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Investigating Rapid Thermoform Tooling Via Additive Manufacturing (3d Printing)

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Abstract: Additive Manufacturing (AM) has matured from a prototyping tool to a soft production tooling in recent years. This research elaborates the role of AM technology (3D printing) in the design, prototyping and development of a rapid thermoform tooling. The Fused Deposition Modeling (FDM) 3D printer was implemented to fabricate thermoform tooling in Polypropylene Styrofoam (PPSF). We contrast the additively manufactured thermoform tooling with conventional tooling using computerized numerical control (CNC) machines. Findings showed that the additive thermoform tooling with PPSF was found to be (1) faster in development time, (2) comparable in quality and (3) lower in total cost. However, the (4) tool yield was 50% less than traditional tooling and production cycle times were 25-50% longer to allow for the additive tooling to cool. This research explores the fabrication thermoform tooling for low-volume environments using additive manufacturing (3D Printing) technology.

Keywords: 3D Printing, Additive Manufacturing, Rapid Tooling, Thermoform Molding

Introduction

3D Printing, also known as Additive Manufacturing (AM) is the process of creating an object in a layer-by-layer fashion using a computerized program code (McKenzie and Desai, 2018). It has the ability to transform complex three-dimensional objects into prototypes for testing and visualization (Almakaeel *et al*., 2018; McKenzie *et al*., 2017; McKenzie and Desai, 2018). The advent of Computerized Aided Design (CAD) with solid modeling tools, has enabled both designers and novices to develop digital designs (Elhoone *et al*., 2019). With the ability to build complex 3D objects, additive manufacturing provides a way of opening a creative space for individuals to bring their ideas to life (Perkins *et al.*, 2014; Desai *et al.*, 2013; Desai and Gomes, 2014). These otherwise may not be attainable through traditional manufacturing methods (Parupelli and Desai, 2017; Perkins *et al.*, 2014; Aljohani and Desai, 2018).

A form of automated equipment that translates CAD designs to either cut, grind, bore, or stamp tools are achieved through Computer Numerical Control (CNC) machines (Desai *et al*., 2014). CNC equipment comes in a variety of configurations and can be equipped with material handlers to process multiple sheets of material. Several cutting and stamping tools can cut and shape materials ranging from soft polymers to hard metals (Ford and Despeisse, 2016). However, due to the process being subtractive, fragile materials and delicate part geometries are difficult to process using CNC machining. Extensive setup time for programming and tool loading is also another part of CNC machining that can slow down production processes. In addition, CNC processes require extensive setup to program and load tools.

Historically, in order to develop tooling for various types of equipment, CNC milling machines were operated. Generally, injection molding, die-casting, thermoform molds and other sheet-based molding equipment are manufactured using precision CNC machines. These equipment provide the necessary degree of precision to fabricate parts with high tolerances in durable materials such as aluminum or steel tooling. However, the hardness of these materials, combined with precise machining makes the production of tooling slow and expensive. The tooling development times can vary from 3-6 months with costs ranging from a few thousand dollars to hundreds of thousands of dollars for large, complex tools. The cost of these types of tools can be recovered when the number of parts to be produced is high. CNC machines-based tooling may be difficult to justify for low to medium volumes of production due to their high investment costs (Bollinger and Duffie, 1988). In low volume manufacturing where design changes are frequent, the use of CNC machines may be limited.

The goal of implementing additive manufacturing techniques is to develop products that are faster in comparison to standard CNC-based techniques. In this paper, we investigate the use of additive manufacturing technology in rapid tooling for thermoform molding. We implement a case study to demonstrate the concept for molding ABS sheets using a Polypropylene Styrofoam (PPSF) tool.

Fused Deposition Modeling (FDM)

To build polymeric parts layer-by-layer, the FDM additive manufacturing process is an efficient and cost-effective process (Desai *et al*., 2018). In the fused deposition model (FDM) process an extrusion head is heated up to squeeze out filaments of polymeric materials. Each layer of filaments is stacked on top of each other to obtain the final 3D part. The overhanging features for the 3D part, also known as support material is deposited along with the model material at each layer. After the completion of the part, the support material is removed either by pealing or through a post-process wash cycle in a solvent material. In the FDM process, the material is extruded at the size of the nozzle and thus layers may have a "stair-step" effect which can be smoothened out with secondary finishing operations. Several materials in the thermoplastics category which include Acrylonitrile Butadiene Styrene (ABS), Polystyrene (PS), Polycarbonate (PC), Poly-Lactic Acid (PLA), ULTEM and nylon (Sheikh-Ahmad, 2009) can be used with the FDM process. The FDM additive manufacturing process has been widely adopted for prototyping and modeling consumer products. The FDM equipment is typically inexpensive with the consumables available in a wide range of materials. Given its ability to process polymers, it is ideal to produce Room Temperature Vulcanization (RTV) tooling, assembly fixtures and thermoform tooling. We implement the FDM 3D printing process to fabricate tooling for the thermoform molding dies with Polypropylene Styrofoam (PPSF) sheets. The fused deposition method results are similar to assembly fixturing and injection molding because it can be used to produce (RTV) tooling for molding at low volumes.

Tooling

Production tooling is referred in terms of part yield and quality. Tool volumes are associated with tooling materials. Softer materials are appropriate for low volumes (<500), while harder materials are capable of higher volumes (500+). Table 1, shows a generalized classification of the tooling based on the materials and volumes used (Fallböhmer *et al*., 2000).

Table 1: Classification of tooling

Volume	No. of units	Material
Low	0-500	Resins
Medium	500-10,000	Aluminum/low-grade steel
High	100,000 +	Hardened steel

Based on the hardness and size of the tooling material, it affects the lead times for the tooling material. Moreover, specialized materials and larger size tools require longer lead times. The different types of tooling are as follows:

Low-volume – Fiberboard, Hard Wood or Aluminum

In order to test an idea or concept before investing in more durable and expensive high-volume tooling, temporary tooling at low-volumes must be utilized. Typical temporary tools are made of medium or high-density fiberboard (MDF or HDF), hard woods or aluminum. The above materials offer limited heat resistance and compressive strength but are easy to machine at a low cost.

Mid-Volume -- Aluminum or Low-Grade Steel

Not only are mid-volume tools limited and/or modifications are expected to occur, but they are useful where future sales are expected to increase. Aluminum or low-grade steels are up to 70% less expensive than hardened steel and can be machined 2-3x faster than hardened steel because of the relative softness of the metals. Depending upon stress the tool is placed under; part yields may generally fail in-between a range of 1,000 to 10,000 units.

High-volume -- Hardened Steel or Metals

For high production speed and yields, high-volume tools are made from extremely hard metals. Generally, metal tooling or hardened steel is produced with specialized CNC machining or Electrical Discharge Machining (EDM). Tool metals include a variety of carbon and alloy steels designed for hardness, deformation and resistance to abrasion.The tools that typically have higher carbide and alloy contents tend to be the most durable once they are hardened through secondary chemical and heat treatment.

CNC machines allow for CAD designs to be processed with particular tool materials in traditional tool manufacturing. Completing a tool from design towards final manufacturing can take several weeks depending on the material and machining lead times. Typically, the metal tool goes through several stages of machining with additional detail added at each step. Machining of the workpiece into the final tool shape can take several weeks because the cutting tool often leaves a "stair-step" effect on the workpiece, requiring additional steps to the workpiece in order to produce parts with a smooth finish. Finally, after the tool is machined, the tool is fitted with gates, pins, and other hardware to allow the tool to be used for high-speed, repetitive manufacturing operations. The final result is an extremely accurate, durable, has high production speed and is capable of sustaining high temperatures and pressures while in use. The lead-times for high-volume tools can range between 12 to 16 weeks.

Methodology - Rapid Tooling Fabrication

To develop rapid tooling in this research, the Fused Deposition Modeling (FDM) additive manufacturing technique was used. A Stratasys Fortus 400M FDM printer was used with a work envelope of 14w” x 14d” x 16h”. The accuracy of the machine was set to fine detail with a precision of 20 microns. The materials used in the production of tool prototypes were ABS-M30 which is an ABS equivalent with 25 to 70% higher strength than ABS and isapt for functional prototyping. Polypropylene Styrofoam (PPSF) material was used intooling production. PPSF has the highest rating for heat and chemical resistance of FDM materials available, offering the highest material resistance to withstand the high temperatures of the thermoforming process. Figure 1 shows the Stratasys Fortus 400M FDM printer that was used in this research.

Fig. 1: Stratasys Fortus 400M FDM printer

To obtain a desired shape, heat and pressure are used through the thermoforming process to mold a flat sheet of thermoplastic. Within this research, all parts were designed for production as male molds. The sheet material was heated until the plastic sheet was pliable and then lowered onto a male mold with vacuum pressure. The use of a male mold reduced the design complexity of parts and tools, resulting in minimal wastage of materials. As noted above, creating tooling for thermoforming can be time consuming and costly. Typical short-run tools can be made out of wood but require program milling and operation to create wooden tools. Aluminum tools are typically used for large manufacturing runs. Both of these types of tools may require lead times between 12 to 16 weeks and be deemed expensive if tooling needs to be outsourced. For low volume thermoform tooling (100-1000 units) we employ the FDM technology wherein the parts can be accommodated within the build envelope with greater speed and lower cost than standard tooling. One limitation to this method is that tooling is limited to FDM production limits. In the case of the Stratasys Fortus 400M machine, the maximum thermoform part dimensions were limited to 14” w x 14” l x 16”h.

Results and Discussion

Prototypes were created from FDM and CNC machining processes in order to test the performance of the respective thermoform tooling. In order to evaluate the performance of different materials for prototyping, we considered materials that would be available for both processes. The materials available for prototyping with the FDM printer were HDPE, ABS and PP. To compare additive FDM and traditional CNC prototypes, prototypes were produced with both processes using HDPE, PP and ABS material. Teak was chosen as additional material for comparison in our research. Below, Table 2 shows the different characteristics of the candidate tooling materials used in testing and the ways in which they compare.

Using the FDM and CNC processes, prototypes were produced out of these materials. In order to determine the best material, the prototypes were later tested to gain a better understanding of their performance andmaterial manufacturability. Key material criteria included testing for durability, UV resistance, antimicrobial, bonding, forming and cost. ABS was identified as the best material for prototype performance and low cost of production based on the results of the durability, antimicrobial, bonding, forming, low-cost and UV resistance tests.

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After producing and testing prototypes, thermoform tooling was designed using SolidWorks CAD modeling. The SolidWorks CAD modeling software was used to design the thermoform tooling upon the completion of producing and testing prototypes. This was done by importing the model of the prototypes into SolidWorks, by using tooling creation and simulation tools to design and test the thermoform tooling. Assembly of the individual parts is important to make the tool functional in a production environment. Different types of mold designs were tested to ascertain that the tolerances were achieved for mold assembly. These molds types and their respective characteristics are stated below:

1- **Male mold:** These are the simplest of thermoform tools and require 1-5' of draft per side for part release. A pattern tool can be attached directly to the thermoform tooling bed
2- **Female mold:** These molds require less draft as compared to male molds are more accurate
3- **Compression mold:** These mold types require a mating male and female tool to form parts. These types of molds are the highest precision thermoform tools

The different mold designs require increased heat and pressure to thermoform parts and produce more precise parts. The male mold design was chosen for demonstrating the case study. PPSF was chosen as the suitable material based on industry survey and its compatibility with FDM process. It was believed that this would give the PPFS tool the highest chance of success when used in thermoforming. PPSF is a durable AM tooling material and thus provides greater production life and part yield.

Table 2: Characteristics of materials for tooling

Characteristics	HDPE	ABS	PP	Teak
Durability	Excellent	Good	Good	Good
UV Resistant	Good	Good	Good	Stain
Antimicrobial	Good	Good	Good	Natural
Bonding	Poor	Good	Good	Medium
Forming	Medium	Good	Good	Poor
Cost	Medium	Low	Low	Medium

The initial design observed all thermoform design guidelines for traditional thermoform tooling. A 50% scaled-down version of the molding tool was designed in order to evaluate its performance for testing before creating a full-size tool.

The scaled-down PPSF tool, were found to maintain their shape under high temperatures in the thermoform modeling process. The PPFS tool was mounted to the thermoform table with wood screws in the corners of the tool. A sheet of 1/8 ABS plastic was heated to 105°C for 90 sec and then lowered onto the tool surface. Further, vacuum was applied for 30 seconds. The oven was then released and the part cooled for 120 seconds. After cooling, the ABS sheet was removed from the tool for the last trimming. While the plastic sheet was released from the thermoform bed, the polymer sheet did not release easily from the tooling. The stress from pulling the plastic off of the tool was too excessive for the plastic mounting plate to effectively hold the load.

Figure 2 shows the PPFS thermoform tool fabricated using additive manufacturing. Suction holes can be seen provided at suitable locations on the mold geometry to assist drawing the polymer sheet onto the thermoform tool. The perimeter of the tool shows the tool mounting holes.

The PPFS thermoform tools were attached to the machine tool bed using fasteners. Figure 3 shows the lowering of the ABS sheet onto the thermoform tools.

Parts were trimmed from the sheet using an air-powered Roto-zip trimming tool, in order to complete the thermoform tooling operation. All parts were trimmed and filed in less than 120 sec. It is important to note that final parts molded using this tool had a “stair-case” effect finish on the slanted surfaces. The mold was sanded to obtain a smooth finish and erase any minor defects.

Figure 4 shows the final ABS part after the trimming operation. As can be seen, the final parts was manufactured to the specifications and had precise dimensions for assembly and downstream operations.

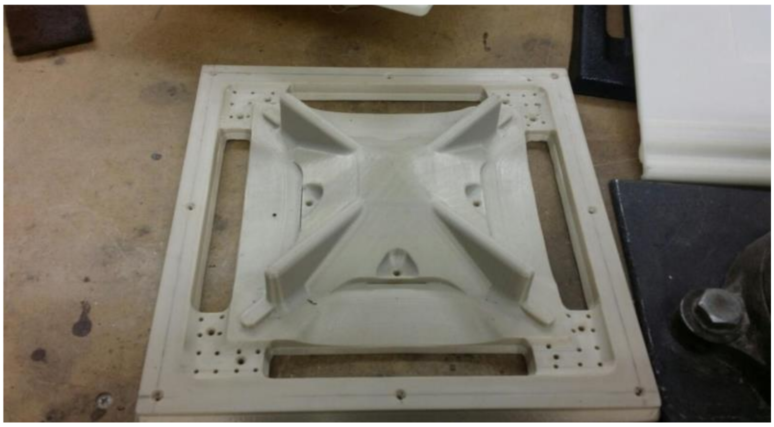

Fig. 2: PPFS thermoform tool with suction holes for vacuum.

Fig. 3: Lowering the heated ABS sheet on the thermoform tools

Fig. 4: Final ABS part after trimming operation

The thermoform tool was improved upon by incorporating the following features after the beginning tests:

- To produce a more durable tool, the tooling was produced on the Stratasys Fortus at full size with solid fill
- Additional vacuum vents and holes were added to improve forming
- The tool design was sanded to allow for smoother release from tooling
- Draft angles were increased from 3% to 5% to help improve release of the polymer sheet from the tool
- To reduce tool stress, mounting holes were added and countersunk

Conclusion

A thermoform tooling was fabricated using additive manufacturing in polypropylene styrofoam (PPSF) material. Parts and tools produced with the Stratasys Fortus 3D printer showed no clear differences using the traditional CNC processes. Once both tools were scanned for dimensional and visual defects it showed less than 1% difference in tools and revealed no difference between the tools. The additive manufacturing-based tooling provided a good alternative to conventional CNC-based tooling based on its low cost and rapid turnover. This work can be extended further to produce thermoform mold housing that allows standard thermoform inserts to be placed into the mold housing. The "stair-case" effect in AM tooling can be minimized by incorporating post-processing operations such as sand-blasting. Our research has demonstrated the use of additive manufacturing for low to medium batch production.

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Author's Contributions

Gene Haeberle: Contributed to the development of prototypes, 3D printing of the soft tooling and testing of the thermoform tooling.

Salil Desai: Designed the overall theme of the research and contributed to the writing of the manuscript.

Ethics

This article is original and contains unpublished material. The corresponding author confirms that all of the other authors have read and approved the manuscript and no ethical issues involved.

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