APPLICATION GUIDE:

Thermoforming

TIME REQUIRED ■□□ COST ■□□ SKILL LEVEL ■■□

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OVERVIEW

Thermoforming is a relatively simple manufacturing process that is inexpensive when compared to other plastic molding and forming methods. Although thermoforming is often associated with manufacturing of packaging items such as blister packs and disposable coffee cup lids, the cost and time advantages are realized in a broad spectrum of products in an equally broad range of industries. When using a Fortus 3D Production System with FDM technology to construct thermoforming tooling, the process becomes simpler, more efficient and increasingly cost-effective.

PROCESS DESCRIPTION

Thermoforming is a collection of manufacturing methods that heat and form sheets of extruded plastic. Thermoforming processes include drape, vacuum and pressure forming.

Drape forming relies on gravity to pull the sheet against the tool. Vacuum forming, as the name implies, draws the heated sheet against the tool with the assistance of a vacuum. Pressure forming combines vacuum and pressure to simultaneously pull and push the plastic sheet to the contours of the tool.

This process guide documents the steps for vacuum forming since it is the most common thermoforming method. However, many of the details presented may also be applied to drape and pressure forming.

In vacuum forming, heated plastic sheet is drawn down onto a male or female tool that has vent holes around the periphery and in areas requiring crisp detail. The application of a vacuum offers improved feature definition and greater wall thickness consistency. Vacuum forming also allows the use of thicker sheet stock and reduces forming time, when compared to drape forming.

Simple and straightforward, vacuum forming should be considered when prototyping or manufacturing plastic parts. Virtually any thermoplastic that is available as extruded sheet stock may be used (see figure 1). And unlike injection or blow molding processes, wall thicknesses can range from foils to thick-gauge stock—thicknesses ranging from 0.0005 to 0.50 inch (0.0127 to 12.7 mm)—with no molding stresses to combat. Another advantage of vacuum forming is that part and tooling costs remain reasonable for large parts.

There are a few considerations when choosing vacuum forming. The process does not support variable wall thicknesses, and the part's geometry must allow a straight pull (no undercuts or side action). Additionally, vacuum forming cannot manufacture strengthening ribs or mounting bosses that are common in injection molded parts. The final consideration—when using forming equipment designed for prototyping, such as the those offered by Formech International Limited—is that the side of the part that does not contact the tool surface will lack detail and definition. Dual-sided texture and feature definition are only available with matched tools, which are used with production vacuum forming equipment.

Vacuum Forming Materials:
- ABS
- Polyvinylchloride (PVC)
- Polycarbonate (PC)
- Polyethylene (PE)
- Low Density Polyethylene (LDPE)
- High Density Polyethylene (HDPE)
- Polypropylene (PP)
- Polystyrene (PS)
- Polyphenylene Oxide (PPO)
- Polyphenylene Ether (PPE)
- Polymethyl-Methacrylate (PMMA)
- Acrylic
- Closed Cell Foam Polyester (PBT, PET)
- Polyester Copelymer (PETG)
- Thermoplastic Olefin (TPO)
- Thermoplastic Elastomer (TPE)
- Thermoplastic Rubber (TPR)

Figure 1: Examples of thermoplastics suitable for vacuum forming.

Packaging thermoformed using an FDM mold.

For large production runs, vacuum forming tools are machined from aluminum. However, the low pressure and temperature of the forming operation facilitates the use of tooling constructed from many materials, including ABS, polycarbonate (PC) and polyphenolsulfone (PPSF/PPSU). Although tool life will not equal that from an aluminum tool, these three materials, which are available from the FDM process, are ideal for prototyping and short-run manufacturing. Depending on the Fortus material used for the tool and the thermoplastic used in the part, tool life can range from 100 to 1,000 parts (figure 6 shows a tool that has been used for over 500 parts with no visible signs of wear.).

The FDM process eliminates much of the time and labor associated with machining of vacuum forming tools. Data preparation is completed in minutes, so tool construction can begin immediately after tool design. Automated and unattended operations also eliminate the time needed for fixturing, set-up and operation of CNC milling machines. Another advantage of FDM is that modified build parameters will produce a tool that is porous. The porosity eliminates the time needed for drilling of vent holes, which are necessary for other vacuum forming tools, while improving part quality with an evenly distributed vacuum draw.

Combining the advantages of the FDM technology with those of vacuum forming, prototyping and short-run manufacturing can be completed quickly, efficiently and cost effectively.

APPLICATIONS

Packaging is the leading application for vacuum forming. The clear plastic bubble (blister pack) that contains a product is vacuumed formed. The disposable plastic lid on a coffee cup is vacuum formed as are the plastic and foam containers used in delicatessens and fast food restaurants. While the packaging industry is the leading consumer of vacuum formed parts, the applications extend across many product types and throughout many industries.

Automotive applications for vacuum forming include instrument panels (IPs), wheel covers and door liners. In aerospace, covers and cowlings are commonly vacuum formed. Used for boat hulls, the marine industry shows that vacuum formed parts can be large. There are many applications in electronics, including anti-static conveyance trays. For custom machinery, covers and shrouds are made quickly and cost-effectively with the vacuum forming process. The list of applications for vacuum forming is virtually endless, as illustrated in figure 2.

Industries and Applications:

- Aerospace:
  Interior trim panels, covers, cowlings
- Agriculture:
  Seed trays, lawn mower enclosures, covers
- Automotive:
  Wheel covers, storage racks, door interiors, wind/rain deflectors, electronic housings, liners, seat backs, dash surrounds
- Building and Construction:
  Drainpipe anti-drip fittings, roof lights, internal door liners, door panels
- Marine:
  Boat hulls, hatches, electrical, enclosures, dashboards
- Confectionery:
  Chocolate molds
- Computer:
  Transparent keyboard covers, enclosures
- Electronics:
  Enclosures, anti-static trays
- Furniture:
  Chair backs, cutlery trays, kitchen panels, storage modules
- Medical:
  Radiotherapy masks, pressure masks, prosthetics, medical devices
- Machinery:
  Machine guards, electrical enclosures
- Packaging:
  Pop displays, trays, cosmetic cases, blister packs, food containers
- Plumbing:
  Bathroom fittings, bathtubs, whirlpools, showers surrounds, shower trays

Figure 2: Examples of vacuum forming applications.

AEROSPACE – VEHICLE DESIGN AND PRODUCTION

Military aircraft and airborne vehicles are sophisticated tools that are used for intelligence, surveillance, targeting, and reconnaissance. A defense contractor applies FDM and vacuum forming to prototyping and manufacturing of these complex systems.

The company uses a Fortus system and Formech vacuum forming system to reduce time, cost and labor demands for components that include air ducts, engine cowlings and antennae covers.

In one application, vacuum forming replaces pre-preg (pre-impregnated) carbon fiber lay-up. This manufacturing method is a labor-intensive process that requires cavity fabrication, hand lay-up of the pre-preg material and a lengthy heat curing cycle. The process takes days and numerous man-hours to complete. Using the Titan to construct a tool, vacuum forming begins in as little as one day after a design is completed, and it is done with minimal labor requirements. Since vacuum forming of the parts takes only minutes, prototype and production ducts, covers and cowlings are made in less time than it takes to fabricate a fiber lay-up tool. This company demonstrates that vacuum forming is not just for prototyping vacuum formed parts. It can replace other processes.

CONSUMER GOODS – PACKAGE DEVELOPMENT

Saving time and money are desirable outcomes. But phenomenal gains arise when the process is changed. And that is what FDM and vacuum forming have done for the package development efforts of one mass-market, consumer goods company.

Prior to implementation of FDM technology, creating tooling for vacuum forming required a full man-day just for drilling of vent holes. Many of the tools used are multi-cavity, forming a dozen or more parts in one cycle. With all of the cavities, there are 1,000 to 2,000 vent holes to be drilled. With FDM tooling, the operation was eliminated.

However, the biggest benefit is not in labor savings. It is in process improvement. The typical product development cycle has package design and development as one of the last tasks before product launch. Being last meant that any delays in prior processes reduced the time available for package design. With FDM, the company now produces prototype products and prototype packing well before final design release. Removed from the critical path, there is more time to design and prototype innovative packaging. The results are less time pressure on the package development team and more creativity in package design.

For consumer products that are picked from a display rack, package design is often the key difference that motivates the consumer to buy a product. FDM for vacuum forming enables the company to stand out on product shelves.

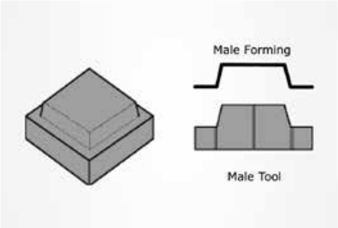

Figure 3: Illustration of a male tool.

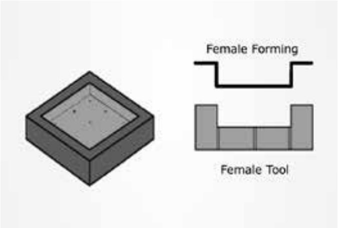

Figure 4: Illustration of a female tool.

PROCESS GUIDE

Vacuum forming is a simple, five-step process: tool design, tool building, tool preparation, part forming and part finishing. For many parts, the entire process can be completed in one to two days at a cost of U.S. $100 to $1,000 for the first part. Additional parts will have a typical cost of only $1.00 to $3.00, including process labor.

The vacuum forming process, as described below, is specific to the capabilities and operations of Formech vacuum forming machines. This information is applicable to the full line of Formech equipment, from the small, manually operated devices to the large-format, semi-automatic machines. However, the process guide also applies to the operation of a wide array of vacuum forming systems.

1. TOOL DESIGN

Vacuum forming uses three types of tools: male, female and matched. The selection of tool type is based on design specifications and consideration of the vacuum forming process.

Male tools (figure 3) offer detail and texture on the inside of the part (contact surface) while female tools (figure 4) offer the opposite. An additional consideration is that male tools are likely to have thicker sections at the periphery of the part and thinner sections in the center. The opposite is true of female tools. Matched tools incorporate both male and female tools for consistent wall thickness with detail and texture on both sides of the part. Match tools are also used to prevent compression of foam cells when forming foam materials. However, matched tools are not used with prototype vacuum forming machines.

In cases where there is a deep draw, plug assist can be used to overcome excessive thinning at the bottom of a pocket and to eliminate webbing between multiple cavities on a tool. The plug is a male form that presses through the sheet stock and into the mating cavity in the tool.

Once the type of tool has been selected, it must be designed. Starting with CAD data of the part, the geometry is offset to compensate for the thickness of the sheet stock, and draft angles are added to improve part release from the tool.

Compensation for sheet thickness is only necessary when the sheet is not restrained by the tool. For example, if a prototype is made from a male tool and the critical dimensions are on the inside surface of the formed part, no compensation would be necessary. When compensation is required, it is important to note that the thickness of the sheet stock will not be the final thickness of the part. As the sheet is drawn over or into the tool, there will be some material thinning, and the thickness will vary across the part.

Note that the rate of thinning is a function of the size, surface area and detail of the part geometry and the type of plastic and thickness of the sheet stock.

Vacuum forming sheet thickness may range from 0.0005 to 0.50 inch (0.0127 to 12.7 mm). However, for prototype applications, the Formech machines are limited to sheet thicknesses between 0.0005 to 0.25 inch (0.0127 to 6.35 mm).

After a prototype is vacuum formed, it will shrink and grip the tool. To facilitate part release, draft angles are incorporated into the tool design. Ranging from 0° to 5°, the amount of draft is determined by the vertical rise of the feature and the amount of contact area between the part and the tool. In many cases, the blow release function of a Formech machine can eliminate the need for draft angles. An important design rule is that any cavities in the tool should be no deeper that 75% of the width of the cavity opening (figure 5). Higher aspect ratios (height : width) will result in excessive sheet thinning and may cause sheet tearing.

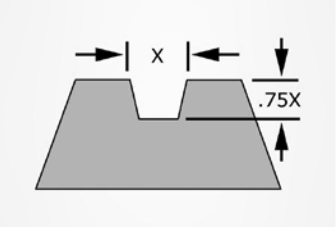

Figure 5: Cavities must have an aspect ratio of less than 75

2. TOOL MAKING

With the exception of venting and the addition of the perimeter rib, the tool is designed like any machined mold. Cooling channels may be constructed in the FDM tool, but it is simpler and faster to use a standard mounting plate with cooling lines. Once the tool has been designed, it is exported as an STL file and processed for production on a Fortus system.

As with production of a prototype or tool on any rapid prototyping system, the STL file should balance file size and facet size. The goal is to produce an STL file with no visible facets while avoiding excessively tight facet tolerance that inflates the total file size. In most cases, a facet deviation of 0.001 to 0.002 inch (0.0254 to 0.0508 mm) will suffice.

Prior to processing the STL file, the material for the tool is selected. ABS is suitable for the majority of vacuum forming applications. It offers mechanical properties that exceed the requirements of vacuum forming and thermal properties that match those of injection molded ABS. The glass transition temperature (Tg) of ABS is 220°F (104°C). Although this Tg is less than or equal to that of many vacuum formed materials, the heat applied to the sheet is localized, which means that the tool is not exposed to the elevated temperatures required to soften the thermoplastic.

Figure 6: FDM tool, made in PPSF/ PPSU, has formed more than 500 parts with no sign of wear

For demanding applications, PC or PPSF/PPSU (figure 6) may be selected. Both offer higher glass transition temperatures than ABS, which extends tool life and accommodates the forming of high temperature thermoplastics. PC (Tg = 320°F/160°C) and PPSF/PPSU (Tg = 445°F/229°C) offer increased resistance to thermal degradation—often resulting in a glazing of the tool surface from repeated heating and cooling cycles—that extends the life of the tool. When forming high temperature materials, such as polycarbonate or HDPE, PC or PPSF/PPSU should be selected.

With just one exception, the STL file is processed in Insight software in the same manner as any other prototype or tool. Increasing road width (the width of the extruded path) yields a tool that is porous on all non-vertical surfaces (figure 7). This porosity allows the vacuum to be drawn through all areas of the tool.

Figure 7: Close up of the tool in figure 6 shows the porosity that results from modified build parameters.

Porosity is advantageous when vacuum forming. For other tool creation methods, vacuum holes (small vents in the tool) are added around the periphery of the tool, in areas of detail, and in central areas of the tool where the vacuum pressure may be too low to pull the sheet to the tool. In order to obtain a prototype with good detail, all air must be removed during the forming cycle. If air becomes trapped (in corners for example), the sheet stock will not draw down onto the tool surface. The quantity and placement of the vents directly affects the quality of the formed part. Vent placement also affects the cycle time of the forming process.

With an FDM tool, porosity is designed into the rapid prototype, eliminating the need to locate and drill vent holes around and across the part. Using modified FDM build parameters, the tool offers excellent feature detail and fast vacuum cycles while eliminating the labor and time for drilling vents.

The sparse fill build style should be used wherever possible. Minimizing the amount of material in the part decreases both build time and tool cost without affecting the performance of the vacuum forming tool. Note, however, that sparse fill parameters should be modified to increase wall thickness so that tool damage is avoided. Once the tool has been processed in Insight, it is built on a Fortus system.

3. TOOL PREPARATION

After completion of the FDM build, the tool is finished and mounted to a tooling base. Since vacuum forming can pick up fine detail, it is important to finish the FDM tool to appropriate levels. While there are many techniques for finishing FDM parts, vacuum forming tools should only be filed, sanded or ground. Other FDM finishing techniques could plug the pores in the FDM tool, which would impede the vacuum flow. After sanding the FDM tool, any debris should be blown out of the pores.

The next step is to mount the tool onto a base board. The mounting board is cut to the size specified for the vacuum forming system that will be used. It can be made from any rigid material that will withstand the heat of the vacuum forming process. Common materials include plywood, Masonite® and aluminum. As with the tools, the mounting plate requires venting for the vacuum. However, unlike the vents in the tool, a single one-inch hole is all that is required.

4. VACUUM FORMING

Vacuum forming parts may be done with manual, semi-automatic or fully automatic machines (figure 8). The selection of the machine will be based on availability or expected throughput and desired level of process control.

The two key factors that affect vacuumed formed part quality are the heating cycle and the forming cycle. In both steps, if the plastic sheet is either too cool or too hot, the quality of the formed part will suffer. The heating cycle's time and temperature will vary with material and sheet thickness.

Although there are guides available for common materials, some trial-and-error may be required. Once the sheet is in a pliable state, the speed at which the tool press into the sheet and the vacuum is drawn must be fast enough to prevent sheet cooling but slow enough to allow the material to conform to the tool. As with the heating cycle, the forming cycle time may require experimentation to get the desired results.

To begin the vacuum forming process, the tool is placed in the machine, and the extruded plastic sheet stock is firmly clamped in a frame located above the tool (figures 9 and 10). Next, infrared ceramic heating elements warm the plastic sheet to soften the material to a point at which it will slightly sag, but not droop (figure 11). At this temperature, the sheet deforms to the contours of the tool.

Forming the part begins with a pre-stretch (figure 12). Air is introduced between the tool and plastic sheet to cause the sheet to billow away from the tool. This stretching improves the consistency of the wall thickness across the part.

Immediately after the pre-stretch, the tool is raised into the plastic sheet (figure 13), and a vacuum, approximately -24 to -30 inches of mercury, is pulled through the tool (figure 14). The plastic sheet draws tight to the tool surface to form the plastic part.

When using plug assist, the plug is forced down through the plastic sheet into the matching cavity in the tool before the vacuum is applied (figure 15).

To prevent deformation of the part, it is allowed to cool prior to removal. The cooling cycle can be accelerated with air or a fine mist blown onto the part. Once rigid, the part is released with air pressure forced up through the tool (figure 16).

5. PART FINISHING

After part removal, excess sheet stock that surrounds the vacuumed formed part is then trimmed. Depending on the quantity of parts, this can be done with hand tools, bandsaws, air-powered routers, CNC routers or semi-automatic Roller presses. The part is then cut, drilled, polished and deburred as needed. The completed part may then be painted or decorated.

Figure 8: The Formech 686 is an example of a semi-automatic thermoforming system. A system such as this works well with FDM-produced tooling.

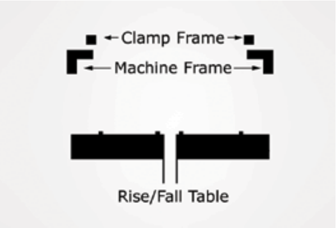

Figure 9: Diagram of vacuum forming machine.

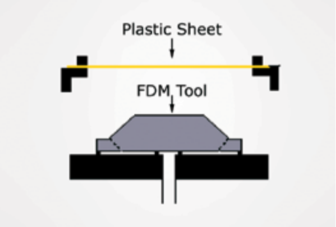

Figure 10: Thermoplastic sheet is clamped in frame.

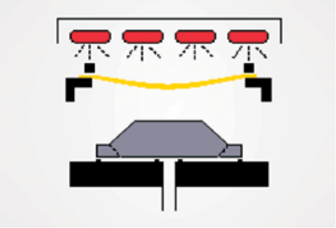

Figure 11: Heating elements warm thermoplastic sheet.

CONCLUSION

In just five simple steps, vacuum forming delivers plastic parts for prototyping and short-run manufacturing. Whether the application is prototype blister packs or production engine cowlings, plastic parts are delivered quickly and cost-effectively.

Applying FDM to the creation of vacuum forming tools offers additional advantages. Eliminating the time and labor required of machined tools—CAM programming, set-up and operation—and eliminating the vent drilling operation, FDM expedites the vacuum forming process while decreasing costs and labor demands.

With this process guide and the necessary tools, companies in all industries can capitalize on the efficiency, simplicity and cost-effectiveness of vacuum forming.

For information on Formech vacuum forming machines, visit the company's web site at http://www.formech.com.

Images and information in figure 1-5 and 8-16 are courtesy of Formech International Limited.

FDM PROCESS DESCRIPTION

Fortus 3D Production Systems are based on patented Stratasys FDM (Fused Deposition Modeling) technology. FDM is the industry's leading Additive Fabrication technology, and the only one that uses production grade thermoplastic materials to build the most durable parts direct from 3D data. Fortus systems use the widest range of advanced materials and mechanical properties so your parts can endure high heat, caustic chemicals, sterilization, high impact applications.

The FDM process dispenses two materials—one material to build the part and another material for a disposable support structure. The material is supplied from a roll of plastic filament on a spool. To produce a part, the filament is fed into an extrusion head and heated to a semi-liquid state. The head then extrudes the material and deposits it in layers as fine as 0.005 inch (0.127 mm) thick.

Unlike some Additive Fabrication processes, Fortus systems with FDM technology require no special facilities or ventilation and involve no harmful chemicals and by-products.

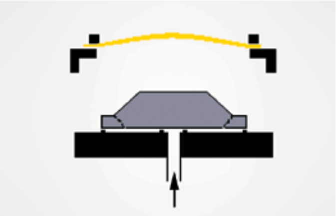
Figure 12: Air is forced upward for the material pre-stretch.

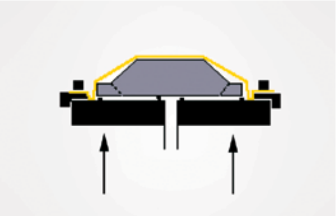
Figure 13: The tool rises, pressing into the sheet.

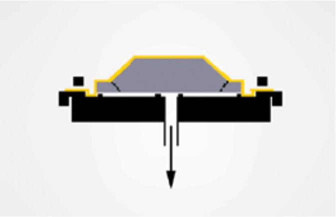
Figure 14: Vacuum is drawn to remove air from between the tool and sheet.

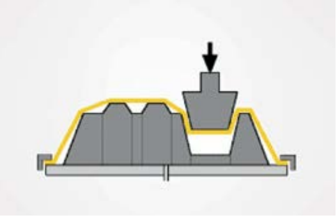
Figure 15: Plug pushes into sheet and tool cavity.

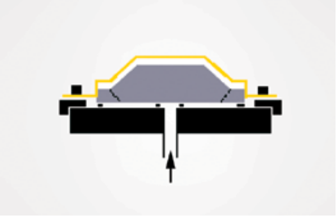
Figure 16: Blow release forces air between tool and formed part.

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