Detailed overview for using Fused Deposition Modeling tooling for heavy-gauge thermoforming.

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1. OVERVIEW

1.1. FDM patterns provide custom tools directly from CAD models.

1.2. Using Insight, interior fills can be processed with varying levels of porosity allowing for vacuum to be pulled throughout the tool without the need for drilling vacuum-assist holes.

1.3. CAD data and FDM provide coordinated tooling solutions for thermoforming by coordinating the parent geometry to output forming tools, scribe or offset trim tools, and vacuum-holding jigs.

2. CAD CONSIDERATIONS

2.1. Most types of forming plastics will contain some level of shrink during the thermoforming process. It is recommended that shrink compensation be applied during tool design. If the native CAD file is not available, the STL file can be scaled to provide the required compensation.

2.1.1. Mold shrinkage for male molds is 0.4%-0.6% and female molds, 0.5%-0.7%

2.2. Drafting side walls is recommended to assist in tool extraction. Minimum draft of 1-3 degrees should be designed into the tool. Additional draft angles of 5-7 degrees will greatly assist tool extraction, along with the added benefit of minimizing the likelihood of webbing.

2.3. Minimum radius for tool design is generally equal to the nominal thickness (i.e. 0.71mm [0.028” in.]) thickness.


2.5. CAD output files will be in the STL file format.

For a simple model, such as the box shown in Figure 1, its surfaces can be approximated with twelve triangles, two on each side, as shown in Figure 2. The more complex the surface, the more triangles produced, as shown in Figure 3.

2.5.1. STL files should be exported as binary.

2.5.2. If your part was rougher or smoother than you had hoped, you can change the angle, deviation and chord height to create the right outcome. Faceting is determined by the relative coarseness of curved areas of the adjoining triangles. The most common variables are deviation or chord height, and angle control or angle tolerance. Coarse faceting is almost always caused by the angle setting being too high, or the deviation/chord height settings being too large, or a combination of both.
2.6. Several benefits to both build time and material cost savings can be incorporated into the CAD design of the tool. Insight preprocessing software provides for automatic support generation. This calculation scans the geometry and automatically generates support structures needed to build geometry such as cavities and overhanging structures. Traditional tools used for thermoforming are typically built out of solid materials. This is not required when building with FDM and can be optimized through a couple of different processing styles. One way to optimize the tool is to design in ribbing. This topic will be explained further in the next section. Another method is to build the tool using the Insight™ sparse-fill build style. This technique is explained in Section 4.

3. TOOL DESIGN OPTIMIZATION AND CONSIDERATIONS

3.1. Tool Optimization Using Ribbing:
If your CAD program allows for Finite Element Analysis (FEA) of the tooling design, this is the best way to calculate potential tool deflection under forming loads. Using the conversion from –inHg to PSI, most thermoforming machines are only able to achieve -25 - -28inHg. This would equate to 15 PSI that could be used to calculate the pressure load on the surfaces of the tool in the analysis tool. Other considerations that could influence tool design are the life expectancy of the tool and whether the tool will be fixtured in the framing system of the thermoforming machine or free floating on the bottom foundation plate. For tools that will be fixtured to the forming machine, it is recommended to use a minimum of 0.25-in. ribs and walls. Rib spacing is a complex parameter that is geometry dependent and the use of FEA tools is recommended to optimize spacing requirements. For a conservative structure, rib structures should be placed on a 1-in. centerline spacing. As a general rule, spacing can be increased as tool height and surface area is reduced.

3.2. Tool Fixturing
If the tool will be fixtured into the framing system of the thermoforming machine, hardware inserts or hard points for drilling and tapping locations should be accounted for in the CAD design of the tool. The FDM process can be paused during the build to allow for the insertion of nuts or other fastening hardware. (Higher temperature FDM materials such as PC, ULTEM 9085 and PPSF tend to show a witness line of a shrink point at the insertion point on the part due to temperature fluctuation of the build envelope during insertion. Insertion should not be practiced if high tool accuracy is required. Tools built with PPSF should not incorporate insertion, as there is high potential of the foundation sheet to loose vacuum during insertion due to temperature change.)

4. INSIGHT PROCESSING

4.1. The primary benefit of using FDM tools is the ability for the tool to be processed and built with porosity throughout the entire tool. Traditional tools require drilling vacuum-assist holes throughout the tool to allow for vacuum transfer through the tool. With FDM, this
is automated with the Insight software and the processing style of building with positive air gaps in the raster fills throughout the build. This enables channels throughout the entire tool for the vacuum to be drawn through. If an FEA tool is not used in the design of the tool to calculate surface loads, the best recommendation to ensure tool integrity would be to process the tool in Insight using the Part interior style of Solid-normal under Modeler Setup and then add the internal porosity through one of two methods:

4.1.1. In the Toolpaths main menu, choose Setup. Once in the Toolpath Setup menu, click on the advanced parameters button. Once in this menu, locate the Internal raster airgap parameter and set it to +0.010 in. (+0.254 mm). This is a key parameter that allows for vacuum to be pulled throughout the tool.

4.1.2. A second way to build porosity into the tool build is through custom groups. Under the Toolpath menu, click the New button. This will open the Create New Group window. Under “Air gap between,” enter +0.010 in. (+0.254 mm) in the Adjacent rasters box.

Next, select all curves on the model so that they become highlighted on the screen, then click the Add button under the Custom groups menu. Additional information on this feature can be found by searching “custom groups” in the Help Menu.

4.2. System Mode Selections With ULTEM Material

Tools should be built using the Normal system mode. This allows for increased oven temperature to prevent part curling from the base.

4.3. When processing tools with PPSF material, it is highly recommended to use the “Auto Cool Down” mode on the FDM machine to prevent temperature shock to the tool during removal, which could result in fracturing.

5. POST PROCESSING THE FDM TOOL

Generally the only post processing needed on FDM tools is a light sanding. All tools used for test in this application were sanded with 120-grit aluminum oxide sand paper using a 5.5-in. dual-action sander. The main concentration of the sanding was blending the area of the seam to match adjacent surfaces.

5.1. Fillers

Fillers are not recommended, as this blocks the FDM tool’s natural porosity.
6. RELEASE SPRAYS

Two types of spray release were used during testing:

6.1. The first release tested was Sprayon S00206 all-purpose silicone lubricant. This worked with acceptable results on all FDM materials tested. A light coat was sprayed on the tool on every other pull.

6.2. The second release tested was Sprayon S00708, which is formulated with P.T.F.E. and was found to release better than the silicone formula on all FDM materials tested. A light coat was sprayed on the tool on every other pull.

6.3. Other untested considerations are

6.3.1. Zyvax

6.3.2. Miller Stephenson

7. TESTING

All testing and thermoforming design expertise was in partnership with Kintz Plastics Inc., Howes Cave, New York (www.kintz.com).

7.1. All test pulls were processed with Kydex T in 0.250 in. (6.35 mm) sheet stock. Kydex T is a fire-retardant thermoplastic sheet for general thermoforming, commonly used in aerospace applications. Drying is generally not required except in high humidity. If the material must be dried, it should be dried at 68 C (155 F), or about 15 C below the product’s HDT for 16 hours for 3.20 mm (0.125 in.) thickness. Two-sided (sandwich) heaters are recommended above 2.00 mm (0.080 in.) nominal thickness. Additional Kydex material information can be found at: www.kydex.com/technical-data/technical-briefs.aspx.

7.2. All test pulls were processed on a Monark SPF Series thermoformer with LP heating. The Monark system uses both top and bottom heaters that allow for more uniform heating of the plastic sheet.

7.3. As shown in Figure 4, our test tools were invert mounted on the top frame of the machine to allow for the natural draping of the heated plastic to compliment the deep draw. This helps to minimize chill spots on the pulls by minimizing the time of contact between the sheet and tool, prior to vacuum being pulled. The FDM tool was bolted to a plywood base consisting of 5 layers of 0.75-in. plywood that was glued and screwed together to coordinate with the thermoforming framework. Tooling is shown in Figure 5. This configuration enabled the tool to be extracted from the sheet form using the pneumatic lift of the machine, once the plastic had adequately cooled. This configuration duplicated a production setup, which allowed for repeated processing of the tool.
8. FDM TOOLING MATERIALS

<table>
<thead>
<tr>
<th>Material</th>
<th># of Pulls Tested</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABS M30</td>
<td>1 – Failure.</td>
<td>Sheet bonded to ABSM30 tool.</td>
</tr>
<tr>
<td>PCABS</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>PC</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Ultem 9085</td>
<td>12</td>
<td>A series of 7 successive pulls were performed on the tool successfully. (First 5 pulls were used to set up the production program. All pulls were successful with slight webbing in the finished forms.)</td>
</tr>
<tr>
<td>PPSF</td>
<td>3</td>
<td>On third pull, hardware inserts were pulled out of the tool during tool extraction.*</td>
</tr>
</tbody>
</table>

*There was minimal adhesion between the sheet material and tool, therefore the tool material is not believed to have failed with regards to temperature. A combination of tool design for the insert locations and/or a problem of repeated thermo cycling of the PPSF material resulting in decreasing material properties, are presumed to be causes for the tool failure. PPSF material is a compatible material for thermoforming due to its high temperature capabilities. It is not recommended for use with mechanical extraction machines. Instead, practice manual tool extraction.

9. PROCESSING TIMES AND TEMPERATURES

Below is program of times and temperatures used on the Monark SPF thermoforming machine. The same times and temperatures were used for all FDM tooling materials.

9.1. Heating the Sheet

9.1.1. The Kydex sheets were heated in the oven for 230 seconds. The temperature when removed from the oven and just prior to draping over the tool and pulling vacuum was 180°C +/- 5. Vacuum was then applied gradually to lessen the chance for webbing in the corners of the tool. It was recommended for geometry that incorporates deep draws, to utilize an additional “web killer” fixture. This is a secondary frame tool that is offset from the largest footprint of the tool. The tool aid is then used to pre-stretch the hot plastic down to the tool base prior to pulling vacuum.

9.2. Cooling the Sheet After Applying Vacuum

9.2.1. After 20-30 seconds of pulling vacuum, cooling fans were turned on to help cool the sheet faster.

9.2.2. A total of 300 seconds were used in the cool down program before releasing vacuum on the tool.
9.3. Tool Extraction

9.3.1. To assist with the automated tool extraction, air pressure between 20 and 30 PSI was applied to the tool before any movement of the table. Use caution when applying pressure to the tools to prevent possible rupture of the tool and form. Pressure should be applied gradually. Typically, a slight expansion of the walls of the form will appear during pressurization. This process allows air to separate the area between the sheet and tool. After two or three air bursts were applied, the table was slowly raised, allowing for the tool to be extracted from the sheet form.

10. SUCCESSIVE PROCESSING OF THE ULTEM 9085 TOOL

10.1. A series of seven successive pulls were performed using the program described in section nine. The ULTEM 9085 tool was not cooled with any additional time or other cooling methods between pulls. The goal was to duplicate a short-run production scenario using a single-station thermoforming machine. The temperature of the tool was recorded prior to draping the hot sheet plastic and drawing vacuum, then again after tool extraction for each pull. Figure 6 shows the recorded temperatures.

11. TESTING SUMMARY

All FDM materials, with the exception of ABS M30, were able to successfully pull and extract the tool for at least one thermoformed part. Figure 7 shows parts after trimming. All parts did exhibit some level of webbing in the corners of the formed parts. The press operator was confident that the webbing could be eliminated with the addition of a “web killer” fixture. It is recommended that PC and PCABS material be used for lower temperature materials and single-quantity formings.

PPSF material showed good results regarding temperature compatibility, but exhibited tool failure during extraction on the third forming. Several factors or a combination of factors could be influencing the failure. Tool design with regard to the solid wall thickness before the hardware inserts are placed could be lengthened to allow for added material strength. Additionally, material strength may have reduced due to temperature cycling during the forming process. Additional testing is needed to better understand this phenomenon.

ULTEM 9085 material performed the best during our testing. A total of 12 pulls were formed. All mechanical tool extraction by the forming machine was successful with no observed damage to the tool. Five pulls were initially processed on the tool, before swapping the tool out to test other FDM materials. The tool was then refixedtured in the machine and an additional seven pulls processed without any additional cooling time between pulls. This was done to test the ability for the tool to perform in a traditional production environment and test cycle time of the tool and process. This resulted in as good or better processing times as traditional tooling materials. No additional cooling devices, such as water channels or coolers, were used with any FDM tools. The capability to process the FDM tools with internal

<table>
<thead>
<tr>
<th>Pull</th>
<th>Pre-Pull Tool Temperature</th>
<th>Post-Pull Tool Temperature</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>51°C</td>
<td>60°C</td>
</tr>
<tr>
<td>2</td>
<td>55°C</td>
<td>66°C</td>
</tr>
<tr>
<td>3</td>
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<td>67°C</td>
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<td>4</td>
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<tr>
<td>6</td>
<td>57°C</td>
<td>75°C</td>
</tr>
<tr>
<td>7</td>
<td>57°C</td>
<td>73°C</td>
</tr>
</tbody>
</table>

Figure 6: Pre- and post-pull tool temperatures

Figure 7: Thermoformed parts after trimming
porosity is believed to enable the tool to not absorb the heat transfer during the forming process as fast as traditional materials, which also results in the tool being able to cool faster with only air cooling by fans.

If hardware or fasteners are to be integrated into the tool build via pause commands entered during Insight preprocessing, it is highly advised to design 3-4 times the wall thickness of solid material wall before hardware embedment. Again, it is important to reiterate that inserting of hardware or fasteners in PPSF tools is not recommended. It may result in build failure due to loss of the build foundation's vacuum from envelope cooling when the door is opened.

It is important to note that this testing was performed with one geometry and one production-style forming machine. Results may vary depending on the geometry, equipment, material type, and forming environments.

Thermoforming tool design and testing was performed in partnership with Kintz Plastics.