3 Machine Specifications – Effect of Parameters

The thermoforming process is different from other plastic-processing techniques. The thermoplastic sheet is the most important element of the thermoforming process. Without it, thermoforming would not be possible.

Thermoforming deals with the changes that can be effected in the sheet materials. In thermoforming the material is not melted, but raw thermoplastic sheet materials are converted into finished products at their softening point and, moreover, low pressure is required to thermoform, because the mould material is less sturdy compared to other plastic processing. Relatively low forming pressures are needed and large sizes can be economically fabricated. Since the moulds are exposed to relatively low forces, they can be made of inexpensive materials. Mould fabrication time is therefore very short, minimising lead times. Thermoforming is often selected for fabricating prototype and display parts due to its low tooling costs. However, as part volumes increase, processes such as injection moulding become more economical.

Packaging from thermoforming is penetrating the narrow web market with great results because the printers and converters are constantly developing new trends in packaging to attract consumers [1].

Figure 3.1 shows the major steps involved in the thermoforming process from heating to trimming.

Thermoforming has become one of the fastest, if not *the* fastest, growing methods of processing plastics. With the development of the thermoforming technique, more and more relevant theoretical

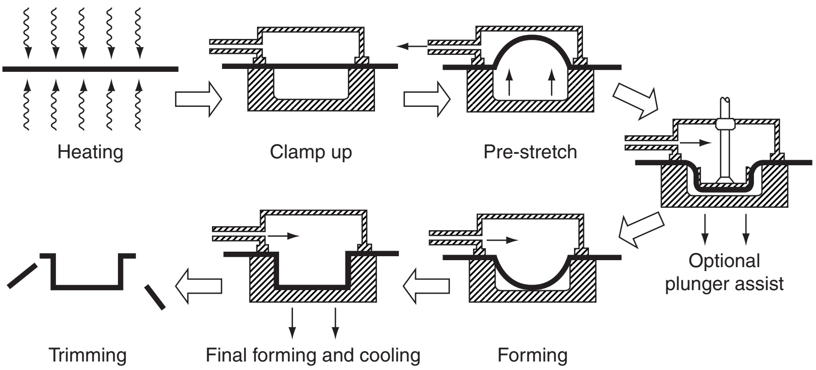

Figure 3.1 Main steps for thermoforming process Reproduced with permission from L-T. Lima, R. Auras and M. Rubino, *Progress in Polymer Science*, 2008, 33, 838. ©2008, Elsevier Ltd [2]

research on thermoforming control is carried out. Since the repetitive production of sheets meeting standards is very demanding in the industry, the implementation of cyclic control on the machine has naturally become an important objective for researchers [3].

Each thermoforming process has its own characteristics. The parameters and the process will determine the suitability of the thermoforming conditions. It is necessary to establish the process conditions to ensure the quality of the finished products.

Acrylonitrile-butadiene-styrene (ABS) can be easily processed during thermoforming due to the fact that its melt strength increases with decreasing temperature and increasing extrusion rate and it has a good sagging resistance. It has the highest melt strength in the low extrusion temperature region approaching the thermoforming region [4].

The thermoforming process is widely used in the packaging, pharmaceutical, toy and automotive industries to form numerous containers of different sizes, from small food trays to automotive dashboard skins and inner door panels, among others [5].

The thermoforming process consists of heating an extruded sheet of thermoplastic material and applying a pressure differential to force the material into some mould cavity. There are many variations of this process in which the sheet may be heated by conduction, convection or radiation; forced with plugs or slides; and inflated with positive air pressure or vacuum [6].

The basic principle involved in thermoforming is to heat the thermoplastic sheet until it softens and force the hot and pliable material against the contours of a mould by using vacuum, air or mechanical forces. Then the sheet will be allowed to cool against the mould and the plastic retains its shape.

Thermoplastics can be thermoformed according to the principles of positive, negative or free forming, with or without the use of air pressure or vacuum. Male forming gives a thicker bottom, whereas female forming implies thicker walls. Free-formed thermoplastics need to be kept in their desired shapes until they have reached a temperature lower than 70 °C. **Figure 3.2** shows the schematic basic configuration of a thermoforming machine.

Advances in thermoforming technology have been made through improved machinery and the limitations are being challenged almost daily. Innovations and improvements in machinery include:

- Improved ways of clamping the polymer sheet material;
- Improved heaters and heat distribution patterns and controls;
- Sensors for monitoring and controlling the sheet residence time in the oven;
- Better control of stretching forces and pressures;
- Improved trim dies;
- Improvement in moulds and mould materials;
- Improved plug-assist materials.

Annealing is not needed when parts are formed. If stress cracks occur on a thermoformed part, the part can be reconditioned at 70 °C.

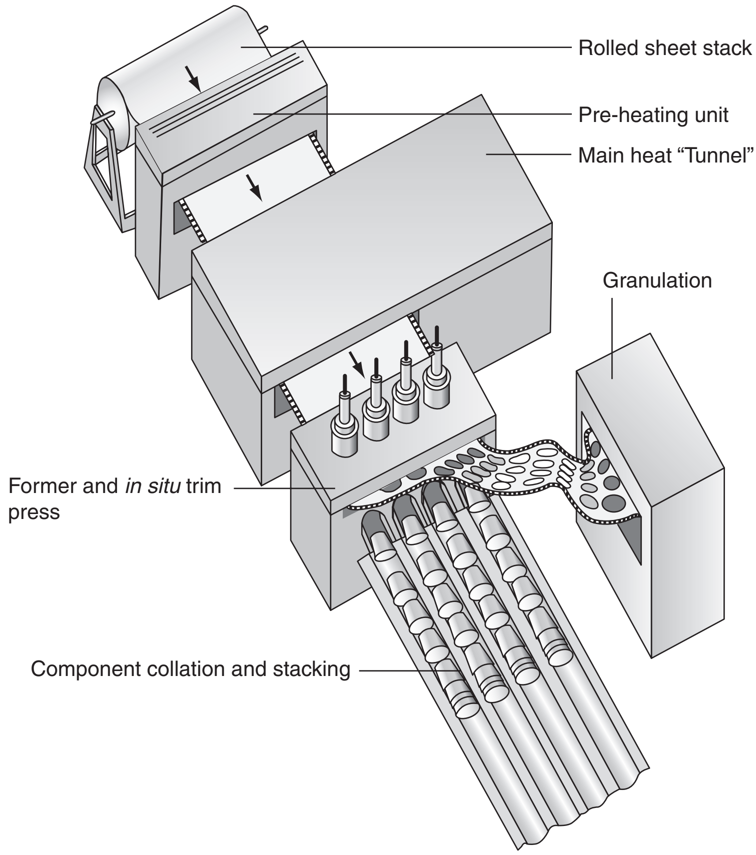

Figure 3.2 Schematic diagram of the thermoforming process. Reproduced with permission from *Polypropylene Sheet Extrusion and Thermoforming for Packaging Applications*, Basell Polyolefins, Rotterdam, The Netherlands, 2005, 054 PP e. ©2005, Basell Polyolefins [7]

Thermoforming is a collection of manufacturing methods that heat and form sheets of extruded plastic. Thermoforming processes include drape, vacuum and pressure forming. The techniques of the forming process can be grouped into several types, as described below.

3.1 Methods of Vacuum Forming

3.1.1 Straight Vacuum Forming

One of the oldest techniques is straight vacuum forming, i.e., where the sheet is held against the top of a female mould at the start of the heating cycle. However, this technique is seldom feasible with high-density polyethylene due to the appreciable sag of the sheet while heating. Therefore, drape forming is the first practical technique using these materials.

3.1.2 Vacuum (Thermo) Forming

In vacuum forming, after the plastic sheet is heated to soften it, it is drawn down onto a male or female tool that has vent holes around the periphery and in areas requiring crisp detail. The air is sucked out of the mould through the vent hole to form a vacuum, causing the moulding material to conform to the mould and assume its shape. Air is allowed in again to the remove the part. 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. **Figure 3.3** shows the straight vacuum forming process with variable configuration.

Advantages:

- Requires low temperature and pressure;
- Lower cost of mould and machine and these remain reasonable for large parts;
- Used to manufacture large parts;
- Faster mould cycles.

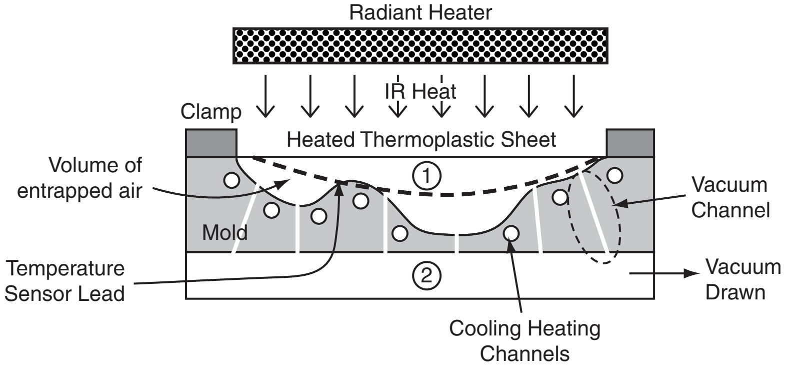

Figure 3.3 Schematic of the vacuum forming process for thermoplastic resin in sheet form (straight vacuum forming). Reproduced with permission from D. F. Walczyka and S. Yoo, *Journal of Manufacturing Processes 11*, 2009, 9. ©2009, Elsevier Ltd [8]

Disadvantages:

- High cost of plastic sheet and scraps;
- Part shapes limitation;
- Part defined by mould on only one side;
- Non-uniformity with inherent wall thickness;
- Residual stresses.

Any thermoplastic extruded sheet may be used in simple and straightforward vacuum forming when prototyping or manufacturing plastic parts. Unlike injection- or blow-moulding processes, wall thickness can range from foils to thick gauge stock.

There are a few considerations to be made before choosing vacuum forming. This process does not support variable wall thicknesses. The geometry of the part must allow a straight pull and no undercuts or side action are allowed. Unlike injection moulding, vacuum forming can not manufacture strengthening ribs or mounting bosses. The side of the part that does not contact the tool surface will lack detail and definition when using forming equipment designed for prototyping. For large production runs, vacuum forming tools are machined from aluminium. Dual-sided texture and feature definition are only available with matched tools, which are used with production vacuum forming equipment.

Packaging is the leading application for vacuum forming. Blister packs are produced by this method. For vacuum-formed products, the packaging industries are the main consumers and the applications extend across many product types, which include automotive, aerospace, marine industry, electronics and many more. The list of applications is virtually unlimited.

Vacuum forming delivers plastic parts for prototyping and short-run manufacturing and the thermoformed products are delivered quickly and cost effectively.

3.1.3 Pressure Forming

In pressure forming (vacuum or pressure) (see **Figure 3.4**), the positive air pressure is to be applied between 99,974 and 2,068,427 Pa. Lower temperatures with higher forming pressure and faster mould cycles use air pressure, often with the addition of a plug-assist in pressure forming. The plug-assist forces the material deeper into the mould cavity.

Even though it is possible to have fine detail and surface finish in injection moulding with pressure, it usually requires much higher annual volume than thermoforming to be economically feasible.

Injection moulding becomes a more serious contender for the application as its volume increases. Then the piece part cost differential can be applied to the substantially greater cost of the injection moulds. The cost of the tooling for injection moulding rises substantially with increasing size, and the payoff volume, the point at which the additional tooling cost is offset by piece part savings, goes

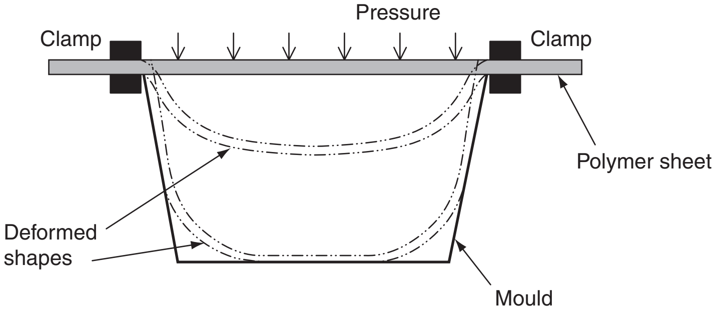

Figure 3.4 Pressure forming. Reproduced with permission from M.K. Warby, J.R. Whitemana, W-G. Jiang, P. Warwick and T. Wright, *Mathematics and Computers in Simulation*, 2003, **61**, 210. ©2003, Elsevier Science BV [9]

up accordingly. Thermoforming can, however, make substantially larger parts than can injection moulding.

3.1.4 Plug-assist Pressure Forming

In plug-assist pressure forming, a plug forces the hot sheet into a female cavity. The plug further forces the plastic sheet against walls of the mould while air pressure is applied. To optimise the material distribution, plug design and plug speed can be varied.

For plug-assist thermoforming, plugs manufactured from syntactic foam are used and coated with a slip coating to prevent sticking in some deep draw applications. Plug shape has had more impact on part quality than has the material of construction. Plug shape is dependent upon the particular part being moulded.

3.1.5 Plug-assist Vacuum Forming

Plug-assist forming pulls additional material into the female cavity in the manufacture of thin wall thickness articles. The plug should be around 20% smaller than the mould. The mould is heated just under the forming temperature of the sheet. The plug forces the hot sheet into the mould cavity and air is drawn from the mould to form the part. Both pressure and the vacuum plug-assist process allow deep drawing and short cycle time with good wall thickness control, require close temperature control and are more complex than straight vacuum forming. **Figure 3.5** shows a typical process involved in plug-assist vacuum forming processing.

Plug-assist vacuum forming creates better wall thickness uniformity, especially for cup or box shapes. The plug materials include wood, metal and thermoset polymer and the plug is 10–20% smaller than the cavity. The temperature of the plug is important in plug-assist vacuum forming.

The deep draw shortcoming of the female mould can usually be overcome by the use of plug-assist. Plug-assist is commonly used in deep drawn articles, or where the distribution of materials needs to be altered. In using complicated moulds with grooves, pockets or recesses, the plug should be designed to carry more material into these areas. A temperature below the suggested range can result in chill marks and thin spots in the material.

Pettersen and co-workers made a comparison of oxygen barrier properties and wall thickness distribution of different thermoformed trays manufactured with three drawing depths and two different thermoforming methods, with and without plug-assist [11]. They found that temperature had more influence on the oxygen transmission rate (OTR) than humidity. In the packages, the OTR increased with increasing drawing depth. OTR may have influence by orientation other than thinning. Plug-assisted thermoforming had an effect on the OTR in a thick laminate of polypropylene (PP)/polyethylene (PE), which was probably due to exceeding the maximum drawing depth of this material.

The influence of plug design was investigated, namely plug volume, plug taper, plug depth and plug temperature on the wall thickness distribution, weight and compression strength, in thermoformed

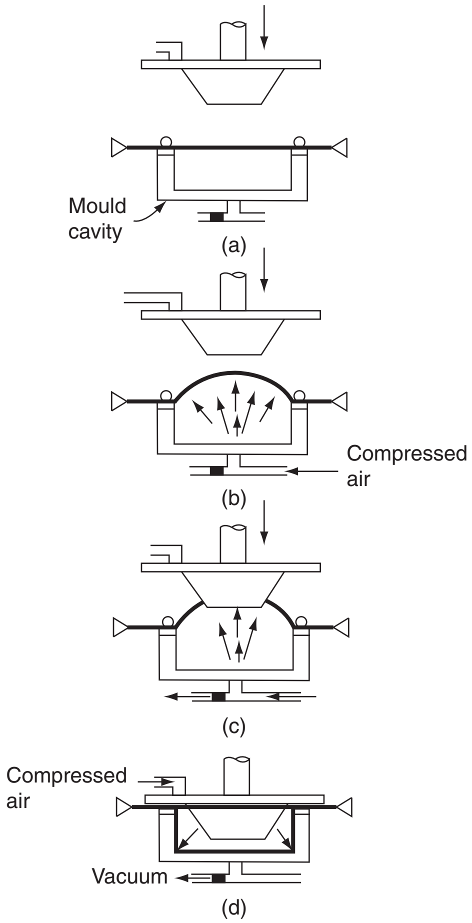

Figure 3.5 Plug-assist vacuum forming. Reproduced with permission from G. Sala, L. Di Landro and D. Cassago, *Materials and Design*, 2002, **23**, 21. ©2002, Elsevier Science [10]

PP cups and it was observed that the plug volume was the most importance factor for part shape. Plug depth had a significant effect on the bottom and corner thicknesses and part weight. Plug temperature and plug taper had a significant effect only on the compression strength [12].

In plug-assist thermoforming, surface friction strongly affects the final part thickness distribution. The effect of the plug material, plug temperature and sheet temperature on the coefficient of friction between the plug and the sheet with three different plug materials (epoxy syntactic, engineering thermoplastic non-syntactic and engineering thermoplastic syntactic) with a range of friction coefficients affects the thickness of the thermoforming polypropylene sheet [13].

Prototype thermoforming trials of a soy protein isolate-based sheet material were conducted to evaluate the effect of moisture level, draw ratio, plug-assist and vacuum rates on the forming of cup-shaped containers. The forming behaviour of the soy sheet was compared with that of PVC and PP materials. Cycle time and draw ratio comparisons were made. The soy protein isolate sheet material exhibited similar thickness reductions to PP and PVC for comparable draw ratios. Plug-assist forming did not improve the wall thickness reduction of soy protein isolate as it did for PP and PVC. Moisture change, from a high of 15% to 10%, did not significantly affect the forming behaviour of soy protein isolate sheet material [14].

The stretching operation is often performed by the movement of a mechanical plug, which contacts some areas of the sheet. During contact it is known that conductive heat transfer between the plug and sheet material is an important factor in determining the process output. The process is characterised by large deformations, non-isothermal conditions and non-linear material behaviour, making final part performance difficult to predict. There are many variations of this process in which the sheet may be heated by conduction, convection or radiation; forced with plugs or slides; and inflated with positive air pressure or vacuum [6].

The selection of plugs for thermoforming of cups for products such as yogurt is related to the problem of pre-stretching with plug assists. Empirical plug design is considered with reference to plug geometry and plug penetration, triggering of forming pressure, plug material (polyoxymethylene or syntactic foam) and plug temperature [15].

An instrument has been developed to obtain the friction coefficients between sheet and plug in the plug-assist thermoforming process, to facilitate process simulation. Discs of the polymer and the plug material are pressed together under a known load, at a controlled temperature, and one disc is rotated whilst the torque is measured on the other. This enables determination of the friction coefficient as a function of temperature and shear rate [16].

3.1.6 Pressure-bubble Plug-assist Vacuum Forming

When deep articles with good thickness uniformity are required, the pressure-bubble plug-assist vacuum is used. The sheet is placed in the frame and heated. Controlled air pressure is used to create the bubble. The bubble has been stretched to a pre-determined height; the normally heated male plug-assist is lowered to force the stretched sheet into the cavity. The variation in the plug speed and shape can improve the distribution of the material. The plug has to be made as large as possible to stretch the plastic material close to the shape of the finished part. The plug penetrates around 80%. The air pressure is applied from the plug while a vacuum is drawn on the cavity. The female mould helps to escape the trapped air by venting.

3.1.7 Free Forming

In free forming, very low pressure, about 2.76 MPa, is used to blow a hot plastic sheet through the contour of a female mould. The sheet forms a smooth bubble-shaped article with the help of air pressure. Since the air touches only the side of the pad, there will be no mark-off unless a stop is used to form a profile in the bubble. **Figure 3.6** shows a photograph of free forming.

3.1.8 Matched-die Forming

Matched-die forming is similar to compression moulding. **Figure 3.7** shows a schematic representation of the matched-die forming process.