A Guide to Thermoform Processing of Polypropylene

Introduction

Thermoforming is the process of heating plastic sheet to a pliable state and forming it into shape. Thermoforming offers processing advantages over injection molding and blow molding, which include lower pressures, lower mold costs, production of multilayer structures, and ease of fabrication of large parts. By using a multi cavity tool, smaller, thin wall parts, such as those used for food packaging, can be formed in large volume with relatively short cycle time.

The critical issues addressed in the development commercial polypropylene grades include sheet quality, wall thickness and part uniformity, regrind use and dimensional stability.

The Thermoforming Process

The typical thermoforming sequence involves the clamping, heating, shaping, cooling and trimming of an extruded plastic sheet. Two methods are used for polypropylene: solid phase pressure forming and melt phase thermoforming.

Solid phase pressure forming was developed as a forming technique that did not require the plastic sheet to reach the melting point. Higher forming pressure (80-100 psi or 5+ bars) is used in solid phase forming. This allows plastic to be formed at a temperature just below the melting point (typically 330°F or 165°C). At this temperature, the forming process imparts molecular orientation to the polypropylene. Due to orientation, dramatic increases in part stiffness (crush resistance) and tensile strength allow for a reduction in part thickness and weight. Orientation also increases the clarity of random copolymers.

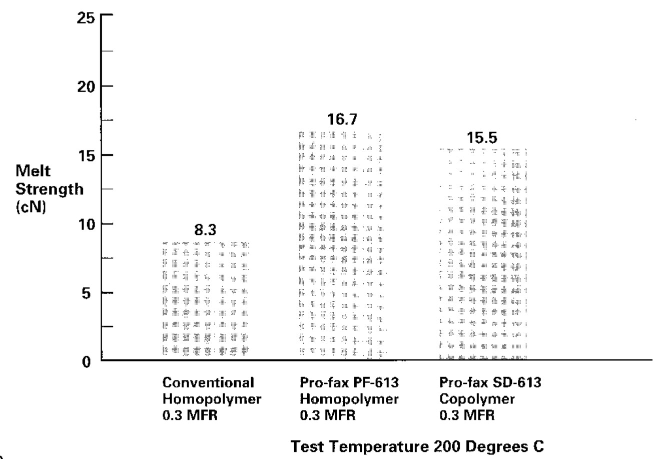
Melt phase thermoforming is performed above the melting point of the polymer. Conventional polypropylene grades are difficult to thermoform at temperatures above the melting point because of sheet sagging and thinning during the forming process. In the past, processors compensated for this deficiency by operating at too low a temperature. This often resulted in poorly finished part quality. “True” melt phase thermoforming, however, does have important advantages. Since lower pressures are required, tool design can be simplified and tool life extended. Part quality also improves with melt phase forming due to improvement in sidewall thickness uniformity.

Heating the sheet to the melt temperature removes stresses imparted in the sheet during the extrusion process. In contrast, solid phase forming actually imparts stress in the final part. Stress causes thermoformed parts, such as microwave nd retort containers, to distort when reheated. Parts made by melt phase thermoforming techniques remain dimensionally stable in high heat applications.

Polymer Selection
Melt strength provides resistance to sagging of the sheet in the thermoforming oven. Sheet sag is a function of sheet temperature, sheet surface area, sheet thickness and sheet orientation. High melt strength is a rheological improvement to polypropylene. In the molten state, it increases polymer extensional viscosity. Figure 1 illustrates the melt strength differences

between conventional 0.3 MER polypropylene and Himont's discontinued, high melt strength 0.3 MFR products designed for melt phase thermoforming.

Figure 1: Melt Strength of Selected Polypropylenes



Since the thermoforming process typically yields large amounts of trim, it is economically vital that the trim be reusable. Excellent polymer melt stability and the use of minimal heat by the processor are essential for reprocessing. Thermoforming polypropylene grades need to be formulated for maximum melt stability. To maintain the processability of the regrind, moderate melt temperature (less than 500°F or 260°C) and typical shear history (conventional polypropylene screw design) in the extruder are important.

MELT PHASE THERMOFORMING

Sheet Quality

The thermoformability of polypropylene is directly related to the quality of the extruded sheet. Sheet gauge uniformity (5% maximum variation) is important to minimize part-to-part variation. The degree of orientation in the sheet also affects thermoforming. Orientation is measured as a percentage of shrinkage in the machine and cross-direction of the sheet when heated to a temperature between 340 to 365°F (170 to 185°C). For sheet less than 0.100 in. (2.5 mm) thick, shrinkage should be 5 to 10% maximum.

Orientation is imparted during the extrusion process and is directly related to the die gap to final sheet thickness ratio, melt temperature and roll tension. High levels of orientation will cause distortion of the sheet during heating and subsequent poor temperature uniformity of the sheet entering the thermoforming tool. This will result in poor thermoformed part quality. To minimize orientation, die gap to sheet thickness ratio and melt temperature should be minimized. The recommended die gap is 10 to 15% greater for sheet thickness. "A Guide to Sheet Extrusion Processing for Polypropylene" is available for a more complete discussion of the process.

Heating

The thermoforming process can be divided into heating, vacuum/pressure forming, cooling and trimming. The most important concerns in sheet heating are to reach the required melt phase forming temperature and to obtain uniform sheet temperature. The amount of heat energy required to reach proper sheet temperature for thermoforming varies by polymer type. Figure 2 illustrates the heat content versus temperature of various polymers. Polypropylene requires more heat energy than many other plastic materials. Therefore, longer heating times are normally required to obtain optimum thermoforming conditions.

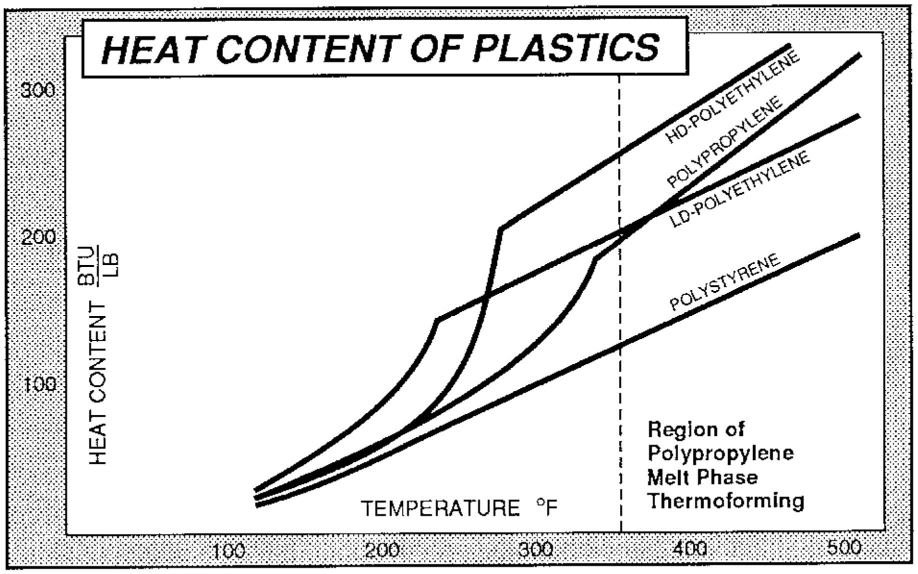
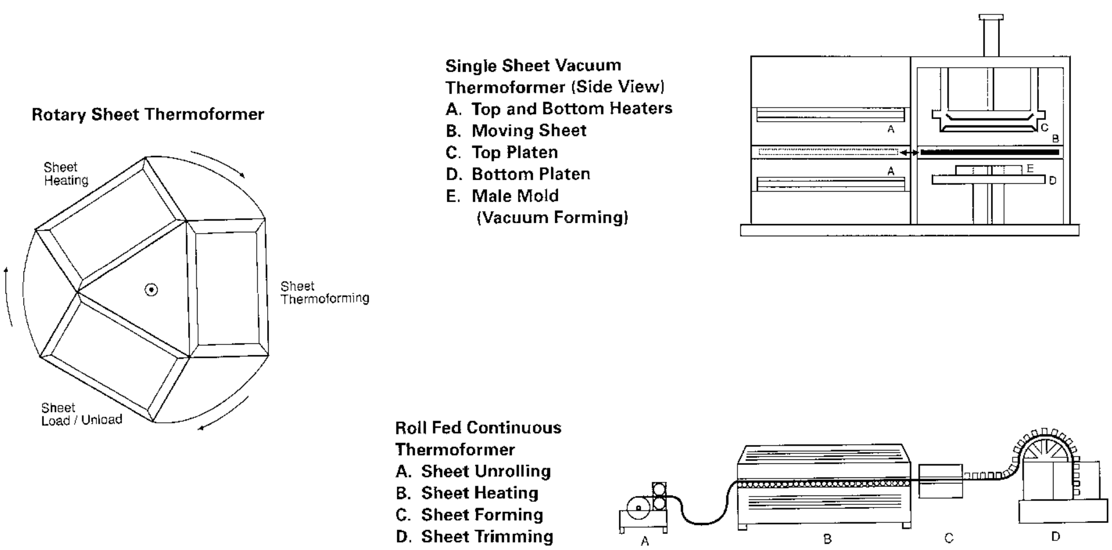


Figure 3 illustrates how the thermoforming process can be sheet fed (single stage and cyclic thermoforming) or roll fed (continuous). Larger parts and thicker sheet engage the rotary process. Generally, smaller parts using sheet less than 0.125 in. (3 mm) thick use a continuous process. In a continuous process, the length of the oven or number of oven stops is important. A minimum of four stops is recommended for sheet thicker than 0.030 in. (0.75 mm). Separately controlled heater zones are desirable for top and bottom, sides and middle, and front and back.

Figure 3: Thermoforming Processes



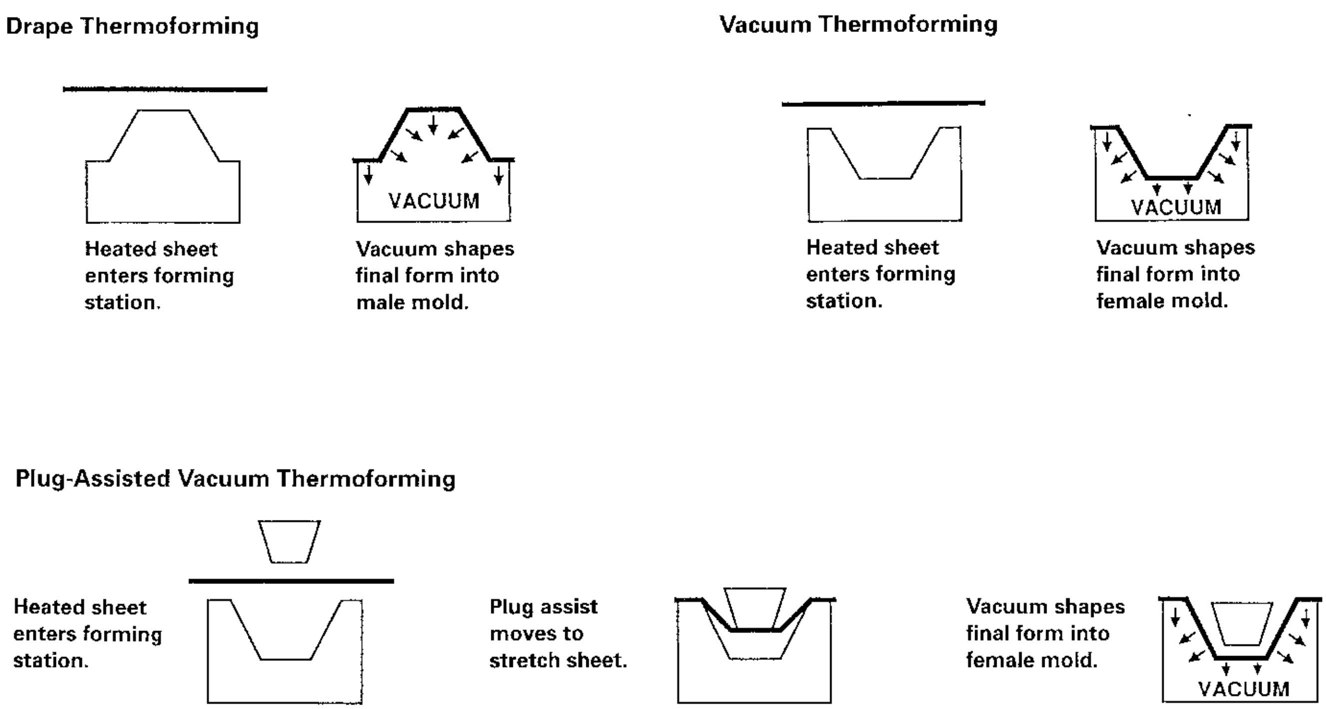
The longer heating times necessary for polypropylene have made sag bands, air support systems and other sheet support mechanisms popular for thermoforming. Since proper heating is critical to the quality of thermoformed parts, these aids are valuable in wide sheet processes. Generally, sag support hardware is not necessary using high melt strength polypropylene for sheet widths under 36 in. (1 m). Sag support is recommended for sheet widths above 36 in. (1 m).

Thermoforming

Thermoforming is accomplished by vacuum, positive air pressure, plug-assisted (pressure) vacuum forming or combinations and variations of these, once the sheet reaches thermoforming temperature (340 to 360°F or 170 to 185°C). Figure 4 illustrates some popular methods. Larger parts, thermoformed as single sheets, generally use a pre-stretch bubble process to accomplish uniform material distribution.

Plug-assisted vacuum, forming generally provides the best results for smaller, deep draw, well defined parts. Plug assists are mechanical forms used to push the molten plastic uniformly into deep draw mold cavities. Plug material of construction, design and timing can be critical to optimization of the thermoforming process.

Figure 4: Popular Thermoforming Methods



It is helpful to construct the plug from materials that are easily machined to control part thickness uniformity. Hard wood and syntactic foam are popular plug materials for prototype and production molds respectively. Foam plugs can be machined and have insulative properties to prevent overheating of the plug or quenching of the plastic.

The plug shape, although similar to the shape of the mold cavity, should be smaller in size and without part detail. The plug shape influences the distribution of the polymer. For example, a flat plug face will form a part with a heavy bottom, whereas a spherical face plug will provide even distribution and a sidewall thickness for deep draw.

The plug speed (timing) is typically set in accordance with the rate of vacuum bleed (vacuum between sheet and mold). For a semi-crystalline polymer such as polypropylene, fast plug speeds generally provide the best material distribution in the part. After the plug is extended, the vacuum forces the molten sheet into the mold for part definition and cooling.

Cooling

In melt phase thermoforming, the mold provides the heat transfer for cooling the formed part. Therefore, the mold temperature plays an important part in thermoforming. Mold temperatures affect the appearance of the part, the length of the forming cycle and the dimensional stability of the part. Polypropylene mold temperatures are typically 90 to 150°F (30 to 65°C). Cycle time is generally controlled by cooling limitations, as the part should be cooled to below its distortion temperature (200 to 220°F or 90 to 100°C) before removal from the mold.

Trimming

Trimming the part successfully from the plastic web depends upon the temperature of the sheet and the type of trimming equipment, Thinner sheet (less than 0.04 in. or 1 mm) is easily trimmed with adequate cooling time (1-2 minutes). Thicker sheet is cooled using surface cooling such as air or water spray for post-trimming on a continuous basis. Thick sheet (greater than 0.125 in. or 3 mm) and large parts are often trimmed after cooling for several minutes in ambient conditions or on a sizing tool. The trimming tool is also important to obtain good finished parts. Thin parts (less than 0.03 in. or 0.75 mm) is trimmed using sheet rule dies; thicker parts generally require shearing dies. Tool and die clearances should be minimized; less than 0.0005 in. (0.0125 mm) is recommended.

Due to the shrinkage of polypropylene (approximately 0.01 in/in.), webs greater than 30 in. should be slit before trimming. This allows greater trim precision and easier guidance through a continuous trim press. Plastic trim should be minimized by part and mold design, because the economics of the thermoforming process depend upon use of regrind. If total regrind from the process is kept below 50%, the efficiency of the thermoforming process and part quality should be optimized.

Recommended Polypropylene Melt Phase Thermoforming Conditions*

Sheet Temperature	340 to 360°F (170 to 185°C)
Heater Temperature	
Top	800 to 1,000°F (425 to 540°C)
Bottom	600 to 800°F (315 to 425°C)
Side	700 to 1,000°F (370 to 540°C)
Heater Distance From Sheet	
Top	6 to 12 in. (3 to 5 cm)
Bottom	10 to 14 in. (4 to 6 cm)
Mold Temperature	90 to 150°F (30 to 65°C)

*Intended as a general guideline. Process parameters depend upon part design and sheet thickness, size

Melt Phase Thermoforming Troubleshooting

Poor Part Detail

Sheet temperature too low	Check heater efficiency, or local heating problem. Increase heating time or oven temperature
Insufficient vacuum	Check vacuum holes. Increase size or number of vacuum holes. Increase vacuum pressure. Check for vacuum leaks.
Low pressure	Increase forming pressure. Use plug assist.

Excessive Sheet Sag, Scorched Sheet

Sheet temperature too high	Check heater control. Decrease heating time or oven temperature. Decrease oven temperature in the center of the sheet.
Incorrect polymer selection	Use lower melt flow rate (higher molecular weight) or high melt strength polypropylene grade.
Polymer degradation during extrusion	Limit increase in melt flow rate to less than twice that of virgin polymer
Web width too great	Use sag support system.

Abnormal Color or Surface

Incorrect sheet temperature	Check heater controls. Adjust cycle time. Adjust oven temperatures.
Poor sheet quality	Check sheet extrusion conditions: roll stack or die scratches. Improve transport of sheet to thermoformer.
Sheet stretched non-uniformly	Change plug design. Increase sheet temperature. Increase plug or mold temperature. Choose different polymer.
Rough mold surface	Polish mold. Use alternate material of construction.
Drag marks	Add or adjust sag support equipment.
Dirt, contamination	Clean mold. Check sheet contamination.
Polymer degradation conditions.	Decrease level of regrind. Check sheet extrusion
Moisture	Re-extrude sheet with dried polymer or with vented extruder.

Poor Polymer Distribution in Part

Variation in sheet thickness	Specify lower sheet gauge tolerance
Hot or cold spots in sheet	Check sheet temperature uniformity. Adjust oven temperature or control,
Sheet sag	Decrease sheet temperature. Add sag support system. Change to a different polymer grade
Sheet slippage	Mount mold on top platen. Adjust frame alignment. Increase clamp pressure
Cold mold Increase mold temperature.	Check mold cooling
Poor plug design	Change plug shape and/or material of construction.

Polymer Sticks to Mold or Plug Assist

Part not sufficiently cooled	Decrease sheet temperature. Decrease mold and plug assist temperature. Increase mold cooling time
Poor mold surface	Roughen or smooth the mold surface. Change material of construction.
Excessive shrinkage	Check mold cooling.
Poor release	Adjust vacuum break. Coat mold and plug assist for non-stick surface.

Sheet Tears While Forming

Incorrect sheet temperature	Increase or decrease sheet temperature.
Sheet hang-up in oven	Decrease sheet temperature. Add sag support system. Check polymer guide.
Vacuum blows holes in sheet	Decrease vacuum pressure. Adjust vacuum.
Incorrect polymer grade	Use fractional melt flow rate, high molecular weight grade, high melt strength grade.
Poor plug design	Redesign plug shape. Decrease penetration.

Sheet Webbing, Wrinkling, Distorting

Sheet temperature too high	Check heater control. Decrease heating time or oven temperature. Increase heater distance
Poor mold design, excess draw	Use plug assist. Increase drape angles of mold. Speed up plug assist or mold. Isolate or move cavities in the mold Redesign mold and/or grid.

Chill Marks, Striations

Low mold temperature	Increase mold temperature. Check coolant flow in the mold
Low plug temperature	Increase plug temperature. Increase plug speed. Change plug material of construction
High sheet temperature	Check heater control. Decrease heating time or oven temperature
Uneven sheet temperature	Check heater control. Adjust heaters for even heating. Check for uniformity of sheet

Part Shrinkage, Warpage

Insufficient or uneven mold cooling	Increase mold contact time. Decrease mold temperature. Check coolant channel. Use controlled surface cooling after forming
Poor pert uniformity	Change plug design. Check sheet gauge uniformity. Increase sheet temperature. Check evenness of vacuum. Check polymer choice
Poor part/mold design	Check coolant flow and vacuum. Increase part thickness around rim. Add ribs to stiffen part
Thermoforming in semisolid phase	Increase sheet temperature
Incorrect polymer	Choose polymer with desired level of expected shrinkage