4-19-2022

Cost Efficient 3D Printed Mold for Thermoforming

Julianna Buck
Western Michigan University, juliwooli4@gmail.com

ZeRajha Smith, Julianna Buck, Chris Frego

EDMM 4920 Senior Design Students

Western Michigan University

D-208 Floyd Hall

Kalamazoo, MI, 49008

April 22, 2022

Ms. Dana Hammond

Professor, EDMM 4920 – Senior Design

Faculty Specialist & Academic Advisor

Western Michigan University

E-221 Floyd Hall

Kalamazoo, MI, 49008

Dear Professor Hammond:

As outlined in the EDMM 4920 syllabus, our team is submitting the attached report entitled *3D Printed Thermoforming Molds –Final Report*.

This report gives an overview of the need for this project and what the team plans to create for the sponsor in order to highlight the effectiveness of the use of 3D printed molds for production and meet the project objectives. It also details the criteria that the parts produced during this project must meet in order to be considered a successful part and how we plan to produce a mold that creates parts that meet these criteria. Lastly, background information on the topics of thermoforming and 3D printing are provided to help aid in your understanding of the topics.

Warm Regards,

ZeRajha Smith, Julianna Buck, Chris Frego

3D Printed Thermoforming Molds – Final Interim Report

Julianna Buck

Chris Frego

ZeRajha Smith

Ms. Dana Hammond, EDMM4920 Professor

Mr. Jay Shoemaker, Faculty Advisor

Table of Contents

Executive Summary

Traditional machined thermoforming molds are extremely expensive to produce. For small business owners who will have a very low volume of production this is not always a viable solution. To counteract this, the 3D thermoforming mold team strives to create a detailed manuscript complete with all the necessary information on how to produce a quality thermoforming mold through 3D printing. This manual will include information on producing a mold with parameters such as time to 3D print, type of printing materials, a cost analysis of producing the mold, and pre- and post-processing of the mold in preparation for production. The research conducted for this project was broken down into two topics. The first topic of research consisted of information solely on the process of thermoforming. This included topics such as material thicknesses generally used in the process, possible defects, and the importance of clamping mechanisms. The second topic was solely information on 3D printing and included information such as the availability of different 3D printing materials, typical settings used to produce quality parts, and pre- and post-processing that may be needed. Utilizing the knowledge of these two topics, a general guideline on the ideal behaviors of both the mold and the parts (to be) created was constructed. These guidelines serve as a basis for laboratory testing results which will determine if the usage of 3D printed molds are a viable solution for low-cost, low-volume production. In addition to the manual that will be produced, physical parts produced in the lab will also be presented and given to the sponsor to see the results first-hand. Any recommendations for improvement will be noted in the manual detailing the process.

Introduction

The Thermoforming Process

Thermoforming is the process of forming plastic products by heating plastic sheets (with thicknesses ranging from 0.005 inches to 0.500 inches), then using a mold retrofitted with vacuum holes to suck the plastic sheet into its final form (Rosen). This process is used for mass production manufacturing of thin products and a key factor of these products is that they are recyclable and/or disposable. This means that the plastic types that will be most used in this process will be thermoplastic polymers or plastics that can be reheated and easily reshaped such as High-Density Polyethylene (HDPE), Acrylonitrile Butadiene Styrene (ABS), Polypropylene (PP), etc.

Common Thermoforming Advantages

Despite there being different distinctions of the thermoforming process, the process has many advantages and disadvantages. The advantages of thermoforming start with the fact that it is a remarkably simple manufacturing process to learn (The Advantages and Disadvantages of Thermoforming, 2021). This means that with a small amount of training, operators will be able to monitor and assist the process very easily where needed. The second advantage to thermoforming is that the simplicity of the process lends itself well to having short product cycle times. Multitudes of parts can be made in short periods of time provided enough plastic sheeting (among other materials) is available. Third, the thermoforming process allows for all thermoplastic polymers to be used. This gives manufacturers a wide range of materials to choose from with some of the main factors in material selection being cost and application. Lastly, this process is viable for products of large sizes. Other plastic processes tend to have a size limit on the parts they can produce but thermoforming provides a way around that.

Common Thermoforming Disadvantages

The first disadvantage of this process is that it is more costly than other plastics processes like extrusion or injection molding (The Advantages and Disadvantages of Thermoforming, 2021). The second drawback to thermoforming is that with this process, manufacturers are limited to plastic material in the form of plastic sheeting. Other forms of plastic such as pellets are much cheaper than rolls or sheets. This leads to the third disadvantage which is that products made with this process are subject to thin wall designs. This can pose a problem for parts made for applications where they need to withstand a large amount of force or will be used as a stabilizer of some sort. Lastly, thermoforming allows the possibility of unevenness to occur in parts. This occurs when the plastic sheet is thicker in some areas and not in others. This can lead to some parts being labelled as defects and effectively extend production time and create a loss of revenue.

Project Overview

The purpose of this section is to detail how this project will utilize the information in the report such as that of the thermoforming material considerations, the 3D printing process methodology and so on, to solve an issue that is currently being faced in the industry. This section will identify the target audience, the major issue that the target audience is facing, and the project deliverables. This section will conclude by detailing the objectives that will be used as a guide in producing the project deliverables.

Need & Benefit

The development of this project stems from a roadblock that small businesses in the thermoforming (also called vacuum forming) industry face today. The cost of acquiring a traditional thermoforming mold made of aluminum (per industry standards) ranges from $2,000 to $10,000. A simple cost analysis comparing the amount of money these small business owners will make to the cost of acquiring a mold will illustrate that, for many of these small business owners, this is not a viable option for production. Therefore, they are left to find an alternative that is more cost-effective while still producing the same quality.

3D printing is a solution to this problem. 3D printing allows users to produce prototypes and customizable parts faster and more efficiently over the traditional mold-making process. This makes the process an attractive means of producing thermoforming molds. Mass production of 3D printers and the corresponding materials have made the cost of acquiring them low so when comparing the cost of producing a traditional aluminum mold to the cost of producing a 3D printed mold, it is quickly distinguished that the 3D printed molds will be cheapest and reduce the cost by thousands of dollars. Despite the benefits that the application of 3D printing thermoforming molds would provide small business owners (and the fact that this process has been on the market for quite some time) adoption of this process has been slow. A big reason for this is due to there not being a detailed methodology to follow when choosing to 3D print a mold. Having a detailed methodology when producing molds is important as it will help create the best parts with molds that will last the longest. It will also ease the apprehension of creating plastic parts on plastic molds that have to be heated, which to some may seem like an instant failure or waste.

Project Deliverables

The deliverables of this project will be detailed process documentation on how to produce a quality 3D printed mold. Parameters that will be outlined in the documentation will include time, materials, cost, and pre- and post-processing of parts. Also included in this manual will be recommendations on how to improve the process (such as expedition of part creation, possible automation, etc.) if the process is deemed to be a viable option. This will be in the form of a manual (either digital, hard-copy, or both). The second deliverable of this project will be the samples produced in the lab and show the progression of the experimentation and how the best settings and quality improved over time. This will give the sponsor a chance to witness the improvements themselves and gain a better understanding of the changes that took place.

Project Objectives

There are multiple objectives that the team will be considering throughout the duration of this project. The first will be determining which material(s) will be best suited for the creation of the mold. Another objective will be determining which machine settings and pre- and post-processing will produce a part of the same quality as that of a traditional mold. The third objective will be an analysis of the efficiency and effectiveness of the molds compared to parts of a traditional mold. Lastly, research will be done on other forms of making molds for thermoforming to identify if this method is the most efficient and cost-effective for making a mold. All results will be presented in the final documentation and presentation for this experiment.

Background Information on Thermoforming

In this section, there will be discussion of the various aspects and considerations that one must be aware of when using this process to manufacture parts in general. It will begin with a conversation on what the roll-fed and sheet-fed distinctions of thermoforming are and their differences from one another. Discussion on what process is used for which type of products in the industry will conclude each category. The next section will then progress to the topic of the materials used in thermoforming and how their sub-atomic arrangements lend themselves to how the material will behave. This section will also discuss how the material's behavior will constitute process considerations. Lastly, a section on the role that clamping plays in the thermoforming process will conclude the background information.

Roll-fed vs Sheet-fed Thermoforming

The process of thermoforming is broken up into two different distinctions: Roll-fed and Sheet-fed thermoforming. Roll-fed thermoforming utilizes plastic sheeting with a thickness range of 0.005 to 0.100 in (Rosen). Since the thicknesses of the sheet used in roll-fed thermoforming are small, this category has also been called thin-gauge thermoforming (Thin Gauge Thermoforming, 2021). This process is used in applications where there will be high-volume production runs and the number of products manufactured will be anywhere from 5,000 to millions of parts (Rosen). It is sensible that the thin-gauge process is used for high production runs because the thinnest material will take the shortest amount of time to heat up which will, in turn, allow products to be formed faster. It also guarantees that the heat from the oven will penetrate through the whole sheet allowing it to be fully formed to the desired shape. Examples of roll-fed thermoforming include Blister packs, single-use food containers, and medical packaging (Thin Gauge Thermoforming, 2021).

Sheet-fed thermoforming, on the other hand, utilizes plastic sheeting with a thickness range of 0.125 to 0.500 in (Rosen). The thickness of the plastic material is also called thick-gauge thermoforming (Thermoforming, 2021). It is used in applications where there will be low-volume production runs (Rosen). This is, in part, due to the process requiring an elevated level of intensive labor and energy consumption which therefore leads to exceptionally slow production speeds especially when compared to roll-fed thermoforming (Rosen). The increased thickness requires that there be longer heat times to ensure that the plastic sheet is heated up to a high enough degree that the heat will travel through not just the depth of the sheet, but also the required length of the part being created. If this is not taken into proper consideration, this results in issues such as uneven sag (the ununiform temperature gradient in the plastic sheet, which results in the sheet drooping [sagging] down in some areas and not in others) or poor part detail (due to the plastic sheet being too cool for the force of the vacuum to pull the hot plastic into the mold to form it) among others (Mahmood, Mix, & Giacomin). With this process, there must be additional precautions and process steps taken to eradicate or severely minimize the possibilities of defects which factors into the high labor intensity. Some examples of products made with sheet-fed thermoforming include scientific equipment enclosures and pick-up truck bed liners (Rosen)

Materials and the Importance of Clamping

Materials play a large part in any manufacturing process. This is because different materials will have different mechanical, thermal, physical, etc. properties that manufacturers must account for when designing their production process. In thermoforming, though there are different plastics that are used with the process, almost all these plastics are defined as thermoplastics. This section will describe what thermoplastics are, as well as the subcategories within thermoplastics and their advantages and/or disadvantages. This section will conclude by analyzing the importance of clamping in this process. Clamping is important in manufacturing because the clamping mechanism holds the part while it is subject to other processes that often include the use and/or generation of force. This section will detail the major considerations that manufacturers must be aware of when choosing to thermoform a product.

Thermoplastics Overall

Though both distinctions have their differences, there are some commonalities between them especially regarding materials and other process considerations. First, both processes work best with thermoplastics. As mentioned previously, these are materials that are easily heated and formed or reheated and reformed (in recycling applications) and can be so indefinitely. What allows them to be easily heated and formed is that they are comprised of lengthy monomer chains (small molecules which have been joined together by intermolecular forces) which behave in a malleable manner. These chains will deteriorate when heated (which is when the plastic begins to melt or fully melts and becomes pliable) and will re-solidify when cooled (which is what allows the plastic to keep its shape afterwards). It is these properties that make thermoplastics one of the only materials used in the thermoforming process for both thermoforming subcategories.

Thermoplastic Material Subcategories

There are numerous thermoplastics, and each has their own properties that make them useful for different applications but all of them can be classified as either amorphous or crystalline. As mentioned previously, thermoplastics have long monomer chains. When a thermoplastic is considered amorphous, it refers to the areas on these chains where molecules will be comprised in an irregular fashion (think cooked spaghetti noodles placed on a table without any shape considerations) (Difference between amorphous and crystalline polymers, 2016). The random nature of amorphous structures lends itself to the wide temperature ranges it can be subjected to as well as the wide forming window that manufacturers can take advantage of (Rosen). This means that manufacturers can form a product as quickly or slowly as necessary for their process and this, in turn, gives them greater control over their process(es). Amorphous thermoplastics also create the advantage of being isotropic which means the shrinkage that occurs in parts made of amorphous thermoplastics will be equal in both the direction of flow and transverse direction, which decreases warping, and creates a high impact strength (The Difference between Amorphous and Semi-Crystalline Polymers, 2017). It also leads to these materials having some negative characteristics such as much lower hardness, chemical resistance, and having a high sensitivity to stress cracking (Difference between Amorphous and Crystalline Polymers, 2016).

Crystalline structures on the opposite hand are molecular chains that have some form or shape, and to a degree, rigidity associated with them (Throne). The form and rigidity of these materials give it a specific melting point before it begins to soften up enough for forming and therefore, increase the energy needed to melt them (Difference between Amorphous and Crystalline Polymers, 2016). This restricts the process because manufacturers must increase the length of time given to get the plastic to the correct temperature for forming. It also makes it so that any other additional processing must be centered around the forming window of the plastic and may lead to additional resources and process customization needed to control the process. Crystalline thermoplastics are also anisotropic and will create greater amounts of shrinkage in directions opposite of flow (The Difference between Amorphous and Semi-Crystalline Polymers, 2017). This leads to undesirable effects such as warpage, uneven sag (drooping), and therefore dimensional instability (The Difference between Amorphous and Semi-Crystalline Polymers, 2017). Advantages of crystalline thermoplastics include increased hardness and chemical resistance (Difference between Amorphous and Crystalline Polymers, 2016).

Additional Considerations: Clamping

Clamping plays a vital role in the thermoforming process and therefore there are special considerations that need to be considered when conducting the thermoforming process. The first consideration is that the materials from which the clamp is made need to be able to withstand the heat temperatures of both the oven and the plastic sheet. If the incorrect material is used to make the clamp, the clamp may have adverse reactions from either the heat of the oven or heated plastic such as expansion or contamination from affinity between its chemical molecules and the chemical molecules of the plastic. It is also one of the ways that thermoforming manufacturers minimize sagging (drooping) of the part (Mahmood, Mix, & Giacomin). Proper clamping design will account for the melting/expansion of the plastic and the tolerances needed when forming the part. Lastly, the clamping mechanism needs to be strong enough to withstand the force from the vacuum when the plastic is sucked into the mold and formed.

Background on the Prototype Mold

In 2019 two students, part of the Society of Plastic Engineers, decided to move forward with a project that could potentially be used at the Annual Technical Conference or ANTEC. These two students are alumnus Ivan Krylov and current senior Christopher Frego. The goal was to find how viable using a 3D printed mold for thermoforming could be. The prototype originally created was designed in three pieces that fit into each other and secured with epoxy. The mold was printed at the Parkview campus using an Ultimaker 3D printer using Polylactic-Acid (PLA) as the printing material. PLA was chosen because of its price and easy accessibility. After the mold was glued together it was painted with a heat resistant spray paint in an attempt to extend the longevity of the prototype during testing. This Senior Design Project will be starting with the partially fabricated prototype mold previously created. It will start with analyzing the mold, testing the current prototype then working to redesign the mold based on the failure points of the first prototype. This project is being continued to find if 3D printing a thermoforming mold is a more cost effective and viable option for small business.

Methodology

In this section the process for the project is broken down into the main phases that transpired throughout the process. These main objectives can be broken down into seven different phases. The phases of the project are as follows: preparation of the original mold, design of a new vacuum table, original mold redesign, vacuum pump issues & first complete mold remodel, vacuum pump system, second mold design remodel, final mold design remodel.

Preparation of the Original Mold

The mold that was originally to be used for this project was not functional. While the mold had been properly printed and assembled, a heat-resistant spray paint had been applied to the top of it. The idea behind the use of the paint was that the paint would protect not only the surface from the part-removal process but also to potentially decrease the cooling time needed in between production runs. The issue is that the paint covered up the vacuum holes and did not allow air to flow through the mold. The first step taken in solving this problem was to locate the vacuum holes. Since the paint covered the holes completely, they were not easily located with the naked eye. That is where the use of the CAD model came into play. The CAD model produced the coordinates of each hole from a reference point (the top corner of the model) and the coordinates were able to be uploaded onto a CNC machine. This allowed the holes to be accurately tapped (when the drill of the CNC just barely cuts into the surface of the mold). This small contact removes the thin layer of paint that was covering the vacuum holes. At this point another problem occurred with the vacuum holes. After doing some research on the printing of the mold it was discovered that the thickness of the filament being used to print the mold was not factored into the diameter of the vacuum holes on the mold. This means that the holes in the mold had to be fully drilled through and into the vacuum chambers instead of simply breaking the surface of the paint. The type of CNC machine used during this process was a Storm VMC (Vertical Machining Center). The mold is shown mounted in the CNC model in Appendix 1 Figure 1.

Design of a New Vacuum Table

After the mold had been successfully modified and deemed operable, it was time to test it. During the first test of the mold another issue was noted. There wasn’t enough vacuum suction being generated to pull the heated plastic sheets onto and around the mold surface. It was decided after consultation with the advisors of the project that the vacuum table that was being used was old and more than likely allowing air to escape through it. The design for the vacuum table is simple as it is essentially a hollow box that has a vacuum system attached to it. For the project, the CAD model for the vacuum table was started to determine the materials needed to build the table. The new vacuum table was constructed out of plywood. The current model for the vacuum table is shown in Appendix 1 Figure 2.

Original Mold Redesign

In between the completion of the vacuum table and the testing on the original mold was taking place, a new mold design was being made. It was decided that the original mold was overdesigned and overcomplicated. This overcomplication only added to the stress of using the mold and had to be simplified. One way that this would be accomplished would be redesigning the vacuum system within the mold. The old system was removed and instead the vacuum holes on the surface of the part would lead to the hollowed backend of the mold. This allowed for the vacuum to have almost no impediments when drawing the plastic sheet around the mold which was much different from the old system where the vacuumed air would have to travel through a complicated channel system before being completely drawn out. It also reduced the weight of the mold overall. A picture of the original and redesigned molds can be found in Appendix 1 Figure(s) 3 and 4.

Vacuum Pump Issues & First Complete Mold Design Remodel

After the vacuum table was constructed, another attempt to test the mold was initiated and it was noted that there was still not enough vacuum suction being generated. To remedy this another pump was added to the thermoforming machine. While the new pump was an improvement, it did not solve the issue. Testing on a different machine was then conducted. On the new machine, suction was much better, and it was decided to test the mold on this machine. When testing was once again conducted on the mold and though the suction power was much better on the new machine it was still not enough to draw the plastic down onto the mold. After consultation with the advisors of the project and fabrication professional Mike Konkel, it was determined that the mold was too large and required a vacuum force greater than could be generated on the machines. After this discussion, a smaller mold design was decided on. The mold is much simpler and approximately one-third of the size of the original mold. The design is shown in Appendix 1 Figure 5.

Vacuum Pump System

After the smaller mold design had been 3D printed, it was time to test it. During the tests it was discovered that there was still an issue with the vacuum not being able to draw the plastic sheet down around the mold. An analysis of the system was done, and it was discovered that there were leaks of air in the system from multiple places. The largest leak came from a cracked pipe adapter that connected the vacuum pump to the vacuum piping system. This was fixed by replacing the adapter and reattaching the piping to the pump. After this had been successfully fixed, the vacuum pressure was increased from 15 inches of mercury (in Hg) to 27 inches of mercury. A picture of the vacuum system (in the overall thermoforming system and by itself) can be observed in Appendix 1 Figure 6.

Second Mold Design Remodel

With the vacuum system replaced and a considerably smaller mold printed, testing was resumed once again. The next issue discovered was that the mold design chosen was too tall and did not have enough vacuum holes to pull the plastic onto its surface. A new design was created that was smaller and had more vacuum holes. While more successful runs were able to be conducted with this model, it failed after 8 parts prompting for another re-design. The mold suffered from not only deformation but also split in the upper middle section. The redesigned mold is shown in Appendix 1 Figure 7. The failures of the mold were due to an inadequate number of supports and mold cooling time. The lack of mold supports under the surface of the mold caused the surface of the mold to droop and deform. Supports reinforce the mold surface and slows the amount deformation the mold experiences. The mold cooling time is the time that the mold is allowed to cool in-between runs. This allows the plastic to reharden and solidify so that in the next run, its deformation will not drastically increase, and the rate of deformation can be controlled.

Final Mold Design Remodel

Knowing that more support and cooling time needed to be incorporated, a final design and process change was made. For support, a "skeleton" was made. This support skeleton was a solid, half-inch thick column directly under the section of the mold that the product would be formed over. This prevented the surface of the mold from deforming (or at least slowed into an almost nominal amount) while also serving as a way to keep the structural integrity of the mold from collapsing on the sides when the vacuum was used. A picture of this mold design is shown in Appendix 1 Figure 8. Figuring out the cooling times, however, took much trial and error. After several runs, it was discovered that a 2-minute cool down time provided the best result. The mold temperature while forming would be 100+ degrees Fahrenheit. After 2 minutes cooling, the average temperature would be approximately 70 degrees.

Results

This section will analyze the results of this project, give time and cost comparisons of the 3D printed mold material used in this project (polylactic acid) vs other mold materials and lastly, analyze the amount of product that would have to be sold in order to make a profit given the mold costs when made from various materials.

Project Results

After perfecting the mold design, and running 100 parts, it was determined that a thermoforming mold can indeed be 3D printed. The testing parameters were that the critical dimensions could not decrease by 10% or the mold would be considered a failure. Critical dimensions are dimensions of the most critical areas of the mold. These dimensions can be found in Appendix 1 Figure 9. It can be noted from looking at the chart that dimension C had the largest reduction in size at 4.45%, dimension D had the smallest reduction in size at 0.27%. The largest dimension shrinkage is less than half of the defined failure percentage. The results of all dimensions are shown in Appendix 1 Figure 10.

Mold Material Cost Comparison

Looking at the results from a cost analysis perspective also validates the use of 3D printed molds. The mold used for this experiment used 312 grams of filament. A 1-kilogram roll costs about $20. This means that the mold created costed only $7.80 to manufacture. Compare this to the price of the amount of aluminum needed to cast this mold ($69.64), and it will be found that this is an 88.80% decrease in cost. When compared to the cost of the amount of aluminum (also known as the billet weight) needed to CNC the mold shape ($219.89), it's a 96.45% decrease in cost. A cheaper alternative to aluminum can also be analyzed in this analysis. Hardwood like mahogany is also commonly used as mold material. The amount of mahogany needed to make this mold would cost $32.99. The 3D printed mold is 51.97% cheaper. This is shown in the chart in Appendix 1 Figure 11.

Mold Manufacturing Time Comparisons

From a time perspective, the opposite is true. It takes more time to manufacture the mold than it would for the alternatives if they were to be made using a CNC machine. The mold used in this project took 43 hours to print. Using computer software, a simulation was made to get the machine times for the aluminum and the mahogany. An aluminum mold would take 2.81 hours to create, and a mahogany mold would take 2.3 hours to make. The caveat to this is that if these molds were to be made in the real world, production would be outsourced to a company. This means that a different company would make the mold and then ship it back to the thermoforming business. The average turnaround time for an aluminum mold is 6 weeks and for a wood mold, it is 4 weeks. On the other hand, there is no additional time needed when 3D printing a mold. The 43 hours to make the mold are all that is needed because it can be done in-house and used immediately. So while it may look like it will take more time to create a 3D printed mold, it will take less as the business owners will not have to worry about the long lead times associated with aluminum or wood molds. This is depicted in the chart in Appendix 1 Figure 12.

Mold Cost Per Part Comparisons

The last point in favor of using 3D printed molds stems from the notion of being able to make profitable parts. It is a known industry trend that the more your mold costs, the more parts you will have to sell in order to make a profit. Using an operations simulation software, it was determined that at $7.80 to make, to make a profit with the 3D printed mold, small business owners would only have to sell 78 parts. Wood molds priced at $205.49 would mean business owners would have to sell 2,055 parts to make a profit. Aluminum molds priced at $631.64 would require even more parts to be sold, 6,316 parts to be exact. This shows that small business owners would make a profit even with small orders of 100 parts (or less) versus traditional molds where thousands of parts would have been sold before a profit is generated. A chart that illustrates this point can be found in Appendix 1 Figure 13.

Conclusion

With 3D printing growing exponentially, it is only a matter of time before business takes full advantage of this technology. And while 3D printed molds have already seeped their way into the thermoforming industry, their full potential has not yet been reached or quantified. That is why this project examined not only the manufacturing/design aspect of 3D printed molds, but also the financial efficiency and its extent in the thermoforming industry. The results of this project show that if a parameter is set that a mold failure is when its size decreases 10%, a 3D printed mold is cost effective for approximately 200 parts. The cost effectiveness of the mold depends heavily on the effectiveness of the design. The design must have things like adequate support in the right places, the proper amount of draft, proper sizing for the amount of vacuum a business' thermoforming machine produces and so on and so forth. Without the necessary attention being paid to these attributes, the mold will fail, and businesses will fail to be able to produce parts.

Recommendations

The first recommendation is that when a business decides to use a 3D mold, it is recommended that they use mold release as they would an aluminum mold. This makes it easier to remove the plastic part from the mold without adding unnecessary and damaging amounts of force on the mold and part. They should be aware, however, that the part will be slippery when the mold release is used. The next recommendation is that businesses who decide to incorporate 3D molds into their business should read the process document that was created by the senior design team responsible for this project. It will have information on topics such as tools & equipment used, safety considerations, and process settings which will ease some of their concerns and be of use to them as they get started.

Acknowledgements

We would like to thank Mr. Jay Shoemaker and Mr. Michael Green from Western Michigan University for their ongoing advice and support for this project. We also want to thank Mr. Michael Konkel and Allin Karhl for their support and access to their tools at Western Michigan University. Finally, we thank Western Michigan University alumnus Ivan Krylov for developing and printing the first prototype and beginning the project back in 2019. Without the support from these people the success of this project could not be close to where it is now.

References

Askeland, D.R. (1996). *The science and engineering of materials.* Boston, MA: Springer.

BigRep. (2021, September 30). *Intro to thermoforming, vacuum forming & Mould making!* BigRep. Retrieved November 5, 2021, from https://bigrep.com/posts/thermoforming-vacuum-forming/.

Difference between amorphous and crystalline polymers (last update November 12, 2016).

[Pediaa website.] Retrieved from https://pediaa.com/difference-between-amorphous-and-crystalline-polymers/

Formlabs. (n.d.). *Guide to 3D printing materials: Types, applications, and properties*. Formlabs. Retrieved November 5, 2021, from https://formlabs.com/blog/3d-printing-materials/.

Intrepidsourcing. (2021, October 4). *The role of 3D printing in Plastic Manufacturing*. Intrepid Sourcing & Services. Retrieved November 5, 2021, from https://intrepidsourcing.com/the-role-of-3d-printing-in-plastic-manufacturing/.

Mahmood, O., Mix, A.W., & Giacomin, A.J. (2010). Sag in thermoforming. *Polymer Engineering &*

Science, Volume 50 (Issue 10), pp. 2060-2068. Retrieved from

https://onlinelibrary.wiley.com/doi/full/10.1002/pen.21734

Nkomo, N.Z., Gwamuri, J., Sibanda, N.R., & Nkiwane, L.C. (2017). A study of applications of 3D printing technology and potential application in the plastic thermoforming industry. IOSR Journal of Engineering, Volume 07 (Issue 08), pp. 16-22. Retrieved from

https://www.researchgate.net/profile/Nkosilathi-Nkomo/publication/319187618_A_Study_of_Applications_of_3D_printing_technology_and_potential_applications_in_the_plastic_thermoforming_industry/links/599a854d0f7e9b3edb190632/A-Study-of-Applications-of-3D-printing-technology-and-potential-applications-in-the-plastic-thermoforming-industry.pdf

Rosen, S.R. (2002). *Thermoforming: Improving process performance.* Dearborn, MI: Society of

Manufacturing Engineers

The advantages and disadvantages of thermoforming (last update 2021). [Pacific Research Laboratories,

Inc. website.] Retrieved from https://www.pacific-research.com/the-advantages-and-disadvantages-of-thermoforming-prl/

The Difference Between Amorphous & Semi-crystalline Polymers (last update August 23, 2017).

[Impact Plastics website.] Retrieved from https://blog.impactplastics.co/blog/the-difference-between-amorphous-semi-crystalline-polymers

Thermoforming (last update August 4, 2021). [Borke Mold Specialists, Inc. website.] Retrieved from

https://borkemold.com/thermoforming-2/

Thin gauge thermoforming (last update 2021). [Owings Patterns website.] Retrieved from

https://owingspatterns.com/thin-gauge-thermoforming/

Throne, J.L. (1996). *Technology of Thermoforming.* Cincinnati, OH: Hanser/ Gardner Publications, Inc.

Appendix

Appendix 1: Results

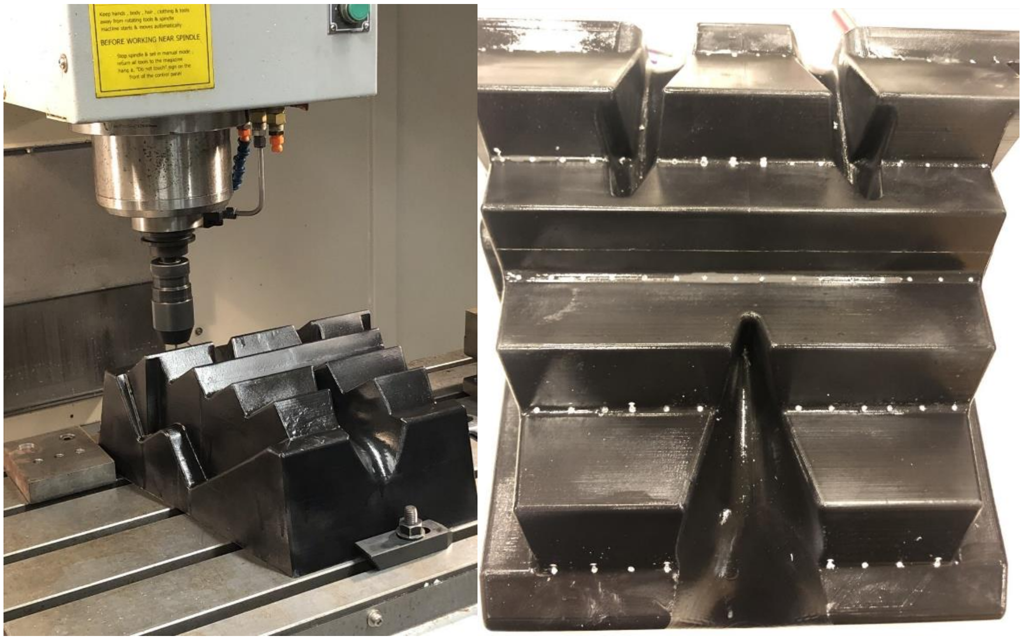


Figure 1: Prototype Mold Mounted in CNC

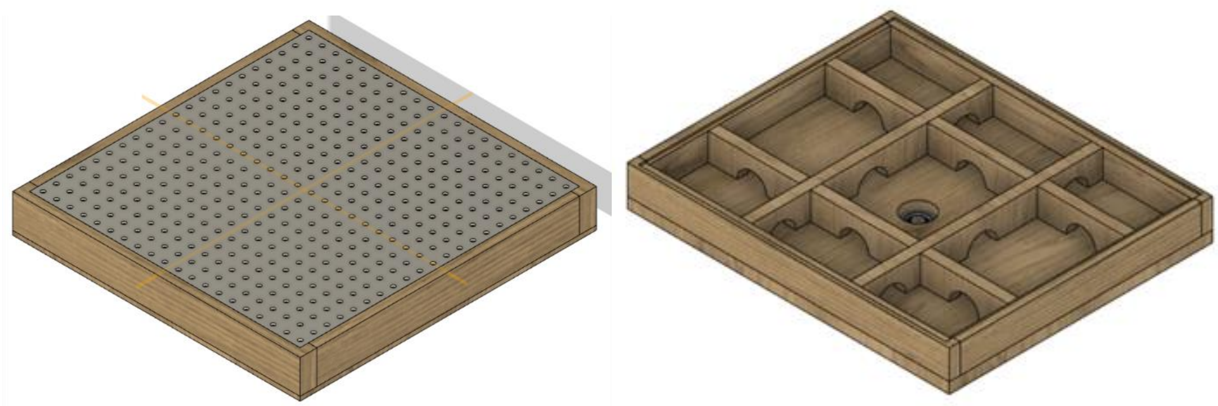


Figure 2: Vacuum Table Fully Assembled (Top) and Inside View of Table (Bottom)

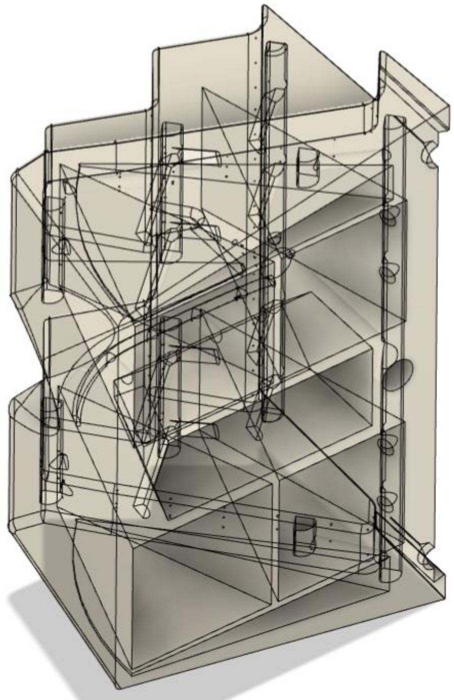


Figure 3: CAD Model for Part 1 Before Model Update

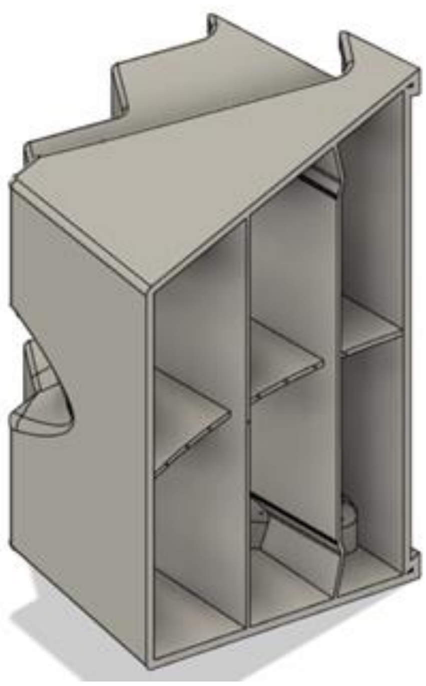


Figure 4: CAD Model for Part 1 After Model Update

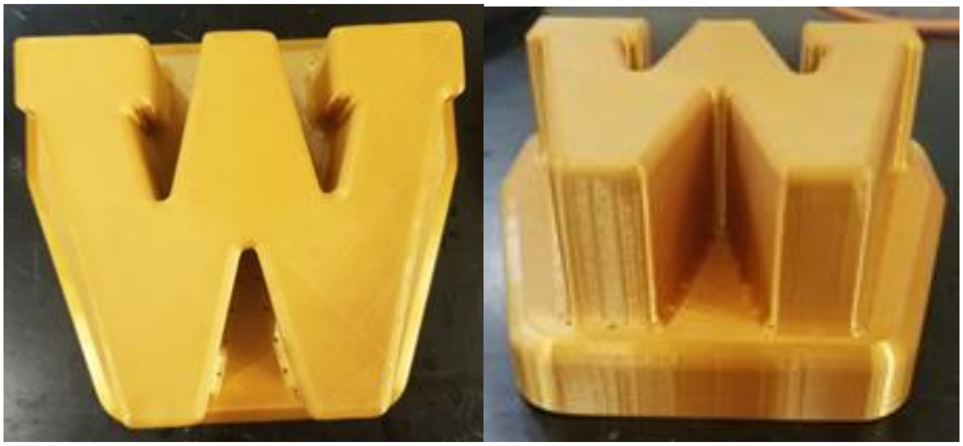


Figure 5: First Complete Mold Redesign – Too Large

Figure 6: Vacuum Pump System Within the Thermoforming System (Left) and By Itself (Right)

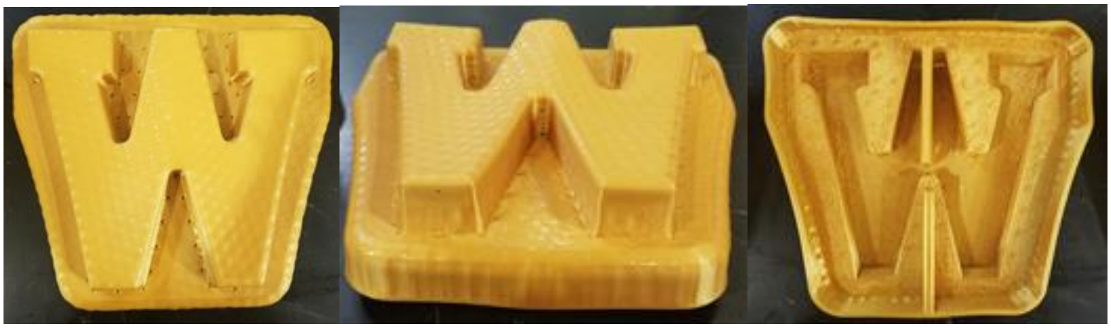
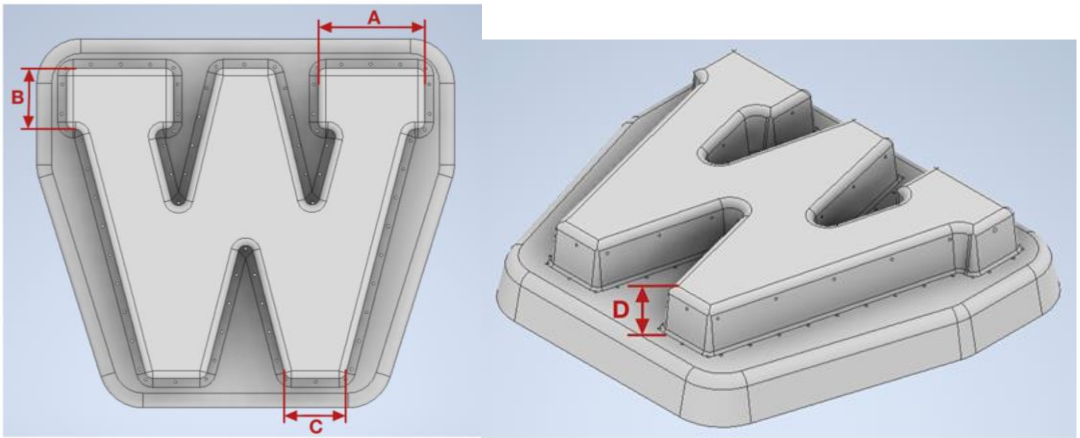


Figure 7: Second Mold Design Remodel with Inadequate Supports

Figure 8: Final Mold Design Remodel with Adequate Supports (the "Support Skeleton")



Critical Dimensions	
Level	Distance (in)
A	1.733
B	0.984
C	0.991
D	0.744

Figure 9: Critical Dimensions of Mold

Part #	Heat %	Time (s)	Cool Time (m)	A (in)	B (in)	C (in)	D(in)
5	80	13	2	1.720	0.955	0.988	0.740
20	80	13	2	1.686	0.951	0.982	0.745
30	80	13	2	1.698	0.939	0.997	0.740
40	80	13	2	1.685	0.953	0.945	0.737
50	80	13	2	1.673	0.935	0.982	0.735
60	80	13	2	1.689	0.938	0.955	0.731
70	80	13	2	1.685	0.933	0.964	0.736
80	80	13	2	1.652	0.935	0.927	0.761
90	80	13	2	1.672	0.921	0.951	0.738
100	80	13	2	1.683	0.901	0.944	0.738
Total Deterioration:				3.95%	3.56%	4.45%	0.27%

Figure 10: Critical Dimension Measurements and Total Deterioration Percentages

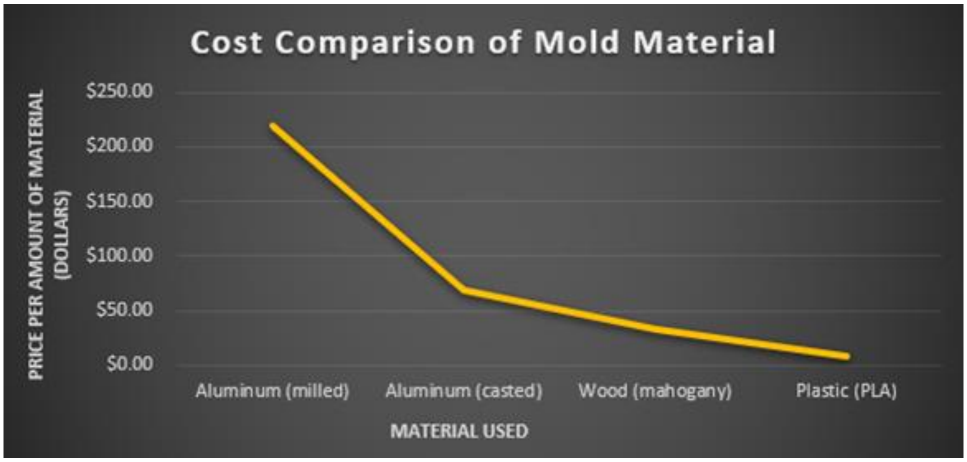
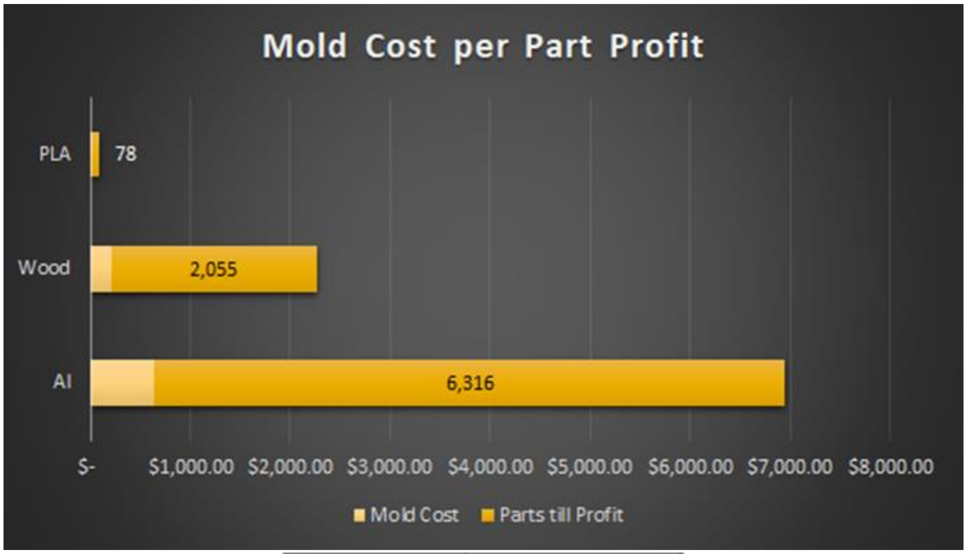


Figure 11: Cost Comparison of Mold Materials

Figure 12: Times to Manufacture a Mold with Various Materials



Material	Mold Cost
PLA	$7.80
Wood	$205.49
Al	$631.64

Figure 13: Mold Costs Per Part Profit