Impact of Processing Parameters on the Quality of Vacuum Formed Products for Different Plastic Sheets

Author

ZAKRIA SHAH

(Registration No: 00000361622)

Department of Design and Manufacturing Engineering

School of Mechanical and Manufacturing Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

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By

ZAKRIA SHAH

(Registration No: 00000361622)

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Supervisor: DR. SHAHID IKRAMULLAH BUTT

Co-Supervisor: DR. MIAN ASHFAQ ALI

Department of Design and Manufacturing

School of Mechanical and Manufacturing Engineering

National University of Sciences & Technology (NUST)

Islamabad, Pakistan

(2024)

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Signature: Dr Shahid

Name (Supervisor): Shahid Ikram Ullah Butt

Date: 20 - Aug - 2024

Signature (HOD): Dr Shahid

Date: 20 - Aug - 2024

Signature (DEAN):

Date: 20 - Aug - 2024

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Examination Committee Members

1 Name: Mian Ashfaq Ali Signature:

2. Name: Muhammad Salman Khan Signature:

3. Name: Syed Hussain Imran Jaffery Signature:

Supervisor: Shahid Ikram Ullah Butt Signature:

Date: 20 - Aug - 2024

DrShahid

Head of Department

20 - Aug - 2024

Date

COUNTERSINGED

20 - Aug - 2024

Date

Dean/Principal

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Student Name: Zakria Shah Signature: ______________

Examination Committee:

a) Internal Examiner 1: Dr.Mian Ashfaq Ali Signature: ______________
(HOD Dept of ME, SMME, NUST Islamabad)

b) Internal Examiner 2: Dr.Muhammad Salman Khan Signature: ______________
(Dept of DME, SMME, NUST Islamabad)

c) Internal Examiner 3: Dr.Syed Hussain Imran Jaffery Signature: ______________
(Dept of DME, SMME, NUST Islamabad)

Supervisor Name: Dr.Shahid Ikramullah Butt Signature: DrShahid

Name of Dean/HOD: Dr.Shahid Ikramullah Butt Signature: DrShahid

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DEDICATION

Dedicated to my exceptional Parents, Family, Friends, and My Supervisor Dr.Shahid IkramUllah Butt whose tremendous support and cooperation led me to this wonderful accomplishment.

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ABSTRACT

At present, there is a growing tendency among industries to integrate eco-friendly practices to comply with the increasingly stringent environmental standards that are being introduced. In this context, a variety of sustainable machining methods have been investigated with the objective of optimizing processing parameters. The objective of this study is to optimize processing parameters for the manufacturing of plastic sheets using a vacuum-forming process. This method is cost-effective and versatile, offering superior surface finishes, reduced manufacturing costs, and increased productivity. It addresses issues that arise from the use of unoptimized parameters, which are typically determined through a process of trial and error or based on the experience of the operator. In this study, the heating temperature, heating time, sheet thickness, and distance between ups were identified as the optimal parameters for optimization. Uniformity and the number of wrinkles were selected as performance assessment attributes. The experiments were conducted in accordance with the Taguchi L16 orthogonal array (OA) experimental design plan. It was determined that the thickness of the sheet and the distance between the ups are significant consequences in determining the quality of vacuum-formed parts. The experiments demonstrated that the sheet type, color, and size of the venting hole in the male mold had a negligible impact on the formation of wrinkles. The results of the ANOVA demonstrated that uniformity and the number of wrinkles were significantly influenced by the sheet thickness and distance between ups. The Taguchi analysis identified the optimal process parameters that enhanced the product quality, as evidenced by the results of the conformance tests. Additionally, regression analysis was utilized to predict outcomes and assess the model. The developed regression models are recommended for implementation in manufacturing industries to optimize parameters, reduce material waste, enhance productivity, and improve cost-effectiveness.

Keywords: *Thermoforming, Vacuum Forming Process, Formech 508fs machine, Polyvinyl chloride Sheet Optimization, Design of experiments, Taguchi method, ANOVA, Regression model*

CHAPTER 1: INTRODUCTION

The current phenomenon in many industries is to adapt environmental conservation measures due to the increased environmental standards. These regulations are forcing organizations to adopt green frontiers by lowering wastage, energy usage, and emissions. To achieve all these standards, various industries are having to look for sustainable machining techniques that are environmentally friendly without compromising on efficiency or quality.

In this regard, the study seeks to determine the processing parameters that are most suitable for the vacuum-forming process with special reference to the production of plastic sheets. The emphasis is made on the determination of optimal conditions of vacuum-forming equipment for increasing the effectiveness of the production process and reducing the negative impact on the environment. The objective of fine-tuning these processing parameters and other machining conditions is to produce high-quality plastic sheets with the least energy and material utilization. From an environmental angle, it is noble to look for ways of making the vacuum-forming process as environmentally friendly as possible, while at the same time, producing quality Plastic products. This balance between sustainability and product excellence is important in addressing the industrial and environmental goals and thus the effort is not only technically relevant but is also ethical in terms of promoting sustainable manufacturing practice.

1.1 Vacuum Forming Process

Vacuum forming is a subset of thermoforming where a plastic sheet is clamped and heated to its glass transition temperature. This heating process makes the plastic become pliable. The softened plastic is then placed over a mold and vacuum pressure is applied to draw the sheet tightly over the contours of the mold. This process is maintained until the plastic solidifies and takes the shape of the mold [1] [2] [3].

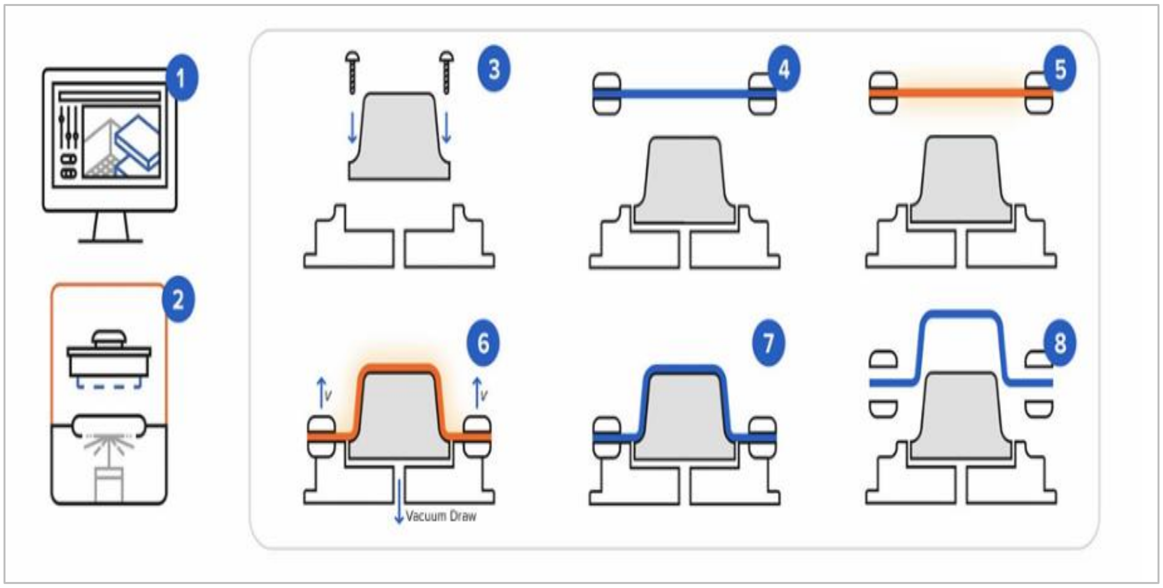


Figure 1.1: Process workflow of vacuum forming process

①-Mold design ②-Mold Manufacturing ③-Mold mounting ④-Sheet clamping ⑤-Heating ⑥-Forming ⑦-Cooling ⑧-Demolding

1.2 Plastic Materials in the Vacuum Forming Process

Vacuum forming can be used with a wide range of polymeric materials such as ABS, ASA, PET, PETG, HDPE, PVC, PC, PP, PS, HIPS etc. It is important to understand the rheology, and flow behavior, of these materials. A good understanding of the process rheology leads to material-saving cycle time reduction. Each material brings its unique properties and advantages to vacuum forming, depending on the application's specific [4] [5].

ABS is a hard, rigid thermoplastic, which is amorphous and has good impact strength and weather ability due to the presence of rubber. It has a shrinkage rate of 0. 3% to 0. 8% and in different grades of which most of the common ones are fire retardant and UV-stabilized grades. ABS finds use in the manufacturing of products like luggage, automobile parts, sanitary ware parts, aircraft parts etc. Likewise, ASA is a hard and strong thermoplastic with excellent weatherability, UV stability, and impact strength and it is better in weathering and color fade resistance than ABS. Examples of its uses are furniture for outdoor use, automobile accessories, advertisement billboards and structures, and building construction where durability and a variety of colors and finishes are desirable [6] [7] .

Others important thermoplastics are Polystyrene-Polyphenylethene. This is an amorphous polymer that is characterized by low forming temperature and high cycle time, hence cheap to use in the manufacture of products such as disposable items, toys, and packing materials. Acrylic is another high-quality hard plastic with excellent clarity and is suitable for vacuum forming and can be used for signs, roof lights, domes, baths sanitary ware, and diffusers though it is more expensive. Further, PVC (Polyvinyl Chloride) is a hard, strong, and chemical-resistant thermoplastic that offers good clarity in thinner gauges and is widely used for packaging applications and for outdoor or industrial applications where thicker materials are used. Another factor that makes PVC more versatile is its low cost of production [8] [9] [10].

Figure 1.2: Plastic Materials in the Vacuum Forming Process

1.3 Advantages of Vacuum Forming Process

There are many advantages of vacuum forming over other forms of plastic forming: The first advantage of using it is that it is relatively cheap to manufacture hence it gives high productivity and a very good surface finish, thus can be used to manufacture a host of products. While most forming processes work under high pressure, vacuum forming works at considerably less pressure making it suitable for the production of products such as low-pressure cups and packs [11] [12]. Moreover, the idea of employing extruded plastic sheets instead of starting from powder or resin also does not incur much tooling expenses. Another feature of the process is that it is very efficient, and the time taken to process the products is relatively short, and the production of quality products is done within a short time and in equal measures [13].

1.4 Formech 508FS Vacuum Forming Machine

The Formech 508FS is a high-precision vacuum-forming machine that is used to shape thermoplastic sheets. It is widely used in product design, packaging, prototyping, and education. Despite its small size, it can provide rich features such as programmable settings and infrared heating, which can make it suitable for the production of complex, precise parts. These are touch panels with user program saving, secure clamps on the material, and heating from both the top and bottom through quartz heaters. It is safe as it comes with Overheat protection and automatic shut off. Also, the Becker pump and the connection to the compressed air provide stable vacuum pressure, which helps to avoid defects in formed parts.

Figure 1.3:Formech 508FS Machine

1.5 Applications of Vacuum Forming Technology

A variety of products are formed by using this technique in different industries [14] [15].Due to low manufacturing cost, high manufacturing efficiency in a limited time, and high surface quality. vacuum forming has a wide range of applications. Some of them are given below [16] .

1.5.1 Vacuum Forming in Medical, Aeronautical, and Automotive Industries

Vacuum forming is used in the production of wheelchair parts, prosthetic limbs, dental castings, medical equipment for the disabled, pressure masks for burn victims, and radiation masks for cancer patients [17].Interior trim panels, covers, and cowlings as well as NASA Space Shuttle interior sections are common applications. Wheel hub covers, ski boxes, storage racks, wind tunnel models, terrain vehicle parts, truck cab door interiors, wind and rain deflectors, scooter shrouds, mudguards, bumpers and protective panels, battery and electronic housings, utility shelves, liners, seat backs, door inner liners, and dash surrounds, windshields, motorcycle windshields, golf cart shrouds, seats, and trays, tractor shrouds and door fascia, and camper hardtops and interior components are just a few of the many automotive applications for it [6] [18] .

1.5.2 Education, Architectural Model Makers and Electronics Industry

In teaching, vacuum forming is an important training aid for students studying polymers and processing plastics. In the electronics industry, it has been employed in the manufacturing of anti-static component trays and housing of specific devices. It also produces enclosures, a transparent keyboard cover, screen surrounds, and other accessories. In architecture, it is used in making small parts of model prototypes, roof lights, PVC door panels, door liners and concrete paving stone molds, unique bricks, etc. It also manufactures drainpipe anti-drip fittings and molded features of porches, fireplaces, and ceilings. Also, vacuum forming is applied in the production of boat hulls, covers, hatches, electrical enclosures, and dashboards in the marine industry [6] [19].

1.5.3 A Versatile Technique Shaping Industries from Agriculture to Design

In agriculture, vacuum forming is used for manufacturing of machine parts, lawnmower covers, flower tubes, animal transport containers, clear growing domes, calf milking containers and coverings. In the household sector, it can be used to make cutlery tray inserts, kitchen unit panels, storage modules and chair and seat backs. In the design field, vacuum forming is used in the production of prototypes and limited pre-production runs of the other plastics process. However, it is also employed in a range of scientific and natural history museum contexts [6] [19] [20].In the manufacturing of various products, vacuum forming is popularly employed in packaging product display trays, cosmetic cases, vacuum-formed packaging, electronics, blister packs, food packaging, and fast-food trays. It is also used in the production of bathroom accessories such as bathtubs, spa baths, shower trays, and retrofit shower parts. Also, vacuum forming is used to make POS displays, external signs, props, sets, and costumes, and for molding cast-craft souvenirs [18] [21] [22] [23].

1.6 Problem Statement

This thesis deals with the enhancement of the vacuum forming process because of problems arising from uncontrolled machine parameters that cause variations in the wall thickness, wrinkle formation, chill marks, burn marks, thinning, and discoloration, hence the poor quality of the end product. In the case of vacuum forming, the Heating Temperature, Heating Time, Sheet Thickness, and Distance Between Ups can be adjusted to increase the quality and durability of the final product. The optimization exercise will be affected using the Formech 508fs machine which has been determined to be capable of tweaking these variables across certain plastic sheets and product characteristics. It is for this reason that the study aims at reducing, or eradicating, these defects through fine-tuning of the parameters involved in the vacuum forming process with the view of increasing the efficiency and reliability of the process.

1.7 Scope

From this study, the following objectives have been sought: To identify and tackle various challenges that may arise while practicing vacuum forming and those arising from un-optimized machine parameters. These problems appear because of the utilization of trial-and-error methods and the qualitative assessments of operators, which cause fluctuations in the quality of products. The main goals of this research are as follows: The maximization of Heating Temperature, Heating Time, Sheet Thickness, and the Distance Between Ups. It is within this context that the study aims at improving on various parameters that affect vacuum-formed parts to increase the quality as well as the standard of such products.

The optimization experiments will be performed with use of the Formech 508fs machine, which is perfect for adjusting these parameters for different plastic sheets or product properties. The knowledge that is expected to be attained from this research is believed to help enhance better practice of the vacuum forming process.

1.8 Objectives

The utmost objective of the research is to optimize the processing parameters **(**Heating Time, Heating Temperature, sheet thickness, and distance between ups) for Plastic sheets that have not been standardized and are based on trial and error or the experience of the operator. Research will be carried out using the Design of Experiments and Tools Methodology to study the relationship between the impact of different parameters and the desired product.

The following are the principal goals of this study:

1. To determine the optimal ranges for vacuum forming processing parameters based on desired product characteristics and ideal process parameters for heating temperature, heating time, sheet thickness, and distance between ups.
2. To Ensure that the formed products have a uniform thickness distribution and reduce defects like wrinkles.
3. To offer helpful recommendations and a solid foundation for additional study and industrial vacuum forming applications.

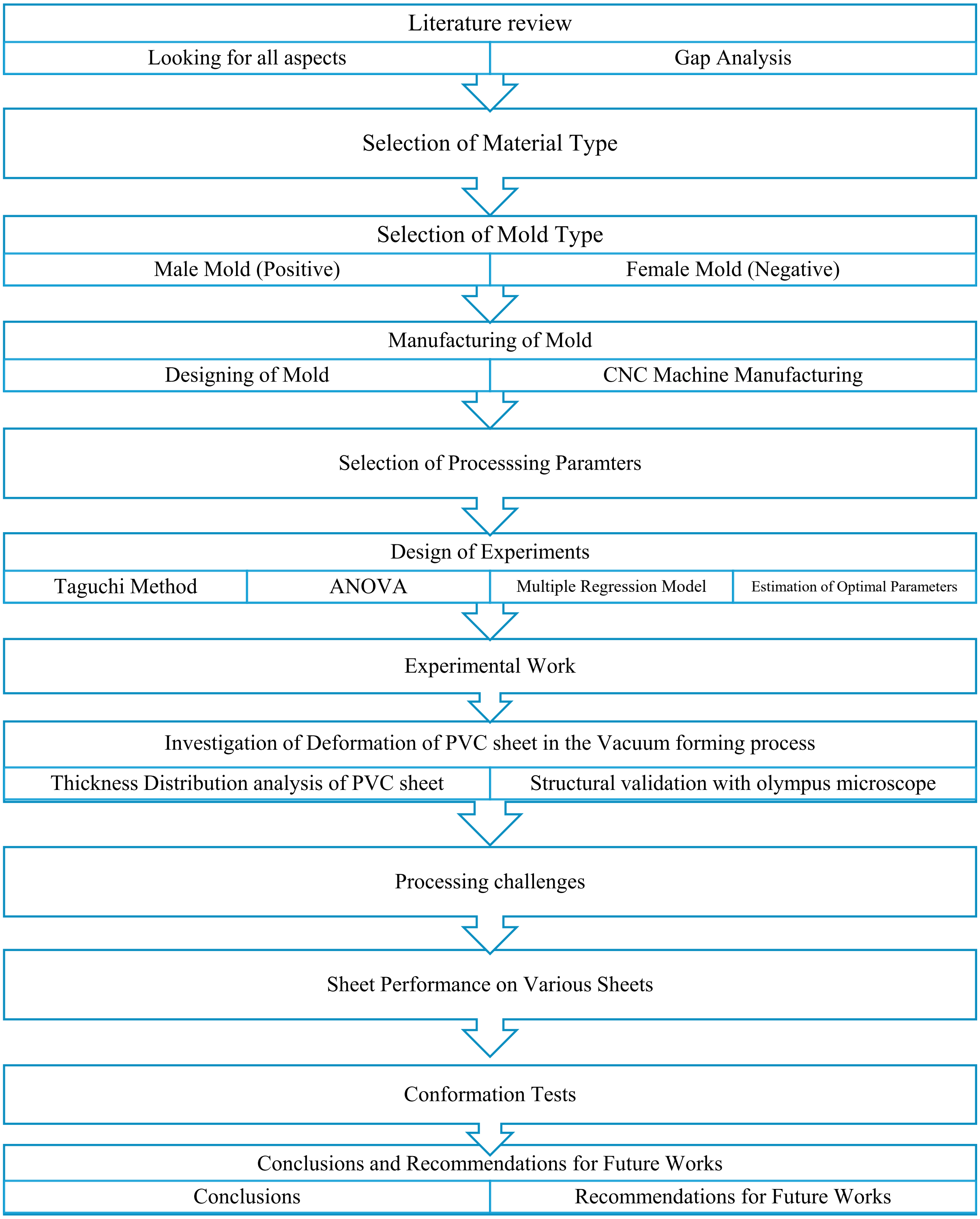
1.9 Significance

The research addresses vacuum-forming challenges like material waste and time consumption by using the Taguchi method and Design of Experiments to optimize parameters like heating time, heating temperature, distance between ups, and sheet thickness. The objectives of this optimization are to decrease waste, shorten production times, increase effectiveness, and minimize costs. The study intends to improve the effectiveness and quality of vacuum-formed products across industries by methodically optimizing these parameters based on desired product characteristics. Furthermore, its methodology may serve as a model for other research, enhancing productivity and manufacturing procedures.

The importance of the study comes from its attention to important factors such as Heating temperature, heating time, distance between ups, and sheet thickness. These factors are optimized through the application of the Taguchi method to guarantee reliable and error-free production, which improves product quality and lowers waste. Furthermore, the study eliminates the need for operator experience by standardizing machine settings, which promotes reliability and reproducibility across production runs. A thorough understanding of material and mold selection and machining parameters helps manufacturers make well-informed decisions that improve durability and performance while cutting costs.

Vacuum forming is less time and time-consuming of all the molding processes since it takes a shorter time to produce products. This makes it especially desirable for industries that require the creation of small-sized products or the modification of existing ones on short notice and with high levels of expensive overheads. This process involves using experienced mold makers and involves making molds to the correct sizes and dimensions and having the correct draft angles. After that the vacuum forming is done and then comes the other process such as cutting, polishing, painting, checking the quality of the mold, and finally assembling it and sending it out to its destination. The most common application of vacuum forming is in the formation of lightweight plastics that provide great strength in relative to the mass.

1.10 Research Methodology



CHAPTER 2: LITERATURE REVIEW

In early ages, plastic applications were made by heating, shaping, and cooling it on a specific mold or product. Subsequently from 1936 to 1940, this process was known as thermoforming, and it was first used in 1930. And still, it is on the rise daily [24]. The development of thermoforming as we know it today began with World War II inventions like acrylics and aircraft canopies. Growth dramatically increased after World War II because of breakthroughs in new materials and uses [25]. During the 1970s, thermoforming machine manufacturers increased the technology to satisfy the growing market, which led to the development of high output, automated thermoforming machines, and better cost control through efficient production and scrap management. In the 1980s, the emphasis on automation persisted, and improvements in pellet-to-product equipment and process controls were made, which allowed for the development of new products and additional cost-cutting [26].

The growing demand in the global thermoformed plastics market is expected to reach USD 17.9 billion by 2027 at a 4.9% CAGR. A few regions are dominant in the global market; as of 2019, North America (the United States, Canada, and Mexico) accounted for approximately 54% of revenue, placing it in first place. Asia Pacific (China, Japan, India) and Europe (the United Kingdom, Germany, France, and Italy) are two other regions that are significant players in the global thermoforming market [27].

The thermoforming process has been greatly enhanced by improvements in heating techniques. Because infrared (IR) and quartz heaters are more efficient and produce faster, more consistent heating, they have largely replaced traditional convection ovens. Beall (2008) claims that by guaranteeing uniform heat distribution, these technologies shorten cycle times and improve the quality of the finished products [28] [29] [30].

Mold design has been made even more efficient by the combination of computer-aided design (CAD) and computer-aided manufacturing (CAM), which has decreased development times and costs. to create complex mold geometries more quickly and easily, rapid prototyping technologies like 3D printing are being used more and more [29] [31] [32].

The advancement of new heating systems that enable localized and accurate heating is essential for obtaining uniform temperature fields and desired material response during the molding process [32]. Temperature control is crucial in thermoforming since variations in temperature can cause defects or weaknesses in the final product; therefore, heating methods should be efficient to achieve the best results [33]. Different heating techniques employed in thermoforming like infrared and quartz heaters are known to be effective and uniform [34].

Despite its widespread use, achieving consistent quality in thermoformed products remains challenging due to processing parameters. The biggest disadvantage of thermoforming is the non-uniform wall thickness, formation of wrinkles, chill marks, and burn marks. The variation of wall thickness can be controlled with design, manufacturing choices, and machine parameters, but due to the nature of the stretching process, it cannot be fully eliminated [25] [35]. It is widely recognized that the current thermoforming process uses trial and error to define the heating temperature leading to a non-uniform thickness of the parts [36] [37].Several studies have been conducted to improve the quality of thermoformed products by analyzing various processing parameters. The thickness distribution in thermoformed trays is influenced by processing factors such as sheet temperature, mold temperature, heating time, thermoforming pressure, evacuation rate, plug temperature, plug speed [2] [38] [39].

It was determined that plug velocity and temperature are the factors that influence the thickness distribution in thermoformed foam, and the best results are obtained at a plug velocity of 0. 027 m/s and a temperature of 123°C, although there are issues with poor quality uniformity and film cooling disadvantages [40]. Previous studies had been conducted on variable geometry molds for wood-polypropylene composite panels, and it was noted that the appropriate melt strength and temperature range were critical to the process [41]. A study showed that material, vacuum pressure, plug stroke, sheet thickness, holes, and mold shape affect the wall thickness distribution, while heat transfer and contact friction are the most important factors [42]. The importance of heating time and mold type revealed that longer heating time leads to better thickness distribution in female molds while shorter heating time does the same for male molds using high-impact polystyrene sheets When preparing polypropylene thermoplastic containers, pay close attention to the vacuum pressure, heating temperature, and container size. Findings suggest that the ideal temperature range for the polypropylene thermoplastic sheet is between 165°C and 175°C [43]. Subsequently, it was shown that the impact of pressure-bubble vacuum forming on the wall thickness distribution in polystyrene sheet parts. It deals with the variation of thickness in the wall because of the difference in stress, particularly between the base and the walls. The results of the study reveal that the use of a bubble leads to a substantial decrease in thickness variation compared to parts without it [44]. Another study emphasized temperature regulation and vent holes in the molds to enhance the plastic deformation and the quality of the containers [45].

Additionally, the study is centered on minimizing thickness variation in thermoformed products through the determination of the cooling coefficient and shrinkage in the x and y directions. It describes thickness compensation techniques including compensation recesses and tool depth control and provides mathematical models for thickness variation in axisymmetric parts. It also emphasizes the importance of cavity location and item dimensions in the design of the molding tool to reduce thickness differences [46]. The Taguchi method is used to optimize the standby temperature, heating temperature, and heating time using a Formech 508fs machine and polypropylene plastic sheet. It finds that by adjusting the heating temperature to 90%, the heating time to 45 seconds, and the standby temperature to 60%, strawberry packaging burn marks are reduced to 13% using SNR for accuracy [37]. The thermoforming process for producing glass fiber-reinforced thermoplastic parts was examined, highlighting defects such as wrinkles, thickness variations, and residual stresses affecting product quality . Another study also compared the effect of three distinct thicknesses of Polypropylene Terephthalate (PET) sheets were produced. Compared to 0.2mm and 0.3mm sheets, the 0.15mm sheet heats up more quickly. The 0.2mm sheet works best when heated for 245 seconds at 218°C, with adequate suction and air leakage control. Variations in temperature and suction pressure have an impact on the outcomes the thinner sheets heat up faster and the heating time and temperature depend on the thickness of the sheets [47]. Additionally, studies on nonuniform heating and material's response to temperature gradients indicated that ceramic heaters improve thickness profile, while computational modeling offers a better understanding of thermoforming processes [48]. study examined the thermoforming performance of plastic-coated fiber-based materials, highlighting that poor performance often stems from process limitations rather than material issues. Recommendations include optimizing pressure supply, cooling methods, and mold dimension adjustments to enhance outcomes [49]. A recent study examined the impact of (male) and cavity (female) molds on wall thickness and defect occurrence in thermoforming. Plug molds resulted in less wall thickness variation but faced challenges like webbing and part release issues, while cavity molds, though less prone to webbing, often had uneven thickness due to stretching [50].

Despite advancements in the thermoforming process, optimizing thickness distribution, webbing, and chill marks in a thin sheet remains a critical objective. It can be difficult to guarantee the quality and consistency of vacuum-formed parts because a variety of factors, such as material choice, mold design, and processing parameters, can have an impact on the final product's characteristics [6]. A few of the drawbacks are the uneven wall thickness, the expense of producing sheets, the requirement for trimming and the related expenses, the restriction on part geometries, and the restricted selection of thermoplastics [32] [51]. When undesirable creases or pleats appear in the finished product, it is known as webbing, a defect that frequently occurs in vacuum forming. The reason for this problem is that the plastic material is not distributed evenly throughout the molding process. This happens frequently when the hot plastic is dragged unevenly over the mold while under vacuum pressure. Usually seen around the edges, particularly between the tool and the base area, webbing resembles the web found on duck feet. Several factors, such as the mold being too tall about the base area, sharp vertical corners with little draft angles, excessive heat, too much plastic material, multiple molds spaced closely together, uneven heating, the plastic sheet stretching quickly, and uncontrolled vacuum airflow, can cause webbing [52] [53].

This research aims to optimize processing parameters like heating time, temperature, sheet thickness, and distance between ups to minimize uneven thickness, webbing, and chill marks using a male mold with symmetric geometry, enhancing product quality and understanding of the thermoforming process.

The existing thermoforming method frequently has limitations because it mostly relies on trial and error to identify processing settings. To tackle this issue, a great deal of research is being done on the numerical modeling of thermoplastic heating, which should result in improvements to heating technologies. It is also expected that thermoforming will continue to be developed primarily for use in packaging, especially for improving food preservation and sterilizing procedures.

2.4 Research Gap

Even with vacuum forming advancements, there are still a few important areas that require research:

a) Very few studies on the optimization and impact of processing parameters (heating time, heating temperature, sheet thickness, and distance between molds) on the vacuum-forming process.
b) There isn't much in-depth research on how heating temperature, heating time, sheet thickness, and distance between ups interact with different plastic sheets when using reliable techniques like the Taguchi method.
c) Formation of Wrinkles/webbing in symmetry molds
d) Optimization of uneven thickness on thin plastic sheets
e) There is a dearth of research on standardizing machine settings to lessen reliance on operator experience and trial-and-error.

CHAPTER 3: METHODOLOGY

3.1 Constraints for the Current Study

The present study used a Formech 508Fs thermoforming machine and the materials employed define the research restrictions. Along with a maximum depth of draw and material thickness, the machine supports a particular sheet size and shaping area.

Table 3-1: limitations for the present study

Machine Constraints	
Machine	Formech 508Fs
Temperature Range of Machine	1 to 100 centigrade
Heating Time Range of Machine	1 to 300 seconds
Sheet size	508x457mm
Forming Area	482x432mm
Max. depth of draw	290mm
Max. Material thickness	6mm
Research Constraints	
Plastic Sheet	Polyvinyl chloride (PVC)
Type of mold	Male Mold
Material for Mold	Medium Density Fiber
Height of Ups	30mm
Upper Diameter of Ups	58 mm
Lower Diameter of Ups	74 mm

3.2 Selection of Material Type (PVC Sheet)

In this study, Polyvinyl chloride sheets with different thicknesses were vacuumed and formed. Because it is a highly durable and rigid thermoplastic with good clarity in thinner gauges. Good chemical and fire resistance. Highly resistant to solvents. Thicker materials are more rigid with good impact strength that is suitable for outdoor industrial use [54]. The selection of PVC plastic sheets for this project was deliberate and strategic, driven by several key advantages. PVC is chosen for its affordability and widespread availability in the market, making it a practical choice for various applications. Particularly prevalent in the packaging industry, PVC is valued for its strength and durability as a thermoplastic material. Even in thinner gauges, PVC exhibits excellent transparency, making it suitable for packaging applications where visibility is important. Additionally, PVC's compatibility with specialist inks makes it adaptable for printing purposes, albeit with the need for specialized equipment and expertise. Moreover, PVC boasts impressive chemical and fire-retardant properties, along with high resistance to solvents, enhancing its suitability for a range of industrial applications. Its cost-effectiveness further contributes to its popularity in packaging manufacturing, while thicker variants are favored for outdoor and industrial uses due to their robustness and resilience. Thus, PVC emerges as a versatile and practical choice, aligning with the objectives of the vacuum-forming project.

3.2 Processing Parameters and their Levels in the Current Study

There are several processing parameters in the vacuum-forming machine, some of which are related to the machine itself, while others are related to the material and mold. We purposefully chose to exclude several parameters from our vacuum forming process on the Formech 508fs machine because of the machine's preset settings. Parameters like clamping pressure, pre-stretching, plug assist pressure, Compressor pressure, sheet sagging distance, and sheet stretching ratio were not taken into consideration since they are fixed and standardized within the machine's functioning. Furthermore, as our Formech 508fs machine does not have these features and our transparent PVC material of choice cools quickly through ambient air, factors like cooling fan speed and cooling fan were overlooked. The properties of the material we selected, and the ease of use of our product design.

Numerous studies have demonstrated the critical roles these factors play in defining the effectiveness and quality of vacuum-formed products. These elements have continuously been emphasized as important determinants of material behavior and the quality of the end product in vacuum-forming operations. Our thorough analysis of the literature highlighted the significance of these chosen variables in obtaining desired results, while also noting that other aspects may significantly affect the resulting conclusion. We wanted to make sure that our vacuum-forming optimization efforts were well-informed and focused, so we matched our experimental emphasis with well-established findings from the literature. The processing parameters and their corresponding levels were selected based on the trial experiments. The processing parameters and their corresponding levels used in this investigation are listed in Table 3-2. The impact of these variables on the thermoforming process can be systematically experimented and analyzed.

Table 3-2: Processing parameters and their respective levels in this study

Parameters (Controllable factors)	**Symbol**	**Unit**	**Levels**			
			1	**2**	**3**	**4**
Heating temperature	A	°C	70	80	90	100
Heating time	B	(sec)	6	10	14	18
Sheet thickness	C	(mm)	0.06	0.10	0.13	0.15
Distance between ups	D	(mm)	21	36	42	46
Response Variables						
Top Thickness	TT					
Base Thickness	BT					
Inclined Thickness	IT					
Mean Standard Deviations	MSD					
Inclined Thickness (Uniformity)	ITU					
Number of Wrinkles	W					

3.3 Selection of Mold Type

The male mold was selected instead of the female mold to achieve better part features. The cup produced by the female mold has a thicker sidewall than the bottom, whereas the cup produced by the male mold has a thicker bottom. The sharper corners of the male mold cup indicate better part features than the female mold's corners [43]. In addition, prior to thermoforming, square grids were printed on sheets, exposing that in the female mold., square grids on the bottom area stretch to double their area, indicating biaxial stretching while in male mold cups, square grids on the sidewall stretch to double their area in one direction, indicating uniaxial stretching. the linear drawn ratio of the female mold is greater than that of the male mold which means that the plastic sheet would stretch more in the female mold as compared to the male mold [50]. The surface of a molding that does not come into contact with the mold is generally smoother because it cannot acquire such features as dust particles on the tool. This factor alone may determine whether a male or female mold is needed. Negative molds gradually reduce thickness towards the base as the material adheres to the walls and elongates at the base when the vacuum is created. To achieve a more uniform thickness a male should be used to stretch the material mechanically before applying a vacuum [54].

3.4 Designing of Molds

Several mold sizes were employed with identical materials. The drawings and CAD model of the molds were made using SolidWorks 2024 software. The medium-density fiber molds were machined using a 1325 CNC router machine to design four different molds. Mold 1 has 16 ups and the distance between ups is 21mm each as shown in Fig 3.1. Mold 2 has 9 ups and the distance between ups is 36mm as shown in Fig 3.2. Mold 3 has 9 ups and the distance between ups is 42mm each as shown in Fig 3.3, and Mold 4 has 12 ups and the distance between ups is 46mm each as shown in Fig 3.4 and each mold has a height of 30mm each.

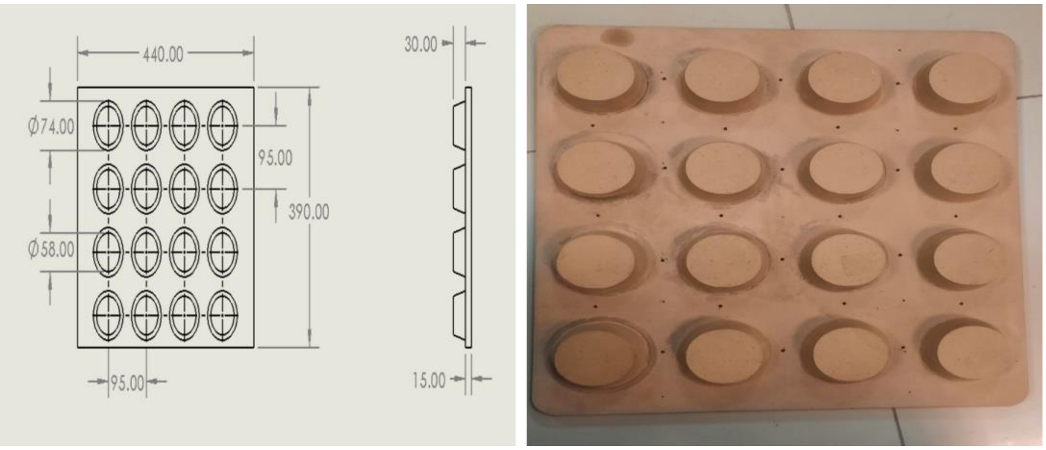


Figure 3.1: Drawing and CAM model of Mold 1

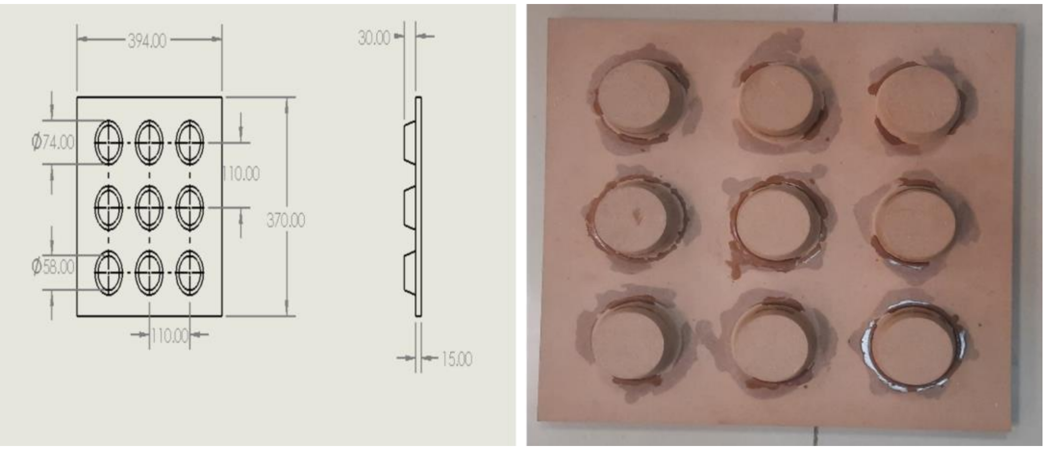


Figure 3.2: Drawing and CAM model of Mold 2

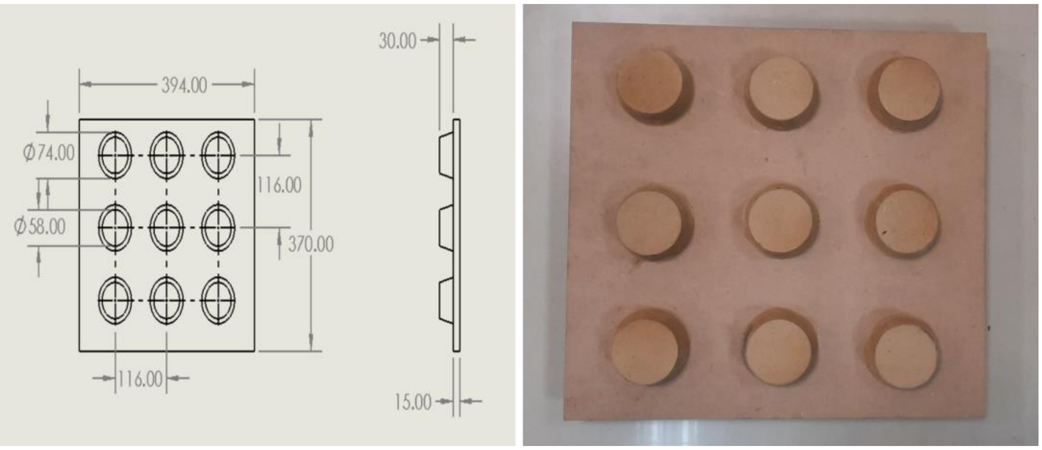


Figure 3.3: Drawing and CAM model of Mold 3

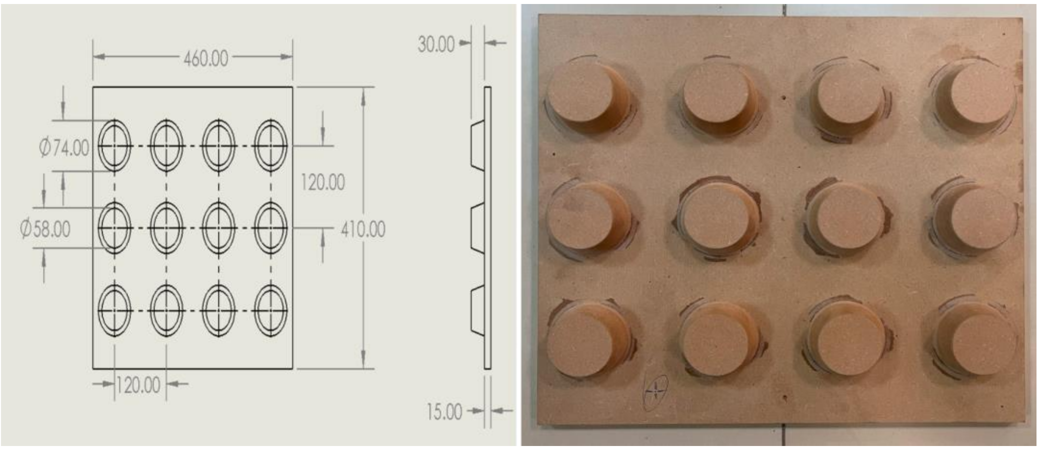


Figure 3.4: Drawing and CAM model of Mold 4

3.5 Manufacturing of Mold

The goal of the mold design process is to produce an affordable mold that satisfies customers. The product's shape in vacuum forming is determined by the mold's shape and cavity, which also aid in cooling the product from the forming temperature to room temperature for simple removal [55].Depending on the features of the product, positive/negative or female/male molds can be used in vacuum forming. Prototype molds, which are constructed from less expensive, more easily adjustable materials like wood, MDF, and epoxy resins, are used more frequently than production molds, which have a longer lifespan [56]. Due to their dimensional accuracy and durability, aluminum and steel molds—which are frequently milled using CNC machines—are chosen for high-volume production. Choosing the primary face (interior or exterior) is an important part of mold design. Male molds prioritize the inner face, whereas female molds prioritize the outer face. Mold cavities have tiny holes drilled for venting so that air or vacuum can escape during the forming process. The quality of the finished product is affected by the mold material, which takes cost, heat resistance, surface finish, dimensional stability, and durability into account. Block and casting aluminum, fiberglass, wood, MDF, epoxy, composite, silicone rubber, and steel are examples of common materials [57]. Draft angles for simple part release, minimizing undercuts, accommodating wall thickness, and guaranteeing adequate venting are important aspects of mold design. The texture and appearance of the finished product are directly impacted by the surface finish of the mold. The selection of mold materials is contingent upon various factors, including cost, availability, and machinability. MDF is a reasonably priced option for prototype molds because of its easily machined surface and smooth texture [57].

3.5.1 Selection of Material for Mold

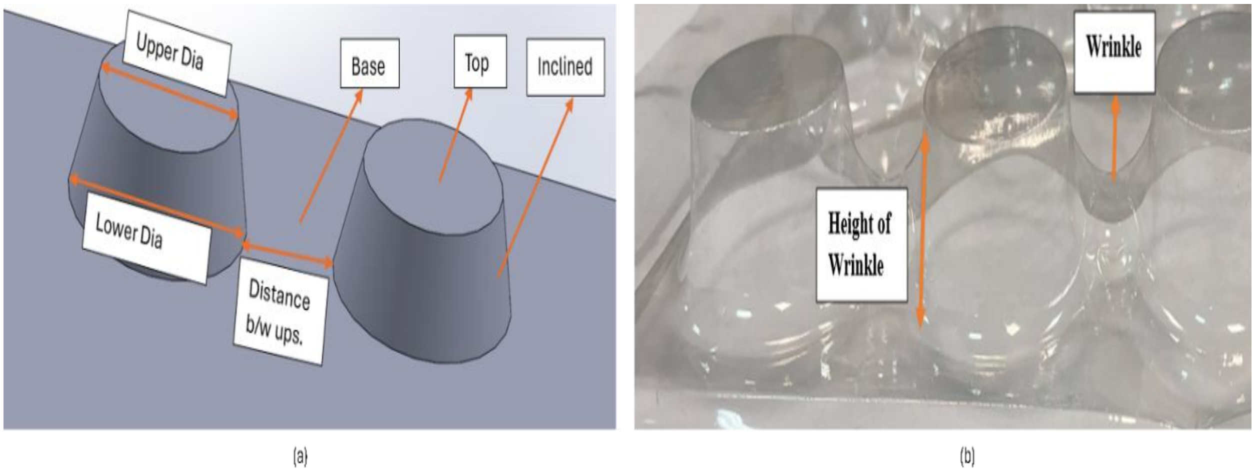
Various materials can be used to create thermoforming molds, depending on the desired results. Medium-density fiberboard (MDF), hardwood, epoxy resins, and wood are inexpensive, readily adjustable materials that are commonly used to create prototype molds for low-volume production. For this mold, MDF was chosen because of its low cost, ease of machining, and smooth surface. Made of wood fibers, wax, and resin that have been compressed under intense heat and pressure, MDF is an engineered wood product. It provides a surface that is flawless and allows for flexibility in finishing methods like veneering or painting. MDF is a popular material for cabinets and furniture because it is less expensive and more consistent than solid wood, but it can be damaged by moisture and needs to be protected in damp areas. In this instance, the mold was constructed.

3.5.2 CNC 1325 Router Machine

Having a working area of 1300 mm by 2500 mm, the "1325" CNC router machine is appropriate for a variety of tasks, including cutting, carving, and engraving wood, plastic, metal, and composite materials. This machine's repeatability and accuracy in operation are guaranteed by its CAD/CAM software. For various materials and project requirements, the power of the spindle, which holds and rotates the cutting tool, can be adjusted. The process of creating three-dimensional reliefs or shapes on a material with a CNC machine is known as 3D relief machining utilizing the ball nose tooling approach. Whether you're making molds, working with wood, or creating decorative applications, this technique is especially helpful for producing complex and textured surfaces. While "relief machining" refers to the process of removing material to create intricate shapes, "3D" in this context refers to working on surfaces that have depth, width, and height. Having a rounded end, the ball nose tool is a crucial tool in these machining processes because it can create intricate 3D shapes and smooth contours.

3.6 Specification for Analysis

The geometric dimensions and features of the "ups" used in the vacuum forming process of our study are illustrated in this Fig 3.5 which identifies some of the parts of the ups including the upper and lower diameters, the base, top, inclined surface, and the distance between two ups. (b) illustrates a formed sheet with wrinkles on it and the height and position of these wrinkles between the ups. (b) also gives an illustration of how wrinkles appear in the formed sheet with a focus on the height of the wrinkles.



(a)

(b)

Figure 3.5: Geometric features of ups and wrinkle formation

3.7 Signal-Noise Ratio Analysis for Optimizing Multiple Factors

Genichi Taguchi proposed a loss function that measures the difference between the experimental and target values and then transforms it into the signal-to-noise (S/N) ratio. Taguchi has classified the S/N ratio into three groups based on the responses' requirements: These include: higher-better, lower-better, and medium-the-better [58] [59]. The signal-to-noise (S/N) ratio is especially used in the Taguchi method to analyze the effect of each factor [60].Since the Uniformity, the Number of wrinkles typical of interest in this investigation, should be as close to zero as possible, a "smaller the better" formula using equation (1) is used for the S/N ratio calculation as follows [61] [62].

Signal-to-noise ratio for the smaller the better = - $S/N = -10\log_{10}(1/n \sum_{i=0}^{n} y_i^2)$ (1)

where n =No. of observations

y=Observed data for each response

3.8 Analysis of Variance

Analysis of variance (ANOVA) is the most efficient parametric technique that can be used in the analysis of data from experiments [63].ANOVA will be applied to experimental situations utilizing OA, although this analysis method can be used with any data set with some structure. Analysis of variance is a statistical technique that is used to identify the extent of dependence on factors that influence performance [64]. In ANOVA, the F value is the higher the significance degree. In other words, the factor with a higher F value has a greater impact on the performance. Likewise, the closer the p-value is to zero, the higher the significance of the test. In other words, the factors with the lowest p-value have a greater impact on the performance [65].

The impact of processing conditions can be investigated by conducting an ANOVA study that enables the identification of the proportion of each factor to the total process[66]. The analysis involves computing the total sum of squared deviations (SST) from the total mean S/N ratio. This is expressed in equation (2) as:

$$SS_T = \sum_{i=1}^{n} (SS_i - SS_m)^2 \quad (2)$$

Where SS_M = Sum of squared deviations for all parameters

SS_i =Squared deviations for each parameter

3.9 Design of Experiments

The Taguchi method of design of experiments (DOE) was employed. DOE is the method that saves time and resources and conducts the experiments in such a way that a maximum number of data and results are gained from less analysis. Taguchi method belongs to the family of DOE where there are two main variables, response variable, and independent variables [67] [68] . The Taguchi method, which is easy to implement and highly effective, is selected in this study to optimize process parameters [69] [70]. With this approach, fewer tests are conducted and the influence of uncontrollable factors is diminished through orthogonal arrays (OA) [71].Taguchi $L_{16}(4^4)$ orthogonal array (OA) designed the experiments. where L_{16} stands for the number of runs, and 4 represents the number of factors, each at 4 levels.

Table 3-3: Taguchi L16 Orthogonal Array

Experiment No:	**Heating Temperature (A)**	**Heating Time (B)**	**Sheet Thickness (C)**	**Distance b/w ups (D)**
1	70	6	0.06	21
2	70	10	0.10	36
3	70	14	0.13	42
4	70	18	0.15	46
5	80	6	0.13	46
6	80	10	0.15	42
7	80	14	0.06	36
8	80	18	0.10	21
9	90	6	0.15	36
10	90	10	0.13	21
11	90	14	0.10	46
12	90	18	0.06	42
13	100	6	0.10	42
14	100	10	0.06	46
15	100	14	0.15	21
16	100	18	0.13	36

CHAPTER 4: EXPERIMENTATION AND ANALYSIS

4.1 Experimentations

The Taguchi analysis was conducted using the Minitab 17.0 software tool and the means of S/N ratio plots and analysis of variance (ANOVA) results were obtained and presented in the following discussions. Hence, Eq. (1) has been employed to determine the S/N ratio and the findings are presented in Table 4-1. The top thickness (TT), base thickness (BT), inclined thickness (IT), inclined thickness uniformity (ITU), number of wrinkles (W), and their respective Means of standard deviation (MSD) and Signal to Noise Ratios for each vacuum-formed part as shown in Table 4-1.

Table 4-1: Experimental results and the calculated Thickness and MSD

Exp No:	A	B	C	D	TT	MSD	BT	MSD	IT	MSD	S/N for IT	W	S/N for W
1	70	6	0.06	21	0.055	0.002	0.046	0.002	0.042	0.005	27.535	15	-23.52
2	70	10	0.10	36	0.099	0.001	0.078	0.009	0.076	0.003	22.384	4	-12.04
3	70	14	0.13	42	0.101	0.018	0.086	0.004	0.075	0.027	22.499	0	-
4	70	18	0.15	46	0.14	0.009	0.128	0.006	0.117	0.014	18.636	0	-
5	80	6	0.13	46	0.127	0.004	0.116	0.007	0.103	0.007	19.743	0	-
6	80	10	0.15	42	0.153	0.004	0.117	0.005	0.112	0.004	19.016	0	-
7	80	14	0.06	36	0.046	0.005	0.037	0.007	0.033	0.005	29.630	6	-15.56
8	80	18	0.10	21	0.098	0.003	0.081	0.005	0.08	0.012	21.938	15	-23.52
9	90	6	0.15	36	0.148	0.006	0.119	0.008	0.117	0.005	18.636	4	-12.04
10	90	10	0.13	21	0.126	0.005	0.096	0.007	0.095	0.006	20.446	15	-23.52
11	90	14	0.10	46	0.092	0.013	0.081	0.012	0.066	0.013	23.609	0	-
12	90	18	0.06	42	0.049	0.008	0.041	0.004	0.039	0.005	28.179	0	-
13	100	6	0.10	42	0.098	0.003	0.089	0.015	0.083	0.017	21.618	0	-
14	100	10	0.06	46	0.056	0.005	0.051	0.005	0.048	0.004	26.375	0	-
15	100	14	0.15	21	0.144	0.010	0.106	0.011	0.103	0.013	19.743	15	-23.52
16	100	18	0.13	36	0.118	0.015	0.103	0.013	0.093	0.018	20.630	4	-12.04

4.2 Investigation of the Deformation of PVC Sheet in Vacuum Forming Process

This work aims to investigate the amount of deformation that occurs to a PVC sheet during vacuum forming through changes in marked grid lines. Originally the sheets were identified with a cross check of ½ inch by ½ inch. The regions that are in first in contact with the mold are not subjected to any stretching at all. On the other hand, the lines on the inclined surfaces of the “ups” appeared distorted particularly in the middle of the structure; this probably means that such areas were stretched by tension and compression forces. Intersecting lines between the “ups” also had small distortions, a sign of negligible deformation and a thickness of the base area equal to that of the initial sheet.

4.2.1 Sheets Performance on Mold 1

The figures illustrate the impact of the distance between ups on sheet formation depending on the molds used. Figures 4.10(a) and 4.10(b) show mold with a 21 mm distance between ups, where wrinkles are visible. In Fig 4.10 (c) the sheet had straight lines of equal width. After vacuum forming the lines are almost undistorted at the Top of the ups, suggesting little deformation in these areas. This supports the idea that the regions first in contact with the mold do not undergo deformation as illustrated in Figure 4.10(d). On the other hand, the lines on the inclined surfaces of the ups were significantly changed, indicating that the sheet was stretched in these regions. This suggests that the material is subjected to tension and compression forces more on the slopes than on the Top as shown in Figures 4.10(d) and 4.10(e). The lines in the base areas between the ups did not change significantly, indicating that these areas were not stretched and had a thickness comparable to the thickness of the original sheet as illustrated in Fig 4.10(f).

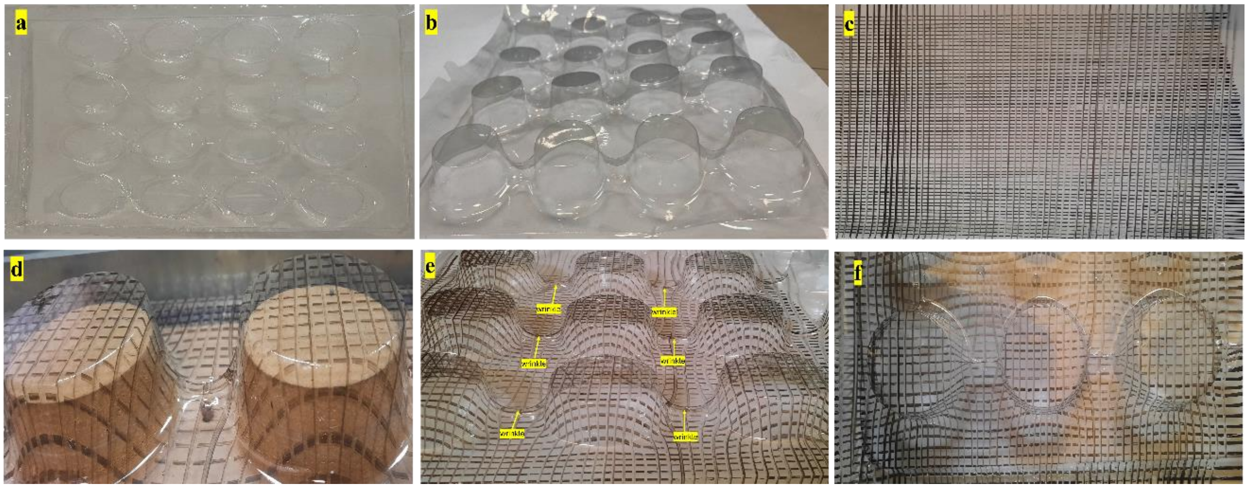


Figure 4.1:Sheet performance on Mold 1

4.2.2 Sheets Performance on Mold 2

The figures illustrate the impact of the distance between ups on sheet formation depending on the molds used. Figures 4.11(a) and 4.11(b) show mold with a 36 mm distance between ups, where wrinkles are visible. Figures 4.11 (c) the sheet had straight lines of equal width. After vacuum forming the lines are almost undistorted at the Top of the ups, suggesting little deformation in these areas. This supports the idea that the regions first in contact with the mold do not undergo deformation as illustrated in Figure 4.11(d). On the other hand, the lines on the inclined surfaces of the ups were significantly changed, indicating that the sheet was stretched in these regions. This suggests that the material is subjected to tension and compression forces more on the slopes than on the Top as shown in Figure 4.11(e). The lines in the base areas between the ups did not change significantly, indicating that these areas were not stretched and had a thickness comparable to the thickness of the original sheet as illustrated in Figure 4.11(f).

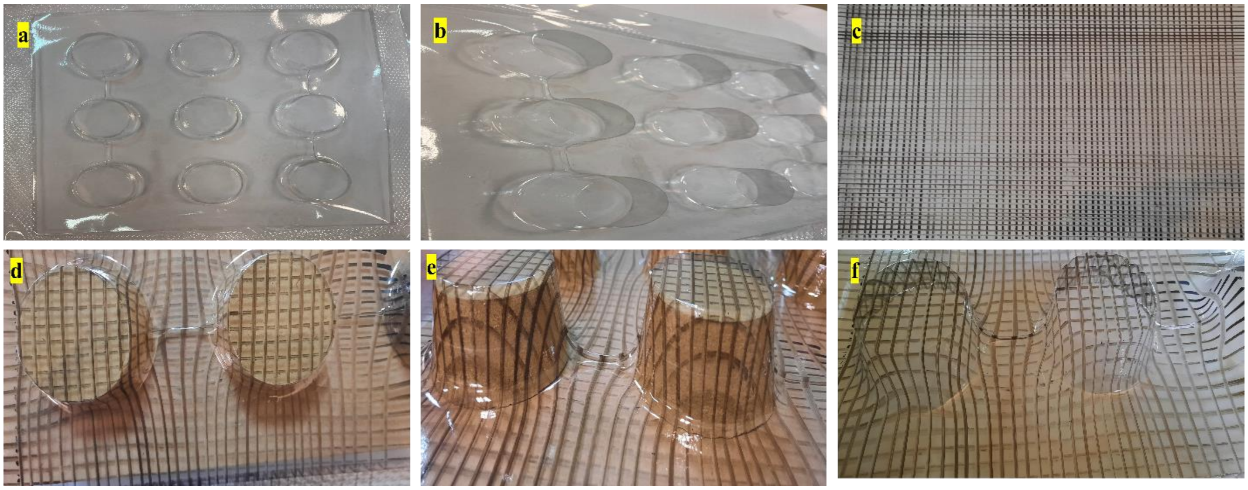


Figure 4.2: Sheet performance on Mold 2

4.2.3 Sheets Performance on Mold 3

The figures illustrate the impact of the distance between ups on sheet formation depending on the molds used. Figures 4.12(a) and 4.12(b) show mold with a 42 mm distance between ups, with no visible wrinkles. Figure 4.12(c) shows that the sheet had straight lines of equal width. After vacuum forming the lines are almost undistorted at the Top of the ups, suggesting little deformation in these areas. This supports the idea that the regions first in contact with the mold do not undergo deformation as illustrated in Figure 4.12(d). On the other hand, the lines on the inclined surfaces of the ups were significantly changed, indicating that the sheet was stretched in these regions. This suggests that the material is subjected to tension and compression forces more on the slopes than on the Top as shown in Figure 4.12(e). The lines in the base areas between the ups did not change significantly, indicating that these areas were not stretched and had a thickness comparable to the thickness of the original sheet as illustrated in Figure 4.12(f).

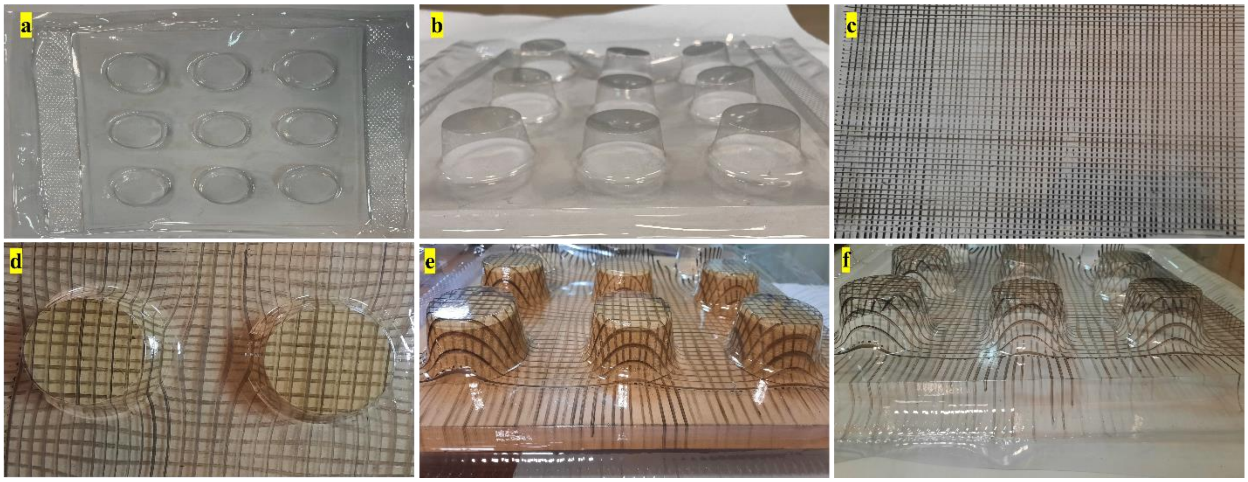


Figure 4.3:Sheet performance on Mold 3

4.2.4 Sheets Performance on Mold 4

The figures illustrate the impact of the distance between ups on sheet formation depending on the molds used. Figures 4.13(a) and 4.13(b) show mold with a 46 mm distance between ups, where no wrinkles are visible. Figures 4.13(c) the sheet had straight lines of equal width. After vacuum forming the lines are almost undistorted at the Top of the ups, suggesting little deformation in these areas. This supports the idea that the regions first in contact with the mold do not undergo deformation as illustrated in Figure 4.13(d). On the other hand, the lines on the inclined surfaces of the ups were significantly changed, indicating that the sheet was stretched in these regions. This suggests that the material is subjected to tension and compression forces more on the slopes than on the Top as shown in Figure 4.13(e). The lines in the base areas between the ups did not change significantly, indicating that these areas were not stretched and had a thickness comparable to the thickness of the original sheet as illustrated in Figure 4.13(f).

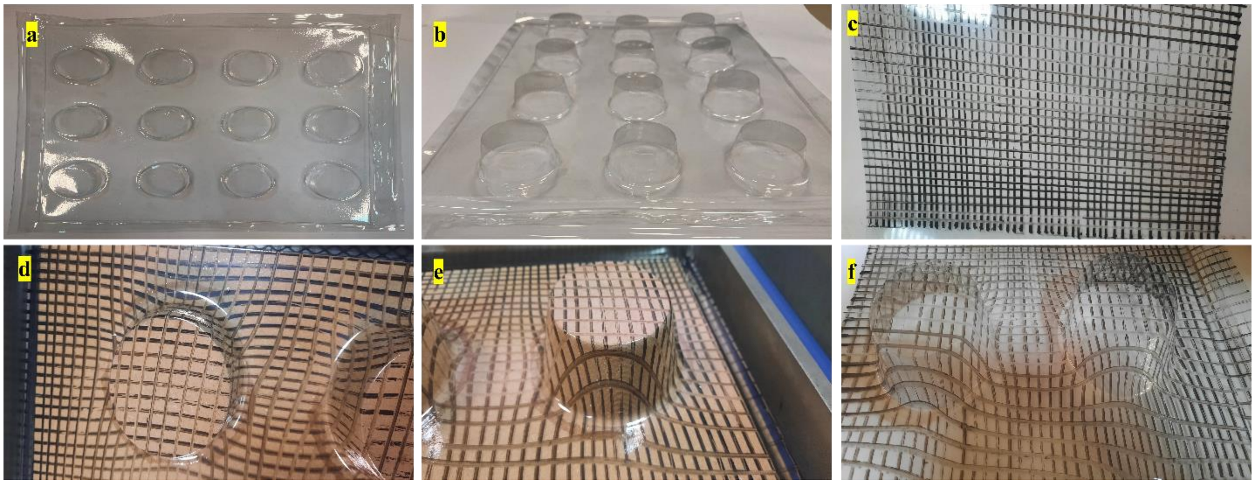


Figure 4.4: Sheet performance on Mold 4

4.3 Thickness Distribution Analysis of PVC Sheet

From the deformation of the PVC sheet in the vacuum forming process, the thickness of the sheet was measured using a standardized micrometer at different points. At the top of the ups, as shown in Figure 4.14, The thickness measurements showed that the thickness was still close to the original thickness, which supported the initial findings that these areas underwent little deformation, On the other hand, thickness measurements taken at different points along the inclined areas showed that the thickness was significantly reduced, suggesting that the PVC sheet was stretched in these areas. This supports the conclusion that the material was stretched and pulled more on the slopes than in any other part of the experiment. Further, measurements taken at the base areas at different points indicated that the thickness of the sheet did not change much, implying that these areas did not stretch much and retained a thickness close to the thickness of the original sheet.

This consistent observation affirms the hypothesis that during vacuum forming, the PVC sheet deforms most in the inclined areas, moderately in the base areas, and least at the tops of the ups, as shown in Figure 4.14, thus supporting the hypothesis that the base areas, like the tops of the ups, do not deform significantly.

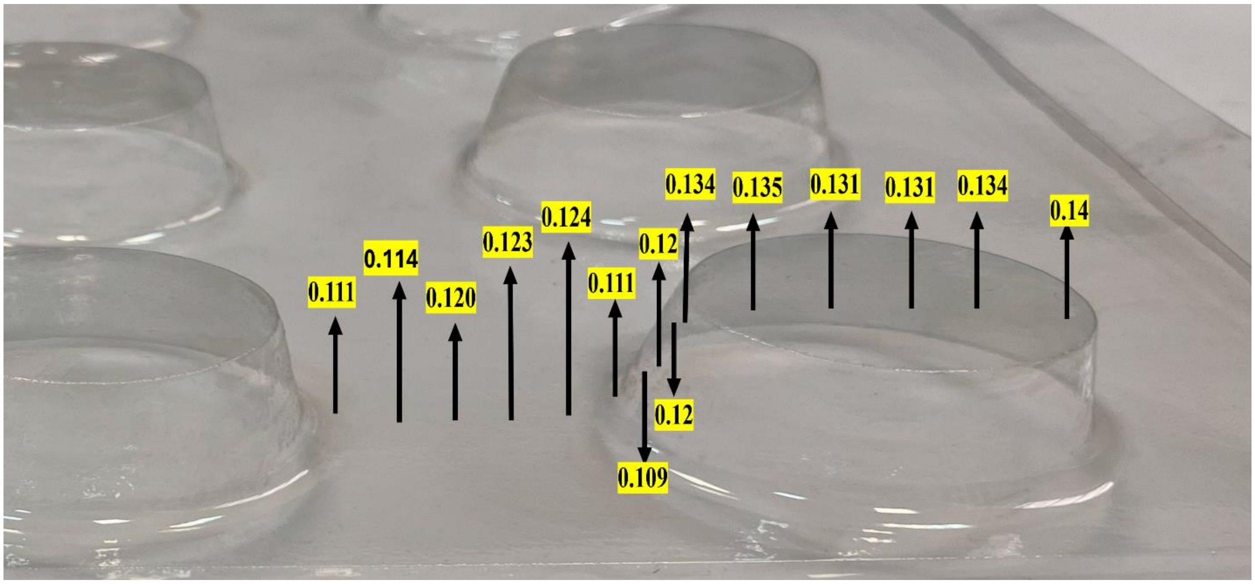


Figure 4.5: Thickness variations in PVC sheet

4.4 Structural Changes Validation with Olympus Microscope

The images were taken using an Olympus and the observation technique used is referred to as PO which is likely to stand for ‘Polarized Light’ to improve the contrast of the sample used in the analysis. The image type is characterized as ‘Extend Height,’ probably meaning that the sample is extended to a particular height in the image. The image size is 1200 by 1200, and each pixel is 953 by 953 nanometers. The microscope used an objective lens identified as DSX10×LDOBJ20X to give 20× magnification. The total degree of enlargement that has been achieved in the image is 280 times. The scale bar used in the image represents 200 micrometers which gives the viewer an idea of the size of structures that can be observed in the sample.

The micrographs below show the structural changes of a sample before and after the vacuum forming process. The first shape of the sample is depicted in Figure 4.15(a) which is rounded in nature. After post-forming, Figure 4.15(b) shows that the top structure is still relatively rounded in nature, meaning there is little deformation. Figure 4.15 (c) shows considerable stretching in the inclined regions, which indicates high stress and tension. Figure 4.15(d) shows that the base area undergoes moderate deformation, which is more than the top but less than the inclined areas. These observations imply that during vacuum forming, the top layer undergoes the least deformation, the base layer undergoes moderate deformation, and the inclined layers undergo the most deformation.

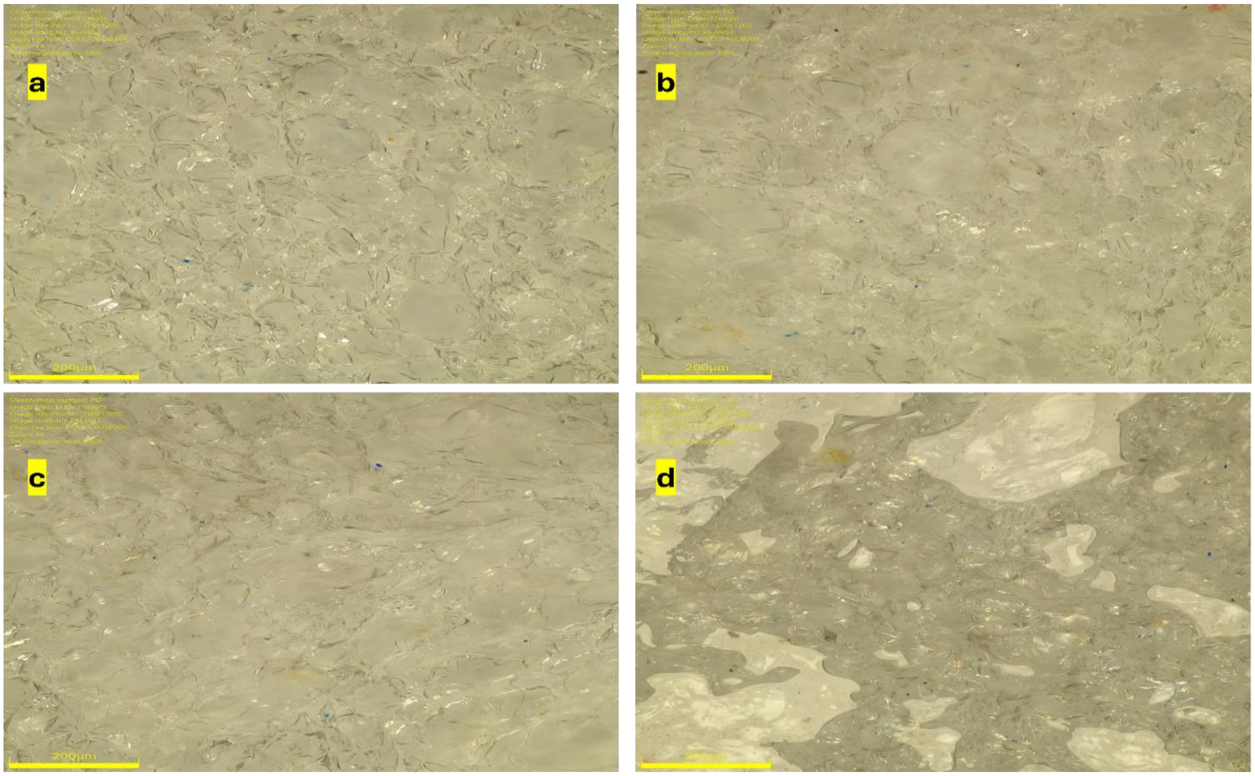


Figure 4.6: Micrographs of Vacuum Formed parts

4.5 Processing Challenges

When the values of heating temperature, heating time, and distance between ups were smaller, the thermoformed samples did not replicate the contour of the mold completely. Therefore, the uniformity, which was the difference between the maximum and minimum thickness of the thermoformed sample, became larger. While with greater values of these parameters, the samples deformed too much. As a result, the uniformity also became high. In addition, when the heating temperature and heating time were too high or the distance between ups was too close, discoloration phenomena occurred.

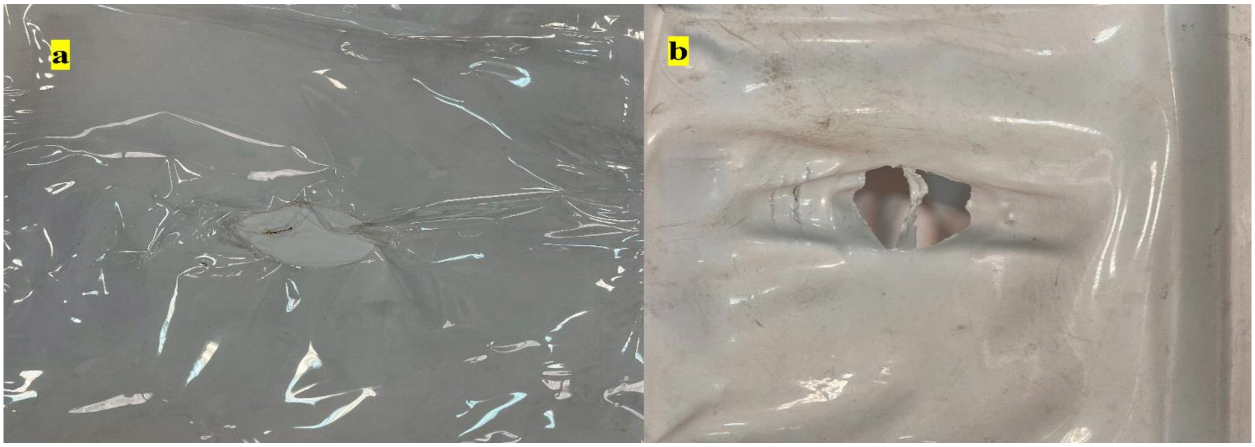


Figure 4.7: Excessive temperatures lead to sheet tearing

Figure 4.8: Plastic sheets unable to conform to the Mold shape due to insufficient heat.

4.6 Effect of Plastic Sheet Properties on Wrinkles

various plastic sheets were subjected to the vacuum forming process to investigate the influence of material type and color of material on wrinkle formation. Plastic sheets of different types and colors were utilized, including milky ABS sheets with a thickness of 1 mm and red and blue PVC sheets with a thickness of 0.30 mm.

During the experimentation, wrinkles were consistently observed on all tested plastic sheets, irrespective of their material type or color variation. This indicates that wrinkles occurred regardless of whether the plastic was ABS or PVC and regardless of its color. Wrinkles consistently formed on 1mm and 2mm Milky ABS sheet.

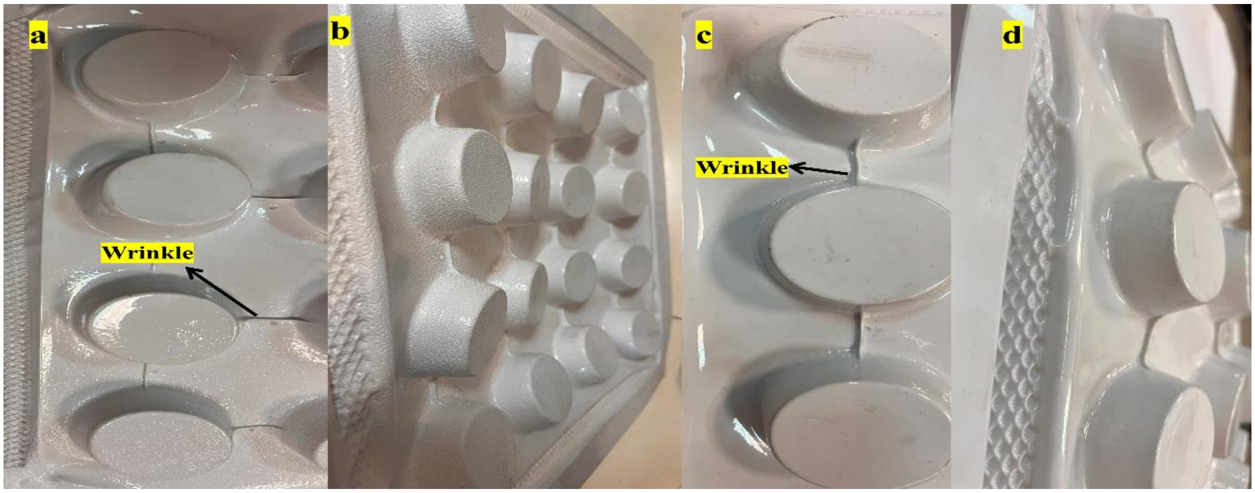


Figure 4.9: Wrinkles consistently formed on Milky ABS sheet

Figure 4.10: Wrinkles on Milky ABS sheet when distance b/w ups is 42mm

4.7 Effect of Venting Hole Size on Wrinkle Formation

A set of experiments was carried out using a mold that had a 21mm gap between the ups to investigate the possible impact of venting holes on the formation of wrinkles. Initially, venting holes with a diameter of 3mm were introduced between every up, resulting in consistent outcomes across multiple trials. Following this initial phase, an investigation into the impact of varying venting hole sizes was undertaken. The diameter of the holes was systematically increased, reaching a maximum diameter of 7mm for each venting hole. Despite this adjustment, the observed results remained consistent and unchanged throughout the experimental trials. Based on these findings, it can be inferred that the size of the venting holes within the mold has minimal effect on the formation of wrinkles during the vacuum-forming process. Consequently, other factors likely play a more significant role in determining the occurrence of wrinkles in the formed plastic shapes.

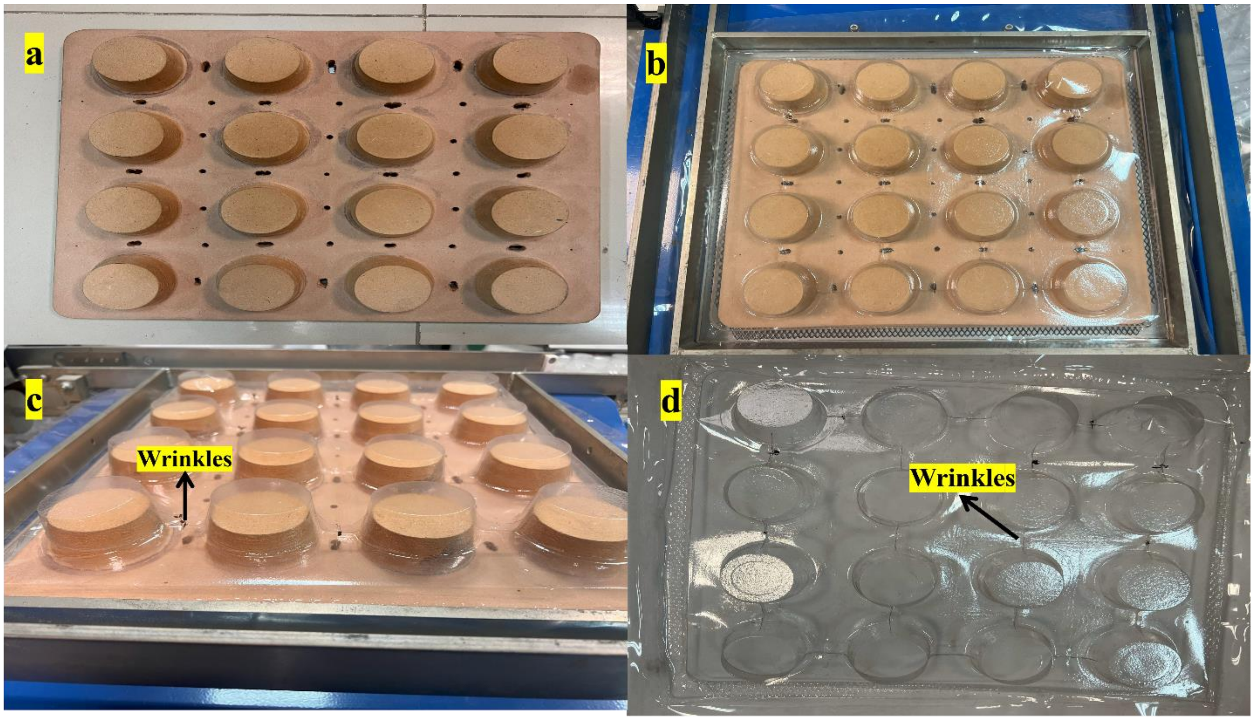


Figure 4.11: Effect of Venting Hole Size on Wrinkle Formation

4.8 Effect of Different Vacuum Forming Machines on Wrinkle Formation

Despite utilizing an additional vacuum-forming machine, characterized by specific specifications. This machine featured small-diameter holes drilled into the metal plate baseboard, coupled with a heating mechanism comprising hollow glass tubes containing resistance wires. These elements were designed to generate heat through the resistance of the wires when electricity passes through them. Furthermore, the linear motion of the heating assembly was facilitated by linear rectangular bars, ensuring smooth and precise movement during the vacuum-forming process., the results remained consistent, with wrinkles consistently forming at distances of 21mm and 36mm between ups, respectively, while no wrinkles were observed at distances of 42mm and 46mm between ups. This suggests that the number of venting holes on the machine does not significantly impact the quality of vacuum-formed parts. Additionally, the data collectively indicate that neither the material properties of the plastic sheets nor the size of venting holes have a substantial effect on wrinkle formation during vacuum forming.

Figure 4.12: Effect of Different Vacuum forming Machines on wrinkle formation.

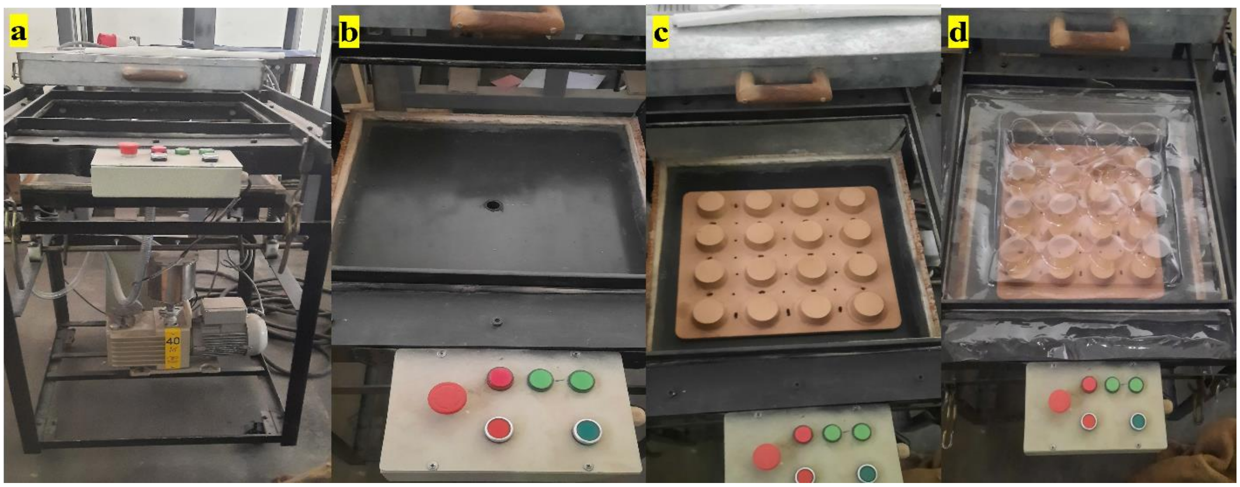


Figure 4.13: Effect of Different Vacuum forming Machines on wrinkle formation

CHAPTER 5: RESULTS AND DISCUSSION

5.1 Selection of Optimum Processing Parameter for Uniformity

The obtained S/N ratio response table for uniformity is presented in Table 5.1 while the mean S/N ratio graph is presented in Fig. 5.1 respectively using Minitab software. A higher S/N ratio implies that the difference between the target response and the actual response is very small. From Table 5.1 and Fig. 5.1, it can be observed that the highest mean S/N ratios for uniformity were achieved at heating temperature(A) of 70°C, heating time(B) of 14 seconds, sheet thickness(C) of 0. 06 mm, and distance between ups(D) at 42 mm. These are the optimal levels depicted as A1-B3-C1-D3. The S/N ratio response table indicates the influence of each parameter on uniformity, and it is noted that sheet thickness has the maximum impact on uniformity followed by heating time, temperature, and distance between ups. Figure 5.2 shows the contribution chart of the processing factors, showing that sheet thickness and heating time have the highest impact on uniformity.

Table 5-1: S/N Ratios for Uniformity, Smaller is better.

Levels	**Parameters**			
	Inclined Thickness (Uniformity)			
	A	**B**	**C**	**D**
1	22.76	21.88	27.93	22.42
2	22.58	22.06	22.39	22.82
3	22.72	23.87	20.83	22.83
4	22.09	22.35	19.01	22.09
Delta	0.67	1.99	8.92	0.74
Contribution	5.72	16.95	76.11	6.31
Rank	4	2	1	3

The Main Effects Plot for S/N ratios provides a comprehensive picture of how each parameter affects the mean S/N ratios with better uniformity featuring lower S/N ratios. The plot shows that increasing the heating temperature and the distance between cups do not significantly affect the S/N ratio and can therefore be concluded that these factors have a relatively small influence on uniformity. Heating time indicates some improvement of the S/N ratio at the middle level, but its enhancement is not very significant. However, sheet thickness has a poor S/N ratio, which shows a large effect on the uniformity as the thickness of the sheet increases. From this, it can be inferred that thinner sheets tend to have a better planarity, which is a very important factor when it comes to sheet thickness.

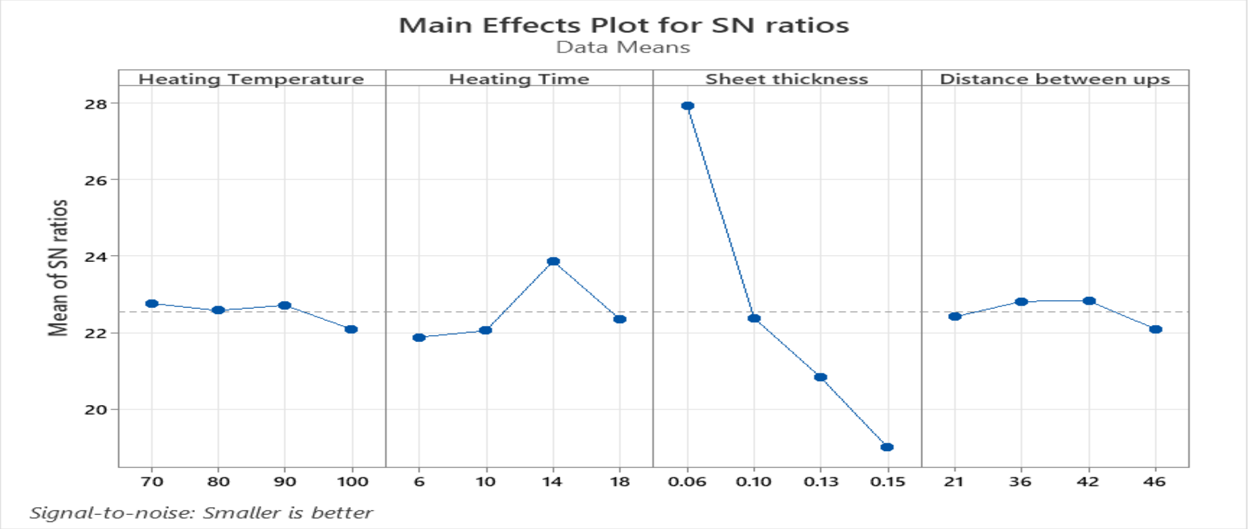


Figure 5.1: S/N ratio for Uniformity

The pie chart stands side by side to the Main Effects Plot as it provides the numerical values of the influence of individual parameters to the uniformity. Sheet thickness comes out as the most significant measure contributing almost three quarter, i.e.,76% of the variation. This is further evidenced by the fact that the percentage of the influence in actualizing uniformity was almost 11% which is far higher than the other parameters. This shows how effective the sheet thickness is in defining the distribution of the product and this explains why this parameter needs to be regulated to a satisfactory range. Heating time comes next contributing 16%. It is thus a factor but not a dominant one as the percentage of success ranges from 85-95%. Distance between cups and heating temperature make a 6.31% and 5.72%, respectively, which means that though they do affect uniformity, their magnitude of effect is considerably less than that of sheet thickness and heating time. Therefore, comprehensible from the figure above, the sheet thickness is the most dominant factor in the study of uniformity in the S/N ratio and heating time is the second most important factor. On the other hand, factors such as heating temperature and distance between cups have much less influence. Hence, to obtain the greatest uniformity, attention should be paid to the regulation of the sheet thickness, and heating time to a lesser extent.

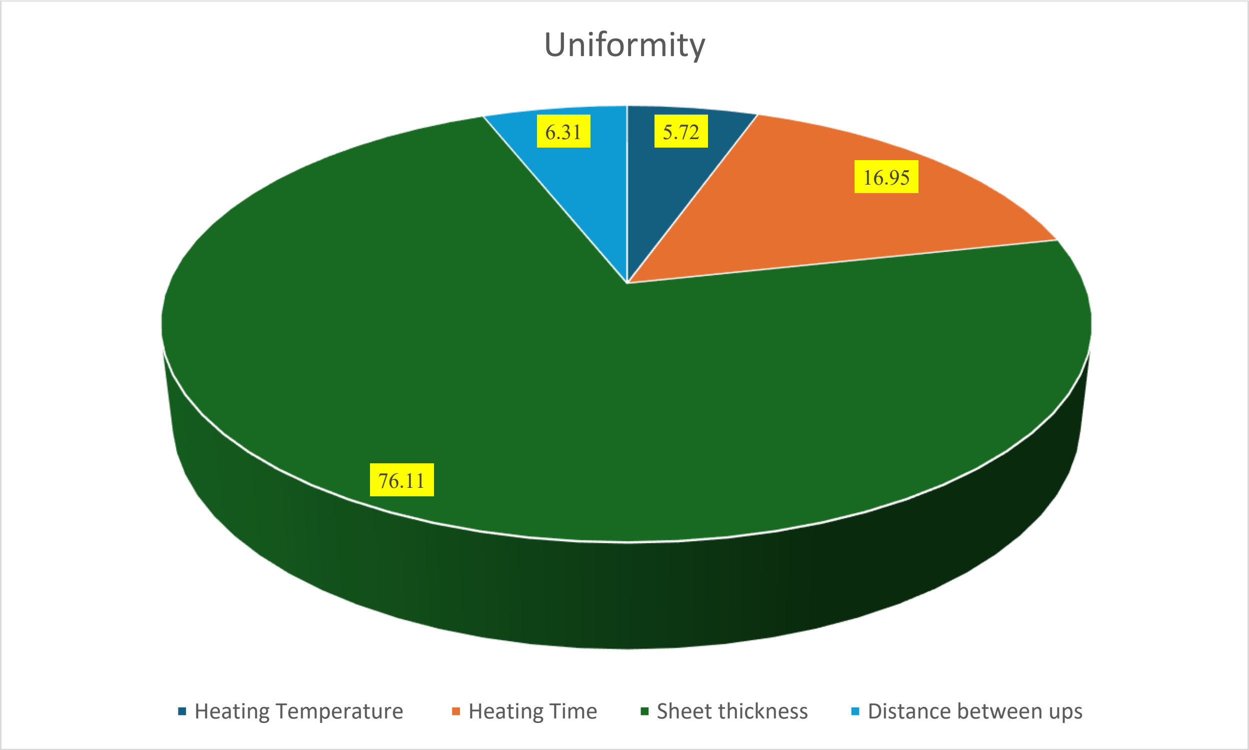


Figure 5.2: Contribution Graph for Uniformity

5.2 Selection of Optimum Processing Parameters for Number of Wrinkles

The obtained S/N ratio response table for the Number of wrinkles is presented in Table 5.2. The Means of the S/N ratio for the Number of wrinkles was in Fig. 5.3. As indicated in Table 5.2 and Fig.5.3, The S/N ratio shows that the distance between ups(D) is the most influential factor in reducing wrinkles, followed by heating temperature(A), heating time(B), and sheet thickness(C) which are of equal importance. The estimated optimum process parameters for achieving the minimum number of wrinkles were identified as heating temperature of 70 Centigrade, heating time of 18 seconds, sheet thickness of 0.15 mm, and distance between ups at 46mm. This predicted optimum combination was represented as A4-B4-C4-D4 for the number of wrinkles. The choice of A4, B4, C4, and D4 was made based on the practicality of the design and the ability to provide a rigid structure and proper fit of the sheets to the mold. In Figure 5.4 the contribution of each factor was established by comparing the minimum and maximum S/N ratio results. The distance between ups has the highest impact on the number of wrinkles.

Table 5-2: S/N Ratios for Number of Wrinkles, Smaller is better.

Levels	**Parameters**			
	Number of Wrinkles			
	A	**B**	**C**	**D**
1	-17.78	-17.78	-19.54	-23.52
2	-19.54	-17.78	-17.78	-12.92
3	-17.78	-19.54	-17.78	0
4	-17.78	-17.78	-17.78	0
Delta	1.76	1.76	1.76	10.60
Contribution	11.08%	11.08%	11.08%	66.75%
Rank	3	3	3	1

The Main Effects Plot presents a graphical display of the effects of each parameter on the mean S/N ratios associated with wrinkle formation. From the plot, the S/N ratios correspond to different levels of heating temperature and heating time implying that heating temperature and heating time do not significantly affect the S/N ratios. This means that changes in these parameters do not influence wrinkles. As with the previous parameters, sheet thickness also demonstrates a stable S/N ratio, which means that this factor also has only a limited impact on wrinkle formation. In contrast, distance between cups has a strong negative effect and, when is at its highest level, the S/N ratio drops significantly to show an increased number of wrinkles with this parameter. This means that the distance between the cups is highly sensitive to the development of wrinkle where larger distances means more wrinkles.

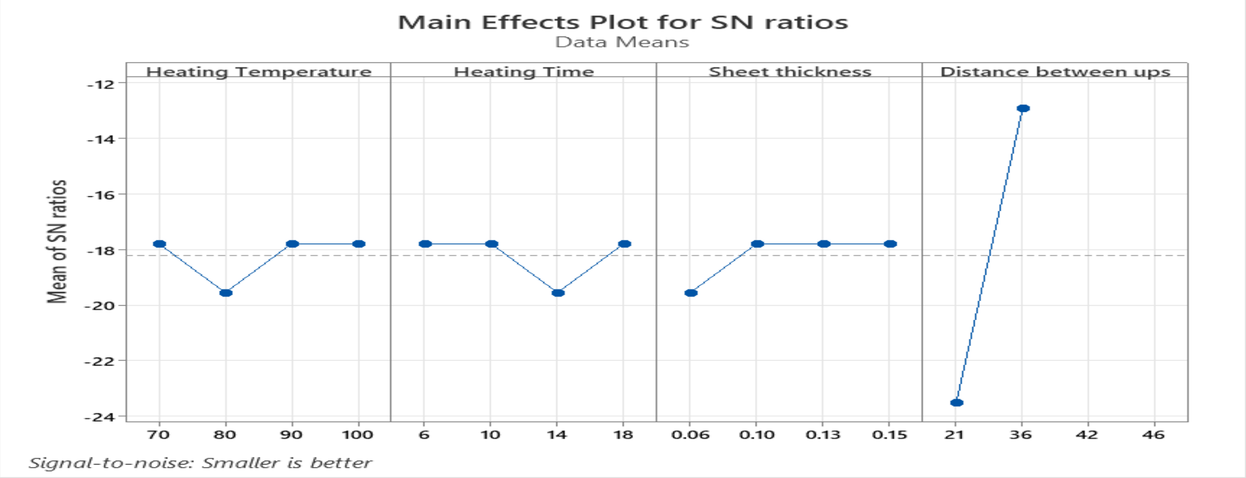


Figure 5.3: Signal to Noise for Number of Wrinkles

The pie chart also offers a quantitative analysis of the individual processing parameters' share in the formation of the number of wrinkles. The distance between cups is far and away the largest with 66. 75% contribution explaining the implication in the wrinkle formation process. This high contribution is in accordance to the drastic reduction of the S/N ratio in the Main Effects Plot, which reveals the importance of controlling this parameter to avoid wrinkles. However, heating temperature, heating time, and sheet thickness each take 11% of the impact or significance. The results are 08%, which mean they do have some contribution to the formation of wrinkles but a minute one compared to distance between cups.

It is evident that distance between ups is the key factor that greatly influences the number of wrinkles in the product. It surpasses the effects of heating temperature, heating time, and sheet thickness which are comparatively small. The main thrust of the attempts to minimize wrinkle formation should be devoted to the control of the distance between cups, while the other factors can be controlled with less accuracy.

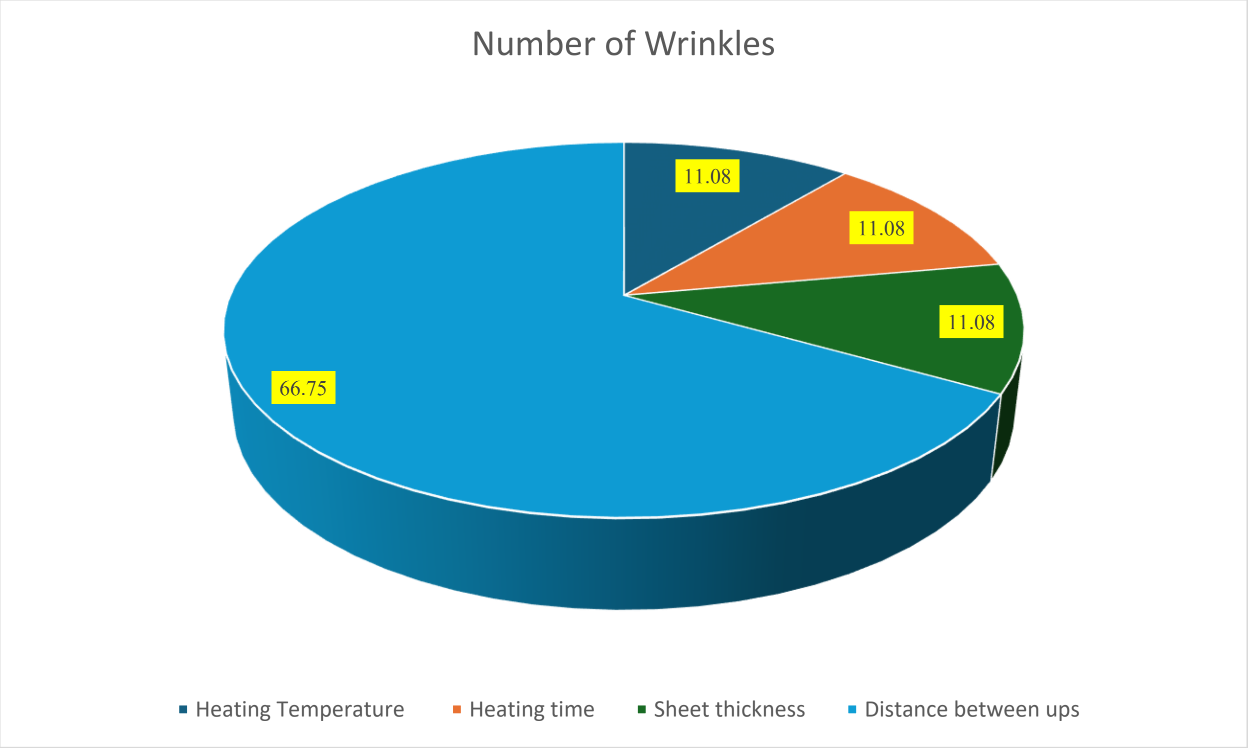


Figure 5.4: Contribution graph for Number of Wrinkles

5.3 ANOVA Study

Analysis of variance (ANOVA) is the most efficient parametric technique that can be used in the analysis of data from experiments [63]. ANOVA will be applied to experimental situations utilizing OA, although this analysis method can be used with any data set with some structure. Analysis of variance is a statistical technique that is used to identify the extent of dependence on factors that influence performance [64]. In ANOVA, the factor with a higher F value has a greater impact on the performance. Likewise, the closer the p-value is to zero, the higher the significance of the test. In other words, the factors with the lowest p-value have a greater impact on the performance [65].

5.3.1 ANOVA Study for Inclined Thickness Uniformity

The findings of the ANOVA investigation for the number of wrinkles are shown in Table 5-6. Degree of Freedom (DF), Sequential Sum of Squares (Seq SS), Adjusted Mean Square (Adj MS), Adjusted Sum of Squares (Adj SS), F-value, and p-value are among the details it offers for each factor. The ANOVA results for the Uniformity are illustrated in Table 5.3. The results show that in Uniformity, the F value of the sheet thickness is larger than the heating time, heating temperature, and distance between ups. Table 5.3 findings reveal that sheet thickness and heating time are crucial for uniformity, followed by heating temperature, and distance between ups respectively. The percentage contribution of heating temperature, heating time, sheet thickness, and distance between ups on Uniformity was 0.047%, 5.66%, 92.59%, and 0.66% respectively as shown in Table 5.3. This analysis supported the results of the S/N ratio study and revealed that sheet thickness and heating time are the factors that influence uniformity.

Table 5-3: ANOVA study for Uniformity

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Rank
Inclined Thickness (Uniformity)							
Heating Temperature (A)	3	0.000055	0.000055	0.000018	1.96	0.298	4
Heating Time (B)	3	0.000669	0.000669	0.000223	23.67	0.014	2
Sheet thickness (C)	3	0.010986	0.010986	0.003662	388.89	0.000	1
Distance between ups (D)	3	0.000079	0.000079	0.000026	2.81	0.210	3
Residual Error	3	0.000028	0.000028	0.000009			
Total	15	0.011818					

5.3.2 ANOVA Study for Number of Wrinkles

For the Number of Wrinkles, the F value of the distance between ups is larger than the Heating Temperature, heating time, and sheet thickness. So, the number of Wrinkles was mostly influenced by the distance between ups followed by heating temperature, heating time, and sheet thickness which are of equal importance. The respective percentage contribution of the distance between up, heating temperature, heating time, and sheet thickness on the number of wrinkles was 0.12%, 0.12%,0.12%, and 99.50 % respectively as illustrated in Table 6. Depending on the ANOVA analysis, it was determined that Uniformity was significantly affected by Sheet thickness, and number of wrinkles was significantly affected by Distance between ups. These insights aid in understanding and optimizing the thermoforming process.

Table 5-4: ANOVA study for Number of wrinkles

Source	DF	Seq SS	Adj SS	Adj MS	F	P	Rank
Number of Wrinkles							
Heating Temperature (A)	3	0.750	0.750	0.250	1.00	0.500	3
Heating Time (B)	3	0.750	0.750	0.250	1.00	0.500	3
Sheet thickness (C)	3	0.750	0.750	0.250	1.00	0.500	3
Distance between ups (D)	3	600.750	600.750	200.250	801.00	0.000	1
Residual Error	3	0.750	0.750	0.250			
Total	15	603.750					

5.4 Validation Test

Through the S/N ratio study, it was found that better uniformity could be achieved using the processing parameters of A1-B3-C1-D3 as indicated in

Figure 5.1: S/N ratio for Uniformity

Figure 5.1: S/N ratio for Uniformity. This result was then verified using a commercial software solution, Minitab®. Validation results using Minitab® Table:5-1. In academic fields, engineers in manufactories only utilize commercial software solutions, such as Minitab®, to minimize the time of DOE and analysis of results. An additional experiment was performed under this condition as a validation test, indicating that the maximal uniformity in the sample was 0.06 mm. This outcome

was better than the uniformity outcomes of all the cases evaluated in the OA shown in Table 4-2. Fig. 5.5 illustrates the thermoformed sample from the validation test and its thickness distribution under the processing parameters in the S/N ratio study. Via the validation test, the Taguchi method showed better results in processing parameters for better uniformity.

Figure 5.5: Validation test

5.5 Optimizing the Distance Between Ups

Comprehending the correlation between wrinkle formation and the distance between ups is crucial for optimizing the vacuum-forming procedure. The critical threshold at which wrinkles begin to form can be identified by methodically shortening the intervals between ups, which offers important insights for wrinkle prevention. This work employed a mold consisting of 4 columns and 3 rows to ensure uniformity and to progressively shorten the intervals between ups, allowing for the examination of the effects of these modifications on the development of wrinkles. The results were combined with Taguchi method optimized settings, taking into account variables like sheet thickness and heating temperature to provide a thorough examination of process dynamics.

Identifying the transition point between 38- and 39-mm intervals between ups, where wrinkles start to show, was a major accomplishment. This discovery is essential for figuring out the best distance to successfully prevent wrinkle formation. The results of the experiment validated the theory that wrinkles appear at distances of 36 to 39 mm, but not at distances of 40 mm or more.

Data showed that when the distance increases, the average height of wrinkles decreases from 20.37mm to 2.14mm, indicating that a minimum of 40mm is required between ups to prevent wrinkles.

This study emphasizes how crucial it is to modify the space between wrinkles in order to prevent wrinkle formation, particularly for ups that are 30 mm tall. Both the quantity and height of wrinkles decrease as the up height to distance ratio rises. Wrinkle formation was successfully avoided with a new mold configuration that had 40 mm between ups, proving the value of this strategy in improving product quality and vacuum forming processes' operational effectiveness.

Identifying the transition point at 37mm and 38mm distances between ups is a significant milestone. This pinpointing offers valuable insights into the optimal distance required to effectively mitigate wrinkle formation. The experimental validation of this transition point enables confident optimization of the distance between ups. Incorporating this finding promises enhanced product quality and operational efficiency in vacuum forming processes. Overall, this research highlights the importance of empirical experimentation and systematic approaches in achieving desired outcomes in vacuum-forming optimization. For this, the distance between ups decreases from 46mm to 36mm, shown in a SolidWorks drawing and a subsequent CAM model in Figures 11(a) and 11(b). Wrinkles were observed at distances of 36mm to 39mm. No wrinkle was observed at distances of 40mm and above as illustrated in Fig 11(c) and 11(d), Table 7 indicates that wrinkles develop at distances of 21mm to 39mm, and the average height of wrinkles reduces from 20.37mm to 2.14mm as the distance between the two objects increases therefore, it can be concluded that there must be a minimum distance of 40mm between ups to avoid the formation of wrinkles. Figure 12 shows the variation of the average wrinkle height with the distance between ups and it approaches zero as the distance increases. This relationship shows that the distance between ups should be adjusted to achieve better results in the use of products in different applications. In other words, as the ratio between height of up and distance between increases the number of wrinkles and height of wrinkles decreases. This methodical process shows how the reduction of distances between ups contributes to the formation of wrinkles. As a result, a 40mm distance is crucial to prevent wrinkles for ups of 30mm height, as shown in Figure 13 by a new mold setup that produced no wrinkles.

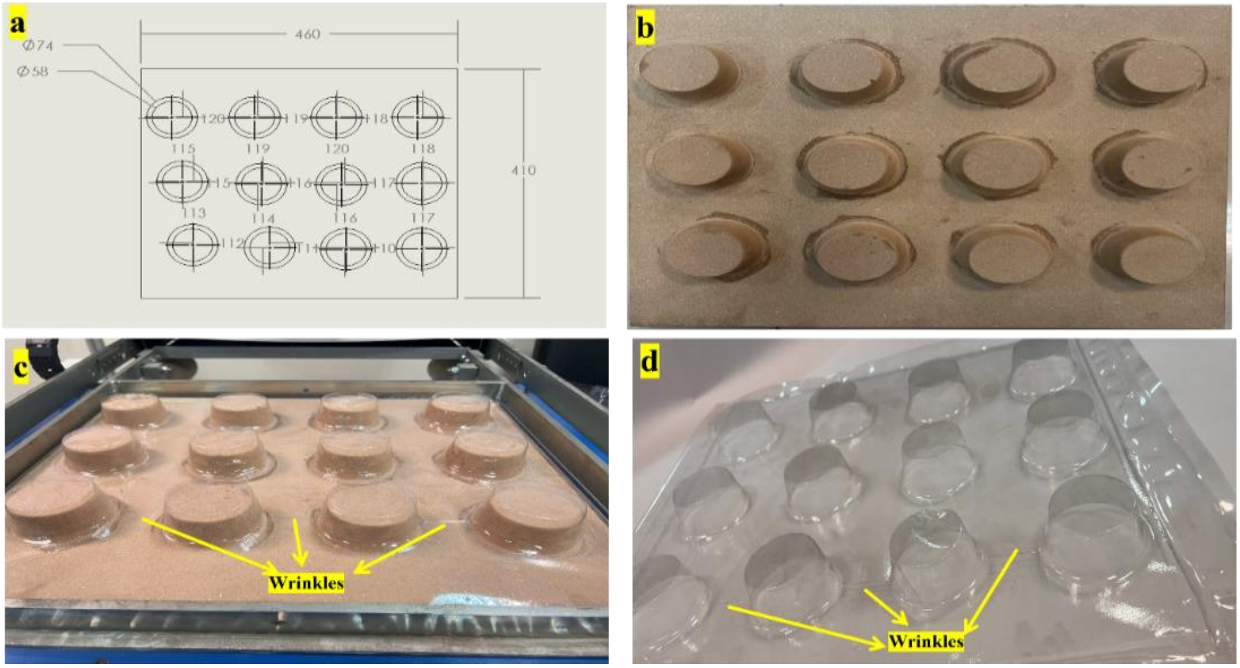


Figure 5.6: Impact of Distance Between Ups on Wrinkle Formation

Table 5-5 indicates that wrinkles develop at distances of 21mm to 39mm, and the average height of wrinkles reduces from 20.37mm to 2.14mm as the distance between the two ups increases therefore, it can be concluded that there must be a minimum distance of 40mm between ups to avoid the formation of wrinkles for a 30mm height of ups. Fig.5.7 shows the variation of the average wrinkle height with the distance between ups, and it approaches zero as the distance increases. This relationship shows that the distance between ups should be adjusted to achieve better results in the use of products in different applications. In other words, as the ratio between height of ups and distance between ups increases the number of wrinkles and height of wrinkles decreases. This methodical process shows how the reduction of distances between ups contributes to the formation of wrinkles.

Table 5-5: Comparison of the distance between ups effectively and wrinkle formation

Serial No:	**Distances b/w ups**	**Height of ups**	**Ratio**	**Average Height of wrinkles**
1	21	30	0.7	20.375
2	28	30	0.933	17.544
3	36	30	1.2	16.287
4	37	30	1.23	4.212
5	38	30	1.267	3.144
6	39	30	1.3	2.144
7	40	30	1.33	0
8	42	30	1.4	0
9	46	30	1.53	0

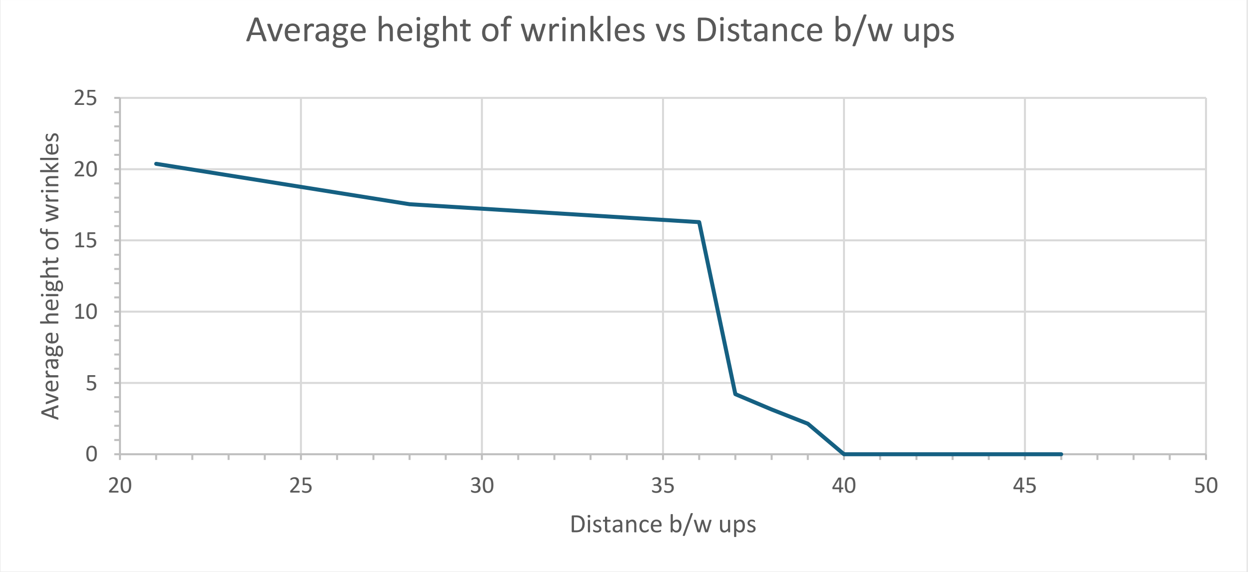


Figure 5.7: Average Height of Wrinkles vs Distance between ups

The figure illustrates two parts concerning the validation of a mold design. In Fig. 5. 8(a); an MDF mold with 12 ups, each 30 mm high is in a grid format with a 40mm distance between each up. Fig. 5.8(b) shows a PVC sheet after forming over the mold, there are no wrinkles between ups. The objective of this validation was to make sure that a 40mm distance between the ups should be maintained so that no wrinkle is formed in the material when ups of 30 mm height are used. The fact that there are no wrinkles on the PVC sheet can be used to substantiate this design proving that 40mm is the minimum distance needed to prevent such imperfections.

Figure 5.8: Validation experiment under the recommended parameters

5.6 Regression Analysis for Uniformity and Number of Wrinkles

The dependent variables of uniformity and number of wrinkles as a function of heating temperature, heating time, sheet thickness, and distance between ups were established in the current study using regression analysis in the Minitab software.

The regression analysis generated predictive equations for uniformity and wrinkle number as shown in Equations (3) and (4), respectively. Using a coefficient of determination (R2), the developed models' competence was evaluated. As the value of R2 is very close to one, it indicates a good fit between the dependent and independent variables. In the current study, the regression models for uniformity and number of wrinkles have high R2 values of 97.11% and 92.65%, respectively. The significance of the coefficients in the anticipated model was evaluated using the residual plot. The residual plots obtained for Uniformity and Number of wrinkles are shown in Fig.13, and Fig. 14 respectively. The Figures showed that the residuals lie close to the straight line for Uniformity and Number of wrinkles, which indicates that the developed model coefficient models are significant.

Uniformity (Inclined)= -0.0070 + 0.000100 * A – 0.000638 * B + 0.7679 * C+ 0.000051 * D (3)

Number of Wrinkles = 28.85 – 0.0050 *A + 0.0125 *B – 5.43 * C – 0.6372 * D (4)

5.6.1: Comparison of Experimental and Regression Models

The table compares the experimental results with the predicted outputs from the developed regression models for two key parameters: The number of wrinkles and their uniformity. The aim is to check the fitness of the regression models to the experimental data in an attempt to ascertain the compatibility of the model's predictions with the actual results. The experiments are listed one by one along with their results for the average uniformity and the number of wrinkles; the predicted results obtained from the regression equations and the differences between the actual and predicted results.

Table 5-6: Comparison of Experimental and Regression Models.

Exp No:	**Average IT Uniformity**	**Predicted**	**deviation**	**Number of Wrinkles(W)**	**Predicted**	**deviation**
1	0.042	0.043	-0.001	15	14.864	0.136
2	0.076	0.072	0.004	4	5.139	-1.139
3	0.074	0.093	-0.018	0	1.202	-1.202
4	0.117	0.106	0.011	0	-1.405	1.405
5	0.103	0.099	0.004	0	-1.497	1.497
6	0.112	0.112	0.000	0	0.994	-0.994
7	0.033	0.040	-0.007	6	5.356	0.644
8	0.080	0.067	0.013	15	14.747	0.253
9	0.117	0.115	0.002	4	4.717	-0.717
10	0.095	0.096	-0.001	15	14.434	0.566
11	0.066	0.072	-0.006	0	-1.284	1.283
12	0.039	0.039	0.000	0	1.533	-1.533
13	0.083	0.078	0.005	0	1.115	-1.115
14	0.048	0.045	0.003	0	-1.166	1.166
15	0.103	0.110	-0.007	15	14.325	0.675
16	0.093	0.093	0.000	4	4.926	-0.926

As for uniformity, it is illustrated that the predicted values are pretty close to the experimental results and the deviation is in a small range in most cases. This can be seen to mean that the regression model is quite reliable in estimating uniformity of the product. At times, the model has a 100% accuracy of the uniformity value, as is seen in experiment 6, while at other times it has a wider variance as noted in experiment 3, thus suggesting that there is variability in the accuracy of the model's prediction. The number of wrinkles comparison is also fairly accurate, although fluctuations are slightly greater than with uniformity. This means that for the regression model, the task of determining the number of wrinkles is more complex. For instance, in experiment 1, the model is nearly perfect in estimating the number of wrinkles with less error and in experiment 4, there is a higher error suggesting that the model has certain errors when estimating a low quantity of wrinkles.

5.6.2 Regression Outputs

The regression outputs for Inclined(uniformity) are presented in Table 9 below. The p-values of Heating Temperature, Heating Time, Sheet thickness, and Distance between ups are 0.613,0. 212,0.000,0.826 respectively. The p-value for Sheet thickness (0.000) is less than the alpha level of 0.05, which shows that the Sheet thickness is significant at 0.05 level. On the other hand, the p-value of heating temperature (0.613), heating time (0.212), and distance between ups 0.826 is greater than the common alpha level of 0.05, which indicates that they are not significant at the 0.05 level of significance.

Table 5-7: Summary of the output of the regression model for Uniformity

Predictor	**Coeff**	**SE Coeff**	**T-Value**	**P-Value**
Inclined Thickness (Uniformity)				
Constant	-0.0070	0.0205	-0.34	0.738
Heating Temperature (A)	0.000100	0.000192	0.52	0.613
Heating Time (B)	-0.000638	0.000481	-1.33	0.212
Sheet thickness (C)	0.7679	0.0634	12.12	0.000
Distance between ups (D)	0.000051	0.000226	0.23	0.826

The regression output for the Number of wrinkles summarized is presented in Table 9. The p-values of Heating Temperature, Heating Time, Sheet thickness, and Distance between ups are 0.861, 0. 861,0.563, and 0.000 respectively. The p-value for the distance between ups (0.000) is lower than the common alpha level of 0.05, which means that the distance between ups is significant. On the other hand, the predictor variables of heating temperature (0.861), heating time (0.861), and sheet thickness (0.567) are higher than the alpha level of 0.05, which makes it non-significant, A p-value of less than 0.05 means that the null hypothesis is rejected. That is, a predictor with a low p-value is likely to be a useful addition to the model because the value of the predictor is associated with the value of the response variable. On the other hand, a larger (insignificant) p-value indicates that the changes in the predictor are not related to the changes in the response.

Table 11: Summary of the output of the regression model for number of wrinkles

Predictor	**Coeff**	**SE Coeff**	**T-Value**	**P-Value**
Number of Wrinkles				
Constant	28.85	2.98	9.67	0.000
Heating Temperature (A)	-0.0050	0.0280	-0.18	0.861
Heating Time (B)	0.0125	0.0699	0.18	0.861
Sheet thickness (C)	-5.43	9.22	-0.59	0.567
Distance between ups (D)	-0.6372	0.0329	-19.36	0.000

5.6.3 Test of Hypothesis

In regression analysis, the null hypothesis (H_0) is that there is no relationship between the independent and dependent variables meaning that the independents do not influence the dependent. On the other hand, the null hypothesis (H_0) is the statement that there is no relationship, meaning that the independent variables make no impact on the dependent variable while the alternate hypothesis (H_1) will state that there is a relationship which means that the independent variables affect the dependent variable. These include t-tests, F-tests, chi-squared tests, non-parametric tests, multiple regression, and ANOVA are used to test the null hypothesis and decide on the acceptance of the alternate hypothesis.

In our analysis, the hypothesis test was used to check the relationship between the response variables that consisted of inclined uniformity and the number of wrinkles with the regressor variables which were heating temperature, heating time, sheet thickness, and distance between ups. Null hypothesis, which was that all the regression coefficients are zero, was rejected because the obtained p-value was less than 0.05. This means that at least one of the variables is significant in the multiple regression equation; this include sheet thickness and distance between up Inclined thickness and number of wrinkles.

Table 5-8: ANOVA for testing the significance of the regression model

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Inclined Thickness Uniformity (ITU)					
Regression	4	0.011005	0.002751	37.22	0.000
Error	11	0.000813	0.000074		
Total	15	0.011818			
Number of Wrinkles (W)					
Regression	4	586.562	146.640	93.85	0.000
Error	11	17.188	1.563		
Total	15	603.750			

The testing significance indicates that the p-value for Inclined Uniformity and Number of less than α = 0.05. so, the null hypothesis (H_0) has been rejected because the $p\text{-value} < 0.05$, indicates that at least one of the variables is significant in the multiple regression equation. This result validates that sheet thickness and distance between ups are important factors in the model for amorphous percentage.

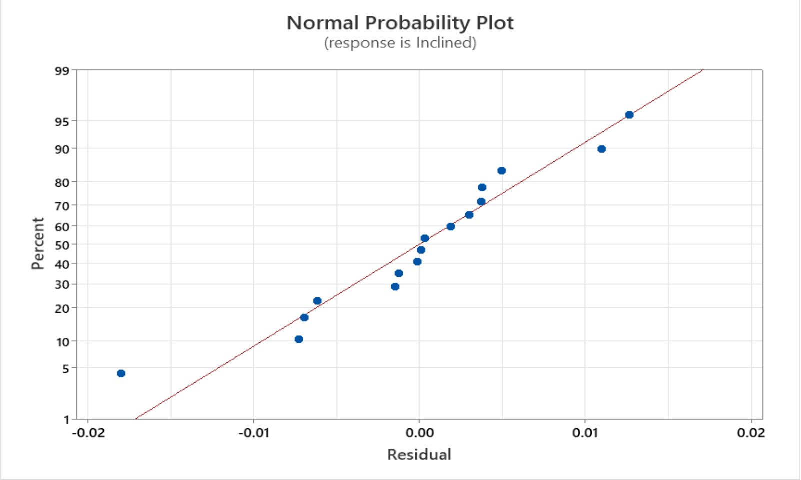


Figure 5.9: Normal Probability Plot of the residuals for Uniformity

The competence of the developed models was assessed using a coefficient of determination (R2). Since the value of R2 is very close to one, it shows that the dependent variable fits well with the independent variables. In the current study, the regression models for uniformity and number of wrinkles have high R2 values of 97. 11% and 92. 65%, respectively. The residual plot was used to assess the significance of the coefficients in the anticipated model. The residual plots for Uniformity and Number of wrinkles are presented in Fig. 13 and Fig. 14 respectively. The Figures also revealed that the residuals are close to the straight line for Uniformity and Number of wrinkles, which confirms the significance of the developed model coefficient models.

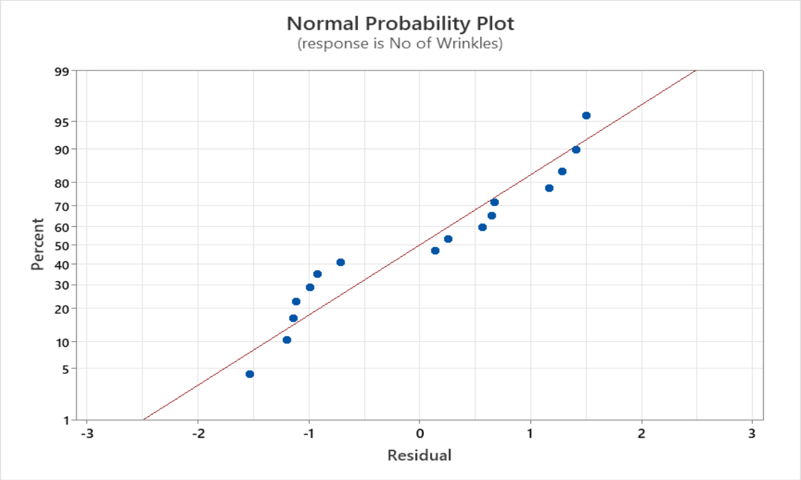


Figure 5.10: Normal Probability Plot of the residuals for Number of Wrinkles

5.7 Estimation of the Optimal Inclined Thickness Uniformity and Number of Wrinkles

For validating the Taguchi predicted optimum processing conditions, conformation tests need to be performed. The predicted (ε) was used to estimate and verify the response at the predicted optimum processing parameters [42], [72].It was calculated by using Eq. (5).

εpredicted= $\varepsilon_1 + \sum_{i=1}^{n}(\varepsilon_0 - \varepsilon_1)$ (5)

Where,

ε_1 = Total mean value

ε_2 = Mean values at optimal level x= No of input processing parameters

The confirmation test of the processing parameters is done to the Taguchi and Multiple regression equations only at optimal levels of factor. Comparison of the experiment results with the predicted values is carried out in tables 12, 13 & 14 where Taguchi method and multiple regression equations have been applied.

The values of p for Uniformity are 0.0241 and 0.0393 for Taguchi and the Multiple regression model. The predicted values for the Number of Wrinkles are -0.375 and -1.5636 for the Taguchi and Multiple regression model. From Tables 12,13 and 14, it was observed that predicted and optimal processing parameters are very close for Uniformity and Number of wrinkles. The errors are 0.239 and 3.75 for the Taguchi method and 0.0087 and 1.563 for the multiple regression model. Also, it is necessary to emphasize that all the mentioned percentages of errors are below 20%.

5.7.1 Conformation Tests Results for Uniformity

The results of conformation test for uniformity using Taguchi method and multiple regression model are presented in Table 5-9. The essence of these tests is to compare the forecasted results with real experimental values. These are made with the help of optimum processing parameters obtained from Taguchi method and multiple regression model and these are validated with the help of confirmation experiment.

For the Taguchi method, the received calculated value of the uniformity at the optimal level of factors is equal to 0 at level A1 B3 C1 D3. 0241. But when the confirmation experiment was done, the value that was obtained was 0. 048. A comparison of the predicted value of X-ray absorption to the experimental value is done by calculating the error as 0. 239. Likewise, as for the multiple regression model, the expected uniformity was a bit higher, and it was 0. 039284, the confirmation experiment also gave a value of 0. 048, thus the error of estimation was relatively small at 0. 0087. These errors show that although the values are slightly lower than the predicted values, the multiple regression model has a slightly improved accuracy of uniformity than the Taguchi method. Nonetheless, the percentage errors are both below 20%, which is reasonable, and therefore, both methods are accurate for optimization.

Table 5-9: Conformation Tests Results for Uniformity

	Taguchi Method			**Multiple Regression Model**		
	Prediction	**Confirmation experiment**	**Error**	**Prediction**	**Confirmation experiment**	**Error**
Levels	A1 B3 C1 D3	A1 B3 C1 D3		A1 B3 C1 D3	A1 B3 C1 D3	
Inclined Thickness (Uniformity)	0.0241	0.048	0.239	0.039284	0.048	0 .0087

5.7.2 Conformation Test Results for Number of Wrinkles

Table 5-10 deals with estimates of the conformation test on the number of wrinkles as per the Taguchi method and multiple regression model. Under the conditions A1 B4 C4 D4 the number of wrinkles predicted is -0. 375≈0 according to the Taguchi method. This negative prediction most probably means that there were no expectations of wrinkles to be formed. This is confirmed by the confirmation experiment where the tester recorded no wrinkles at all. However, this leads to a deviation (error) of 0, On the other hand, the multiple regression model has predicted a slightly negative value of -1. 5636 ≈0, also meaning it is recommended that no wrinkle should be formed. The confirmation experiment confirmed zero wrinkles as well, it therefore had an error of 0 percent. However, since both models are validated with errors less than 10%, they are both appropriate for wrinkle minimization in the process although the Taguchi method has a slightly larger error than the DOE method.

Table 5-10: Conformation Test Results for Number of Wrinkles

	Taguchi Method			**Multiple Regression Model**		
	Prediction	**Confirmation experiment**	**Error**	**Prediction**	**Confirmation experiment**	**Error**
Level	A1 B4 C4 D4	A1 B4 C4 D4		A1 B4 C4 D4	A1 B4 C4 D4	
Number of Wrinkles	-0.375 ≈0	0	0	-1.564 ≈0	0	0

5.7.3 Conformation Test Results for Random Conditions

As in the case of systematic processing conditions, Table 5-11 also presents the results of the conformation test under random processing conditions, and the results based on the Taguchi method and the multiple regression model are compared in terms of both uniformity and the number of wrinkles. For uniformity, from the random condition level, A4 B4 C4 D4 the Taguchi method gives the value 0.119375, and the actual experiment which was performed provides an outcome of 0. 1053. The error here is calculated as 0.014. The multiple regression model, however, predicted a slightly higher value of 0.132084, and the same result obtained experimentally results in a somewhat larger error equal to 0.027. Even though the errors are very small and within the 20% tolerance limits, the Taguchi method claims a somewhat better efficiency in this case.

Under the same random conditions, the Taguchi method for the number of wrinkles gave a predicted value of -0.375≈0, and the experiment once more produced no wrinkles, putting the error at zero again. 375≈0. The residual of the multiple regression model was predicted to be slightly more negative at -1.7136≈0, and since the confirmation experiment observed no wrinkles, the error here is larger at 0. Although both methods are confirmed to be effective within the acceptable levels of error, the Taguchi method seems to be more precise under such random conditions for both uniformity and wrinkle estimation.

Table 5-11: Conformation Test Results for Random Conditions:

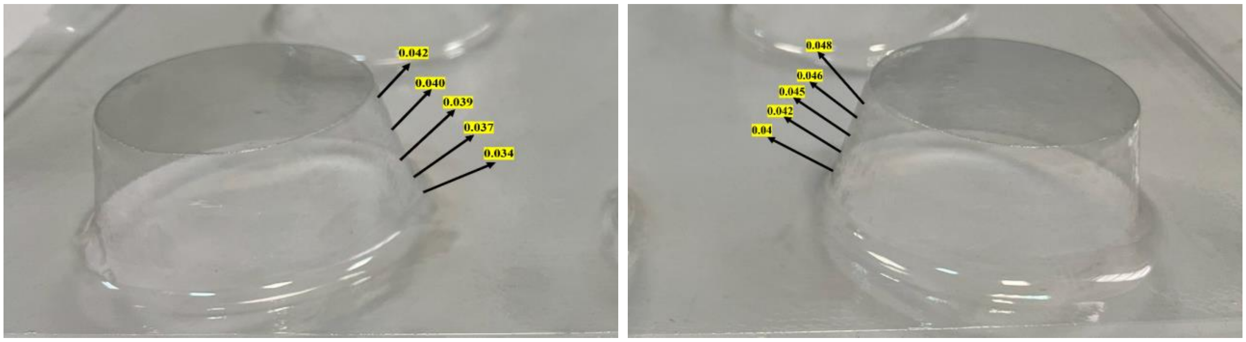
	Taguchi Method			**Multiple Regression Model**		
	Prediction	**Confirmation experiment**	**Error**	**Prediction**	**Confirmation experiment**	**Error**
Levels	**A4 B4 C4 D4**	**A4 B4 C4 D4**		**A4 B4 C4 D4**	**A4 B4 C4 D4**	
Inclined Thickness (Uniformity)	0.119375	0.1053	0.014	0.132084	0.1053	0.027
Number of Wrinkles	-0.375 ≈0	0	0	-1.714 ≈0	0	0

5.7.4 Thickness Uniformity Improvement Post-Optimization

The images are presented to illustrate the difference in the thickness of the PVC sheet before and after the application of the Taguchi optimization technique. These are made on the formed part at the inclined plane which is very essential in ascertaining the evenness and standard of the material used. In Figure (a), which is the condition before optimization, the thickness of the inclined area fluctuates greatly from 0.030 mm to 0.042 mm. This makes the distribution of material on the inclined surface to be unequal. Such fluctuations indicate that the process parameters used before optimization did not guarantee uniform thickness of the material and this can give rise to regions of lower strength in the formed part and hence a lower overall quality and strength.

On the other hand, Figure (b) shows the thickness measurements taken after using the Taguchi method of optimization and as can be seen, the thickness measurements taken on the inclined area are much closer with the smallest being 0.041 mm to 0.048 mm, which proves that the optimization minimizes the variation of the material distribution at the macro level. The uniform thickness can be attributed to the fact that the material will be spread much more evenly across the formed parts and; therefore, the formed parts will probably have better structural strength and perhaps, better durability.

In the present case, the contrast between the two pictures illustrates the efficiency of the Taguchi optimization method. With the help of this method, the processing parameters for optimum formation were determined which greatly helped in increasing the uniformity of the material in the formed parts and thus improving the quality of the product. The concept of optimized conditions is important to reduce the variation of thickness because the properties of the final result depend on the various thicknesses of the material used. In minimizing the percent error the optimization should not exceed 20% for an accurate statistical analysis [73]. Thus, it is found that the Taguchi and the multiple regression model are feasible for optimization through the confirmation test.



(a) (b)

Figure 5.11: Comparison of thickness

CHAPTER 6: CONCLUSIONS

This research systematically examined the vacuum forming process with a focus on some important parameters to refine them in a bid to get better quality products that are free from defects, and the process done in the shortest time possible. Utilizing the Taguchi method and Design of Experiments (DOE), the study focused on four critical factors: Heating temperature, heating time, sheet thickness, and distance between uppers. The Formech 508FS was used as the machine for the PVC tests and for the experimental assessment, PVC sheets were employed.

The research concluded that if the thickness of the sheet is controlled, then the Inclined thickness uniformity of vacuum-formed products is optimized. The use of thicker sheets to arrive at the conclusion that chill marks, which are the imperfections that are related to heating and material flow, could be curbed. On the other hand, the distances between ups was concluded to hinder the formation of wrinkles and improve the aesthetic and mechanical properties of the outcome. The highest efficiency was observed at a temperature of 70°C, time of heating 14 seconds, the thickness of the sheets 0.06mm for inclined thickness uniformity and distance between ups of 42mm. For wrinkle reduction the heating temperature was found to be 100°C, heating time was 18 seconds while the thickness of the sheet was 0. It was found that an ups size of 15 mm, and a distance between ups of 46 mm was best.

The discoloration was affected by high heating temperatures, long heating times, and narrow ups distances. Mathematical models and ANOVA supported the results and it was observed that the mathematical models developed correlated well with the experimental results with a percentage error of less than 10% as observed in the confirmation tests. This is with respect to the generality, efficiency, and accuracy of the Taguchi method as an accurate tool in optimizing vacuum-forming parameters.

6.1 Implications for Industry

The consequences of this research are great for industries that apply vacuum forming. In this way, by implementing the mentioned above-optimized parameters – thickness of the sheet and distance between ups – it will be possible to increase the quality of the products and decrease the defect rates, as well as minimize the costs connected with the wastes of the material and the optimization of the production process. This paper presents a sound reference for using these parameters in industrial processes and gives directions on how to achieve better product quality and productivity.

Contributions and Observations

The present research provides a significant contribution to the understanding of vacuum forming by posing and answering research questions aimed at identifying the role of process parameters in determining the quality of vacuum formed products. From the use of the Taguchi method and DOE, experimentation can be very accurate and can be used to make important improvements to manufacturing. Key observations from the study include:

6.2 Key observations from the study

i. Discoloration phenomenon, which is characterized by high heating temperatures and long heating times with close-ups can be eliminated by increasing the thickness of the sheet and reducing heating settings.

ii. Pointing to the fact that in the vacuum-forming process the distance between ups is the key element defining wrinkle formation.

iii. It was also found that the distance between ups plays a critical role in the formation of wrinkles. Wrinkles were created at first at 21 and 36 mm but not at 42 and 46 mm.

iv. In this case of ABS or PVC material variation, and color contrast, wrinkles always emerged; these results imply that material type and color had no influence on the formation of wrinkles.

v. It was found that the size of the venting hole did not influence the occurrence of wrinkles at all. The outcomes also did not change when the diameter of the venting holes was varied as well.

vi. These results imply that wrinkle creation was not influenced by the type of machine used despite the differences in heating process and construction. Indeed, wrinkles formed at twenty-one millimeters and thirty-six millimeters consistently.

6.3 Future Work

While this study has made significant strides in optimizing the vacuum forming process, several areas warrant further investigation: While this study has made significant strides in optimizing the vacuum-forming process, several areas warrant further investigation:

i. **Sustainability:** Further studies should then be conducted to determine other green practices in vacuum forming and the specific environmental effect of the materials and processes used to come up with sustainable manufacturing.
ii. **Material Characteristics:** Further research into the influences of different polymer materials to the vacuum forming process may give a lot of understanding to the material as well as enhancement of the process.
iii. **Advanced Mold Design**: The study of new mold materials and designs that improve heat transfer and cooling time could also provide further improvements and efficiency.
iv. **Real-Time Monitoring:** Real-time monitoring and controls might be more effective for real-time changes during production and thereby reduce process variability and enhance product quality.

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