://doi.org/10.33924/amt-2021-02-03.

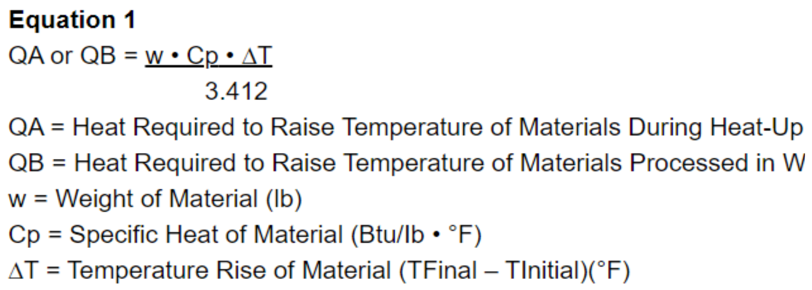
[6] Splintex Ltd. (1973, January). Large capacity vacuum forming machine. *Vacuum*, *23*(1), 25. https://doi.org/10.1016/0042-207x(73)92429-9

Book reference:

[7] Childs, P. R. N. (2013, September 2). *Mechanical Design Engineering Handbook*. Butterworth-Heinemann. http://books.google.ie/books?id=CaSU8lc-fNYC&printsec=frontcover&dq=mechanical+design&hl=&cd=1&source=gbs_api

[8] Beer, F. P., & Johnston, E. R. (1981, January 1). *Mechanics of Materials*. McGraw-Hill Companies. http://books.google.ie/books?id=tYtRAAAAMAAJ&q=mechanics+of+materails&dq=mechanics+of+materails&hl=&cd=1&source=gbs_api

APPENDIX I: GOVERNING EQUATIONS

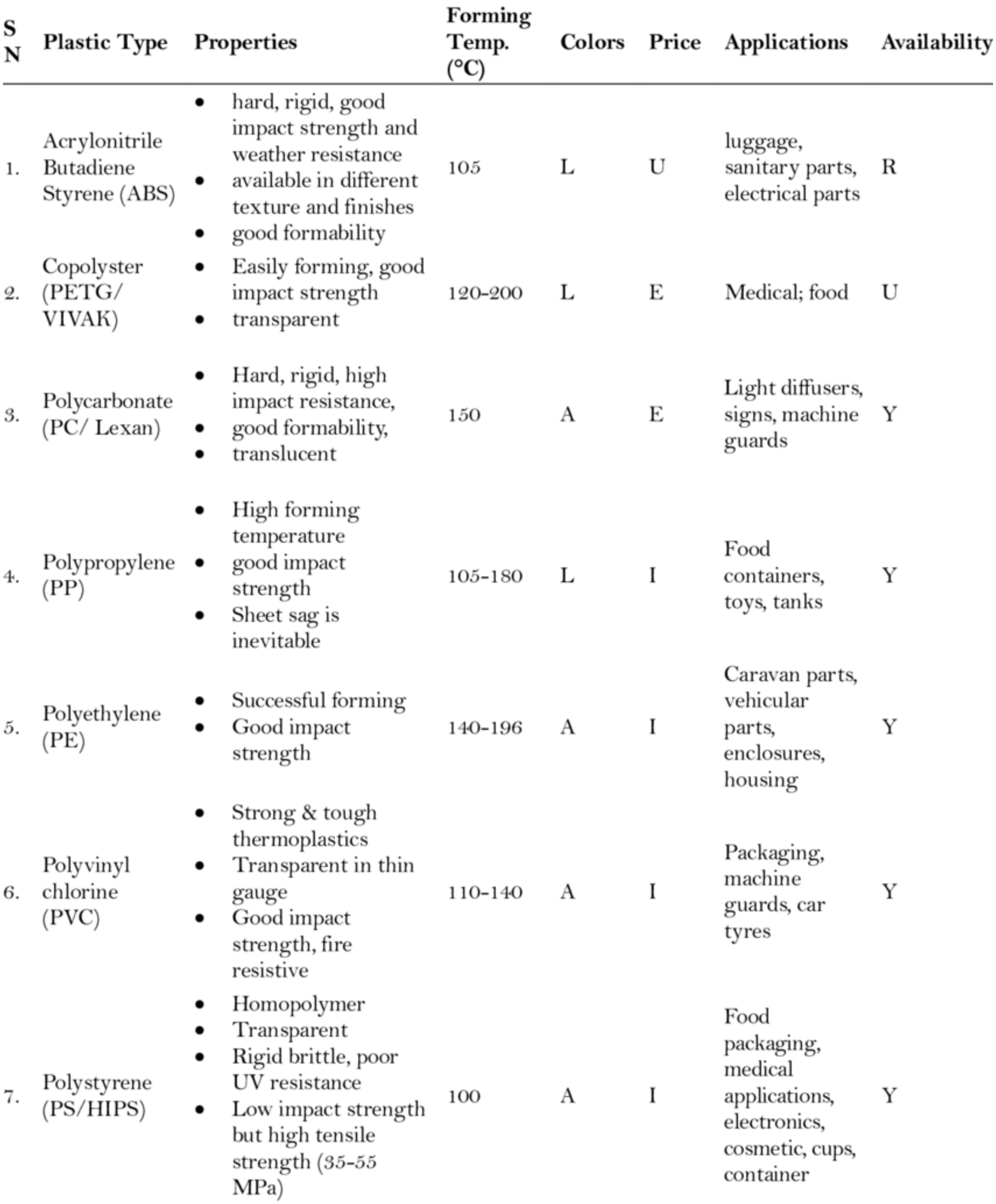


Equation 1

$$QA \text{ or } QB = \frac{w \cdot Cp \cdot \Delta T}{3.412}$$

QA = Heat Required to Raise Temperature of Materials During Heat-Up
QB = Heat Required to Raise Temperature of Materials Processed in W
w = Weight of Material (lb)
Cp = Specific Heat of Material (Btu/lb • °F)
ΔT = Temperature Rise of Material (TFinal – TInitial)(°F)

APPENDIX II: PLASTIC SHEETS CATALOGUE



S N	Plastic Type	Properties	Forming Temp. (°C)	Colors	Price	Applications	Availability
1.	Acrylonitrile Butadiene Styrene (ABS)	• hard, rigid, good impact strength and weather resistance • available in different texture and finishes • good formability	105	L	U	luggage, sanitary parts, electrical parts	R
2.	Copolyster (PETG/ VIVAK)	• Easily forming, good impact strength • transparent	120-200	L	E	Medical; food	U
3.	Polycarbonate (PC/ Lexan)	• Hard, rigid, high impact resistance, • good formability, • translucent	150	A	E	Light diffusers, signs, machine guards	Y
4.	Polypropylene (PP)	• High forming temperature • good impact strength • Sheet sag is inevitable	105-180	L	I	Food containers, toys, tanks	Y
5.	Polyethylene (PE)	• Successful forming • Good impact strength	140-196	A	I	Caravan parts, vehicular parts, enclosures, housing	Y
6.	Polyvinyl chlorine (PVC)	• Strong & tough thermoplastics • Transparent in thin gauge • Good impact strength, fire resistive	110-140	A	I	Packaging, machine guards, car tyres	Y
7.	Polystyrene (PS/HIPS)	• Homopolymer • Transparent • Rigid brittle, poor UV resistance • Low impact strength but high tensile strength (35-55 MPa)	100	A	I	Food packaging, medical applications, electronics, cosmetic, cups, container	Y