PLASTICS THERMOFORMING TOOL DESIGN: PLUG VS CAVITY MOLDS

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ABSTRACT

One of the most fundamental decisions when designing a mold for the plastics thermoforming process is whether to use a plug (male) mold or a cavity (female) mold design. This critical decision is often brushed over in the literature yet has the greatest single impact on part wall thickness and wall thickness variation. Other considerations when deciding on this fundamental design concept include location of thinnest cross section, material shrink rates, a defect known as "webbing", and draw ratio determination. Given access to even the most basic thermoforming equipment, students can design a wide variety of molds to test and evaluate the difference between plug and cavity mold designs for similar part geometry. This paper will discuss such an activity.

Specific Learning Objectives include:
1) The student will understand the relationship between mold design, material deformation and part wall thickness.
2) The student will understand the effect of materials shrink rates and part release from the mold.
3) The student will be able to explain why parts produced with plug molds have less wall thickness variation than those produced with a cavity mold.
4) The student will be able to calculate linear draw ratios on thermoformed parts and explain the relationship of these ratios to wall thickness variation.

I. INTRODUCTION

Thermoforming is one of the fastest growing manufacturing processes in the plastics industry. It is a process in which thermoplastic sheet stock is re-shaped into a new geometry using heat to soften (not melt) the sheet and forcing it into or onto a mold where it is cooled and "frozen" into the new geometry. The force may be in the form of mechanical pressure, air pressure (compressed air), atmospheric pressure (drawing a vacuum between the sheet and the mold) or any combination of these forces. The type of force applied greatly effects the amount of deformation (stretching) possible as well as the tool design. Regardless of the force applied to the sheet, the designer must decide whether to use a positive configured mold (plug) or a negatively configured mold (cavity).

II. MOLD DESIGN CONCEPT – PLUG VS CAVITY

The primary purpose of the mold used in the thermoforming process is to create the desired part geometry. This is accomplished by shaping the sheet while it is at or above the forming temperature, holding the sheet in the new configuration and removing enough heat from the sheet to remain in the new geometry. The sheet is typically cooled to approximately 40 degrees Fahrenheit below the materials glass transition temperature before removal from the mold [1]. The rate of cooling has a major impact on the cycle time which is a key cost factor. Remember: plastics are natural thermal insulators so it takes time, therefore money, to increase the sheet temperature but also to remove the heat from the part before ejection from the mold. Since the entire sheet does not become the product, the excess material (known as "trim") must be removed. This may be accomplished in secondary operations or during the molding process using more sophisticated, self-trimming molds.

Since thermoforming is essentially a material deformation "stretching" process and the sheet will stretch at varying distances depending on the part geometry, there will be uneven part thicknesses. This is affected not only by part geometry but also the process selected as well as the mold style, plug or cavity. A basic concept to keep in mind is that the material quickly cools as it touches the cold mold surface and the stretching ceases. The first area of the sheet to make contact with the mold will be the thickest and the last area of the sheet to touch the mold will stretch the furthest and therefore be the thinnest. As illustrated in Figure 1, there is an almost inverse relationship in wall thickness between parts of the same geometry when formed in the cavity type mold on the left when compared to those formed over a plug type mold on the right. [2]

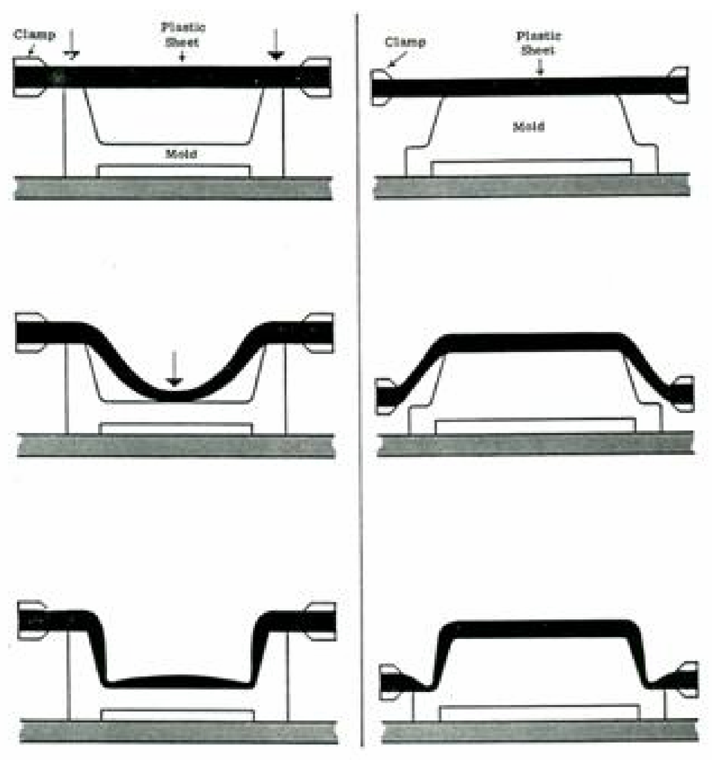

Fig.1 Cavity Vs Plug Mold
(McConnell p.9-2)

Both tool types are commonly used in the thermoforming industry but clearly have an enormous impact on the thinning location of material due to stretching. Two important issues need to be noted in addition to the wall thickness differences. First, plug molded parts can be difficult to release.

Typical Shrinkage Range for Some Thermoforming Materials		
Material	Shrinkage Range-Percent	Shrinkage Normally Used-Percent
ABS	0.3 - 0.8 %	0.5 %
Acrylic	0.3 - 0.8 %	0.6 %
Butyrate	0.2 - 0.5 %	0.35 %
HDPE	2.0 - 3.5 %	2.5 %
HIPS	0.3 - 0.8 %	0.5 %
Polycarbonate	0.6 - 0.8 %	0.7 %
Polypropylene	1.2 - 2.2 %	1.8 %
Polypropylene with 20% talc	0.75 - 1.0 %	0.9 %
Vinyl	4.0 - 5.0 %	4.5 %

Fig. 2 Typical Shrink Rates
(McConnell p. 9-8)

Plastics expand when heated and shrink when cooled. Some materials have a shrink rate as high as 5% when cooled from thermoforming temperatures as indicated in Figure 2. [3] Approximately 50% of the shrinkage occurs while the part is in/on the mold. As the part cools over a plug mold, it shrinks and "grabs" the plug which can make part removal very difficult. Increasing draft angles and modifying the mold texture can improve part removal; however it will not eliminate this as a key issue for designers.

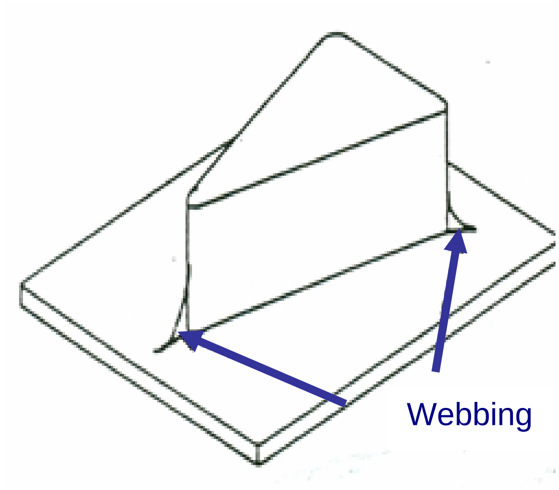

Fig. 3 Webbing Defects
(McConnell p. 5-9)

The second issue that needs to be noted deals with a defect known as "webbing". This is a phenomenon that occurs when the heated material makes contact with itself while forming and permanently bonds together causing a wrinkle. [4] This is a significant problem at corners when the part requires a deep draw as seen in Figure 3. Webbing only occurs when using a plug mold.

III. LABORATORY ACTIVITY

The following lab activity is an excellent method for students to understand the differences in part thickness when determining whether to design a plug or cavity style mold. Several "test" molds have been produced by students to use in this activity.

Fig. 4: Plug & Cavity Test Molds

Figure 4 shows two such molds to produce a flower pot. Both molds are made of composites (fiberglass & polyester) and are mounted on a wooden vacuum base compatible with the processing equipment to be used. The part geometry is very similar between mold types. The finished product is approximately 6" high and 6" in diameter. The thermoforming process in use requires a 12" X 12" sheet to be held in a clamping frame with a 10" X 10" area available for forming.

Fig. 5: Grid Sheet

Each of the two sheets to be used in this activity is marked with a ½" X ½" grid prior to forming as shown in Figure 5. This is similar to an exercise in Richardson's' book [5].

Fig. 6: Cavity Mold

Cavity Mold Example

Figure 6 shows the cavity mold in position on the thermoformer. The wooded box beneath the mold is a vacuum box which is connected to a vacuum surge tank.

Fig. 7: Heated Sheet In Contact With Cavity mold

Figure 7 shows the heated sheet in place over the mold ready to be formed.

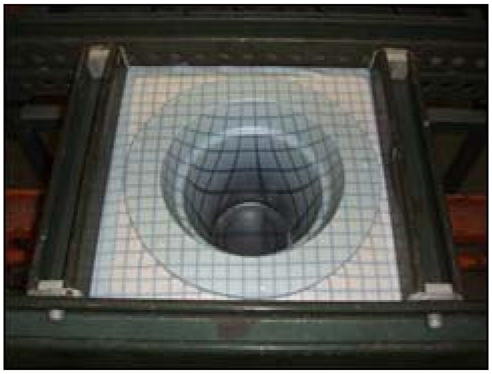

Fig. 8: Part Forming

Figure 8 shows the sheet being drawn into the mold. (The material is actually forced into the mold with atmospheric pressure.) Note the grid pattern! The area of the sheet that first touches the mold has not deformed. The entire part was produced by the material within the cavity area.

Fig. 9: Formed Part

Figure 9 shows the part and the "trim"; again note the grid pattern and the degree of deformation.

Fig. 10: Plug Mold

Plug Mold Example

Figure 10 shows the plug configured mold in place on the thermoformer.

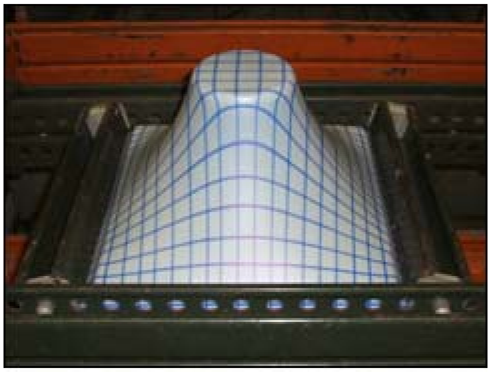

Fig. 11: Part Forming

Figure 11 shows the plug mold being raised into the heated sheet mechanically stretching the material. This process is known as drape forming. Note the deformation on the grid!

Fig. 12 Part Forming

Figure 12 shows the sheet being drawn over the plug mold where it will cool. Note the grid pattern and the area of deformation which extends to the clamping frame. Also note that the bottom of the pot (the area which first touched the mold) has almost no deformation, thus retaining its original sheet thickness.

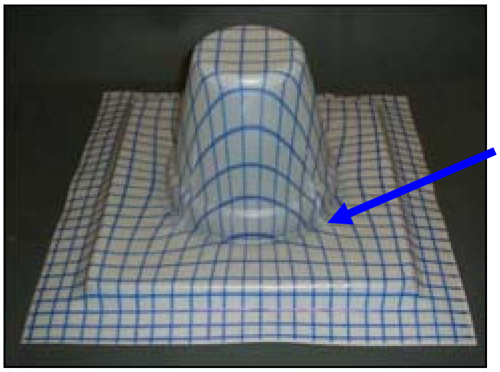

Fig. 13: Formed Part

Figure 13 shows the part and "trim" after removal from the thermoformer. Note the deformation and the quality defect known as "webbing". This is the wrinkled areas on the sides of the pot where it meets the "trim".

Mold Design Comparison

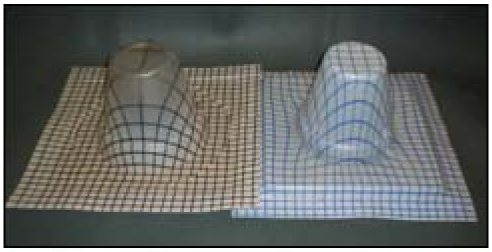

Fig. 14: Formed Parts

Figures 14 & 15 show the cavity and plug formed units side by side for comparison. The deformation location and degree are quite obvious. Note the grid lines and the specific areas of greatest deformation between the cavity molded part on the left and the plug molded part on the right. The bottom of the cavity molded pot is very thin due to extreme stretching while the bottom of the plug molded pot is nearly unchanged from the original sheet thickness.

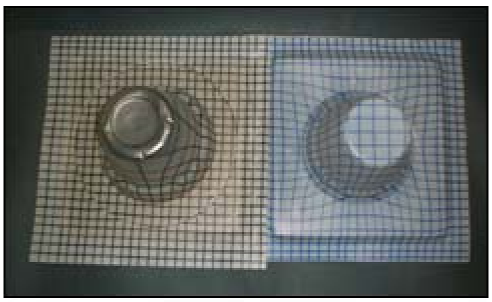

Fig. 15: Formed Parts

Figs. 16 & 17: Trimmed Parts

Figures 16 & 17 show the part (flower pots) removed from the "trim". Note the significant difference in material deformation on the pot bottoms!

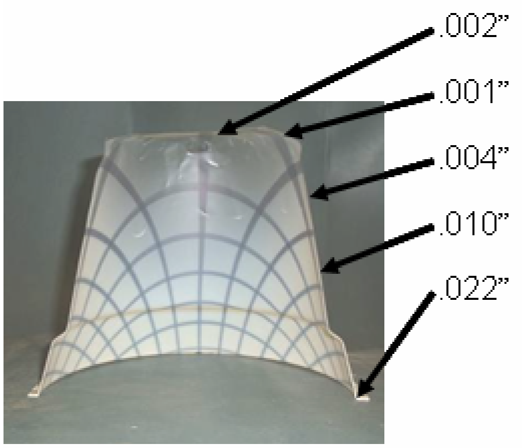

Fig. 18: Cavity Part Cut-away

Figure 18 shows wall thickness dimensions in .000" for the cavity mold. The starting sheet thickness was .022". The thinnest location of .001" represents 4.55% of the original thickness.

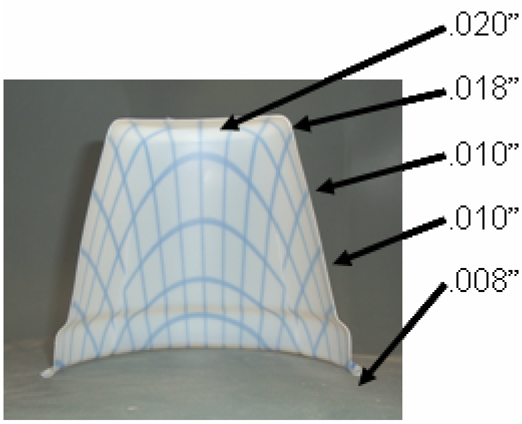

Fig. 19: Plug Part Cut-away

Figure 19 shows wall thickness dimensions in .000" for the plug mold. The starting sheet thickness was .022". The thinnest location of .008" represents 36.36% of the original thickness.

Draw Ratios

There are several Draw Ratios that can be used to analyze parts. These include Areal Draw Ratios, Linear Draw Ratios and Height-to-Dimension Ratios. Each has advantages and is only grossly representative of sheet thinning, however they can be excellent instructional tools for comparing part designs and processes. The following activity can be used with the previous plug and cavity produced parts to better understand the thermoforming process. For simplicity, Linear Draw Ratio is used. Linear Draw Ratio is the ratio of the length of a line drawn on the sheet prior to forming compared to the length of the same line after forming. Only the line length in the forming area is used therefore the length varies between plug and cavity molds. The forming area of a plug mold includes the distance between clamping frames while the forming area of a cavity mold includes only the width of the cavity opening. [6] The previously molded part is illustrated in the following calculations.

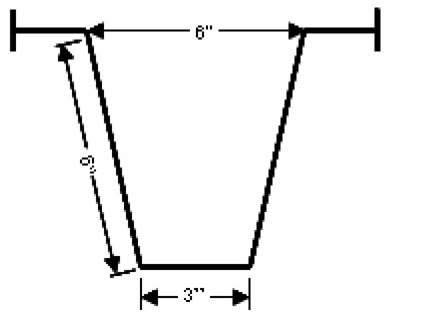

Fig. 20: Cavity Part

Cavity Mold Linear Draw Ratio

Length of line prior to forming = 6"
Length of line after forming = 6" + 3" + 6" = 15"

Linear Draw Ratio = 15/6 = 2.5

In other words, the sheet would stretch 2.5 times its original length.

Plug Mold Linear Draw Ratio

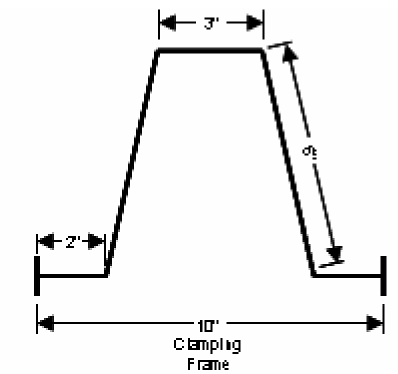

Fig. 21: Plug Molded Part

Length of line prior to forming = 10"
Length of line after forming =
2" + 6" + 3" + 6" + 2" = 19"

Linear Draw Ratio = 19/10 = 1.9

In other words, the sheet would stretch 1.9 times its original length.

IV. CONCLUSION

Thermoforming is essentially a stretching process in which thermoplastic sheet stock is heated to its softening temperature, stretched into a new shape and frozen when the heat is removed. There are many variables in the process including incoming sheet quality, part geometry, forming force and mold type. This paper specifically discussed the impact of mold type on the wall thickness variation within a product. Plug and cavity molds yielding similar parts were built and tested. Both mold types are used extensively and each has advantages and disadvantages particularly in the location of wall thickness variation. As illustrated in the test parts as well as the linear draw ratio calculations, an advantage of plug configured molds is that wall uniformity is typically better because material has a lower draw ratio. [7] However plug molds have particular problems with part release and webbing which are not found when using cavity molds. The lab activities are an excellent method for designers to confirm the impact of mold type on wall thickness. Simple test molds of varying shapes are often created to simulate draw ratios to identify problems before permanent molds are constructed.

REFERENCES

[1] Throne, James, *Thermoforming*, p.120, 1987.

[2] McConnell, William K., *Thermoforming. Society of Plastics Engineers Seminar Notebook*, p.9-2, Jan. 1995.

[3] McConnell, William K., *Thermoforming. Society of Plastics Engineers Seminar Notebook*, p.9-8, Jan. 1995.

[4] McConnell, William K., *Thermoforming. Society of Plastics Engineers Seminar Notebook*, p.5-9, Jan. 1995.

[5] Richardson, Terry L. & Lokensgard, Eric, *Industrial Plastics: Theory and Applications,* 3rd edition, p.255, 1997.

[6] Throne, James, *Understanding Thermoforming*, p.85, 1999.

[7] Strong, Brent, *Plastics Materials and Properties*, 3rd edition, p.567, 2006.