FUNCTIONAL PROTOTYPING AND TOOLING OF FDM ADDITIVE MANUFACTURED PARTS

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ABSTRACT

In this paper, we present two additive manufacturing applications: (1) vacuum forming tooling using AM; (2) rocket functional prototype using AM for computational fluid dynamics (CFD) and wind-tunnel testing. The first application shows how additive manufacturing (AM) facilitates the manufacture of vacuum formed parts, which allows such parts to be easily produced especially in the manufacturing sector. We show how combining the advantages of the CAD and FDM technology, vacuum forming can be completed quickly, efficiently and cost effectively. The paper shows that using modified build parameters, the tools FDM creates can be inherently porous, which eliminates the time needed for drilling vent holes that are necessary for other vacuum forming tools, while improving part quality with an evenly distributed vacuum draw. Using SolidWorks CAD software, the model of the tool is created. The STL file is exported to the Insight software, and we present how the Tool Paths Custom Group feature is applied to optimize the tool-paths file and then sent to the FDM system that prints the tooling from ABS engineering thermoplastic. The tooling is then used in the Formech 686 manual vacuum forming machine to produce the vacuum formed part.

The second application shows how additive manufacturing (AM) has been applied to producing functional model for wind–tunnel testing, as well as providing computational fluid dynamics (CFD) tool for comparing results obtained from the wind-tunnel testing. The present work is focused on applications of FDM technology for manufacturing wind tunnel test models. The CAD model of a rocket was analyzed for its aerodynamic properties and its functional prototype produced using AM for use in wind–tunnel testing so as to verify and tune the aerodynamic properties. Initial wall conditions were defined for the rocket in terms of the air velocity. The flow simulation was carried out and the goals examined are the velocity and pressure fields around the rocket model. The paper examines some practical issues that arise between how the model...
geometry for CDF process differs from that that of the FDM process.

Consequently, we show that AM-based fused deposition modeling (FDM) technology is faster, less expensive and more efficient than traditional manufacturing processes for vacuum forming and for rapid prototyping of function models for wind-tunnel applications.

INTRODUCTION
A new manufacturing paradigm, known as additive manufacturing (AM) has emerged which involves a number of steps that moves seamlessly from the virtual CAD description to the physical resultant part. Together, these new manufacturing technologies, driven by CAD, such as additive manufacturing (AM), rapid tooling (RT), and reverse engineering (RE), constitute what is known as additive manufacturing technologies (AMTs) which are making it possible for companies to significantly cut design and manufacturing cycle times. Since speed to market is an essential element of competitiveness, AMTs are gaining grounds in areas where even the most sophisticated advanced manufacturing method of computer numerical control (CNC) is not feasible in realizing complex real-life products.

Rapid tooling is being used in more and more manufacturing processes. Recent studies include the evaluation of its use in injection moulding [1, 2, 3, 4], vacuum casting [5, 6, 1], sand casting [7], die casting [8], electrical discharge machining [1, 9], investment casting [9] and many others. In [10] the suitability of three-dimensional printing (3DP) for making tooling for the vacuum-assisted resin transfer molding (VARTM) process is considered. This combination has potential advantages, since VARTM has significant prototyping benefits if it can be combined with a fast and low cost tooling option. The paper presents a new process chain for the manufacture of closed mould composite parts using the VARTM process. Authors of [11] show how the vacuum forming process can facilitate the development of automotive vehicles, as well as a simple and fast way to manufacture vacuum formed parts, which allows parts to be obtained by any kind of industry. Some guidelines to consider when choosing vacuum forming for manufacturing are given in [12]. Normally, the first consideration is what type of thermoforming material that will be required in manufacturing. Guidelines on the consideration to decide on the type of printing system to use are given in [13]. Stratasys has given steps to applying FDM technology for vacuum forming tooling [14].

Wind–tunnel testing is an integral part of the design process in many industries, typically used to verify and tune the aerodynamic properties of solid objects [15]. The work described in [16] demonstrates that additive manufacturing technologies (AMT) can be effectively applied for fabricating test models used in aerodynamic experimental investigations. The authors focused on applications of polyjet technology for manufacturing wind tunnel test models. The stereolithography (SL) process was experimented [17] to manufacturing a NACA 0012 airfoil section, which resulted in a surface finish with a noticeable distributed roughness as well as low chord-wise ridges due to resin over cure at the build layer interfaces. A UAV wing is fabricated using Duraform Flex material in an SLS machine and post-processed to remove un-sintered powder [18].

Additive manufacturing has rapidly gained acceptance as an alternative process for constructing durable, accurate wind–tunnel test models. Compared with machining and model making, AM with FDM Technology is faster, less expensive and more efficient. Additionally, AM can preserve small, inaccessible features that are difficult to make at scale with traditional methods. For example, internal passages are easy to produce, whereas these features would complicate the CNC milling process. FDM was specifically used in this work since thermoplastic sheet was used for the vacuum forming operation. FDM is a best fit for wind–tunnel testing when:

- Designs are complex or intricate
- Challenging characteristics include internal cavities, organic shapes or fine feature detail
- Design changes are likely
- Designs are large or bulky

Benefits of FDM models for wind–tunnel testing include:

1. Time and cost savings
2. Ease of creating internal passages for smoke or ink dissipation

Stratasys has given steps to applying FDM technology for wind-tunnel testing [15].

In the remainder of this paper, we describe the steps taken to produce a vacuum forming tool and a rocket using additive manufacturing at the Center for Advanced Manufacturing and Design Technologies (CAMDT), Sheridan Institute of Technology & Advanced Learning for the purpose of demonstrating the usefulness, efficiency, and effectiveness of AM technologies in manufacturing processes as well as in wind-tunnel testing process.

VACUUM FORMING TOOLING USING FDM
Vacuum forming involves heating a sheet of thermoplastic to forming temperature, drawing the sheet onto a tool (or mold) by applying vacuum pressure between the tool surface and the sheet, and finally, removing the model through reverse air pressure when the plastic has sufficiently cooled [12]. This process is relatively inexpensive when compared to other plastic molding and forming methods. Common applications include...
packaging, internal automotive components—such as interior panels and instrument panels—point-of-purchase displays, blister packs and orthopedics.

For many years, vacuum forming was cumbersome due to the time and effort it took to create the tooling onto which the thermoplastic sheets are molded. Up until the mid-1980s, designers used primarily craftsmen to hand-build tooling. The tooling was fashioned out of wood or other materials sufficient to withstand the heat and pressure of the vacuum process. After the model was formed, multiple holes had to be drilled through the tool to allow for the vacuum pressure required during the forming stage. In the end, handcrafting molds proved to be very time consuming and not well suited for situations where multiple design iterations are needed to produce the desired tool.

The relatively recent advent of fused deposition modeling (FDM) technology to manufacture the thermoforming tooling has made vacuum forming a more efficient and increasingly cost-effective process. The low pressure and temperature of the forming operation facilitates the use of tooling constructed from many materials. For large production runs, vacuum forming tools are machined from aluminum. Although the life of tools constructed with ABS, polycarbonate (PC) or polyphenolsulfone (PPSF) will not equal that of an aluminum tool, these three materials are ideal for prototyping and short-run manufacturing.

**Advantages of FDM for Vacuum Forming Tools**

1. FDM eliminates much of the time and labor associated with machining of vacuum forming tools.
2. The tools FDM creates are inherently porous, which eliminates the time needed for drilling vent holes that are necessary for other vacuum forming tools, while improving part quality with an evenly distributed vacuum draw.
3. Using modified build parameters, FDM tools offer excellent feature detail and fast vacuum cycles while eliminating the labor and time for drilling vents.

**Vacuum Forming: A Few Considerations**

Some guidelines to consider when choosing vacuum forming for manufacturing are [12]:

1. The process does not support variable wall thicknesses, and a part’s geometry must allow a straight pull (no undercuts or side action).
2. The side of the sheet of plastic that touches the tool will be the more defined side of the final model or final product.
3. The means available to construct the tooling.

**Choosing the FDM Technology for Vacuum Forming Tooling**

The first consideration is what type of thermoforming material that will be required in manufacturing. Then, the next consideration is the type of printing system to use [13]:

1. Vacuum forming using high-temp sheet materials—such as polypropylene or polyethylene are required—then one should consider a high-end FDM system that can build tooling in multiple high temp materials such polyphenolsulfone.
2. Vacuum forming using lower temperature materials—such as PVC or styrene thermoplastic sheets—a 3-D printing system is likely the best option to choose.

Stratasys has given steps to applying FDM technology for vacuum forming tooling [14].

**Methodology for AM Process Application to Vacuum Forming Tooling**

In this section, we describe the steps taken to produce vacuum forming tooling using additive manufacturing at the Centre for Advanced Manufacturing and Design Technologies (CAMDT), Sheridan Institute of Technology & Advanced Learning and the.

**CAD model of the component**

The vacuum tool was designed using SolidWorks software. The model is a simple one but the principle applies to complex shapes (see Figure 1).

![SolidWorks model of tool](image_url)

**Slice the STL File**

Using the Insight software the tool-paths for building the AM model for different build process parameters were generated. For the vacuum tooling model, 0° orientation was chosen (Figure 2).
Figure 2 Insight STL model of tool

**Tool Paths Custom Groups**

Tool Paths Custom Group tool is used to control the tool path parameters for different zones of our product. In the vacuum forming part, we define five zones using four groups. The following custom groups were created, leading to optimal solution (see Table 1 and Figure 3 for clarity):

Zone 1: is the **crest**, with magenta colour; the air gap (space between adjacent width of material deposited during 3D printing) is medium (0.0100), stopping few layers before the large flat surface.

Zone 2: is the **large flat surface**, with cyan colour; the air gap is tight (0.0050), 1 or 2 layers on each side of the large flat surface.

Zone 3: is the **upper base**, with light red colour; the air gap is coarse (0.0200), stopping few layers before the valley flat surface.

Zone 4: is the **valley flat surface**, with cyan colour; the air gap is tight (0.0050), 1 or 2 layers on each side of the valley flat surface.

Zone 5: is the **lower base**, with light red colour; the air gap is coarse (0.0200), stopping on top of the base support.

Zone 6: is the **air outlet**, with light green colour; the air gap is slightly above the large flat surface and valley flat surface; there is no contour in this zone to allow air to exit from the tool when vacuum is formed, thereby assisting in suction effect. Generally, critical areas have tight air gap.

<table>
<thead>
<tr>
<th>Grp.</th>
<th>Colour</th>
<th>Contour size</th>
<th># contours</th>
<th>Raster width</th>
<th>Raster angle</th>
<th>Air gap</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Magenta</td>
<td>0.0120</td>
<td>2</td>
<td>0.0120</td>
<td>45</td>
<td>0.0100</td>
<td>Crest</td>
</tr>
<tr>
<td>2</td>
<td>Cyan</td>
<td>0.0120</td>
<td>2</td>
<td>0.0120</td>
<td>45</td>
<td>0.0050</td>
<td>Surface</td>
</tr>
<tr>
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<td>Light red</td>
<td>0.0120</td>
<td>2</td>
<td>0.0120</td>
<td>45</td>
<td>0.0200</td>
<td>Base</td>
</tr>
<tr>
<td>4</td>
<td>Light green</td>
<td>NA</td>
<td>NA</td>
<td>0.0120</td>
<td>45</td>
<td>0.0100</td>
<td>Outlet</td>
</tr>
</tbody>
</table>

**Layer by Layer Building of Model**

Using the model STL file and processed data for the tool paths, Figure 4 shows the Vacuum forming tooling produced using FORTUS 400mc machine.

**The Vacuum Thermal Forming Operation**

The steps for vacuum thermal forming operation using AM are as follows [14]:

1. Prepare the 3D–printed tool: Print the thermoforming tool directly from the CAD file on an FDM system.
2. Place and heat the plastic sheet in the vacuum forming machine: Clamp the extruded plastic sheet stock in its frame above the tool. Apply heat until it is malleable.
3. Prestretch: Introducing air between the tool and plastic sheet improves the consistency of wall thickness across the part. Raise the tool to meet the plastic sheet.
4. Form the part: Pull a vacuum through the tool to draw the plastic sheet tightly to the tool’s surface.

In our work, we used Formech 686 manual vacuum forming machine (see Figure 5) and 27x26” (686 x 660 mm) thermoforming acrylic sheet together with the tool that we produced (see Figure 4), to produce the final product (see Figure 6). The part produced was checked and found to match the tool (Table 2 shows the dimensional checks, showing slight variations between the 3D model and the AM part produced).
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Figure 5 Formech 686 manual vacuum forming machine used at CAMDT, Sheridan

Figure 6 Part produced using the AM mould and Formech 686 vacuum forming machine

Table 2 Checked dimensions between 3D-model and AM part

<table>
<thead>
<tr>
<th>Description</th>
<th>3D Model (inch)</th>
<th>AM (printed) part (inch)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bottom length</td>
<td>4.09</td>
<td>4.125</td>
</tr>
<tr>
<td>Bottom width</td>
<td>2.25</td>
<td>2.09</td>
</tr>
<tr>
<td>Top-length</td>
<td>3.82</td>
<td>3.938</td>
</tr>
<tr>
<td>Top-width</td>
<td>1.82</td>
<td>1.938</td>
</tr>
<tr>
<td>Boss top-length</td>
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</tr>
<tr>
<td>Boss top-width</td>
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<td>0.625</td>
</tr>
<tr>
<td>Boss bottom-length</td>
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<td>1.25</td>
</tr>
<tr>
<td>Boss bottom-width</td>
<td>0.78</td>
<td>0.75</td>
</tr>
<tr>
<td>Boss height</td>
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<td>0.25</td>
</tr>
</tbody>
</table>

WIND TUNNEL TESTING WITH FDM PARTS

Wind–tunnel testing is an integral part of the design process in many industries, typically used to verify and tune the aerodynamic properties of solid objects [15]. Whether an object is stationary or mobile, wind tunnels provide insight into the effects of air as it moves over or around the test model. To make models for wind–tunnel testing, automotive, aerospace and architectural firms have relied on traditional manufacturing processes including milling, turning and fabrication. Typical materials are metal, plastic and composites. These operations require programming, setup and operator supervision, which adds to lead time and cost. Both the AM model simulation and wind tunnel tests are used in the early stage of product development to realize a prototype and test whether to proceed with the final functional manufacturing of the part, thereby saving time and costs.

Methodology for AM Process Application to Wind-Tunnel Model Testing

In this section, we describe the steps taken to produce a rocket using additive manufacturing at the Centre for Advanced Manufacturing and Design Technologies (CAMDT), Sheridan Institute of Technology & Advanced Learning and the CFD analysis carried out on the model.

CAD model of the component

First of all, the rocket was designed using SolidWorks software. There are four main components of the rocket model: body tube; nose cone; engine lock ring; and fin. The sketch of the fin is shown in Figure 7. An initial fin thickness of .0275” (0.7 mm) was assigned for extrusion.

The SolidWorks model consisting of the rocket model consisting of major components is shown in Figure 8. The CAD file was converted into STL (.stl) format for the AM process.

Slice the STL File

Using the Insight software the tool-paths for building the AM model at different build process parameters were generated. For
the rocket model, $90^\circ$ orientation was chosen (the $90^\circ$ orientation is shown in Figure 9; with layers built in the vertical direction).

Layer by Layer Building of Model

The fin was the most delicate component to produce since it is classified as a thin element. While the CFD is feasible for thickness of .0275" (0.7 mm), this was found to be infeasible for the tool tip chosen for AM. For the T20 tool tip chosen, the minimum contour width is .0180" and the minimum raster width is .0180". The minimum thickness of the fin should be $(2*.0180" + .0180") = .0540"$. In our design, we eventually decided to use a minimum of .0800" fin thickness and adjusted the fin extrusion to this value; even with this thickness, we had to step down to use T16 tool tip with the minimum raster width of the fin being $(2*.0160" + .0160") = .0480"$ and slice height of .0100". The rocket model was built using the processed STL file (see Figure 9).

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Computation Fluid Dynamics (CFD) of the Rocket Model

The SolidWorks CAD model of the rocket (Figure 8) was analysed for its aerodynamic properties using CFD tools. It should be noted that special expertise is required to do any meaningful CFD analysis of the AM prototype of Figure 9 due to the anisotropic material properties nature of the internal structures of AM parts (meshing requires homogenous internal/external structure, but AM parts are not homogenous); this is outside the scope of the work described in this paper. Initial wall conditions were defined for the rocket in terms of the air velocity. The flow simulation was carried out and the goals examined are the velocity and pressure fields around the rocket model (see Figures 10 and 11).

Figure 9 Additive manufactured rocket functional prototype

Wind tunnel for testing additive manufactured rocket functional prototypes

The purpose of the simulation and the wind tunnel test is compare how useful simulation results are during product design before the functional part is manufactured. An initial wind tunnel test for the rocket model was carried out using the existing equipment in the Mechanical Engineering laboratory at Sheridan (see Figure 12). Air suction takes place to left with air velocity being maximum (15.9 m/s at no load) at the extreme left exit. The air speed at the rocket nose was measured to be 5.7 m/s while at the rocket fin it was measured to be 8.3 m/s. In other words, air flow of 10 m/s at the rocket nose, results in air flow of 14.6 m/s at the rock fin. These values did not correlate well with simulation, due to improper calibration of the wind tunnel. This shows that proper calibration has to be done (part of further work to be done). The next phase of our research work is to carry out a wind tunnel calibration exercise and do more tests on the additive manufactured rocket functional prototypes. It is also envisaged that several prototypes in terms of sizes will be required to acquire intelligence in order to verify and tune the aerodynamic properties of the rocket model being studied.
CONCLUSION

The work reported in this paper has demonstrated that additive manufacturing will become a central hub in interdisciplinary areas of engineering. This paper has only focused on application of AM to two areas of vacuum forming tooling showing how the entire vacuum forming cycle can be achieved in a timely manner with reasonable precision, as well as how this relatively new technology can be applied to functional prototype in wind-tunnel testing of models in a cost-effect, and efficient way. In both applications, we noticed significant reduction in time. Consequently, we show that AM-based fused deposition modeling (FDM) technology is faster, less expensive and more efficient than traditional manufacturing processes for vacuum forming, and also for rapid prototyping of function models for wind-tunnel applications. The scope for further investigations is great especially in considering other tooling for manufacturing processes, as well as other areas of study in engineering. It is envisaged that AM activities at CAMDT, Sheridan will bring different disciplines together in collaborative research in future. As already mentioned, the next phase of our research work is to carry out a wind tunnel calibration exercise.

REFERENCES