Table 8.1 General Extruded Film and Sheet Types [1]

Film/sheet type	Thickness range (mils)	Thickness range (μm)	Film/sheet widths (in)	Film/sheet widths (mm)
Flat film	0.4–6	10–150	48–126	1200–3200
Cast sheet	4–16	100–400	32–88	800–2200
Thermoformable film	4–16	100–400	18–64	450–1600
Thermoformable sheet	16–100	400–2500	24–56	600–1400
Thermoformable sheet	100–300	2500–7500	40–80	1000–2000
Oriented films				
Uniaxial	1.2–24	30–600	24–72	600–1800
Biaxial	1.2–100	30–2500	16–60	400–1500

8.2 Forming Thin Films

Thermoformable sheet is usually considered to be thin-gage when its thickness is less than 60 mils, 0.060 in or 1500 μm and to be heavy-gage when its thickness is greater than 120 mils, 0.120 in or 3000 μm. When the sheet thickness is less than 10 mils, 0.010 in or 250 μm, it is considered to be a film. Table 8.1 gives a general summary of sheet characteristics [1].

Most films are thin enough to have some flexibility and are produced by extruding the polymer melt through an annular ring, then inflating and stretching the tube to achieve thinness and to introduce biaxial orientation and toughness. The configuration of a typical blown film tower is shown in Fig. 8.1 [2]. This equipment is primarily used for polyethylenes. Polypropylene, polystyrene and polyamide films are usually extruded through a slot die onto chill rolls. This type of extrusion is discussed in detail below.

Flexible and rigid polyvinyl chlorides and certain types of ABS are usually calendered. The various elements that make up the desired compound are usually blended in ribbon blenders, then mixed or fluxed in batch mixers such as sigma or Henschel mixers. The mixed or fluxed batch is then discharged to a two-roll mill or a short barrel extruder. The milled product is then fed to a continuously turning calender (Fig. 8.2) [3]. Figure 8.3 shows a schematic of a typical polyvinyl chloride calendering operation [4]. Flexible polyvinyl chloride is usually calender-coated against release paper. The release paper is then rolled together with the polymer sheet and is continuously stripped from the polymer sheet as the sheet enters the thermoforming machine. Thermoplastic polyurethane is extruded from pellets into the nip of the two-roll mill of Fig. 8.2 and is also calender-coated onto release paper. Calendered sheet is usually available in the thickness range of 2 to 50 mils, 0.002 to 0.050 in or 50 to 1250 μm. Of course, calendering or the production of continuous uniform thickness sheet is only one of the ways in which the milled product can be treated. Pelletizing is the most common use of the milled product. Calendering usually yields a lower-cost sheet than extrusion. In addition, the physical properties of thermally sensitive polymers such as polyvinyl chloride are not compromised.

EX1008 (Part 3 of 3)
Yita v. MacNeil
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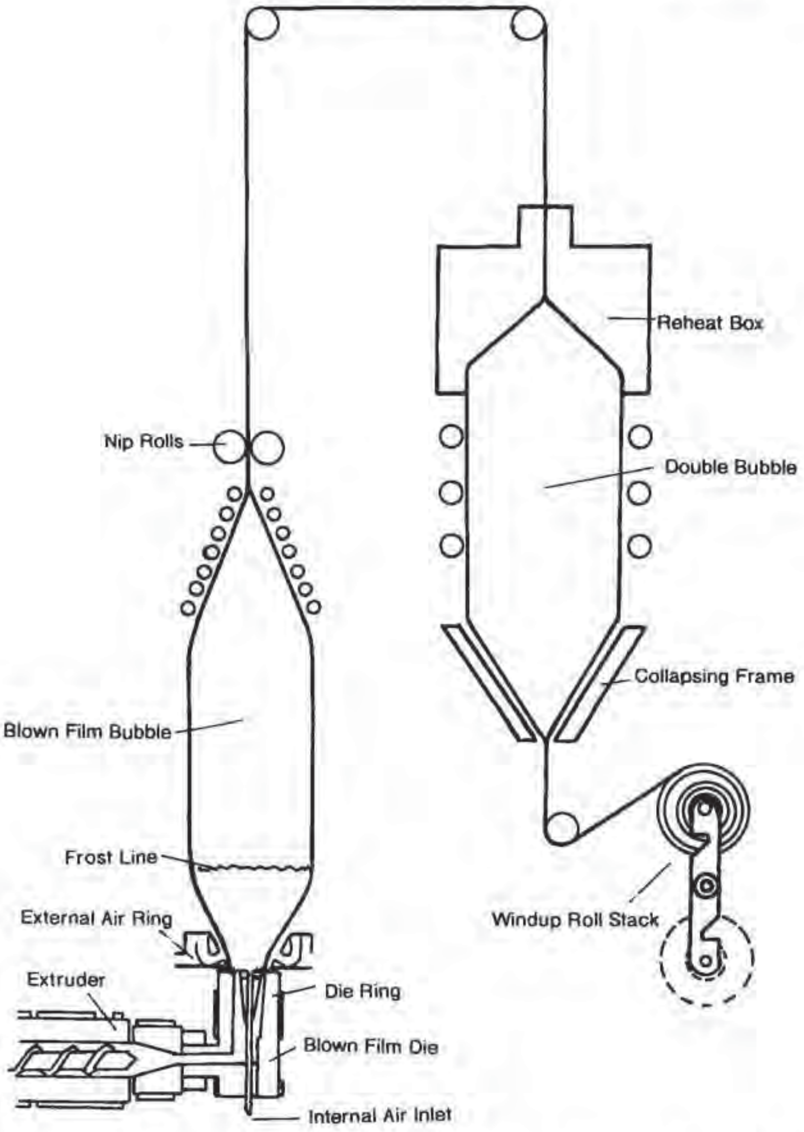
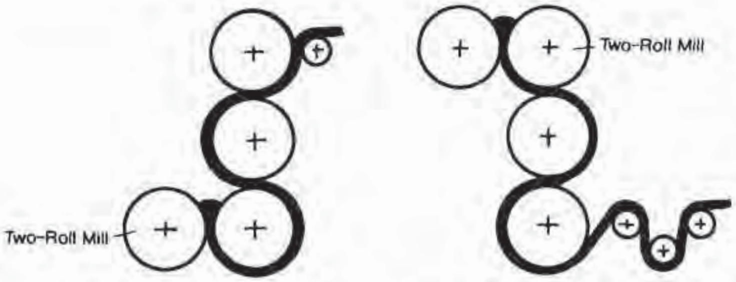


Figure 8.1 Typical blown film tower with optional double bubble stretching section [2]

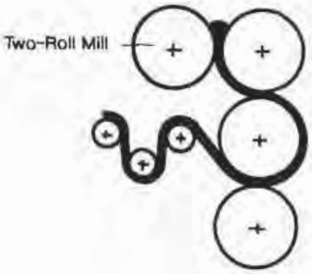
Regrind is difficult to accommodate in calendering, and dirt, gels and contamination can be a problem.

Films are also produced by solution casting. Any polymer that can be solvated or dissolved in a carrier can be cast into film. Typically, polymers that cannot be extruded or melt processed are solution cast into films. Examples include polyimides, polyazoles and latexes. Solution casting is usually a manual batch process although



"L" Calender Roll Stack Inverted "L" Calender Roll Stack

Figure 8.2 Two calendering roll stack configurations. Redrawn from [3] and used with permission of copyright owner



"F'" Calender Roll Stack

"Z" Calender Roll Stack

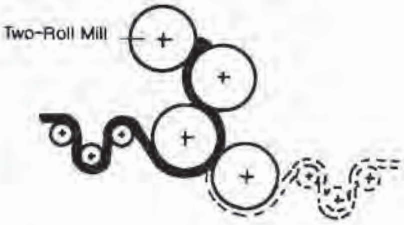


Figure 8.3 Two calendering roll stack configurations. Redrawn from [4] and used with permission of copyright owner

latex casting has been automated. With proper care, the resulting films are quite uniform in thickness and properties. Films having thicknesses of 1 mil, 0.001 in or 25 µm or less are common. Solvent cast films are usually quite expensive. Residual solvent can be a serious problem during reheating of the film in the forming operation.

Thin films are also needed when coextruded sheet is required. In this case, the polymer is melt-extruded with a secondary extruder into a special multilayer die. This is discussed below.

The criteria for judging the quality of thin films are the same as those for heavier gage sheet. These are discussed below. With thin films, there is a greater concern about gels, fish-eyes and other occlusions in the sheet simply because the dimensions of these defects may be equal to or greater than the thickness of the film.

8.3 Forming Sheet

As noted, calendering is used to produce thin-gage sheet to 50 mils, 0.050 in or 1250 μm in thickness. Its use is usually restricted to polymers that require fluxing or masticating and those that are thermally sensitive. Polyvinyl chloride is the dominant polymer produced as calendered sheet. High molecular weight polymethyl methacrylate is sought for clarity and chemical resistance in pools, spas, shower stalls, and most glazing applications. It is produced by cell casting [5]. Generally, methyl methacrylate monomer with its hydroquinone inhibitor removed is mixed with benzoyl peroxide catalyst and heated to 90-95°C. The catalyzed syrup is cast between two highly polished plates separated by flexible polyvinyl chloride or polyvinyl alcohol gaskets. The plates are held against the gaskets with carefully calibrated spring-loaded clips since the polymer increases in density or decreases in volume as its molecular weight increases. Temperature is maintained at 40°C early in the polymerization but gradually raised to 95-97°C after several hours to allow the polymerization to proceed to completion. The sheet is then cooled to below 40°C, removed from the plates and annealed for up to 2 hours at 140°C to minimize internal stresses.

Although the original batch process is still used to produce sheets with special sizes and thicknesses or acrylics that are lightly crosslinked, the continuous cell-cast process dominates the production of most commercial glazing acrylic sheets. The continuous process uses a monomer/polymer syrup containing up to 20% high-molecular weight polymer. Although the abrasion and chemical resistances are thought to be somewhat inferior to the batch cell-cast product, this product is substantially less expensive. Continuous cell-cast acrylic can also be crosslinked to improve impact strength. With proper temperature control, lower molecular weight polymethyl methacrylate pellets and granules are extruded into sheets using conventional single-screw extruders. Such products have lowered abrasion, impact and scratch resistances and may not have the surface quality and clarity of higher molecular weight acrylics. And extrusion-grade acrylics are usually not crosslinked.

Extrusion through a slot die is the primary method of producing sheet of thicknesses from 10 mils, 0.010 in or 250 μm to 500 mils, 0.500 in or 12 mm or more. Table 8.2 lists the scope of continuous screw extrusion techniques. Plasticating single-screw extruders and twin-screw extruders dominate production of sheet for thermoforming. Of the rest, two-stage and tandem extruders are used to produce foam sheet. This is covered in some detail in Chapter 9 on forming foam sheet.

Table 8.2 Types of Continuous Screw Extruders

Single-screw extruders	Multi-screw extruders
Melt fed or plasticating	Twin screw
Single stage	Gear pump
Multi-stage	Planetary gear
Plastic	Multi-screw (>2)
Rubber	

Single-Screw Extrusion

Figure 8.4 is a cut-away schematic of a conventional single-screw extruder. The basic elements are:

- Constant diameter flighted screw,
- Constant bore barrel,
- Zoned heater bands,
- Keyed bearing block,
- Feed hopper,
- Venting ports,

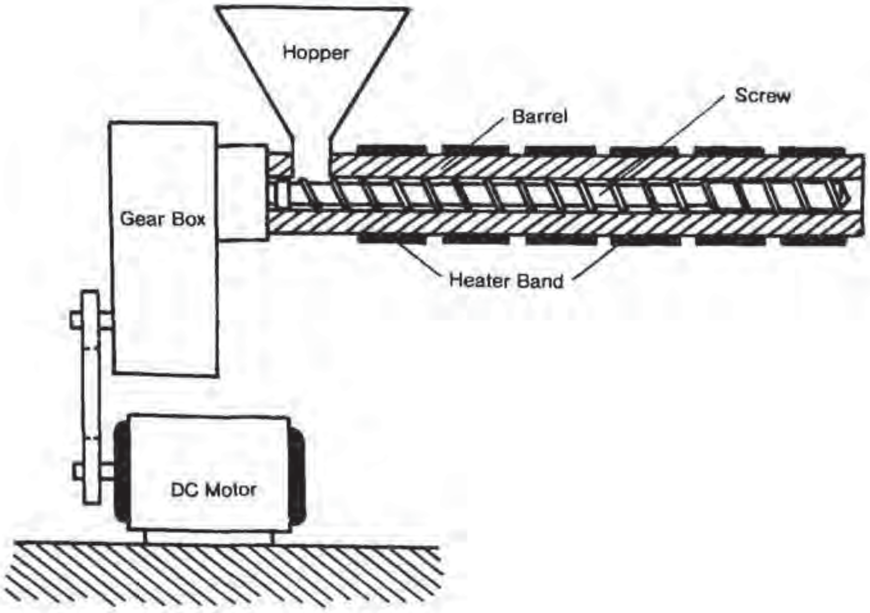


Figure 8.4 Schematic of single-screw extruder for thermoplastics

Table 8.3 Typical Compression Ratios Single-Screw Extruders

Polymer	Compression ratio
Regrind polyethylene fluff	4.5:1
Polyethylene powder	4.0:1
Regrind polystyrene foam	4.0:1
Other amorphous powders	3.5:1
Polypropylene pellets	3.0:1
PVC pellets	2.5:1
Polystyrene pellets	2.5:1
ABS pellets	2.5:1
Crystalline PET pellets	2.0:1
Polyamide (nylon) pellets	1.5:1

- Electric motor,
- Power coupling between motor and flighted screw, and
- Temperature and speed controls.

The most common screw is single-flighted. The screw serves to advance the polymer from the hopper to the die end, compressing, melting and increasing the pressure on it as it advances. The screw root increases along the screw, compressing and pressing the polymer against the heated barrel inner wall. The amount of compression is the *compression ratio*. Table 8.3 gives typical compression ratios for some polymers. The function of the screw is intellectually divided into three segments (Fig. 8.5) [6]:

- *Solids conveying*, where the plastic pellets or powder is augered from the hopper into the barrel. Energy transfer to the polymer is minimal. Friction between the semi-solid polymer and the barrel and screw surfaces dominates. Typically the screw root dimension does not change in this zone.

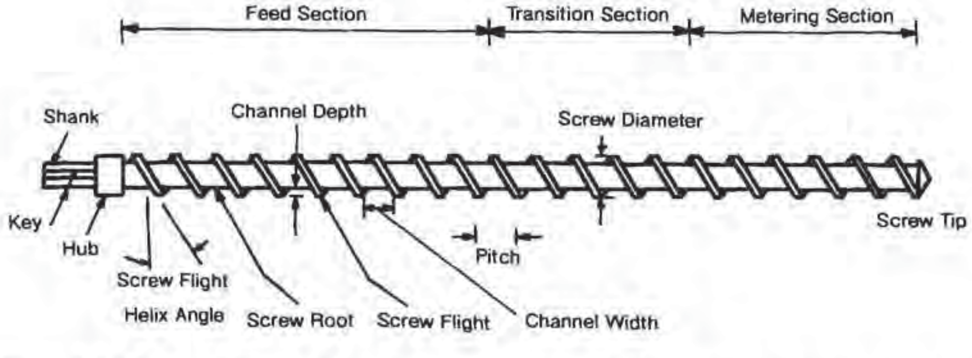


Figure 8.5 Schematic of screw for single-screw extruder with identification of various screw elements. Redrawn from [6] and used with permission of copyright owner

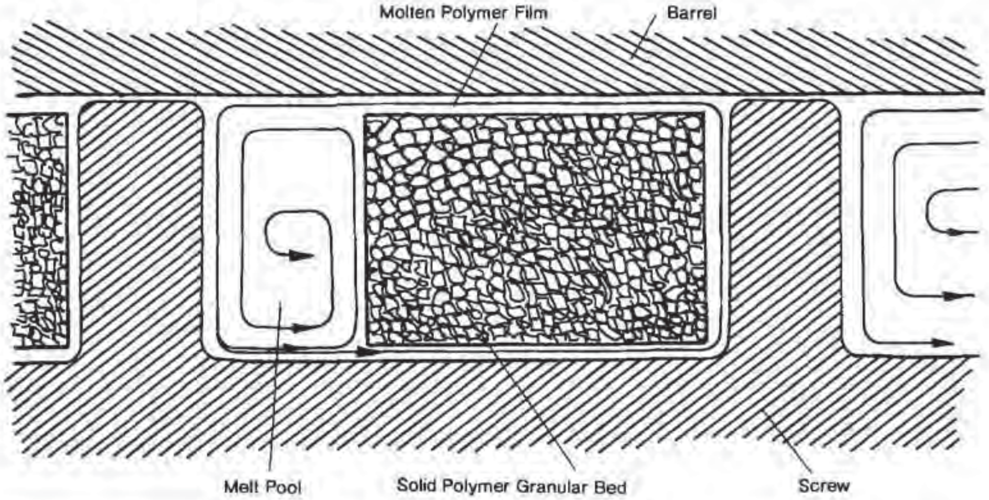


Figure 8.6 Schematic of the interrelationship of solid and melt polymer and screw and barrel in the plastication region for single-screw extruder [7]

- *Plasticating* or melting, where the compressed cake melts against the barrel surface and the melt is continuously conveyed into a pool at the front of the trailing flight (Fig. 8.6) [7]. In this zone, the screw root dimension linearly increases.
- *Melt pumping*, where the molten polymer is homogenized and compressed to build pressure necessary to flow through the extrusion sheet die. In this zone, the screw root dimension remains constant.

These extruders are usually described in terms of screw diameter and the screw length-to-diameter ratio, L/D. In the US, screw diameters are given in inches as 1, $1\frac{1}{2}$, 2, $2\frac{1}{2}$, $3\frac{1}{2}$, $4\frac{1}{2}$, 6, 8, 10, 12 and so on. In Europe and other metric areas, screw diameters are given in mm as 20, 25, 30, 35, 40, 50, 60, 90, 120, 150 and so on. L/D ratios are as low as 12:1 to 16:1 for rubber and thermoplastic elastomeric polymers to 20:1 to 36:1 for most commercial extruders to 48:1 for certain olefinic extruders. 24:1 and 30:1 extruders make up the bulk of sheet extrusion capability in the US while most European extruders are typically 30:1 to 36:1. Increased L/D allows for improved solids conveying and melt homogenization but increases the residence time and shear history on the polymer melt. Table 8.4 gives an overview of the capacities of extruders of various diameters [8]. Extruder throughput rates are also dependent on the type of polymer, as seen in Table 8.5 [9]. These rates represent extruder capacity when the flow rate through the die is not controlling. This is the case for most heavy-gage sheet extrusion. For thin-gage sheet extrusion, on the other hand, extruder throughput rates may be reduced by flow resistance through the die, as seen in Table 8.6 for the extrusion of 15 to 80 mil, 0.015 to 0.080 in or 400 to 2000 μm flat sheet of certain polymers [10]. Example 8.1 shows the relative output for a given extruder screw diameter.

Table 8.4 Typical Extruder Capacities [8]

Extruder size		Average power (HP)	Output		Barrel heater (kW)
(in)	(mm)		(lb/h)	(kg/h)	
$1\frac{1}{2}$	38	10–15	50–75	23–74	7.5
$2\frac{1}{2}$	64	20–30	120–160	54–73	21
$3\frac{1}{2}$	89	40–75	250–400	113–181	45
$4\frac{1}{2}$	114	80–125	400–700	181–318	75
6	152	150–225	800–1200	363–544	140
8	203	300–500	1500–2000	680–907	225

Example 8.1 Extrusion Capacity

Your thermoforming operation requires 40 in × 52 in × 0.060 in ABS sheet. Determine the number of 100 sheet pallets that can be produced from a 4-in extruder. Compare the output with the maximum output of that extruder. Determine the weight of each pallet.

From Table 8.6, the $4\frac{1}{2}$-in extruder with a sheeting die can produce 1320 to 1430 lb/h ABS. The specific gravity of ABS is $1.05\ \text{g/cm}^3 = 65.5\ \text{lb/ft}^3$. Thus the volumetric output is 20 to 22 ft^3/h. The volume of each sheet is 124.8 $\text{in}^3 = 0.072\ \text{ft}^3$. Therefore the extruder will produce 275 to 300 sheets per hour or 2.75 to 3 pallets per hour. The plastic on each pallet weighs 470 lb. According to Table 8.5, a $4\frac{1}{2}$-in extruder can plasticate 1170 to 1430 lb/h. Therefore, the extruder with a sheeting die is running at maximum capacity.

Many single-screw extruders have venting ports or vents at some location along the barrel. Some polymers contain small amounts of volatiles. These are removed prior to the sheeting die to eliminate foaming and to minimize microbubbles, pits and pores in the finished sheet. Venting screws usually have a decompression or let-down region just ahead of the vent, as seen in Fig. 8.7 [11]. Vented or devolatilizing extruders usually have L/Ds of 30:1 or more. Although vents can be plugged and the extruder run unvented, the screw is usually not optimum and so the polymer may be subjected to higher than normal shear and residence time at melt temperature. Vented extruders should not be used to dewater polymers. Polymers having high moisture level potentials should be thoroughly dried prior to being charged to the extruder.

Filtering the Polymer

A filter screen is usually placed between the end of the extruder and the die to catch contaminants, unmelted polymer and some gel particles. The generic screen is a plate with regularly spaced holes. Screens with different sized holes are usually grouped together to form a screen pack. A typical screen pack might have several 100 mesh

Table 8.5 Extruder Output Rates for Several Polymers [9]

Screw diameter		Throughput									
		LLDPE		LDPE		HDPE		PP		FPVC	
(mm)	(in)	(lb/h)	(kg/h)	(lb/h)	(kg/h)	(lb/h)	(kg/h)	(lb/h)	(kg/h)	(lb/h)	(kg/h)
64	$2\frac{1}{2}$	275–340	125–155	475–575	210–260	330–425	150–195	360–440	160–200	415–510	190–230
89	$3\frac{1}{2}$	550–650	250–300	925–1125	420–510	650–800	300–360	700–865	320–390	815–1000	370–450
114	$4\frac{1}{2}$	900–1100	400–500	1530–1870	695–850	1080–1320	490–600	1170–1430	530–650	1350–1650	610–750
130	5.12	1150–1400	525–650	1975–2400	900–1100	1390–1700	630–775	1510–1840	685–835	1740–2125	790–965
152	6	1600–1950	725–890	2700–3300	1225–1500	1920–2350	870–1065	2080–2540	945–1150	2400–2930	1090–1330
203	8	2840–3475	1290–1580	4800–5900	2200–2675	3400–4170	1550–1895	3700–4500	1680–2050	4260–5200	1940–2370

Screw diameter		Throughput									
		RPVC		ABS		HIPS		PMMA		PC	
(mm)	(in)	(lb/h)	(kg/h)	(lb/h)	(kg/h)	(lb/h)	(kg/h)	(lb/h)	(kg/h)	(lb/h)	(kg/h)
64	$2\frac{1}{2}$	220–270	100–120	360–440	160–220	490–615	225–280	415–510	190–230	285–350	130–160
89	$3\frac{1}{2}$	435–530	195–240	700–865	320–390	965–1200	440–550	815–1000	370–450	560–680	250–310
114	$4\frac{1}{2}$	720–880	325–400	1170–1430	530–650	1600–2000	725–900	1350–1650	610–750	925–1125	420–510
130	5.12	925–1135	420–515	1510–1840	685–835	2060–2580	935–1170	1740–2125	790–965	1200–1450	550–660
152	6	1280–1560	580–710	2080–2540	945–1150	2840–3550	1290–1615	2400–2930	1090–1330	1650–2000	750–900
203	8	–	–	3700–4500	1680–2050	5050–6320	2300–2870	4260–5200	1940–2370	2900–3500	1325–1600

Table 8.6 Polymer-Dependent Extruder Throughput Rates [10]

0.4 to 20 mm sheet thickness

Screw diameter (mm)	(in)	Screw L/D	Throughput PP (lb/h)	(kg/h)	HIPS (lb/h)	(kg/h)	ABS (lb/h)	(kg/h)	PET (lb/h)	(kg/h)
75	3	30–36	400–440	180–200	660–700	300–320	480–550	220–250	260–310	120–140
90	$3\frac{1}{2}$	30–36	570–640	260–290	990–1100	450–500	790–880	360–400	400–480	180–220
105	4	30–36	700–770	320–350	1320–1430	600–650	990–1060	450–480	530–620	240–280
120	$4\frac{1}{2}$	30–36	1050–1210	480–550	1650–1870	750–850	1320–1430	600–650	700–790	320–360
150	6	30–36	1430–1650	650–750	2400–2650	1100–1200	1870–2000	850–900	1060–1200	480–540

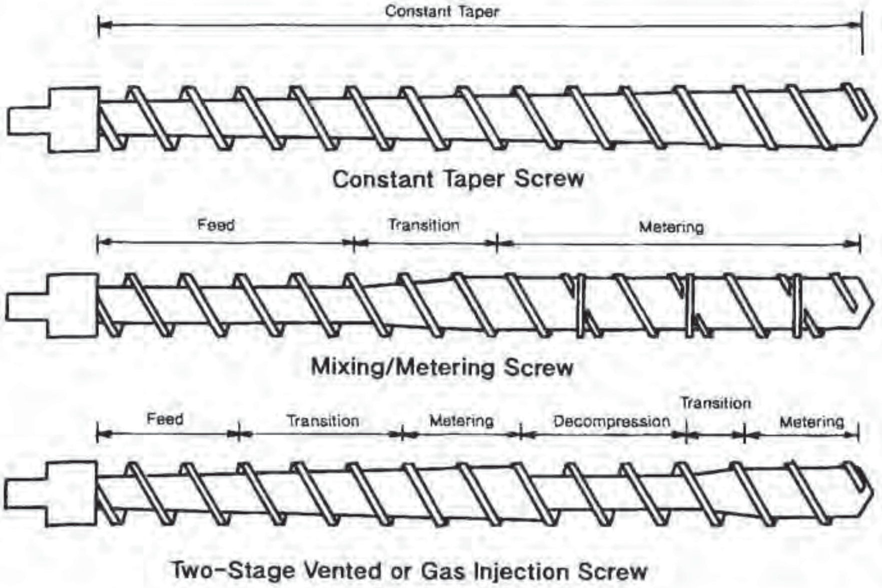


Figure 8.7 Schematics of various screw configurations for single-screw extruders. Figure redrawn from [11] and used with permission of copyright owner

screens placed against several 50 mesh screens. The screen pack is then placed against a breaker plate. Screens can be plates with drilled holes, welded wire mesh, woven wire cloth or porous sintered metal. Filter screens are used throughout the sheet extrusion industry and are especially important when running large percentages of regrind, particularly if the polymer is an intrinsic gel former such as polyethylene terephthalate, polyamide, low-density polyethylene, polypropylene and rigid polyvinyl chloride. Pigmented polymers can also cause substantial filtering problems, particularly in regrind. Pressure drop across the filter screen must be continually monitored to determine when the screen has clogged and needs to be replaced. Continuous screen changers are expensive but useful if the polymer is heavily contaminated.

Flow Improvement Devices

In recent years, there has been great progress in improved plastication and homogenization of the polymer melt, primarily through improved screw design and motor drive and thermal feedback controls. Some typical plasticating and mixing screw sections are shown in Fig. 8.8 [12]. Surging, the bane of quality sheet production, has been greatly reduced. Gear pumps and static mixers are used to further improve melt quality prior to the die. Figure 8.9 is a schematic of an extruder having these features. Static mixers are dissipative devices that improve laminar mixing by separating the melt stream into many layers, reorienting the layers and then

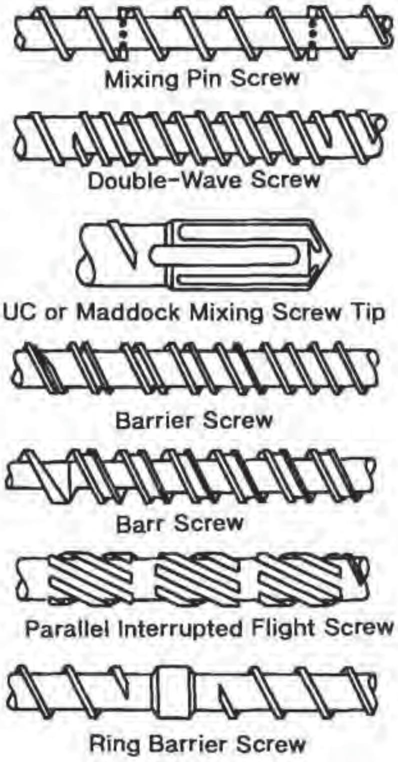


Figure 8.8 Schematics of various mixing sections for single-screw extruders. Figure redrawn from [12] and used with permission of copyright owner

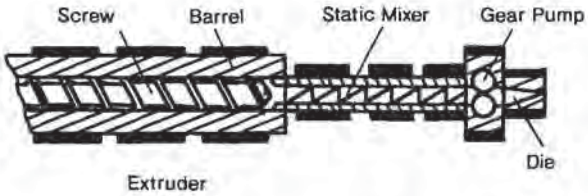


Figure 8.9 Schematic of extruder/static mixer/melt pump/die configuration

recombining the layers in a different order. There are more than 30 types of static mixers [13]. The mixing section of a Kenics mixer is shown in Fig. 8.10 [14]. Improved homogenization or mixing efficiency must be weighed against increased shear history and pressure loss through these devices. Today, static mixers are used when the screw design is not optimum for the polymer, when the melt pumping zone on the screw is too short or when the overall extruder L/D is too short. The relative effectiveness of many of these devices is reviewed elsewhere [15-18].

Gear pumps or melt pumps are characterized as "closely intermeshing counter-rotating twin screw extruder(s)" [19]. Details are shown in Fig. 8.11 [20]. One gear is driven. It drives the other. The polymer melt is engaged by the gear teeth and forced

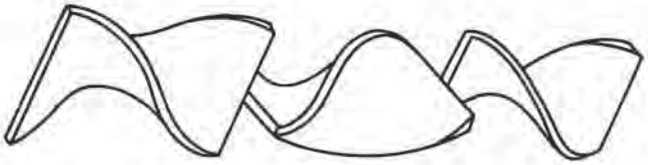


Figure 8.10 Kenics static mixer element configuration. Redrawn from [14] and used with permission of copyright owner

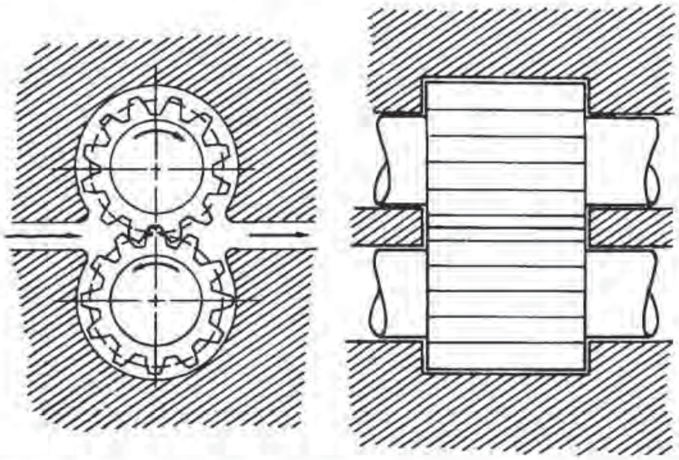


Figure 8.11 Two views of gear or melt pump showing intermeshing gear rotation relative to flow direction [20]

against the pump wall. The remeshing of the gear teeth forces the polymer from the pump. Gear pumps were originally employed to counteract surging and secondary flow effects from screw flights. Today they are used primarily to boost melt pressure prior to the die. Owing to leakage between the gear teeth and pump wall and between the edge of the gears and the pump wall, the pumps are not positive displacement pumps. Although the typical volumetric efficiency is 90% or so, low viscosity melts and high pressure drops can reduce efficiencies to 50% or less [20]. Gear pumps are high shear devices. As a result, it is not unusual to see melt temperature increases of 10°C or more as the polymer passes through the gear pump. These pumps are not recommended for thermally sensitive polymers such as polyethylene terephthalate and rigid polyvinyl chloride.

Pressure and Temperature in an Extruder

The stated purpose of an extruder is to plasticate or melt the polymer and to deliver the conditioned, homogeneous polymer melt at a constant flow rate. The majority of pressure buildup occurs in the melt pumping zone. The melt is advanced by drag flow and retarded by pressure flow. Drag flow is the result of the relative motion between the screw and the barrel. Pressure flow is a measure of the viscous resistance to the flow. A simple pressure drop-flow rate relationship for a purely viscous Newtonian fluid is:

$$Q = \frac{WHF_d V_z}{2} - \frac{WH^3 F_p g_z}{12\mu} \tag{8.1}$$

where W is the width of the flow channel or the right-angle distance between flights, H is the depth of the flow channel or the distance between the screw root and the barrel and is the Newtonian viscosity. $V_z = \pi DN \cos \phi$, where D is the screw diameter, N is the speed of the screw, rev/min, and ϕ is the screw helix angle. 17.65° is the helix angle for a single-flighted screw. $g_z = \Delta P/L$, the pressure drop along the flow channel, and L is the length of the flow channel. F_d and F_p are correction factors that account for screw curvature, leakage and other dissipative effects and are usually less than unity.

Equation 8.1 can be written simply as:

$$Q = AN - \frac{B}{\mu}\Delta P \tag{8.2}$$

This is the *extruder performance characteristic* equation. Simply stated, melt-pump controlled extruder output is directly related to extruder speed and is diminished by high exit pressure and polymer viscosity. Similar relationships are available for power-law fluids [22]. The extruder performance characteristic is shown in Fig. 8.12 [23]. This will be coupled with the die performance characteristic later.

Viscous dissipation or frictional heating of the polymer is always of concern. The maximum temperature increase is determined by assuming that all the power used to build pressure in the polymer is converted to heat [24]. The power is given as:

$$HP = \dot{V} \cdot \Delta P \tag{8.3}$$

If the dissipation is adiabatic or without loss to the environment, the increase in bulk melt temperature, ΔT, is given as:

$$\Delta T = \frac{\Delta P}{\rho \cdot c_p} \tag{8.4}$$

This represents the maximum amount of viscous dissipation anticipated on extrusion. Example 8.2 shows the typical heat buildup order of magnitude of polymer melts.

Example 8.2 Heat Buildup in ABS

Determine the heat buildup in ABS and HDPE if the melt pressure differential is 4000 lb_f/in^2 *[27.6 MPa]. For ABS,* $\rho = 65.5\ lb/ft^3$ *and* $c_p = 0.4$. *For HDPE,* $\rho = 60\ lb/ft^3$ *and* $c_p = 0.98$.

The temperature increase is given from Equation 8.4. For ABS:

$$\Delta T(°F) \cdot 65.5\,\frac{lb}{ft^3} \cdot 778\,\frac{ft}{lb} \cdot \frac{lb_f}{°F} \cdot 0.4 = 4000\,\frac{lb_f}{in^2} \cdot 144\,\frac{in^2}{ft^2}$$

$$\Delta T = 28°F \text{ for ABS}$$

Using the same equation:

$$\Delta T = 13°F \text{ for HDPE}$$

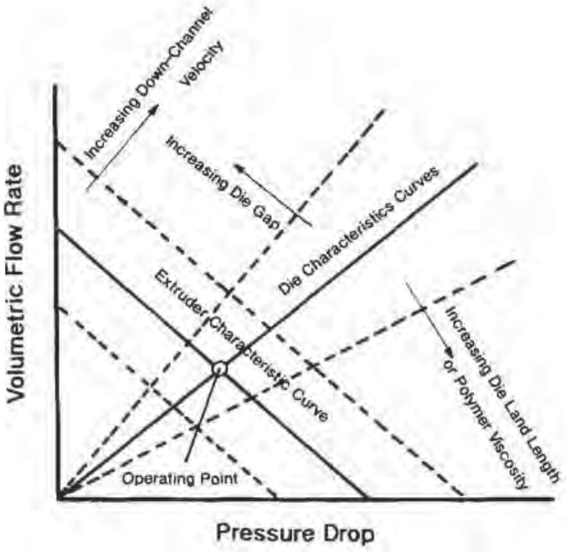


Figure 8.12 Interrelationship between flow rate-pressure drop characteristics of extrusion die and flow rate-pressure drop characteristics of single-screw extruder. Adapted from [23]

Sheet Die Concepts

All the pressure created by the extruder is dissipated in the sheet die. The most common sheeting die has a rectangular slot outlet. Annular dies are used for foams and blown film. Figure 8.13 shows two views of one type of flat sheet die with attendant nomenclature [25]. Figure 8.14 shows an annular die for the production of polystyrene foam [26]. The objective of the slot die is to efficiently and uniformly spread the melt from the cylindrical cross-section inlet to the rectangular slot outlet. Figure 8.15 shows several flow channel shapes for slot dies [27]. The coathanger die is most common in the US. Figure 8.16 is an example of a small coathanger die for producing 440 lb/h or 220 kg/h nominal 0.100 in or 2.5 mm thick polystyrene sheet [28]. The land height is constant at 0.100 in or 2.5 mm. As is apparent, the majority of the pressure loss is in the land. The pressure drop expression for a viscous-only Newtonian fluid is:

$$\Delta P = \frac{12\mu L\dot{V}}{BH^3} \tag{8.5}$$

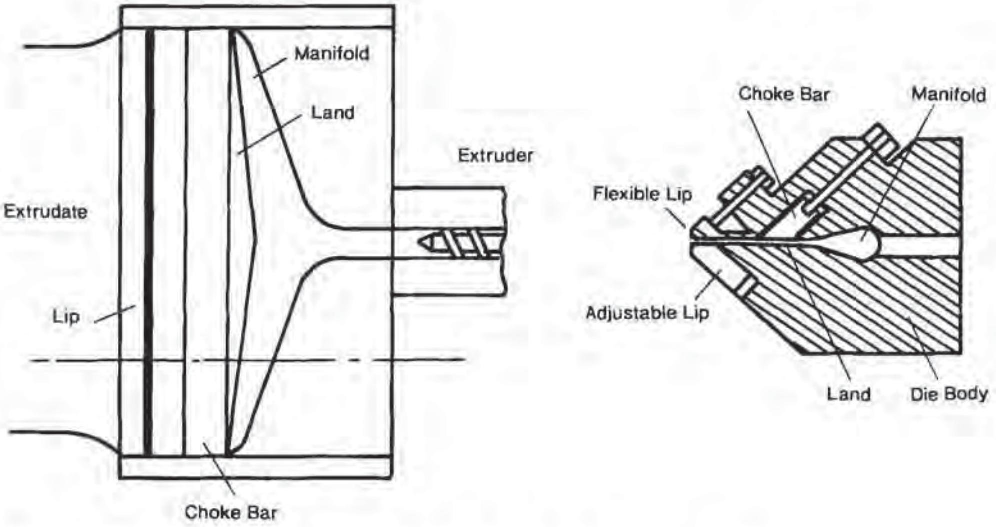


Figure 8.13 Characteristics of one type of flat sheet die. Adapted from [25]

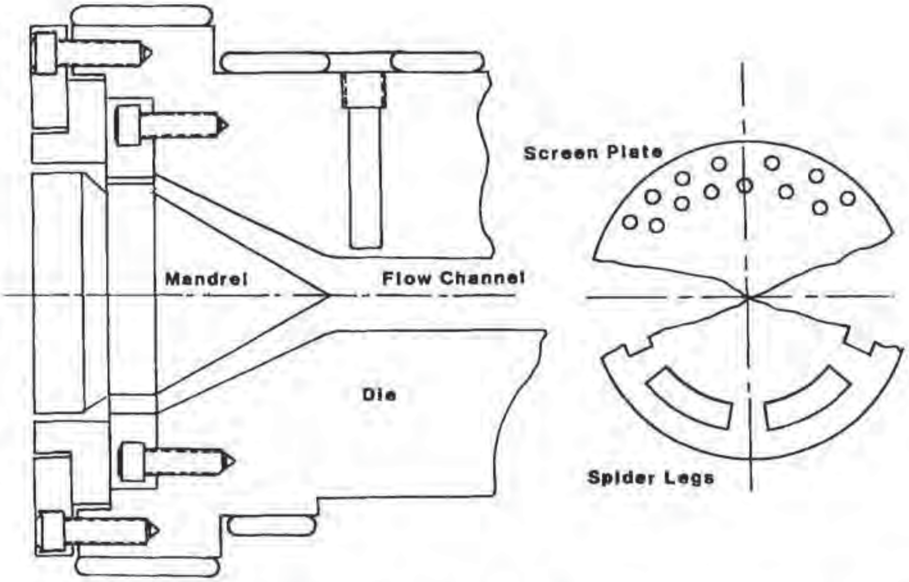
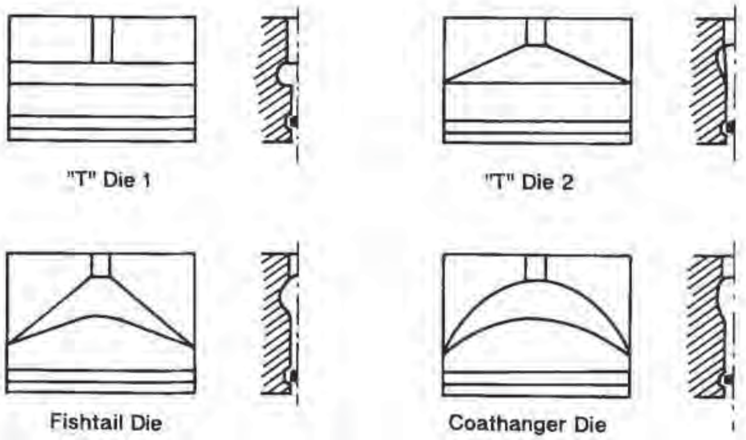


Figure 8.14 Characteristics of an annular sheet die used in low-density foam production. Two methods of holding mandrel in place are shown. Redrawn from [26] and used with permission of copyright owner


"T" Die 1

"T" Die 2

Fishtail Die

Coathanger Die

Figure 8.15 Four types of flat sheet dies. Redrawn from [27] and used with permission of copyright owner

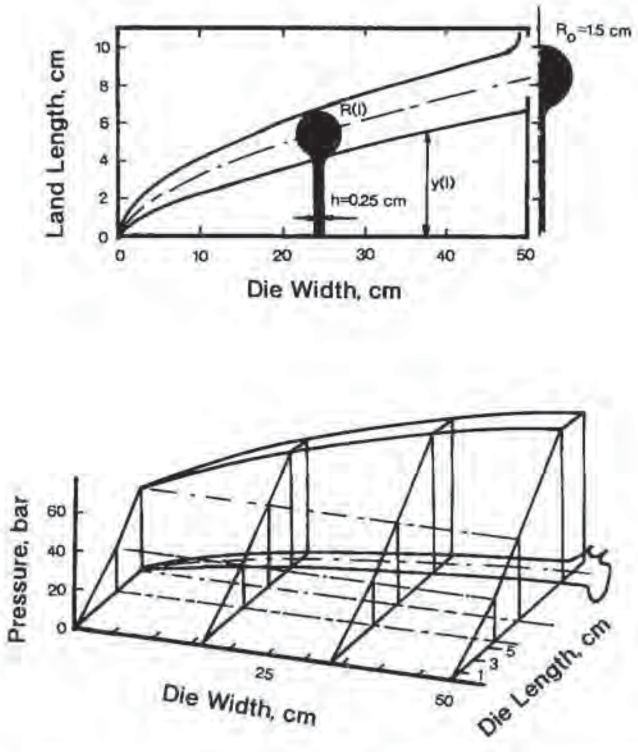


Figure 8.16 Characteristics of a specific type of manifold/land die for sheet production. Redrawn from [28] and used with permission of copyright owner

where is the Newtonian viscosity, L is the length of the channel, $\dot{V}$ is the flow rate, B is the channel width and H is the channel depth. Since the pressure drop is equal everywhere along the die, $L \equiv y_o$. Example 8.3 illustrates the capacity of a slot die.

Example 8.3 Capacity of a Slot Die

Determine the flow rate through a die land with the following dimensions: $B = 50$ in, $H = 0.100$ in, $y_o = 20$ in. The polymer is PMMA with a melt viscosity of 1000 Pa · s and the melt pressure is 30 MPa at 200°C. How many 64 in long sheets are produced per hour?

In consistent unit s, $B = 127$ cm, $H = 0.254$ cm, $y_o = 50.8$ cm. From Equation 8.5, the flow rate is given as:

$$\dot{V} = 30 \times 10^6 \frac{\text{Pa} \cdot 127 \cdot (0.254)^3 \cdot \text{cm}^3}{12 \cdot 1000 \cdot \text{Pa} \cdot \text{s} \cdot 50.8} = 102 \text{ cm}^3/\text{s}$$

$$\dot{m} = \rho \cdot \dot{V} = 1.05 \frac{\text{g}}{\text{cm}^3} \cdot 102 \frac{\text{cm}^3}{\text{s}} = 107.5 \frac{\text{g}}{\text{s}} = 853 \frac{\text{lb}}{\text{h}}$$

The cross-section area of the die is $B \times H = 32.3$ cm². The velocity is:

$$v = \frac{102}{32.3} \frac{\text{cm}}{\text{s}} = 373 \frac{\text{ft}}{\text{h}} = 70 \text{ 64-in long sheets per hour}$$

Equation 8.5 is written symbolically as:

$$Q = C \cdot \Delta P/\mu \tag{8.6}$$

This is the *die performance characteristic* equation, showing that the Newtonian flow rate through a slot die (or any other shaped die, for that matter) is directly proportional to the available pressure and inversely proportional to the melt viscosity. The die performance characteristic is shown in schematic in Fig. 8.12. Example 8.4 illustrates the interrelationship between the extruder characteristics and the die characteristics. The maximum temperature increase due to viscous dissipation is also obtained from these equations as:

$$\Delta T_{\max} = \frac{\Delta P}{\rho \cdot c_p} = \frac{E \cdot \mu N}{\rho \cdot c_p} \tag{8.7}$$

Increased screw speed and viscosity yield increased viscous dissipation, as is expected and observed.

Example 8.4 Matching the Die to the Extruder

The flow rate from an extruder must match the flow rate from the die. Consider an extruder to be melt pump controlled. For a Newtonian fluid, show that the flow rate is independent of pressure and that the maximum pressure is directly proportional to the screw speed.

Solve Equation 8.6 for pressure drop:

$$\Delta P = \mu \frac{Q}{C}$$

where C represents geometric parameters. Substitute this into Equation 8.2:

$$Q = AN - B\frac{\Delta P}{\mu} = AN - \frac{BQ}{C}$$

where A and B represent geometric parameters. Solving for Q:

$$Q = \left(\frac{AC}{B + C}\right)N \equiv DN$$

Note that the flow rate is *independent* of viscosity as well as pressure.

To determine the maximum pressure, substitute this expression into the equation for pressure drop, above:

$$\Delta P = \frac{\mu DN}{C} \equiv \mu EN$$

The maximum pressure is directly proportional to the polymer viscosity and screw speed.

It is apparent that actual matching can be considerably more complex than the examples just cited. Most polymers are non-Newtonian. The melt pumping portion of the extrusion process does not always dominate. In certain cases, pressure buildup during plastication is important. Screw design can involve depressurization zones as in the venting area and the overall pressure drop-flow rate relationship will be altered [29]. Figure 8.17 shows some of these effects [30]. Although computer feedback control of screw speed and barrel temperature and modern screw design have eliminated much of the extruder-induced processing problems, the die operating conditions can introduce some problems. A coupling between a periodic 4.5°C temperature fluctuation in the die and a periodic 4.5% variation in sheet thickness is seen in Fig. 8.18 [31].

Gage Thickness Monitoring and Control

For thin-gage sheet to 30 mils, 0.030 in or 750 μm or so, in thickness, beta and gamma gages are used to measure sheet thickness. The reading is then fed back to control bolts that differentially open or close the die gap at specific places along the die length. Heated bolts are commonly used in this application (Fig. 8.19) [32]. For heavy-gage sheet, sheet thickness can be measured using beta or gamma devices, but manual micrometer measuring of the cut sheet is common, particularly on short runs. Die gap control is done by manually adjusting the die bolts.

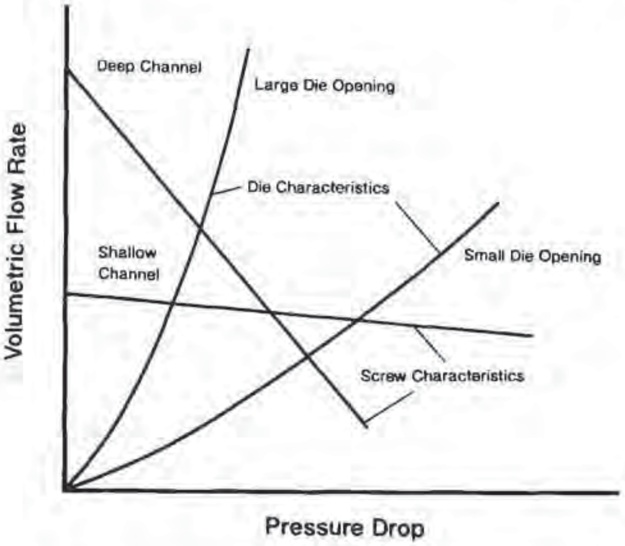


Figure 8.17 Comparison of die and extruder characteristics for manifold/land dies and single-screw extruders. Adapted from [30]

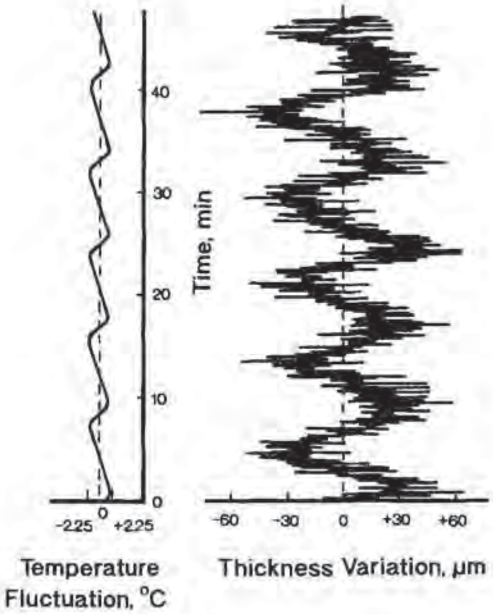


Figure 8.18 One example of interrelationship between process parameter, temperature, and product quality, sheet thickness variation. Redrawn from [31] and used with permission of copyright owner

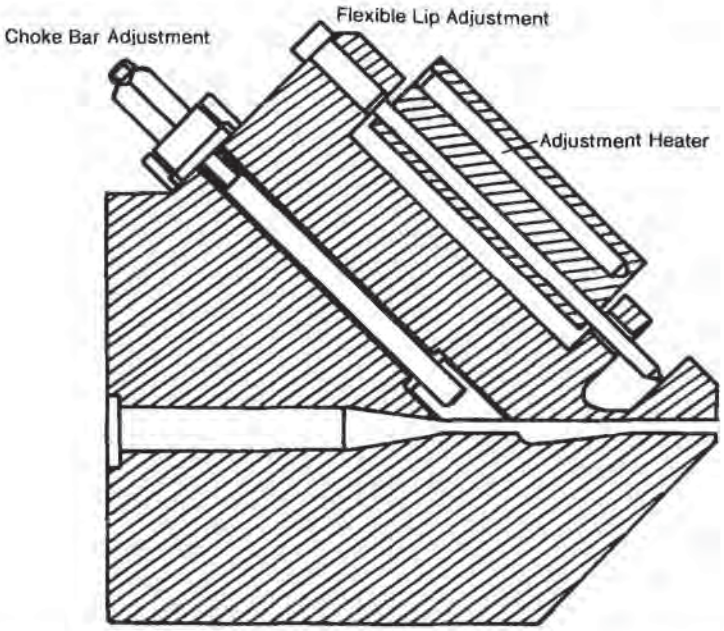


Figure 8.19 Sheet die with thermal bolt sheet thickness control. Redrawn from [32] and used with permission of copyright owner

Twin-Screw Extrusion

Two styles of twin screws are commercial. Figure 8.20 shows parallel constant diameter screws and conical screws [33,34]. Parallel screw machines dominate. There are four major ways in which the two screws interact as shown in Table 8.7 [35,36]. In addition, the non-interacting screws can have tangential contact or can be separated by a gap. These variations are shown in Fig. 8.21 [35]. Twin-screw machines usually have modular screws. That is, the screws are custom constructed of several types of elements such as mixing elements, kneading elements, forward pumping and backward pumping screw elements, lefthanded and righthanded elements and so on. Twin-screw extruders excel in their abilities to customize the way in which the polymer is plasticated and pumped. With proper selection of the various elements, twin-screw extruders provide superior mixing, excellent heat transfer, large melting capacity, excellent devolatilization capability, unique ability to allow for down-extruder addition of fillers, reinforcements, fire retardants and other adducts, low shear history and hence minimal heat generation, and/or accurate stock temperature control[1]. Further, the feed rate to twin-screw

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[1] Note that not all these attributes can be achieved in a single screw configuration. For example, twin-screw extruders are used extensively for compounding, where adequate mixing usually involves high shearing and hence heat generation.

Table 8.7 Twin-Screw Arrangements [35,36]

Corotating intermeshing	Werner & Pfleiderer
	LMP
	Windsor
	Berstorff
	Betol
	Mitsubishi Heavy Industries
	Kobe Steel
	IKG
	Colombo
Corotating non-intermeshing	No equipment
Counterrotating intermeshing	Leistritz
	Krupp
	Anger
	Japan Steel Works
Counterrotating non-intermeshing	Werner & Pfleiderer
	Baker Perkins
	Farrel Corp.
	Welding Engineers
	Japan Steel Works
	Kobe Steel

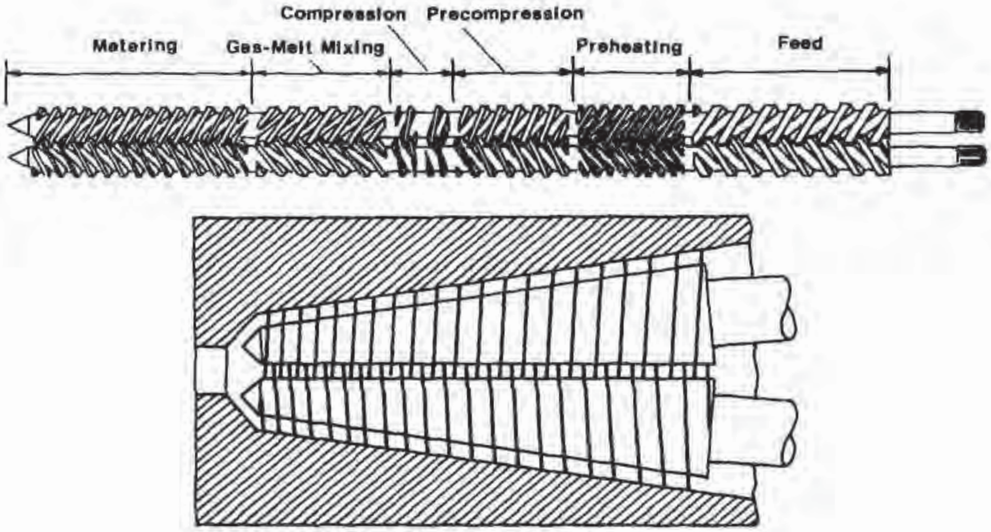

Figure 8.20 Characteristics of parallel intermeshing twin screws (top) and conical intermeshing (bottom) twin screws. Redrawn from [33,34] and used with permission of copyright owner

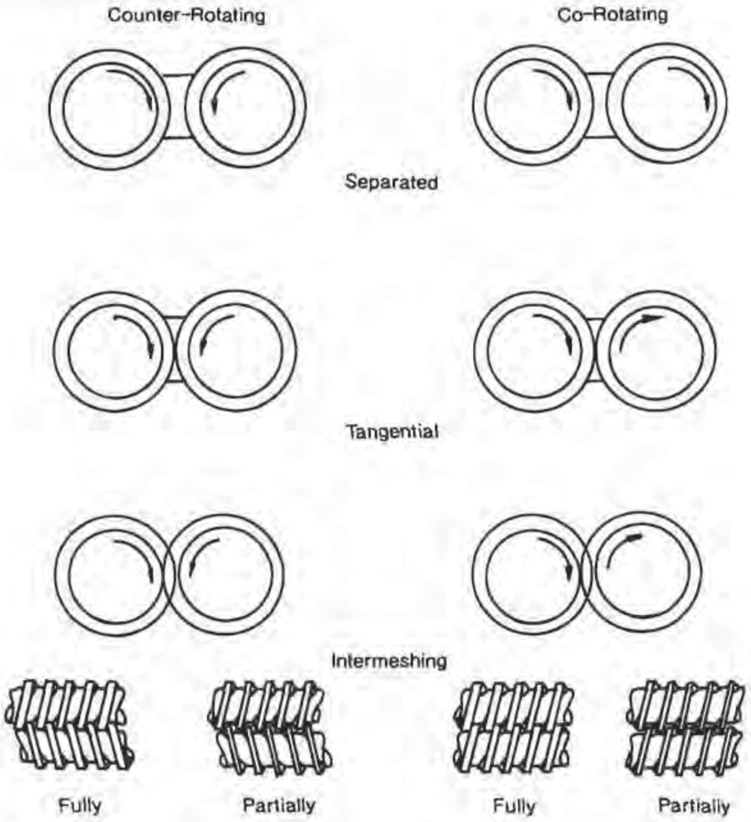

Figure 8.21 Characteristics of several twin screw configurations. Redrawn from [35] and used with permission of copyright owner

extruders is decoupled from the screw speed. Twin-screw extruders are typically starve- and meter-fed. The extruder screw speed can be changed to affect the mixing characteristics with no effect on flow rate. The primary applications for twin-screw extrusion are in compounding, devolatilizing, polymerizing and molecular weight appreciating or "finishing". Compounding includes addition of adducts such as brighteners, ultraviolet and thermal stabilizers, fire retardants, as well as fillers, dry and liquid pigments, solid and liquid foaming agents, and short and long glass fibers. Certain thermally sensitive polymers such as most polyvinyl chlorides and certain acetates and polyamides do best when extruded using twin-screw extruders. Despite major theoretical efforts to explain flow behavior in twin-screw extruders [37,38], the many available elements and machine configurations confounds the prediction of screw geometry when polymer properties, expected shear and heat histories, and processing conditions are known. Likewise, processing conditions and shear and heat histories cannot now be predicted from given screw geometries and polymer properties.

If the twin-screw extruder is used simply as a method of solids conveying, plasticating and pumping polymer melt, typical extruder lengths can be shorter than those of single-screw extruders, that is, 18:1 to 24:1. If the twin-screw extruder is also used to add plasticizer, for example, to polyvinyl chloride, or calcium carbonate to polypropylene, the extruder needs to be longer. Multipurpose twin-screw extruders are typically 24:1 to 30:1. If the twin-screw extruder is used for several functions, such as blending colorant masterbatches and mixing plasticizers into polyvinyl chloride for example, a shorter extruder can be used if its extrudate is fed to the throat of a short-barreled single-screw extruder to build pressure in the compound melt.

The twin-screw extruder is usually mounted directly against the sheeting die, with only a filter screen and breaker plate between.

8.4 Roll Stacks

The sheet extrudate is usually laid against a cold polished metal surface to quench it prior to rolling or guillotining. Commercially, sheet cooling occurs continuously against polished rolls. The rolls are called polish rolls or chill rolls and the assemblage is called a roll stack or chill roll stack. Several roll stack configurations are shown in Fig. 8.22 [39,40]. The most common roll stack in the US is the vertical same-size three roll stack with sheet moving either in the down direction if the rolls are relatively small or in the up direction of the rolls are large. Classically, the extrudate is laid directly onto the polish roll as close to the nip as the die can be placed (Fig. 8.23) [41]. The extruder speed and the roll speed should be matched to minimize any bank, bead or pencil. The rolls serve several functions:

- Shaping. The extrudate may not be uniform in thickness and the extrudate edges or "beads" may be dogbone in shape. The rolls aid in making the sheet more uniform.
- Cooling and rigidifying the sheet. In order for the sheet to retain its shape it must be cooled substantially below its amorphous glass transition temperature or its crystalline melting temperature. The rolls remove the heat by conduction to the coolant circulating within the rolls.
- Producing a uniform sheet temperature and therefore flat sheets. Sheet curling and other nonplanar effects can be caused by improper cooling that results in an unsymmetrical temperature profile through the sheet.
- Gage thickness control. Although nearly all the gage thickness control should be done by setting die gap, some thickness control can be achieved in the nip between the polishing roll and the pressure roll.
- Surface texture. The most common roll stack uses highly chrome-polished rolls to provide a smooth, glossy texture to the sheet. However, where the application warrants, the polish roll is replaced with a textured roll. Textures can range from semi-gloss, "haircell" or matte, to leather- and wood-grain.

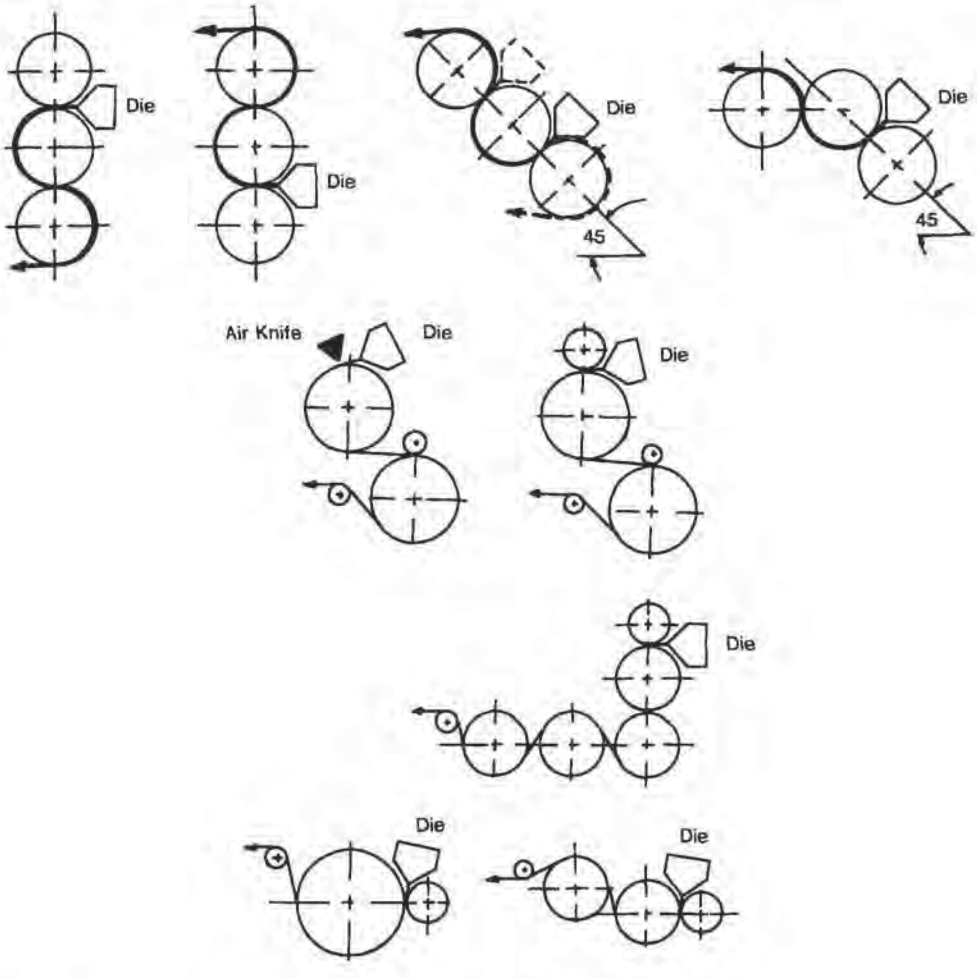

Figure 8.22 Several roll-stack configurations. Adapted from [39,40]

- Machine-direction orientation. In certain cases, such as with oriented polystyrene, machine-direction orientation is needed. By differentially varying the speeds of the various rolls, some orientation can be added. If substantial orientation is needed, standard orienting equipment is used[1].

Residual orientation in both machine-direction and cross-direction can dramatically affect thermoformability of polymer sheet. As a result, differential roll speeds and "banking" or using the nip between the polish roll and the pressure roll to spread the extrudate are not recommended for the production of thermoformable sheet. Figure 8.24 shows a typical temperature profile through an 80 mil, 0.080 in or 2 mm

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[1] See Section 8.9 for information on biaxial orientation.

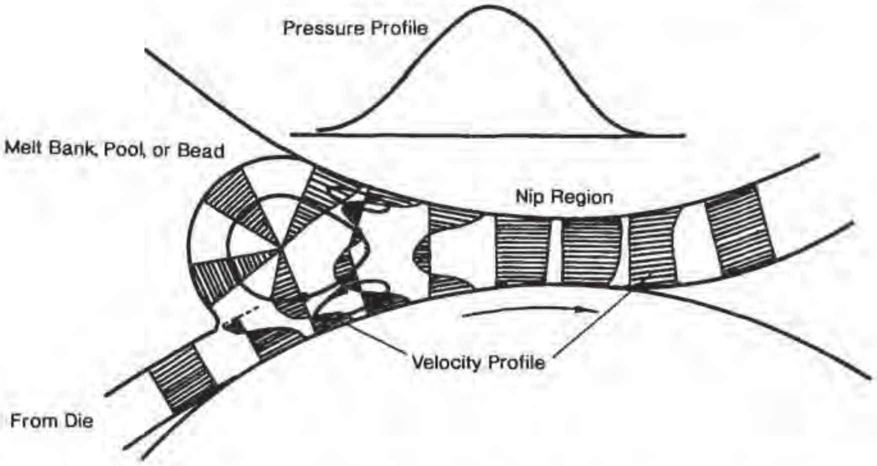

Figure 8.23 Velocity profile of polymer melt in nip region of roll stack. Redrawn from [41] and used with permission of copyright owner

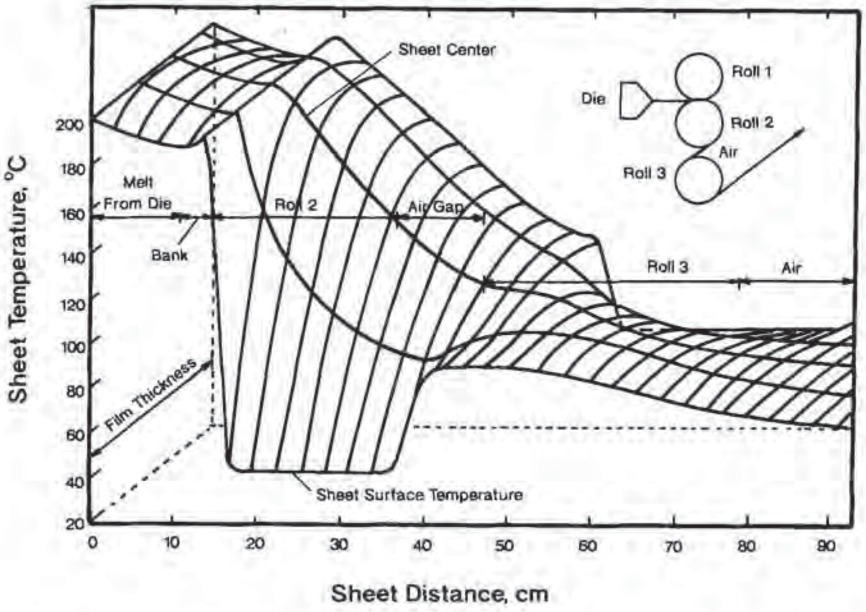

Figure 8.24 Time- or distance-dependent sheet temperature during cooling of 80 mil polystyrene, PS on down-roll chill stack, insert. Redrawn from [42] and used with permission of copyright owner

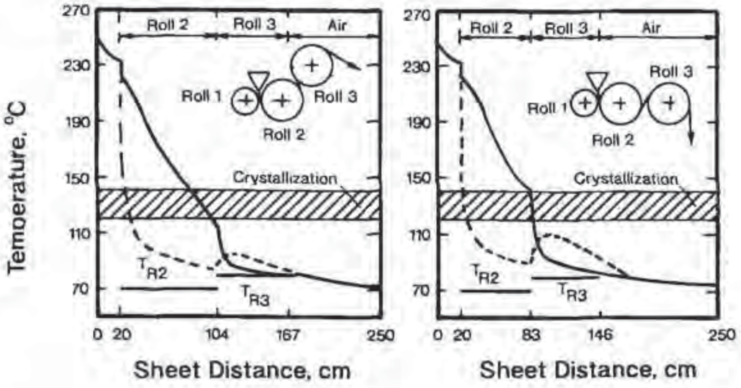

Figure 8.25 Two examples of sheet temperature profile for PP extrusion onto chill roll stacks. Roll stack configurations shown in inserts

polystyrene sheet in contact with a chill roll stack [42]. Banking is particularly critical for certain polymers such as PP and PET. An additional analysis is given for the cooling of CPET in Chapter 9.

For polymers that cool rapidly or crystallize slowly, care must be taken to size the chill roll diameter to the sheet thickness and the rate of extrusion. Figure 8.25 shows the effect of chill roll configuration on the time-dependent temperature of PP sheet [43]. The cooling rate can change the degree of crystallization of PP. For example, if the chill roll temperature is changed from 100°C to 40°C, the cooling rate of 1.5 mm or 0.060 in thick PP initially at 230°C changes from 1°C/s to 10°C/s. This changes the room-temperature density from 0.905 to 0.891 g/cm^3 and the degree of crystallization from 50% to 37% [43]. Changing the morphological characteristics of a polymer such as polypropylene can also change the size of the spherulites, thereby changing the polymer impact strength and haze level. More important to thermoformers, changes in crystallization level and spherulite size may dramatically alter the polymer sag characteristics [44] and therefore the forming window[1]. The effect of chill roll residence time is even more important with very slowly crystallizing polyethylene terephthalate.

8.5 Sheet Trimming

Two general types of trimming are used in extrusion of thermoformable sheet. Gross sheet width control in the machine direction is usually carried out with die deckles. These are steel bars that are either clamped to the die edges or are fitted into the die

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[1] An extended discussion on the problems and desirable properties of polypropylene in thermoforming is given in Chapter 9.

land when the die halves are assembled (Fig. 8.26). Since deckles are usually not carefully machined and heated, melt usually pools behind them. Long residence times at melt temperatures can lead to thermal degradation in even the most heat-insensitive polymers. Some polymers such as rigid polyvinyl chloride and polyethylene terephthalate can suffer substantial thermal damage even at short times, so deckling is not recommended for anything but short production runs. For thin-gage sheet, sheet is trimmed to width with fixed industrial razor blades (Fig. 8.27) [45]. For heavier gage sheet of rigid polymers such as HIPS, RPVC, ABS, PC and PMMA, razor blades are used to score the warm sheet and the edge trim is manually broken off after guillotining or saw cutting. If the sheet is very thick, the edges are band-saw or circular-saw cut just ahead of the guillotine.

Cross-sheet cutting in thin-gage sheet is done at the take-up roll with a flying razor blade or knife. Heavier gage sheet that is pallet stacked is cut either with a mechanical or hydromechanical shear known as a guillotine. To achieve a square edged cut, these shears sit at an angle to the machine direction. Circular and band saws are used to cut very heavy sheet. While hot wires are used on occasion, the cutting rate is usually too slow for very heavy-gage sheet. Dust and polymer slivers are common nuisances in mechanical cutting and fumes and odor are problems with hot wires.

8.6 Take-Off and Take-Up Rolls

Thin-gage sheet is usually delivered to the thermoformer in large-diameter rolls. Some polymers such as polypropylene and certain types of low-density polyethylene have inherent blocking or high cohesion tendencies. This causes the layers of sheet on a roll to stick together, sometimes so tenaciously that the sheet cannot be stripped from the roll without substantial force. Antiblocking agents such as silica and/or fatty acid slip agents such as oleamide are usually added to the polymer if this is a known problem. Since slip agents usually "bloom" to the sheet surface, care must be taken to ensure that their presence does not compromise the function of the end product. For example, the agents must be FDA-approved for food packaging and must not interfere with printing inks or adhesives if the product is to be printed, labeled or sealed to another surface.

Winding tension is always critical in take-off systems. Two winding schemes are currently used (Fig. 8.28) [46]. Most polymers can be wound by driving the roll. Some polymers, such as olefins and flexible PVC, require surface winding. The length of sheet on a roll, L, is obtained from:

$$L = \frac{\pi(D^2 - d^2)}{4s} \tag{8.8}$$

where D is the diameter of the roll, d is the diameter of the core and s is the sheet thickness. The number of plies on a roll, n, is given as:

$$n = \frac{(D - d)}{2s} \tag{8.9}$$

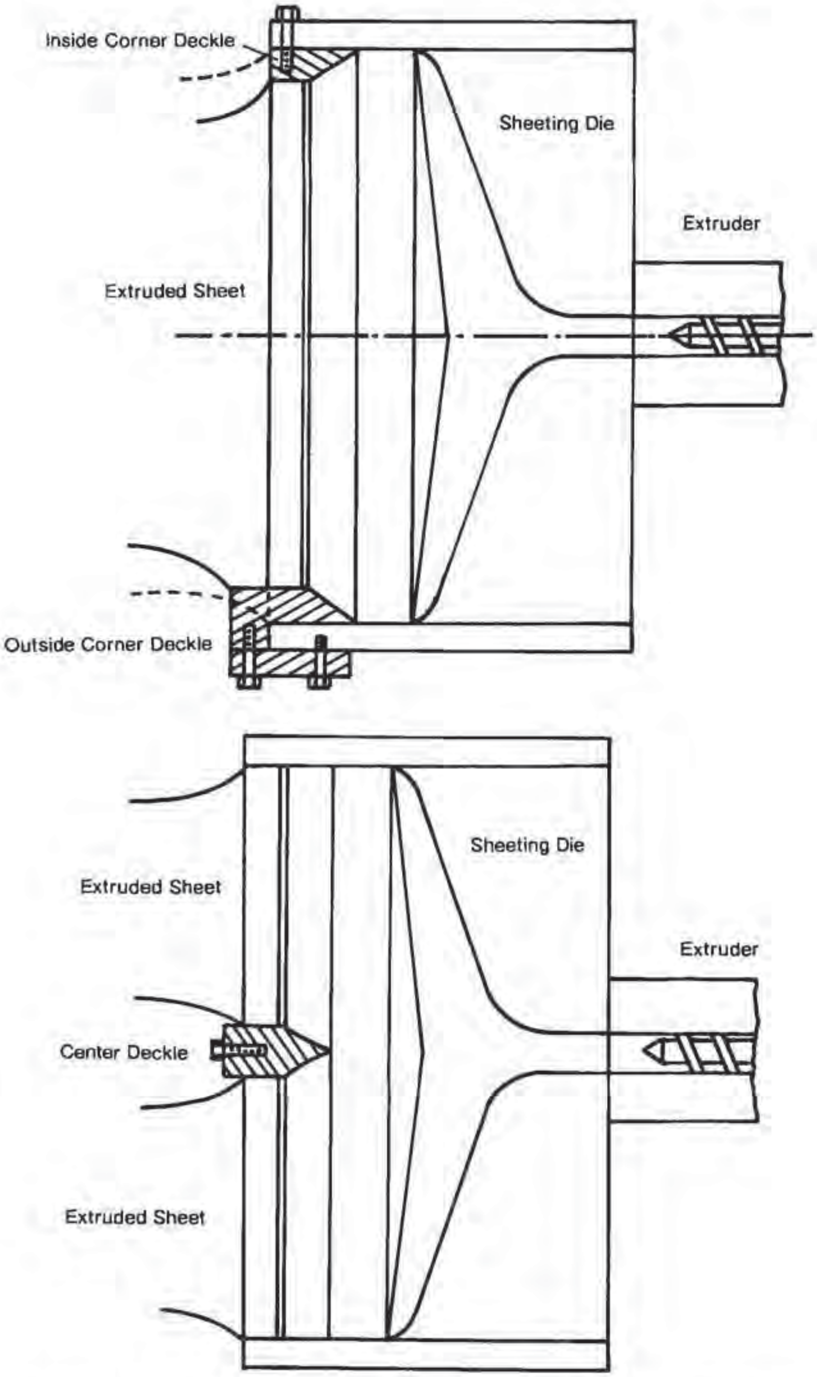

Figure 8.26 Deckle bars for flat sheet extrusion. Top shows inside and outside deckles. Bottom shows splitter deckle

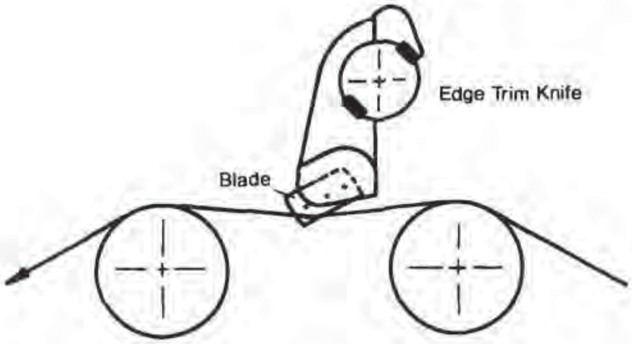

Figure 8.27 Industrial razor blade edge or selvage trimming. Redrawn from [45] and used with permission of copyright owner

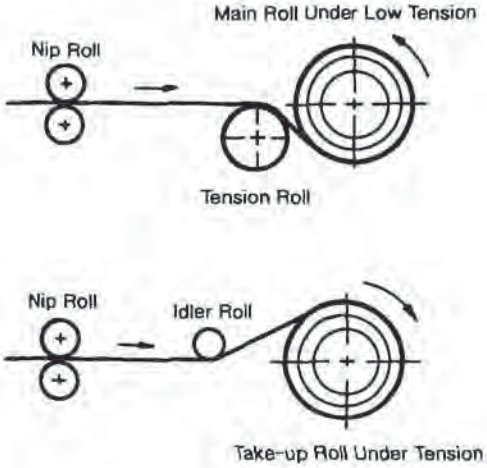

Figure 8.28 Two winding schemes. Redrawn from [46] and used with permission of copyright owner

Example 8.5 illustrates the way in which these equations can be used. Information on tension measurement and control is found elsewhere [47].

Example 8.5 Number of Parts from a Roll of PVC

Flexible PVC is thermoformed into instrument panel skins for the automotive industry. The 0.060 in (1500 m) thick sheet is available on rolls. The thermoformer take-off roll stack is capable of handling 1000 lb rolls on 6 in diameter cores. The thermoform mold uses a 46 × 84 in sheet. What is the diameter of the roll and the number of parts that can be formed from the roll, assuming 100% utilization. The PVC density is 1.4 g/cm^3.

The weight of sheet per foot of length is:

$$W/L = \frac{0.060\ (\text{in}) \cdot 46\ (\text{in})}{144\ (\text{in}^2/\text{ft}^2)} \cdot 1.4 \cdot 62.4 \left(\frac{\text{lb}}{\text{ft}^3}\right) = 1.67 \left(\frac{\text{lb}}{\text{ft}}\right)$$

The length of 1000 lb of sheet is:

$$L = 1000/1.67 = 597\ \text{ft}$$

The diameter of the roll is given as:

$$D = \left[\frac{4sL}{\pi} + d^2\right]^{1/2} = 2.0\ \text{ft}$$

Each part requires 84/12 = 7 ft of sheet. Therefore:

Number of parts per roll = 85+

The number of plies on the roll is:

$$n = \frac{D-d}{2s} = \frac{(24-6)}{2 \cdot 0.06} = 150$$

8.7 Residence Time and Residence Time Distribution Through Extruder and Die

Residing at melt temperature for extended time can be detrimental to the mechanical properties of many polymers, including ABS, RPVC, mPPO, PP and PET. Since a substantial portion of the sheet supplied to thermoformers must be recycled, an understanding of the residence time and residence time distribution in the extrusion process is particularly important. If the extrusion process could be considered as a *plug flow process*, the residence time would be simply the length of the flow channel, z, divided by the flow velocity, v:

$$t_{\text{plug}} = z/v \tag{8.10}$$

For the journey through the extruder, the velocity would be the volumetric flow rate divided by the cross-section of the channel formed by the screw root, barrel and flights. The length would be the unwrapped length of the screw flight, $z = L/\sin\phi$. If $\phi = 17.65°$ for a single-flighted screw, $z = 3.3\ L$. The *mean residence time* is obtained by dividing the volume of the extruder occupied by polymer, V^*, by the volumetric flow rate, $\dot{v}$:

$$t_{\text{mean}} = V^*/\dot{v} \tag{8.11}$$

When the extruder is completely full of polymer, $t_{\text{plug}} \equiv t_{\text{mean}}$. Example 8.6 illustrates these two residence times.

Example 8.6 Plug Flow and Mean Residence Times of a Single-Flighted Screw

Determine the plug flow residence time and the mean residence time of a single-flighted 4-in diameter, 24:1 extruder having a melt pumping channel depth of 0.400 in. The extruder is pumping 1.2 specific gravity PVC at 800 lb/h. Assume zero flight width. Owing to solids conveying, 40% of the channel length is only half-full. How much plastic remains in the extruder for times longer than 2 mean residence times? Three mean residence times?

The channel width is given as [48]:

$$T = \pi D \sin \phi = \pi \cdot 4.5 \cdot \sin 17.65° = 4.29 \text{ in}$$

The channel cross-section is then:

$$A = H \cdot T = 0.400 \cdot 4.29 = 1.71 \text{ in}^2$$

The volumetric flow rate is:

$$\dot{V} = 800 \frac{\text{lb}}{\text{h}} \cdot \frac{1}{1.2} \cdot \frac{1}{62.4} \frac{\text{ft}^3}{\text{lb}} \cdot 1728 \frac{\text{in}^3}{\text{ft}^3} \cdot \frac{1 \text{ h}}{3600 \text{ s}} = 5.13 \frac{\text{in}^3}{\text{s}}$$

The velocity is then:

$$v = 5.13/1.71 = 3.0 \text{ in/s}$$

The channel length is:

$$Z = L/\sin \phi = 24 \cdot 6/\sin 17.65° = 475 \text{ in}$$

And the plug flow residence time is:

$$t_{plug} = 475/3 = 158.6 \text{ s} = 2.6 \text{ minutes}$$

The plastic volume in the channel is given as:

$$V = H \cdot T \cdot (0.6Z + 0.5 \cdot 0.4Z) = 649.8 \text{ in}^3$$

For a volumetric flow rate of 5.13 in^3/s, the mean residence time is:

$$t_{mean} = 649.8/5.13 = 126.7 \text{ s} = 2.1 \text{ minutes}$$

According to Fig. 8.29 [49], about 4.6% or $0.046 \times 649.8 = 30$ in^3 reside in the extruder for at least two mean residence times or 4.2 minutes. 1.3% or about 8.5 in^3 reside in the extruder for more than three mean residence times or 6.3 minutes.

The cumulative residence time distribution, CRTD, is given as:

$$CRTD = 1 - (t_{min}/t)^2 \tag{8.12}$$

From theory, the minimum residence time is given as:

$$t_{min} = \frac{4\mu z^2}{\Delta P R^2} \tag{8.13}$$

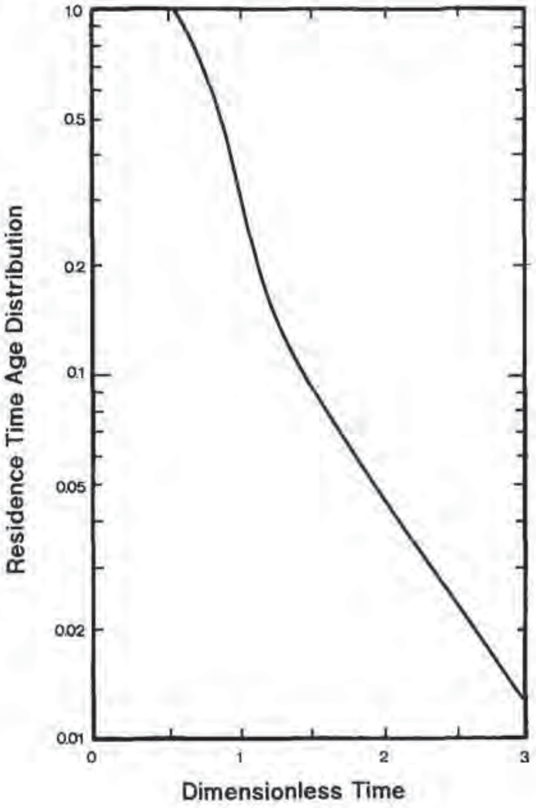

Figure 8.29 Residence time age distribution through a single-screw extruder. Redrawn from [49] without experimental data and used with permission of copyright owner

where μ is the Newtonian viscosity, z is the down-channel length, ΔP is the pressure drop and R is the hydraulic radius of the channel. As expected, residence time increases with extruder L/D and viscosity and decreases with pressure drop and channel geometry. The experimental CRTD for a single-screw extruder is shown in Fig. 8.29 [49]. Twin-screw extruders show similar CRTD shapes. Note that for the single-screw extruder of Fig. 8.29, more than 1% of the polymer remains in the extruder for more than three times the mean residence time. See Example 8.6 for additional information.

The mean residence time in a standard sheeting die is obtained from an expression similar to that for the extruder [50]:

$$t_{\text{mean, die}} = BHy_o/\hat{V} \tag{8.14}$$

The cumulative residence time distribution in a simple flow channel such as an extruder die can be estimated from equation 8.12. Example 8.7 details the calculation of mean residence time and residence time distribution in a slot die.

Example 8.7 Mean Residence Time in a Slot Die

Determine the mean residence time and the fraction of polymer residing in the slot die described in Example 8.3 after 2 and 3 mean residence times.

From Equation 8.14:

$$t_{mean.die} = BHy_o/\dot{V} = 127 \cdot 0.254 \cdot 50.8/102 = 16 \text{ s}$$

From Equation 8.12:

$$CRTD = 1 - (t_{mean.die}/t)^2$$

For $t = 2t_{mean,\ die}$, CRTD = 0.75, or 25% of the polymer remains in the die longer than 32 s.

For $t = 3t_{mean,\ die}$, CRTD = 0.89, or 11% of the polymer remains in the die longer than 48 s.

8.8 Drying

Nearly all solid surfaces *adsorb* moisture under certain conditions. Virgin polymers are sold to the extruder as pellets, powders, granules or chips. All these shapes have very large surface to volume ratios. Polymers transported from cold warehouses or silos to warm extrusion rooms can adsorb large quantities of water that must be removed before feeding to the extruder hopper. Example 8.8 gives an example of the thickness of water film as a function of moisture pickup. Typical water film thicknesses are around 1 μm. For polymers that are not *hydroscopic* such as most polyolefins and many PVC formulations, simply exposing the pellets to warm air is sufficient to evaporate surface moisture. A hopper dryer using warmed recirculated air will suffice. Many polymers *absorb* as well as adsorb moisture. The moisture does not just reside on the pellet surface but diffuses into the pellet volume. Polymers that hydrogen bond well, such as polyamides and polycarbonate, polymers that have great sensitivity to water when molten, such as polyamides, PET, PBT and cellulosics, and most filled and reinforced polymers require extensive drying. Table 8.8 gives normal moisture contents and moisture contents required to provide bubble-free extruded sheet without substantial property deterioration. For amorphous polymers not listed in the table, select a drying temperature of $(T_g - 20)$°C and a drying time of 2-4 h. Figure 8.30 [54] shows the relationship between moisture absorption and relative humidity for several polymers. The long drying times at elevated temperatures are required in order to reverse the moisture diffusion process. For these difficult-to-dry polymers, hopper dryers are usually inadequate. Recirculating dryers are used with the air dehumidified to −40°C dewpoint by contact with refrigerated metal coils, silica gel or molecular sieve beads (Fig. 8.31) [52]. Figure 8.32 [55] shows the interrelationship of PET equilibrium moisture content, drying temperature and the dewpoint of the recirculating air. Note that to achieve a 0.02% moisture content, the

Table 8.8 Drying Conditions for Various Thermoplastic

Drying times are for polymer pellets. These drying times can also be used for sheet. The drying times are then per mm (0.040 in) of sheet thickness.
Two drying temperatures and two drying times are listed for some polymers. With the exception of PET, these are recommendations from differing sources [51-53].

Polymer	Glass transition temperature (°C)	Equilibrium moisture content at 100% RH (%)	Required moisture content for extrusion (%)	Maximum drying temperature (°C)	Typical drying time (h)
PA 6	50	1.0–3.0	<0.08	50, 75	3-4, 2
PA 66	50	1.0–2.8	<0.03	50, 80	3-4, 2
PET*	70	0.1–0.2	<0.005	65, 160	3-4, 4
PS/HIPS	100	0.2–0,6	<0.02	80	2
ABS	100	0.2–0.6	<0.02	80, 90	2
CA	100	2.0–2.5	<0.05	60, 90	3, 1.5
CAB	100	1.0–1.5	<0.05	70, 90	3, 2
PBT	70	0.1–0.3	<0.02	160	4
PMMA	100	0.6–1.0	<0.05	80, 95	3, 2
PC	150	0.15–0.3	<0.05	150	4
PPO	105	0.08–0.2	<0.02	120	4
RPVC	70	0.04–0.3	<0.02	70	2

* Lower drying temperature for amorphous PET. Higher value for crystallized PET

air must have a dewpoint of less than −20°C at 160°C. A very long time is required to achieve this moisture level, however. Careful monitoring of the air dewpoint is required to maintain good efficiencies. Most recirculating beds require periodic regeneration and careful maintenance.

Example 8.8 Moisture Pick-up on Pellet Cube

Consider an ABS cube 0.060 in on a side. Determine its surface-to-volume ratio and the thickness of absorbed water for 1% (wt) moisture pickup. The specific gravity of ABS is 1.05.

The volume of the cube is $V = L^3 = 216 \times 10^{-6}$ in^3
The area of the cube is $A = 6L^2 = 2.16 \times 10^{-2}$ in^2
The area-to-volume ratio is $A/V = 6/L = 100$
The weight of a single pellet is:

$$W = 1.05 \cdot (62.4/1728) \cdot V = 8.19 \times 10^{-6} \text{ lb}$$

The weight of water is $0.01 \times W = 8.19 \times 10^{-8}$ lb and the volume is:

$$V_{\text{water}} = 8.19 \times 10^{-8}/(62.4/1728) = 2.268 \times 10^{-6} \text{ in}^3$$

The film thickness is:

$$t_{\text{water}} = V_{\text{water}}/A = 1.05 \times 10^{-4} \text{ in} = 2.67\ \mu\text{m}$$

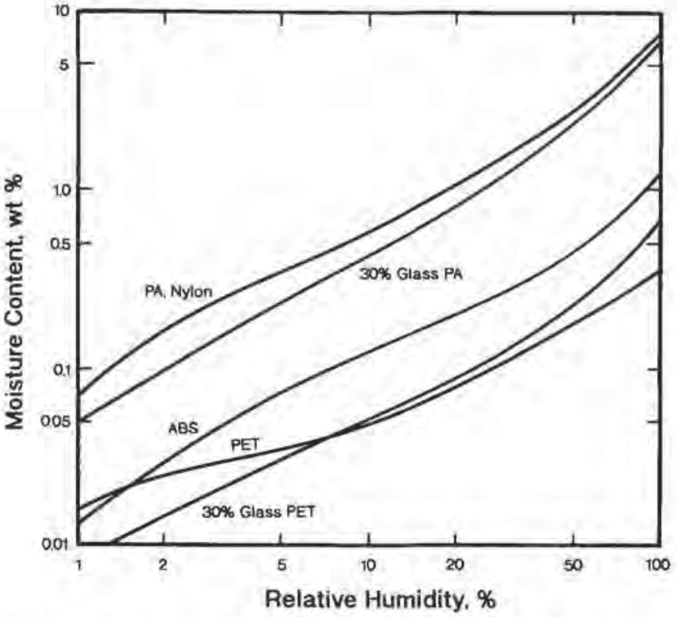

Figure 8.30 Room temperature relative humidity-dependent equilibrium moisture content for several thermoplastics. Redrawn from [54] and used with permission of copyright owner

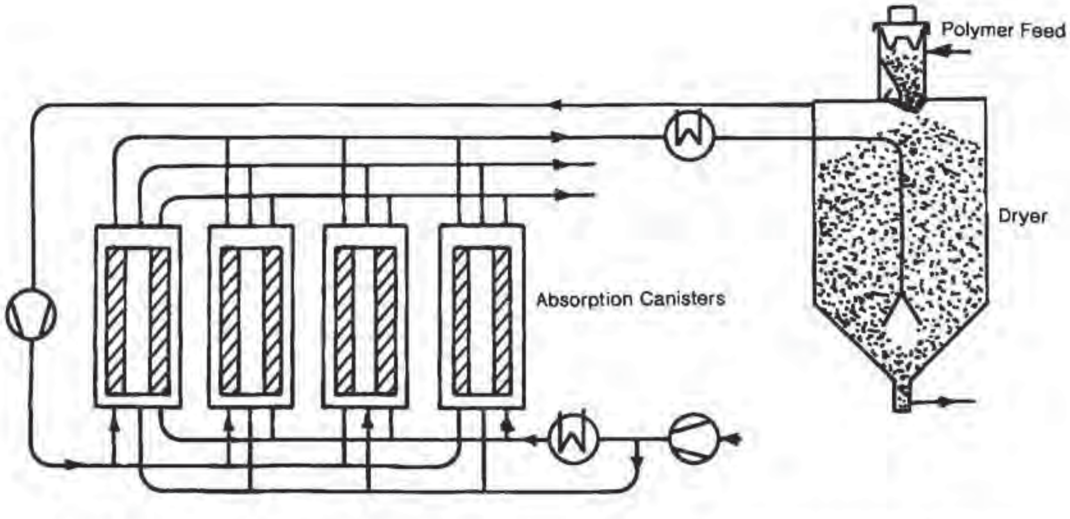

Figure 8.31 Canister dessicant dryer and hopper configuration for extrusion. Adapted from [52] and used with permission of copyright owner

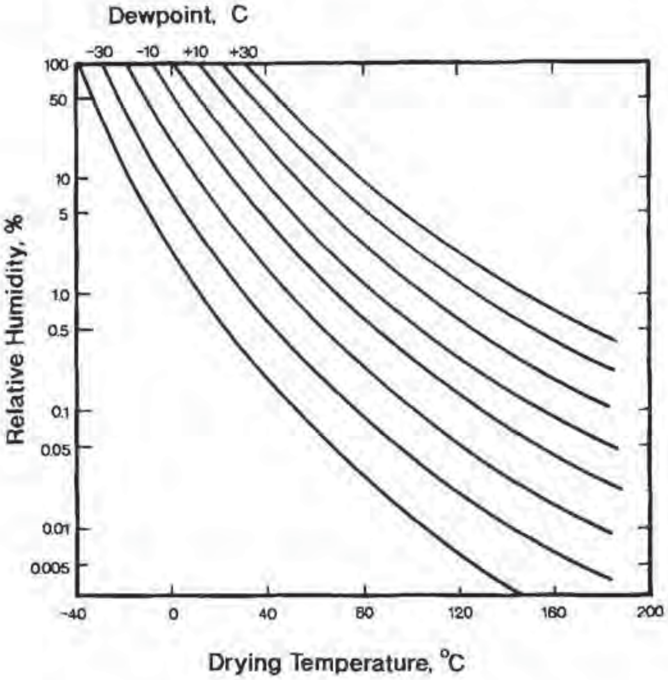

Figure 8.32 Interrelationship between equilibrium relative humidity, air dewpoint and drying temperature for polyethylene terephthalate, PET. Redrawn from [55] and used with permission of copyright owner

8.9 Producing Biaxially Oriented Sheet

Thin-gage oriented polystyrene or OPS, biaxially oriented polypropylene or BOPP, and polyethylene or BOPE, are frequently thermoformed into cake domes, transparent lids and deep drawn containers. Polystyrene impact strength and clarity is dramatically improved by orientation. A dramatic reduction in haze is apparent with oriented polyethylene and polypropylene films. Films to 10 mils, 0.010 in or 250 μm, are usually biaxially oriented by inflating the extrudate from an annular die. Heavier gage sheet requires secondary or post-extrusion orientation. Tentering is the most common biaxial stretching method (Fig. 8.33) [56]. In certain cases, the extrudate sheet is stretched in the machine direction while still hot on heated bridle rolls running at differential speeds, then cooled and stretched in the cross-machine direction. Figure 8.34 [57] shows a typical clip or clamp used in the cross-machine stretcher. Polystyrene sheet is frequently supplied to the tenter as a cold roll. The sheet is then reheated in an infrared oven to 50°C or so above its glass transition temperature prior to sequential machine-direction and cross-direction stretching. For

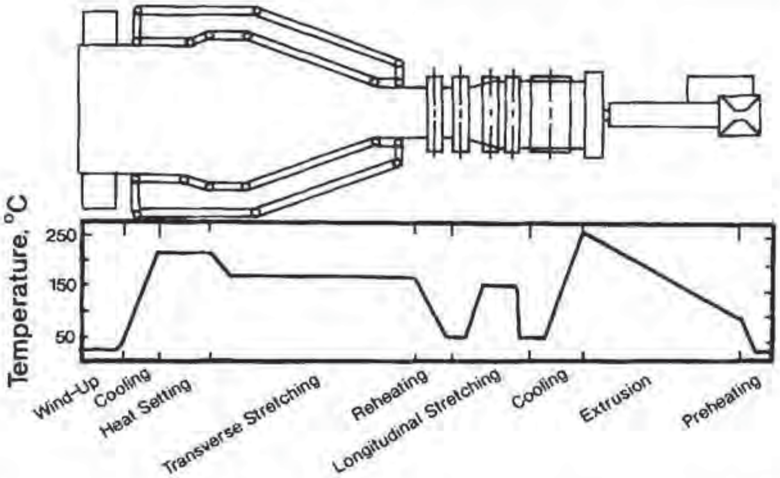

Figure 8.33 Schematic of tenter frame process for producing biaxially oriented sheet and film. Adapted from [56] and used with permission of copyright owner

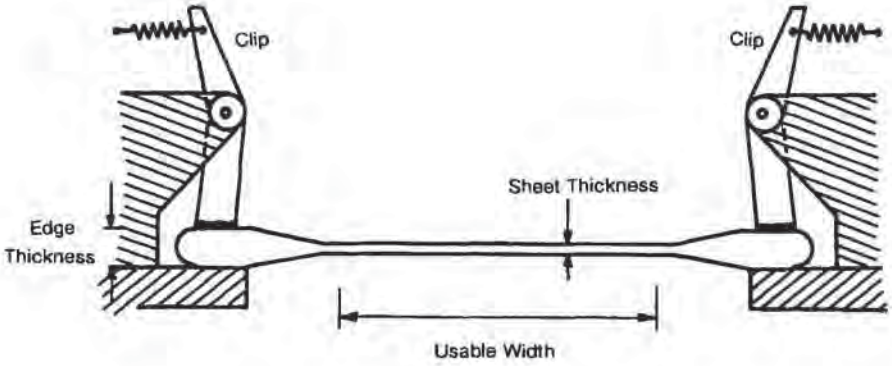

Figure 8.34 Schematic of tenter clips for TD sheet stretching. Redrawn from [57] and used with permission of copyright owner

crystalline polymers such as polypropylene, machine-direction stretching occurs at temperatures just below melt temperature and cross-direction stretching occurs at or just above melt temperature. Table 8.9 gives representative property values for oriented thin films and sheet [58,59]. Birefringence is one way of determining the degree of orientation in transparent sheet goods [60]. Transparent polymers have three indices of refraction along the three primary axes. When the polymer is preferentially oriented, the index of refraction in that direction changes. The change

Table 8.9 Comparative Properties of Unoriented and Oriented Polymer Films and Sheets

Property—Sheet [53]	Polystyrene		Polymethyl methacrylate	
	Unoriented	Biaxially oriented	Unoriented	Biaxially oriented
Tensile strength (MPa)	34.5–62	48–82.7	51.7–69	55–75.8
Elongation at break (%)	1–3.6	8–18	5–10	25–50
Impact strength	0.25–0.5	>3	4	15

Property—25 μm, 1 mil or 0.001 in film [58]	Polystyrene	PET	Polyamide	PP homopolymer		
	Biaxially oriented	Biaxially oriented	Biaxially oriented	Unoriented	Biaxially oriented	
					Two-stage	Simultaneous
Areal stretch ratio	10:1	6.5:1	18:1	—	10:1	10:1
Tensile strength—MD (MPa)	70	200	300	50	140	200
Tensile strength—TD (MPa)	70	220	300	40	270	200
Elongation at break—MD (%)	10	130	70	430	140	80
Elongation at break—TD (%)	10	110	70	540	40	80
Puncture resistance (N)	—	—	—	23	200	—
Low-temperature resistance (°C)	—	—	—	0	−50	−50

in any pair of indices is birefringence in that direction. Polystyrene has an exceptionally high level of birefringence. Polyethylene terephthalate and polyvinyl chloride show moderate birefringence. Polymethyl methacrylate and polycarbonate have weak levels of birefringence and polyethylene and polypropylene show essentially no birefringence. Figure 8.35 shows typical in-direction and cross-direction tensile strength values compared with birefringence values for 0.100 in thick or 2.54 mm injection molded polystyrene [61]. Similar comparisons have been made for elongation at break and impact strength. Birefringence can be easily observed using low-cost polarizing filters placed 90° to one another. The classic effect is very narrow bands of color for high stress regions and wide bands elsewhere[1]. Biaxially oriented sheet shows high stress regions at the points where the clips held the sheet during cross-machine stretching. A very high level of birefringence at those points is an indication that the sheet may have been stretched at too low a temperature.

8.10 Multilayer Sheet Formation

Multilayer sheet is used in extremely thin gage of 1.5 mil, 0.0015 in or 37.5 μm polyamide for speaker cones and computer touch screens to 50 mils, 0.050 in or 1250 μm, for CPET single serving dinner trays to 500 mils, 0.500 in or 12.5 mm, PVC/PMMA for pools and spas. Interfacial adhesion is paramount in multilayer sheet. Polymeric systems in which adducts are slightly different from layer to layer usually bond well when both sheets are hot. Examples include TiO_2-pigmented PET/regrind PET, TiO_2-pigmented PP/CaCO3-filled PP, and virgin ABS/regrind ABS. Some polymers such as PVC and PMMA, nylon and ionomer, and PVC and ABS have excellent adhesion characteristics. When both are very hot, adhesion is very good. Other polymer combinations, such as HDPE/PP, PVC/PS, PP/EVOH/PS, and HDPE/PVDC/PS have poor adhesive characteristics. As a result, these layers are bonded together using a "tie layer" or a ductile hot melt adhesive such as polyethylene, ethylene vinyl acetate, ethylene, methylene and other acrylic acids or certain amino-acid polymers. Multilayer structure selection is discussed elsewhere [63,64]. Table 8.10 gives a cross-list of pairs of traditional polymers and their adhesive characteristics [65].

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[1] Birefringence can be explained in the following way. The oriented polymer molecules separate polarized light into one component that is parallel to the direction of molecular travel and one that is perpendicular. One portion of the light ray travels slightly faster than the other. The retardation will cancel a particular wavelength from the white-light spectrum leaving a combination of the remaining colors. No orientation yields black and high orientation is green. Birefringence is given as:

$$\Delta\eta = \frac{\lambda \cdot R}{D} \tag{8.15}$$

where $\Delta\eta$ is the difference in indices of refraction or the birefringence, λ is the wavelength of light, $= 5500$ Å for white light, R is the level of retardation, and D is the thickness of the film or sheet. R is determined by counting the number of orders and assigning fractional values to various colors. For example, black = 0, yellow = 0.3, red = 0.6 and green = 1.0 [62].

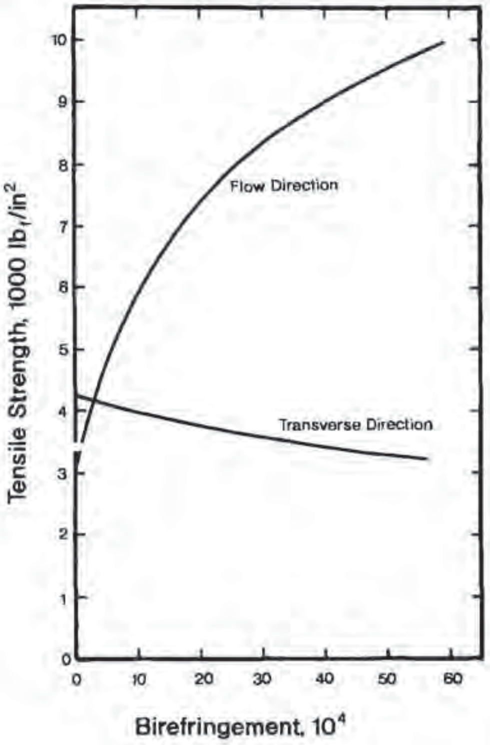

Figure 8.35 MD and TD tensile strength characteristics of injection molded polystyrene, PS as functions of measured birefringence. Adapted from [61] and shown without experimental data

Coextrusion

While coextrusion is not normal for multilayer structures of dissimilar polymers, it is common for multilayer structures of similar polymers. As an example, for some refrigerator liner applications, an ABS gloss layer is coextruded with a core layer containing regrind. An overview of a typical multilayer extrusion system is shown in Fig. 8.36 [66]. The way in which the various melt streams are combined is key to quality coextrusion. Figure 8.37 shows an example of flow streams combined in the extrusion die block [67]. Figure 8.38 shows an example of flow streams combined in a feedblock [68]. Geometry restricts the number of streams to three. The multiple layered stream from the feedblock is then fed to a single manifold die. Dow has shown that it is possible to produce a melt stream of as many as 500 layers using their feedblock concept. Either die concept requires very careful design and superior pressure and temperature control for specific polymers to minimize serious flow instabilities, nonuniform inner-layer thickness, sheet distortion and curling and local inner-layer bleed-through.

Table 8.10 Adhesion Between Pairs of Polymers [65]

Polymers	ABS	CA	EVA	PA 66	PC	HDPE	LDPE	PMMA	PP	mPPO	PS	iPS	PBT	RPVC	FPVC	SAN
ABS	G	G			G	P	P	G	P		P	P	G	G	F	P
CA	G	G	P													
EVA		P	G			G	G		G					G	F	
PA 66				G	P	P	P		P			P				
PC	G			P	G						P	F				G
HDPE	P		G	P		G	G	P	F							
LDPE	P		G	P		G	G	P	G		P				P	
PMMA	G					P	P	G	P	P	F			G	G	G
PP	P		G	P		F	G	P	G	P	P	P		P	P	
mPPO									P	G	G	G				P
PS	P		G		P	P	P	P	P	G	G	G			P	P
iPS	P			P	F			F	P	G	G	G			P	P
PBT	G												G			G
RPVC	G		G					G	P					G	G	
FPVC	F		F			P		G	P		P	P		G	G	G
SAN	G				G			G		P	P	P	G		G	G

G = good to excellent adhesion
F = fair adhesion—depends on processing conditions
P = poor or no adhesion

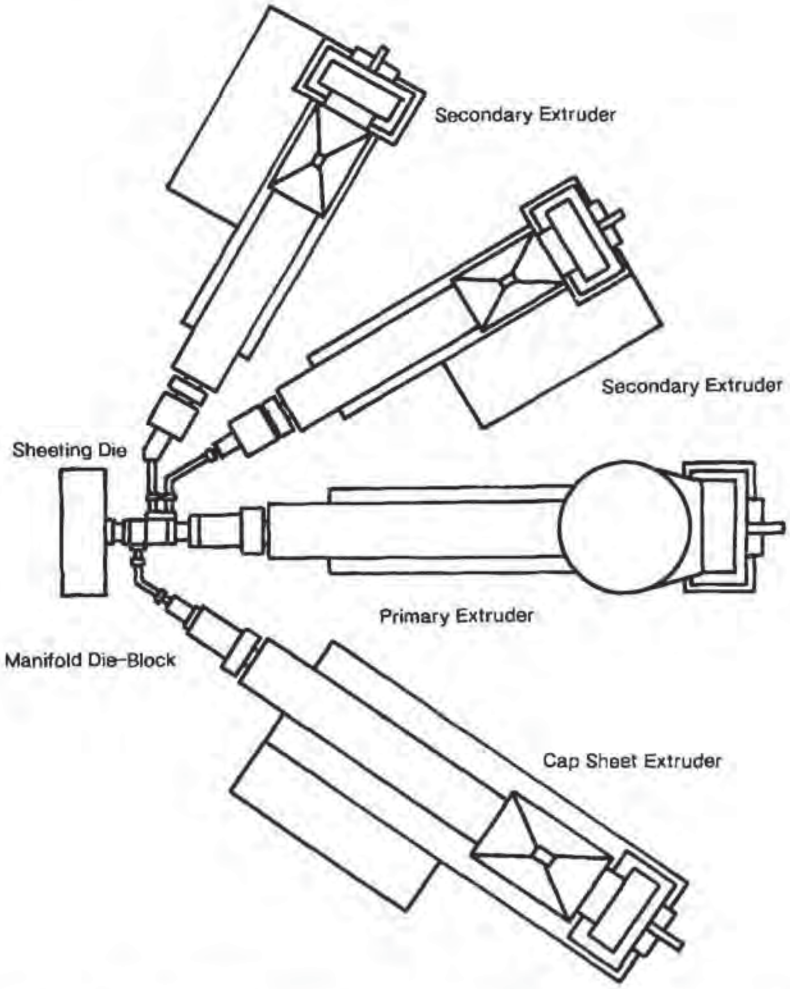

Figure 8.36 Top view schematic of coextrusion equipment and die block. Redrawn from [66] and used with permission of copyright owner

Two general types of multilayer flows are considered in die design:

- Symmetric flow, where the polymer 1 stream is evenly divided by the polymer 2 stream (Fig. 8.39) [69]. For this case, the pressure drop-flow rate relationships focus on the shear layer between the two streams. Flow characteristics such as viscous dissipation and temperature distribution through the sheet are symmetric and standard pressure drop-flow rate relationships can be used, with proper adjustment [70]. Depending on the relative viscosities and flow rates, symmetric flows can rapidly become unsymmetric, with the inner layer migrating toward the wall and folding the outer layer inward.

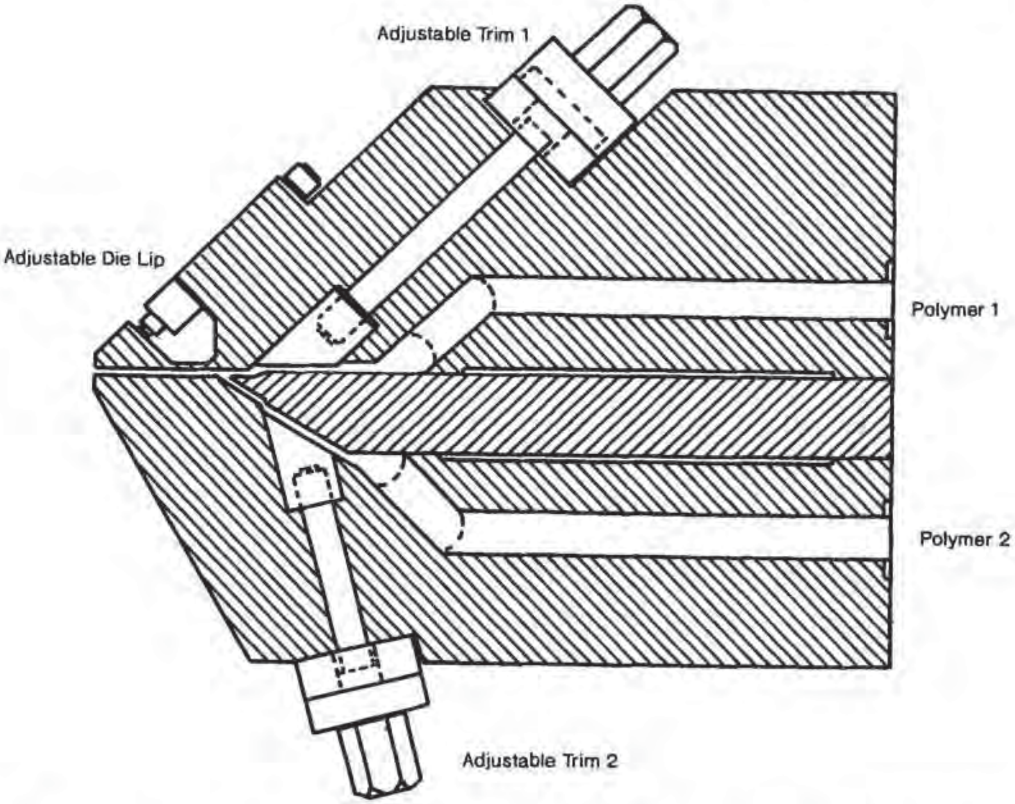

Figure 8.37 Cross-section schematic of multi-flow die block. Adapted from [67] and used with permission of copyright owner

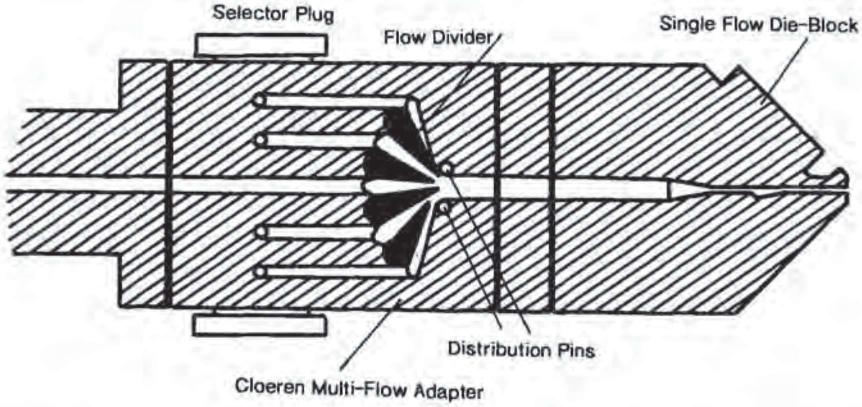

Figure 8.38 Cross-section schematic of Cloeren multilayer feed block. Redrawn from [68] and used with permission of copyright owner

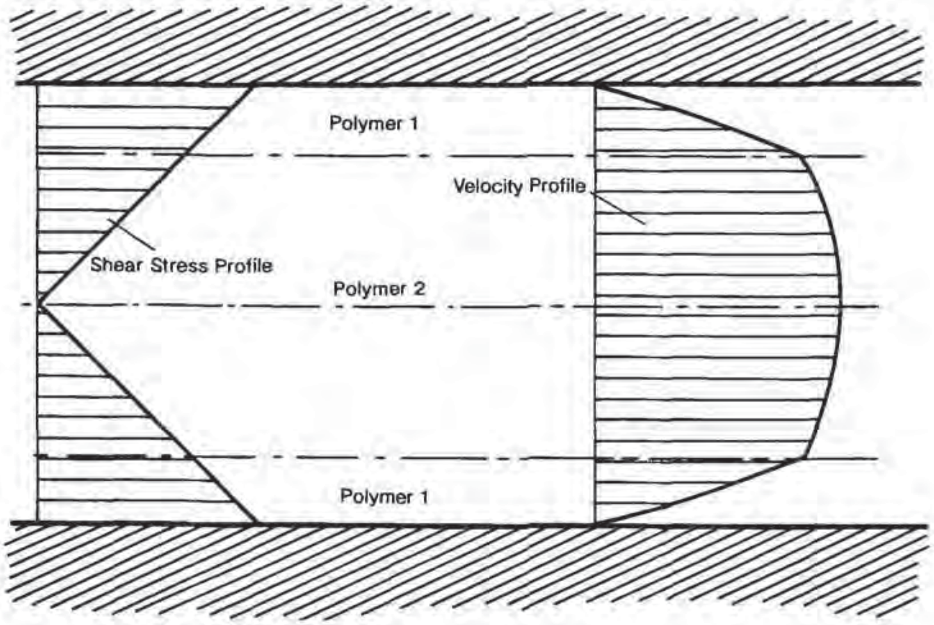

Figure 8.39 Symmetric flow of two polymers, with polymer 2 between two layers of polymer 1

- Asymmetric flow, where polymer 1 and polymer 2 streams flow side by side (Fig. 8.40) [71]. Asymmetric heating and viscous dissipation are expected and pressure drop-flow rate relationships must be altered. The developing polymer temperature profile across the melt for dissimilar viscosities and flow rates as a function of distance downstream is shown in Fig. 8.41 [72]. An example of the effect mismatched viscosity is seen in Fig. 8.42 for unfilled and TiO_2-filled polyethylene [73,74].

Lamination

Lamination is the adhering of an already-extruded sheet to an extrudate. Laminations are frequently used if tie layers are involved or if the extrudate cannot tolerate hot melt coextrusion. As an example of the former, a tie layer is melt coated to solid polypropylene sheet and this is laminated to polyvinylidene chloride extrudate to form barrier sheet. As an example of the latter, cooled polystyrene foam sheet is laminated to a semi-molten polystyrene "cap sheet" in a nip roll to improve the foam sheet cut resistance [75]. Other commercial laminations include solid acrylic (PMMA) sheet laminated to rigid PVC or ABS sheet for spas and PVDC film + tie layer laminated to HIPS for refrigerator liners. Two examples of lamination are shown in Fig. 8.43 [76]. On the left is a lamination process where a reheated solid sheet is laminated to

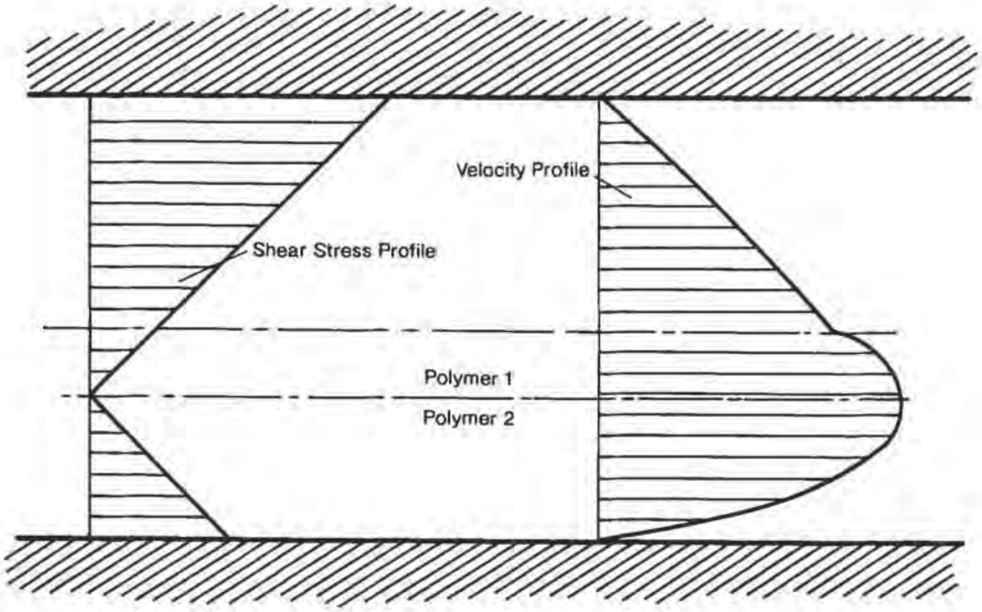

Figure 8.40 Asymmetric flow of two polymers, with polymer 1 and polymer 2 side-by-side. Adapted from [71]

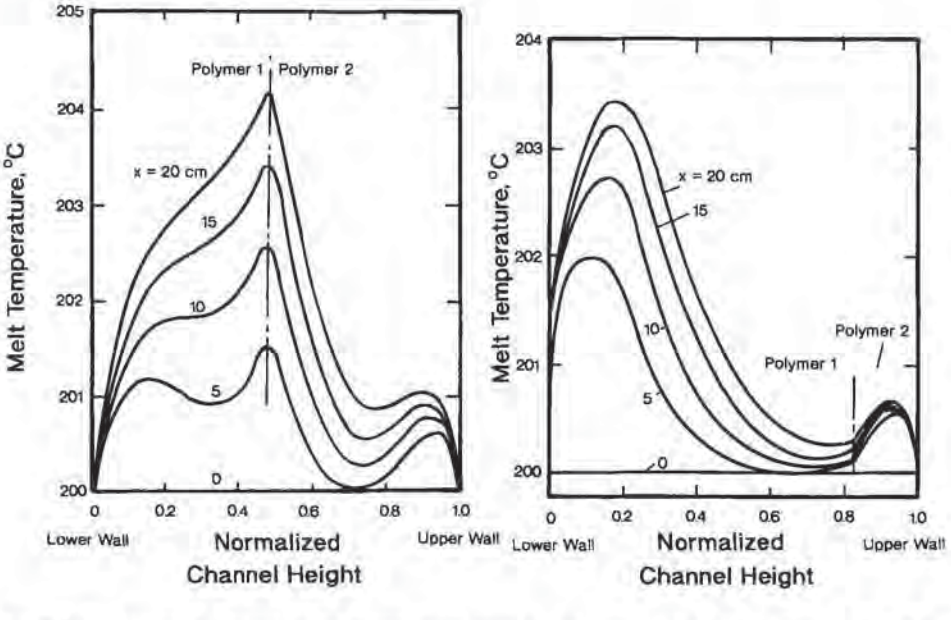

Figure 8.41 Examples of developing temperature profiles for asymmetric flow of two polymers. Left figure shows equal volumetric flow of polymers 1 and 2. Right figure shows unequal volumetric flow. Redrawn from [45] and used with permission of copyright owner

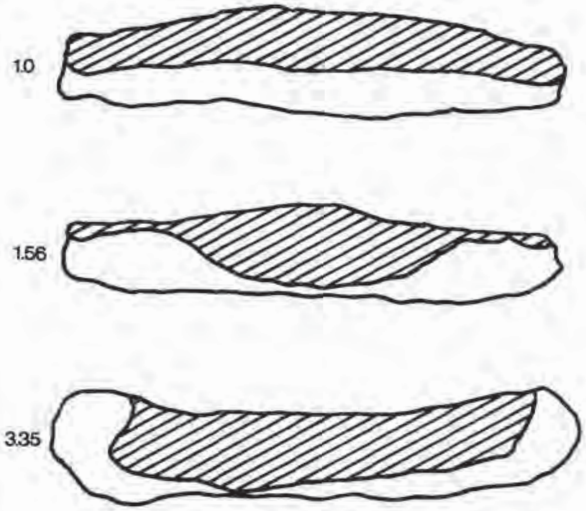

Figure 8.42 Effect of mismatched viscosities of polymer melts on shape of extrudate. Shaded area is unfilled polyethylene. Open area is TiO_2-filled polyethylene. Marginal number is viscosity ratio at extrusion temperature. Adapted from [74]

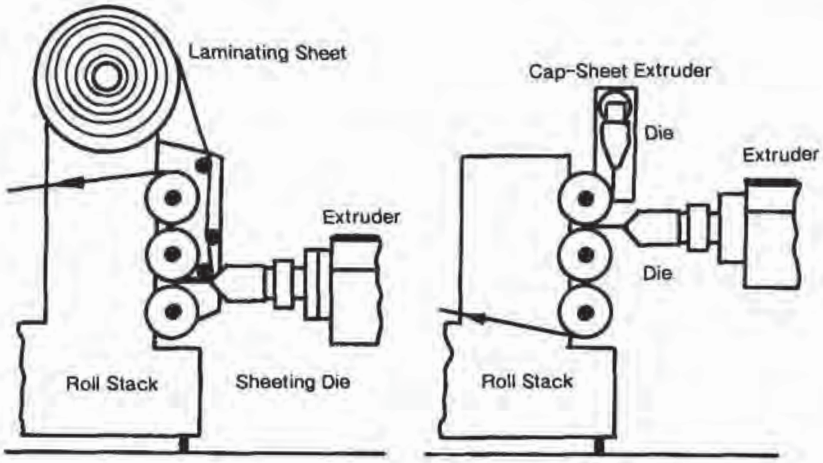

Figure 8.43 Schematics of (left) solid lamination, and (right) hot melt extrusion lamination. Redrawn from [76] and used with permission of copyright owner

the extrudate and on the right is a lamination process where the laminating cap-sheet is extruded directly onto the primary extrudate.

Lamination is frequently used even if the selected polymer combinations have excellent adhesion. Coextrusion feedblocks and die blocks are expensive to design and fabricate and take inordinate time to perfect, and changes in the final product design

Table 8.11 Major US Sheet Extruders* [77]

Sheet extruder	1993 sales, $M	Percent sheet
AtoHaas North America, Inc., Philadelphia PA	205	100
Spartech Plastics, Clayton MI	175	95
Primex Plastics, Corp., Richmond Ind.	159	100
O'Sullivan Corp., Winchester VA	127	90
Cyro Industries, Mount Arlington NJ	125	100
Uniroyal Technology Corp., Sarasota FL	99	100
Gundle Lining Systems, Inc., Houston TX	83	100
HPG-International, Inc., Somerset NJ	81	90
Packaging Corp. of America, Northbrook IL	80	100
SLT North America, Inc., Conroe TX	80	100
Plaskolite Inc., Columbus OH	71	100
Fabri-Kal Corp., Kalamazoo MI	70	100
Aristech Chemical Corp., Acrylic Sheet Unit, Florence KY	59	100
Pawnee Extrusions, Wichita KA	50	100
Sheffield Plastics, Inc., Sheffield MA	50	100
Preferred Plastic Sheet, Greenville OH	49	100
Vinyl Plastics, Inc., Sheboygan WI	43	91
New Hampshire Plastics, Inc., Manchester NH	30	100
Portage Industries Corp., Portage WI	29	100
Lustro Plastics Co., Evanston IL	22	40
Wellman Extrusion, Ripon WI	21	100
Allen Extruders, Inc., Holland MI	19	100
Goex Corp., Janesville WI	19	100
Kleerdex Co., Mt. Laurel NJ	19	100
Witt Plastics Inc., Greenville OH	18	100
Pace Industries, Inc., Reedsburg WI	15	100
Trio Products, Inc., Elyria OH	15	100
Bixby International Corp., Newburyport MA	14	100
Ex-Tech Plastics Inc., Richmond IL	5.5	100
Farber Plastics, Inc., Oceanside NY	5.1	100
Plastics Slip Sheets (US) Inc., Denver CO	3.5	100
Repete Plastics Inc., Geneva IL	3.2	100
Superior Plastics Extrusion Co., Inc., West Boylston MA	2.8	100
Mitech Corp., Twinsburg OH	2.5	100
Envirosafe Products, Inc., Staten Island NY	2	100
Abulco Plastics Industries, Inc., Hazleton PA	1.5	100
Coon Manufacturing Inc., Spickard MO	1.5	100

* Not all sheet manufacturers listed are solely custom sheet extruders

are quite restricted. On the other hand, lamination allows for very rapid changes in polymer combinations, including alternate tie layers and extrudate thicknesses, at relatively low total cost. For long production runs, multilayer extrusion is cost effective. For development work, prototyping, and short runs, laminating is desired. Table 8.11 gives a list of major US custom extruders [77].

8.11 Sheet Quality and Quality Control

There are many adages and old saws that pertain to quality and the importance of quality control, from serenely subjective:

> **"Beauty is in the eye of the beholder"**

to positively threatening:

> **"Pay me now or pay me later".**

The thermoformer must always realize that he is a value-added part of the economic chain from wellhead to refinery to polymerization to compounding to extrusion to forming to assembly to use. He is his sheet supplier's customer and as such, he needs to conduct business in much the same way as his customer deals with him.

The thermoformer knows how to conduct business with his customer. Regardless of the nature and depth of prior experiences of the parts designer, the mold maker, the thermoformer, the customer or the ultimate end user, no plastics fabrication should be attempted without strict, formal *written* protocol on parts design. All these parties must clearly understand the project objectives and any ancillary part performance standards. Guidelines are usually carefully written and agreed on, in writing, by all principals. This should always be done with all principals present, just prior to the issuance of purchase orders for materials, molds and forming times. Processes, applications and materials continue to grow in sophistication. As a result, the thermoformer, his engineer, or his designer is destined to play an increasingly important role as project coordinator. It is incumbent on him to ensure correct protocol, particularly in this increasingly litigious era. In this section, the interface between the thermoformer and the extruder is addressed. Later on, the other aspects of good business are discussed.

It is always good business to maximize profit. Business management teaches many ways of doing this. Thermoformers have an additional variable that most plastic processors lack—reuse of non-product. Careful management of non-product or web can yield substantial economic benefits but can also be the primary source of severe processing and quality control problems. Some classical definitions are:

Virgin. Virgin means "unprocessed". By strict definition, virgin resin is that supplied to the extruder by the resin supplier. Virgin sheet, therefore, is that sheet made only from virgin resin. This excludes all other materials, such as factory regrind of virgin sheet, regrind returns from a specific source or multiple sources and so on. The purchase order for virgin sheet should state:

> **"Virgin sheet to include no trim, regrind or other adulterants. . ."**

If the thermoformer agrees to accept factory regrind of virgin sheet, the purchase order specifications should state so, in terms such as:

> **"Virgin sheet to include no more than 10% factory edge trim, selvage and ends of virgin sheet extruded on this job on this extruder. . ."**

Care must be taken here to ensure that the customer will accept this product. Medical and biomedical applications are usually very specific as to the exact composition of the polymer.

Virgin + Regrind. This specification can be misused unless carefully defined by the thermoformer. Regrind can come from many sources. For example:

Extrusion factory regrind. This implies that regrind is from any extruder in the factory from any operation, including but not restricted to your job.

Regrind from thermoformer. This implies that regrind is supplied to extruder by you, as regrind. It can come from any source within your plant, at any time. You have the responsibility for knowing what you have supplied to the extruder for regrind.

Any-source regrind. This implies that the extruder selects the regrind, without any input from you.

Typically the specific amount of regrind should be part of the purchase order, such as:

> **"The extruder shall use only virgin polymer blended with 30% ± 5% regrind sent to the extruder from the thermoformer and identified by barcode______ . . ."**

Note that the specification does not state ". . . up to 35% . ." as recommended in older specifications. The variability in properties from 0% or all virgin to 35% regrind can sometimes be deleterious to both the extruder and the thermoformer.

Regrind Only. Frequently, the thermoformer may be using a sheet that contains 20% regrind, yet may be producing 40% web. The accumulation of regrind needs to be worked off. If a particular product can tolerate 100% regrind, the thermoformer should contract with the extruder to run a carefully controlled order of regrind only. Both parties must understand that this is a separate and distinct job from those that precede or follow. The specification should read something like:

> **"Extruder shall produce sheet from regrind only, identified from the thermoformer as having barcode numbers ——, ——, and ——, The extruder and thermoformer agree to this special order, which shall be clearly marked on all rolls/pallets as REGRIND ONLY. . ."**

Table 8.12 gives an annotated list of various purchasing specifications that the thermoformer as the customer must review with the extruder as the sheet supplier [78]. Obviously not all these specifications apply to every occasion. And not all are the sole responsibility of the extruder or the thermoformer. Some specifications, such as texture and color, are imposed by the customer or end-user of the thermoformed product. Some, such as impact strength and tensile strength, are imposed by the intrinsic performance requirements of the product. Some, such as gage tolerance and orientation, are critical to the way in which the polymer performs in specific thermoforming equipment. Some, such as melt index, intrinsic viscosity, molecular weight, water absorption, coefficient of thermal expansion, coefficient of friction, and abrasion, are intrinsic to the polymer selected for the application. Some, such as weatherability and fire retardancy, may be a function of the base polymer or its

Table 8.12 Sheet and Film Purchasing Specification Check List[1]

Specification	Certifier/Tester (X = Major, x = Minor) Thermoformer	Extruder	Both	Comments
Degree of orientation				
Required	X			
Allowed	x		X	
Sheet sag characteristics	X			Material consideration but extrusion characteristics may need to be considered too.
Use of regrind, trim, selvage	X			
Dimensional tolerances				
Gage tolerance	X		x	Sheet-to-sheet accuracy to require extruder input also.
Width and length tolerances	X		x	
Sheet flatness tolerance	X	x		Again, extruder input important.
Impact strength				
Drop ball, dart, Izod	X		x	Decision as to who will run test and what test is required must be clearly decided *a priori*.
Moisture level	x		X	Specific drying methods must be spelled out for certain materials.
Foreign matter				
Agglomeration (type, frequency)	X		x	
Contamination (type, frequency)	x		X	Extruder input important particularly for short runs, materials that burn or degrade easily, or polymers with fugitive processing aids, fillers, fire retardants and so on.
Gel count	x	x	X	Again agreement required for polymers that crosslink easily, transparent sheet, film, oriented film.
Finish of surface required embossing			X	Depth of texture, finish the primary control of the extruder.
Smoothness			X	Surface quality the realm of the extruder but certain polymers, regrind difficult to control re: surface quality.
Gloss			X	As above.

Pits	X		x	Good quality product can only be made from good quality sheet.
Dimples	X		x	As above.
Waves	X	x		Quality extrusion should yield minimum waves.
Air Entrapment	X			Quality extrusion should yield sheet with no air-caused defects.
Bumps	X			Quality extrusion should yield flat sheet.
Optics			X	If optics are important, both thermoformer and extruder need to define quality sheet, re: color, transparency, defects, residual stresses, surface marks, and so on.
Mechanical properties Tensile strength, compressive strength, hardness, elongation, yield strength, elastic modulus, coefficient of linear expansion, thermal conductivity, abrasion resistance, weatherability, water absorption, coefficient of friction, electrical properties.	X			If mechanical properties are critical, thermoformer must specify what tests are to be run, at what frequency, how the data are to be reported, and who will pay for it.
Heat deflection temperature at 66 $\mathrm{lb_f/in^2}$ at 164 $\mathrm{lb_f/in^2}$	X			Extruder could run these tests but probably should run by the thermoformer as measure of formability.
Effect of melt index, melt flow, intrinsic viscosity on formability	X			Only the thermoformer can determine this effect.
Hot tensile modulus at forming temperature	X			Extruder cannot be expected to qualify sheet on this specification.
Elongation at forming temperature	X			As above.
Tear resistance				
at room temperature	X			Extruder can run this test if necessary.
at forming temperature	X			Extruder should not be expected to run this test.
Foam compression set	X			Extruder can run this test if necessary.
Foam density	X			Extruder can run this test if necessary.
Closed cell count - foam	X			Extruder probably should not be expected to run this test.

(Continued)

Table 8.12 (Continued)

Specification	Certifier/Tester (X = Major, x = Minor) Thermoformer	Extruder	Both	Comments
Pigment distribution			X	Need to determine what tests to run first.
Filler condition		x	X	Conditions include particle size, size distribution, drying conditions.
Fire retardant condition		x	X	Conditions include method of addition (masterbatch, concentrate, dry blend) and perhaps method of determining effectiveness after extrusion, forming.
Odor			X	Certain polymers have obnoxious odors. Tests for odor may need to be defined.
Laminate properties Moisture (WVTR) Oxygen permeability			X	If water, oxygen barrier is critical, tests need to be defined and carried out for proper certification. In certain conditions, film thickness, pinhole number need to be measured at extruder for qualification.
Packaging Core size Roll diameter Skid weight Single or double polyethylene wrap Drying compound			X	Sheet surface quality, mechanical properties can be compromised if packaging is not adequate.

[1] Adapted from [78]

additive package. Other specifications, such as gel count or specks, may be a combination of specifications and realistic expectations. This is particularly true if substantial regrind is required in the final sheet. In all cases, before a specification can be agreed to, everyone must agree to:

- A specific protocol or way of testing for the desired physical characteristic,
- The specific group who will carry out the test,
- The frequency of testing required to meet the specification,
- A realistic bound or standard deviation for the test,
- An appropriate way of reporting the test results,
- The cost of the individual test,
- The financial and temporal penalty for not meeting the specification, and
- The way in which this cost is to be distributed among the various elements (polymer supplier, extruder, thermoformer, customer, end-user).

Some specifications such as dimensional tolerance, orientation, moisture, coextrusion structure and sheet appearance are considered generic. These are discussed in additional detail below.

Sheet Dimension

When plastic sheet is stretched, it becomes thinner. A sheet that is already thin yields parts that can be substantially thinner than desired. Thick sheet, on the other hand, yields parts that are over-designed and thus more costly than expected. Although significant improvements have been made in recent years in controlling the thickness of extruded sheet, some tolerance must still be given. The extruder and thermoformer usually compromise on overall sheet thickness or gage. It appears that with today's technology, sheet thickness variation can be held to less than 5% on sheet thinner than 3 mm or 0.120 in. On thicker sheet, tolerance can be held to within 0.2 mm or 0.005 in. Edge-to-edge uniformity is also important. Sheet thickness variation across the sheet width can be held to within 2% of the nominal sheet thickness dimension.

Orientation

As noted above, sheet can become preferentially oriented in the machine direction during extrusion. This is usually not a serious problem in roll fed thermoforming processes since the sheet being heated and formed is essentially infinite in the machine direction. Cross-machine direction or TD orientation can be the result of using a narrow die to extrude a wide sheet. In roll fed thermoforming, relaxation of excessively high TD residual stress can cause the sheet to pull free of the pins on the pin-chain. In cut-sheet thermoforming, on the other hand, both types of direction orientation can be serious problems. If the orientation in the sheet is excessive, the residual strain in the clamped sheet can be so great that the sheet can be physically pulled from the clamp frame during heating.

A simple oven test is used as a quality control method [79]. Either 250 mm × 50 mm or 10 in × 2 in strips or 250 mm × 250 mm or 10 in × 10 in squares are cut from as-received sheet. It is recommended that these strips be cut in a fixed pattern every time the test is run. Preferably, strips should be cut from both edges and the center of the sheet. These strips are placed on a metal plate that has been coated with a bake-on mold release such as silicone, polytetrafluoroethylene, or FEP, or with a fine layer of powdered talc. A wooden pizza paddle can be used in an emergency. The plate is placed in the radiant heating zone of the thermoformer for a time typical of the heating time needed during thermoforming. The samples are cooled and measured to determine the degree of orientation[1]. The degree of orientation is the change in sample dimension in a given direction divided by the initial dimension of the sample. Example 8.9 illustrates MD × TD orientation.

Example 8.9 Extruded Cut Sheet Orientation and Squareness

An order has been placed for 0.125 in × 40 in × 40 in ABS sheet with a 2% diagonal squareness, a 2% thickness tolerance, a 2% diagonal flatness and no more than 8% MD and 4% TD orientation. Determine the allowable dimensions of a 10 in × 2 in test strip after heating and the allowable dimensions on the extruded sheet. Do these dimensions meet the squareness criterion of $90° \pm \frac{1}{4}°$*?*

If the 10-in direction of the test strip is in the machine direction or MD, the ranges on after-heating test strip dimensions are 9.2 to 10.8 in (MD) by 1.92 to 2.08 in (TD). Note that if the test strip shrinks to the limit in both MD and TD directions, the sheet thickness increases 13% to 0.142 in.

The diagonal flatness based on $40 \times \sqrt{2} = 56.57$ dimension is 1.13 in. If the free sheet corner is raised by less than this value when the other three are clamped to a flat table, the sheet passes the requirement.

The cut sheet diagonal dimension is $40 \times \sqrt{2} = 56.57$ in. The allowable squareness factor is 1.13 in. This means that the maximum difference in cross diagonal dimensions are 57.13 to 56.00 in. The sheet is a parallelogram, as shown in Fig. 8.44. Consider the short diagonal. The edge in the right angle shown is:

$$x = \sqrt{(56^2 - 40^2)} = 39.192 \text{ in}$$

The base in the small triangle is therefore $40 - 39.192 = 0.808$ in. The angle is $\tan^{-1}\theta = \tan^{-1}(40/0.808) = 88.84°$. This angle is substantially less than the minimum recommended value of 89.75°.

Uniformity and consistency in orientation are important. Sheet-fed frames can be adjusted for a given unequal biaxial orientation. Wide variation in orientation can

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[1] If the sheet exhibits an excessive amount of curl, the technique can be altered. Place the extruded sheet between two friction-free thin aluminum plates that have been shimmed apart with metal stock at least 20% thicker than the polymer sheet. Place the sandwich structure in a conventional convection oven for several minutes. The exact time in the oven depends on the sheet thickness. Keep the sheet between the aluminum plates until thoroughly cooled [18].

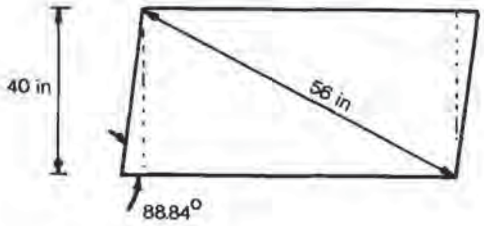

Figure 8.44 Geometry of cut sheet for Example 8.9

lead to sheet pull-out or excessive sheet sagging. The former is important with high melt-strength polymers such as ABS and PC. The latter is important with low melt-strength polymers such as LDPE and PP. It is recommended that orientation uniformity be controlled to within 5%. The shape of the heated strip can also give information about the internal stresses in the sheet. As noted in Chapters 3 and 5, plastics heat and cool quite slowly when compared with other materials. In sheets thicker than 5 mm or 0.200 in, heating relieves or anneals the cooling stresses. This results in a very slight increase in sheet thickness and a measurable necking-in or bowing-out all along the sheet edge. Excessive sample edge curl is also an indicator of nonuniform residual stress through the sheet. Poor processing skills such as low processing temperature, excessive extrusion throughput rate, poor melt homogenization by the screw, high nip roll pressure or excessive roll stack cooling can lead to heated sheet edge deformation.

Sheet Squareness and Flatness

Cut sheet overall dimension is also of concern. Thick-gage sheet is frequently cut to within 3 mm or 0.125 in in the length and width dimensions. This minimizes web held in the clamping frames. Out-of-square sheet frequently cannot be clamped. One quality sheet extruder recommends cross-diagonal dimensions to within 5%. Another recommends that corners be at right angles to within $\pm\frac{1}{4}°$ or $89\frac{3}{4}°$ to $90\frac{1}{4}°$. Example 8.10 shows the importance of sheet tolerance and squareness when buying sheet to fit. Sheet bowing and warping can cause clamping problems. The flatness of the sheet is determined by clamping three corners of the cut sample on a flat surface and measuring the height of the fourth corner above the surface plane. Out-of-flatness of 2% based on the diagonal dimension of the sheet can probably be tolerated. Very thick sheet may need to be oven-annealed prior to forming in order to flatten the sheet enough to close and tighten the clamp frame.

Example 8.10 Minimum Sheet Dimension

The clamp frame on a cut-sheet shuttle machine will clamp on a $\frac{1}{2}$-in sheet width. If the clamp frame is exactly 90° square, determine the minimum sheet dimension needed to clamp a within-tolerance sheet over a 40-in square mold. Commercial sheet tolerance is ± 0.125 in in all dimensions and the corner angle tolerance is $90° \pm \frac{1}{4}°$.

If the sheet is cut to exactly right angles and to exact dimensions, it needs to be $40 + 2 \cdot \frac{1}{2} = 41$ in on a side. For a trim tolerance of ± 0.125 in, the minimum *right angle* sheet must be $41 + \frac{1}{8} = 41.125$ in on a side. For a non-right angle sheet, the sheet dimension must be increased by:

$$2 \times 41.125 \cdot \tan 0.25° = 0.359 \text{ in}$$

The overall *minimum* in-tolerance sheet dimension should be at least 41.48 in on a side or just less than $1\frac{1}{2}$ in greater than the mold dimension.

Moisture

The importance of drying polymers thoroughly before extrusion has been discussed above. Many plastics such as polycarbonate, polymethyl methacrylate, polyethylene terephthalate and ABS are hygroscopic. The extent to which a given polymer absorbs water depends on the nature of the polymer and the time that the sheet has been exposed to the environment. As noted, there are two forms of water attachment. Adsorption is surface water only. Adsorption is usually the direct result of high humidity and cold surface temperature. Water absorption is a diffusion process. The water molecules move from the moist environment, humid air, into and through the entangled polymer molecules that make up the dry polymer sheet. The rate of diffusion depends on the concentration driving force, being the amount of water in the air, and the nature of the polymer. Some polymers such as polyamide and PET have strong affinities to water, through hydrogen bonding along the polymer backbone. As a result, these polymers absorb water readily and to a relatively high level.

It is thought that the water molecules cluster in the void regions between molecular chains. When wet sheet is rapidly heated, as in thermoforming, these microscopic clusters expand to produce microvoids. Additional water molecules diffuse to these voids to produce visible bubbles. In mild cases, an otherwise transparent sheet appears hazy. In extreme cases, that sheet appears translucent, opaque white or blistered. Typically, the sheet producer should stack moisture-sensitive cut sheet directly onto polyethylene film that is then sealed around the stack. Polyethylene film is an excellent moisture barrier film. Moisture-sensitive thin-gage roll-stock should be sealed in a similar fashion. Quality control samples should be taken by the thermoformer at the time of shipment receipt. A visual inspection for moisture can be made at the time the degree-of-orientation test is being made. The inspection should be made again prior to forming. In order to ensure dry sheet, polymer suppliers recommend that specific moisture-sensitive polymers be thoroughly dried immediately prior to thermoforming. Table 8.8 gives some guidelines for the drying temperatures and times of several types of polymers. The drying times are per mm or 0.040 in of sheet thickness.

Sheet Appearance

As detailed above, most applications require specifications on various aspects of sheet surface quality or appearance. Since requirements vary from application to application, no general set of criteria can be established. General sheet appearance can be categorized as follows:

Linear Surface Marks. Die lines and polish roll or calender roll marks are usually linear lines in the sheet direction. Some of these surface defects are minor and can disappear when the sheet is heated. Most die lines can be quite noticeable however. Since they occur when the sheet is hot and being formed, they usually cannot be annealed out. Wavy linear lines appear in some polymers such as PET and PVC if the material is extruded at an excessively high extrusion melt temperature or if insufficient back pressure is applied to the die lips during extrusion. Wavy lines can be attributed to the downstream image of the tip of the rotating screw. These effects are not seen when gear melt pumps, static mixers or screen packs are in place.

Irregular Surface Marks. Other marks seen on the sheet can be categorized as irregular marks. Marks that have exact periodicity are directly attributed to the roll stack. These can be as simple as detritus on the roll itself or as complicated as a plugged waterline or bad bearing in a chill roll. Teardrop- or disk-shaped dents are usually entrained air at the roll stack, indicating that the air knife is not functioning properly. Chatter or ribbon marks on one side of the sheet can be attributed to an unstable bank on that side of the roll. The source of microscopic web, nerviness or tracks can be rapid chilling of the extrudate prior to contacting the nip roll or very low level hesitation in the polish roll. Small splits in the edge bead indicate that the extruder die or deckle is too narrow for the sheet width being extruded.

Holes, Pits and Lumps. These are discrete, isolated, random occurrences in the sheet which do not disappear when the sheet is heated. On the contrary, these defects can lead to sheet splitting during forming. As a result their frequency must be carefully monitored. There are at least three major sources of these defects - contaminated virgin polymer, contaminated or thermally damaged regrind, and moisture in the extruder feed. Of these, contaminated or thermally damaged regrind is usually considered to be the primary problem. Two other sources of contamination are specks and gels. Specks are usually the result of dead zones in the polymer flow stream from the plastication section to the die lip. There are many sources of specks including inadequate purging, thermally sensitive polymer, improperly compounded pigment, mechanically unstable additive package, poor die design, poorly streamlined deckle and choke bars, poorly tapered breaker plate and airborne contamination at the die face or around the hopper area. As expected, specks are most obvious in transparent and white sheet. Thermally sensitive polymers can degrade during reprocessing with the result being the formation of gels. Off-spec virgin resin can contain gel particles. Gel particles are usually resinous, thermally crosslinked polymer that cannot be adequately remelted. Gel particles are a prominent source of defects in polymers such as HDPE, PP, PET and PVC. Gels are most obvious in transparent or hazy sheet.

Color Quality. Advanced color computer matching techniques have minimized the obvious problems in obtaining good color matching. However, it is incumbent on the thermoformer to make certain that batch to batch color uniformity is met. The pigments used to produce colors in thermoformable sheet must be permanent and must not change in tint during typical thermoforming, regrinding and re-extrusion operations. Color intensity across the sheet must always be uniform. In highly oriented thin-gage sheet and film such as oriented PS (OPS), light and dark regions can be produced if the orientation is not uniform. Some tinting dyes used in certain polymers such as PET lose their effectiveness during thermoform heating. As a result, transparent PET can yellow. PVC is highly sensitive to surface temperature and can also yellow. The PET regrind can be re-tinted whereas the PVC discoloration is intrinsic to the polymer and is therefore very difficult to hide. Obviously the problem is apparent with transparent polymers, pure white and dark colors.

Surface Appearance. Gloss and embossing-retention represent the extremes in sheet surface appearance. The degree of gloss can be regulated to some degree by the surface temperature of the finishing rolls and to some degree by the extrudate temperature and the temperature and speed of the first roll the extrudate contacts. Usually the free surface of any extrudate has higher gloss than the contact surface. Polymers such as ABS, mPPO and HIPS usually yield intrinsically semi-glossy sheet owing to their two-phase nature. In some cases, the base polymer will not yield the necessary gloss and so must be laminated or melt coated with a polymer specifically designed to yield a high gloss surface. High gloss can be obtained by high melt extrusion temperature, slow extrusion speed and high polish roll temperature. On the other hand, embossed design details are best retained when the sheet temperature is low, the embossing roll is cold and the polymer has very low elastic memory. The last point was discussed in Chapter 4 and is quite important to retention of the embossing details in the formed product. For example, if the pattern is embossed into a polymer that has excellent memory retention, that pattern will be lost when the sheet is reheated prior to forming. Thus the quality of the image retention from the embossing roll is less important than the technically proper selection of polymer to be embossed.

Annoyance Factors

In addition to the litany of quality factors given above and in Table 8.12, there are always nuisance factors that must be considered *a priori*. Many polymers such as PS, ABS, and PET have very high surface energies when extruded. *Static charge buildup* can yield uncomfortable and annoying shocks. It is a major reason for tenacious dust and dirt accumulation on sheet which can lead to rejected product. Static charge can also be the source for ignition when using a hydrocarbon foaming agent. Some charge effect can be minimized through antistatic processing aids.

Copper wool bleed-off bands and ionized air jets are also used to minimize static charge[1]. Eliminating trim or cutter dust from the heating and forming area can help as well. Minor blocking, or the sticking of one ply to another on roll-fed sheet, can be a minor problem. The drag or stick effect can affect the way in which the sheet is fed to the pin chain. The tugging can elongate the pin rail holes allowing the sheet to differentially move during forming. If the sheet plies can only be separated with heroic effort, the severely blocked sheet must be scrapped and the reasons for the blocking investigated. Typical solutions include proper control of extruded sheet tension during take-up, addition of a blooming agent or external lubricant such as a stearate to minimize incidental adhesion and reduction in sheet temperature at the time of take-up. Aged sheet containing an antiblock agent usually shows more blocking tendency than fresh sheet, simply because the antiblock diffuses from the interface between the plies back into the polymer sheet. High temperature sheet storage will usually exacerbate blocking. Torpedoing or core extrusion can be a nuisance as well. Here the core slowly extrudes from the roll of sheet ultimately making the roll unusable. Typical reasons for torpedoing include excessive anti-blocking agent, nonuniform gage, with one side of the sheet slightly thicker than the other, nonuniform winding tension and a winding station take-up axis that is not parallel to the sheet delivery system.

Lamination Quality

As noted, multilayer sheet and film are used in many ways. UV-barrier films are applied over PS and ABS substrates so that the formed parts can be used outside for signs, pools and camper tops. 0.2 mm, 8 mil or 0.008 in, cap-sheets of PS are applied to one or both sides of low-density PS foam to increase depth of draw and to dramatically improve product stiffness and cut resistance. In order to process crystallizing PET or CPET to proper stiffness without causing brittleness, two layers of PET are coextruded. One layer contains a crystallizing agent and the other may contain an impact modifier[2]. In addition to standard material property monitoring and control of each layer, care must be taken to monitor laminate thickness, adhesion, and thickness distribution across the sheet. A common monitoring device is the ultrasonic gage. This device is particularly effective if the velocities of sound in the laminated layers are substantially different. Of course, thickness can be determined by simply sectioning the sheet and optically measuring the thicknesses of the various layers. Warping and cupping during heating of multilayer sheet can be quite

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[1] For many high-appearance applications, the sheet surface must be protected from scuffing and dust while in transit from the extruder to the thermoformer. Thin LDPE film is used between the layers of both cut sheet and roll-fed sheet. For cut sheet, once the sheet is installed in the clamp frame, the film is manually stripped and segregated for recycling. For roll-fed sheet, the layer is continually stripped as the sheet enters the pin-chain end of the former. The added expense of this protective layer ensures that the sheet will be free from detritus and scuffs prior to thermoforming. It does not guarantee that the formed part will have the same attributes.

[2] See Chapter 9 for more details on thermoforming CPET.

severe if the thermal expansion coefficients of the various layers are not carefully matched, if the laminate thicknesses are not carefully controlled, or if dissimilar polymers are used on opposite sides of the laminate centerline. The oven test used for measuring the degree of orientation can be used as a screening test for laminate curl and delamination potential.

Another important concern to the thermoformer is interlayer delamination during heating and forming. Delamination can appear as swarms of bubbles or blisters in the formed part. In the extreme, two layers can separate completely. This can occur as the formed part cools or during plug-assisted stretching. The primary cause for process delamination is inadequate adhesion during the sheet fabrication process. This may be caused by low interfacial temperature, inadequate compressive forces or short residence time under pressure. However, some of the following causes of delamination have been observed:

- Excessive or uncontrolled heating during thermoforming can severely reduce the interfacial adhesion forces,
- A transparent surface layer can allow radiant energy to penetrate to the interface, resulting in a loss of adhesion,
- A mismatch in thermal expansion coefficients of polymers in different layers can cause one layer to separate from another,
- A wet layer can evolve moisture at the inner layer,
- Fugitive processing aids can evolve gas at the inner layer,
- Air may be trapped between the layers due to inadequate nipping, and
- So on.

As a result, the cause of delamination is not always apparent on first examination.

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9 Newer Thermoforming Technologies

9.1 Introduction

9.2 Thermoforming Crystallizing Polyethylene Terephthalate
  PET Crystallinity
  CPET Patents
  Characterizing Polyethylene Terephthalate
  The Effect of Temperature on Crystallization During Sheet Extrusion
  Cooling CPET on Chill Rolls
  Heating CPET in Roll-Fed Thermoformers
  Forming the Sheet
  Cooling the Formed Part
  Trimming Parts from Web
  Troubleshooting CPET Forming

9.3 Pressure Forming
  Thin Gage
  Heavy Gage

9.4 Forming Filled and Reinforced Polymers

9.5 Laminated Sheet Thermoforming
  Heating Multilayer Sheet
  Forming Multilayer Sheet

9.6 Twin-Sheet Thermoforming
  Simultaneous Twin-Sheet Forming
  Sequential Twin-Sheet Forming
  Seal Area—Adhesion
  Seal Area—Compressive Force
  Seal Area—Design

9.7 Polypropylene Thermoforming
  Sag Test
  Modified Polypropylenes

9.8 Thermoforming Foam Sheet
  Cell Architecture—Actual v. Ideal
  Radiant Energy Transmission
  Internal Cell Gas Pressure
  Forming Window for Foam
  The Forming Equipment

9.9 Other Forming Technologies
  Interdigitation
  Sealed Air Cushion/Dunnage

9.10 References

9.1 Introduction

It has been observed that there have been more advances in certain aspects of thermoforming in the last few years than in the previous five decades [1]. The many reasons for this were detailed in Chapter 1. Certainly new business opportunities have led to substantial improvements in heating and forming methods. In many cases, new products have required dramatic modifications in processing techniques. This chapter focuses on some of the newer processing techniques, such as:

- **Crystallizing polyethylene terephthalate (CPET) forming**, developed for higher temperature microwavable food container applications,
- **Pressure forming** of both thin-gage and heavy-gage sheet. The former technology was developed for markets needing the properties of polypropylene. The latter was developed to compete with injection molding in electronic cabinetry. Both areas have been rapidly broadened recently.
- Laminate or **multilayer thermoforming**. Heavy-gage multilayer parts are used in pools, spas and outdoor structures. Thin-gage multilayer parts are used as barrier containers for foodstuffs and medicine and pharmaceuticals.
- **Twin-sheet forming**, demonstrated decades ago but only recently developed as markets for hollow flat panels have evolved. As noted below, there are many ways of producing thermoformed hollow structures.
- **Forming of filled and reinforced polymers**. This includes filled commodity polymers such as talc-filled PP and high-performance composites such as carbon-fiber reinforced PEEK.
- **Low-density foam thermoforming**. Although this established market is more than 500 Mlb (225 Mkg), there has been relatively few studies to determine the ways in which foams heat and stretch. This is now changing with the development of markets for polyolefin foams, higher temperature styrenic foams, PET foams and certain high-performance fire-retardant foams.
- Forming low-melt strength crystalline polymers, as epitomized by **polypropylene**. Polypropylene market development has always been inhibited by the poor melt strength of traditional homopolymer. Recent developments in high melt strength polymers and copolymers hold promise for both thin-gage and heavy-gage sheet.

And as with any evolving technology, there are newer technologies that are not quite market-ready. Some of these are outlined here as well.

9.2 Thermoforming Crystallizing Polyethylene Terephthalate

In the early 1970s, microwave technology had developed to the point where small microwave ovens were being used to reheat prepared foods in institutions and restaurants. Traditional unit serving containers were of aluminum. The industry sought a container that was "dual-ovenable", that is, a container made of an inexpensive polymer that would be transparent to microwave energy and also capable of withstanding 200°C or 400°F convection oven temperatures. Crystalline polyamide-66 or nylon 66 and polyethylene terephthalate or PET were the logical choices. PET was chosen primarily on price and stiffness at 200°C. PET is a condensation polymer of ethylene glycol and terephthalic acid:

$$\mathrm{X\ HOCH_2\text{-}CH_2\text{-}OH + X\ HOC\text{-}\phi\text{-}COH \leftrightharpoons \left(OC\text{-}\phi\text{-}CO\text{-}CH_2\text{-}CH_2 \right)_x + X\ H_2O} \qquad (9.1)$$

The useful polymer molecular weight range is about 20,000 to 40,000. The primary applications for PET are in films and fibers. In 1993, about 2,700 Mlb or 1.2 Mkg PET was consumed in the US. Of this, approximately 170 Mlb or 0.075 Mkg was converted into sheet for packaging. Of this, approximately 60 Mlb or 0.027 Mkg was converted into crystallized PET, or CPET dual-ovenable packaging [2]. CPET applications have expanded from the ubiquitous "TV dinner tray" to bakery containers and bacon crispers [46]. The competition to CPET is PET-coated paperboard, BMC-thermoset polyester resin, talc-filled PP (in some instances), and styrene-maleic anhydride or SMA.

PET Crystallinity

PET is one of a family of condensation polymers that are characterized as *slowly crystallizing, semi-crystalline* polymers having glass transition temperatures above room temperature and melt temperatures in excess of 150°C. Table 9.1 gives a list of many polymers that meet these criteria [3,4]. PET was one of the first polymers to be exploited in polymer-specific processing schemes. Polymer-specific processes are those that have been invented specifically to circumvent the inherent processing weaknesses in the polymer that prevent it from being run in conventional processing equipment. The best example of polymer-specific processing is the development of stretch-blow molding for PET. Since PET has relatively poor melt strength, it cannot

Table 9.1 Transition Temperatures of Semicrystalline Polymers [3,4]

Polymer	Glass transition temperature (°C)	Crystalline melting temperature (°C)	Crystallization rate at 30°C below melt temperature (μm/min)
Polyoxymethylene (POM) (Polyacetal)	−50	180	400
Nylon 610 (PA 610)	40	225	—
Nylon 6 (PA 6)	50	225	150
Nylon 66 (PA 66)	50	265	1200
Polyethylene terephthalate (PET)	70	265	10
Polyphenylene sulfide (PPS)	90	285	—
Polyetheretherketone (PEEK)	140	335	—

be parison-blow molded with any degree of success. The high gas barrier properties of highly oriented PET provided sufficient incentive to develop an entirely new process, just for PET [5,45]. The high crystalline temperatures of the polymers in Table 9.1 have always intrigued designers and processors. Two characteristics have inhibited commercial realization of high temperature polymer performance. The rates of crystallization of most of these polymers are low when compared with polyethylene. And the *practical* ultimate extents of crystallization, that is crystallinity at an infinite time, X_∞, are also low. Most crystalline-tendency polymers show crystallinity levels of 40 to 90% [6]. With some polymers such as polycarbonate and polyvinyl chloride, the crystallization rate at processing temperature is so low that the polymer is amorphous for all intents. With other polymers such as nylon 6, PA 6 or polycaprolactam and PET, the crystallization rate is sufficiently low enough that the polymer can be readily quenched to an amorphous state. For PET, for example, thermoformers refer to amorphous PET as "APET". With carefully controlled temperatures, nylon 6 can be crystallized to 80% or more. On the other hand, even with carefully controlled temperatures, unadulterated PET usually cannot be crystallized beyond about 40%. For most semicrystalline polymers, the large noncrystalline or amorphous regions surrounding the crystallites are quite rubbery at temperatures substantially above the glass transition temperature but below the crystalline melting temperature. As a result, the semicrystalline sheet or shape in this temperature range is usually *quite tough but not stiff*. HDPE at room temperature range is a classic example. CPET at 200°C is another. These characteristics limit processing and performance of neat, unfilled or unreinforced polymers.

In the past two decades, there have been many attempts to develop a high temperature PET food container. PET exhibits a very great density change with crystallinity, about 0.0012 g/cm^3 or about 0.09% increase with each 1% increase in crystallinity. As a result, when PET is injection molded into a very hot mold and crystallized *in situ*, the mold part is under very high residual stress and is very brittle. If PET is injection molded into a very cold mold, the resulting part is usually amorphous. If this part is crystallized without fixturing, the internal stresses and reduction in part volume lead to excessive shrinkage and warpage. In the 1970s, it was found that PET crystallization rate could be altered with nucleants and other adducts. As a result, relatively heavy gage—to 60 mil, 0.060 in or 1.5 mm—PET sheet could be extruded without substantial crystallinity, typically $<3\%$. Since the glass transition temperature is 70°C, the sheet is typically transparent and brittle-tough at room conditions. This sheet could be heated to a condition where the crystallization rate became significant. If the rapidly crystallizing sheet was then formed against a heated mold, crystallization could be continued until the formed sheet was sufficiently crystalline, typically about 20%, to withstand 200°C or 400°F air for up to 60 min.

This development, commonly called CPET thermoforming, was commercialized in the mid-1980s and paralleled the other PET polymer-specific process of stretch-blow molding. The formed part was unique in that it could sustain continuous use temperatures far in excess of the maximum forming temperature without excessive distortion. This is in contrast to conventional thermoforming, where the locked-in forming stresses relieve at use temperatures 20 to 50°C below the highest forming temperature.

CPET Patents

Since its discovery in the 1920s, polyethylene terephthalate has become one of the most important and one of the most studied polymers. Early on, PET was found to crystallize relatively slowly to a relatively low level. This is used to advantage in the production of high-tenacity fibers, since it allows an added degree of control of the molecular orientation during spinning. In turn, this allows for orientation-induced or strain-induced crystallization as well as thermally-induced crystallization. As noted above, amorphous PET sheet is brittle-tough at room temperature. Thermoforming applications for unoriented sheet include food, drug and medical packaging. APET is considered as a recyclable replacement for unmodified PS and RPVC for many applications. Uniaxially oriented PET is used as recording and photographic film tape base. Blown films are biaxially oriented, have high levels of orientation-induced crystallization and exhibit improved gas barrier properties. The stretch-blow molding process utilizes biaxial orientation to achieve high barrier levels for CO_2 and is commercially one of the most successful polymer-specific processes developed. Keep in mind, then, that there are two ways of achieving crystallinity in PET and other polymers. Orientation-induced crystallization is common in biaxially oriented structures. Thermally-induced crystallization is used to produce high-temperature thermoformed containers.

Fine inorganic powders are known to alter the thermally-induced rate of crystallization of PET [7]. Incompatible organic polymers such as polyethylene and polypropylene are also used to change the neat PET crystallizing rates [8-11]. In 1976, McTaggart patented a multistep method of producing a thermoformed crystalline PET part beginning with a PET containing 2 to 16% (wt) poly-4-methylpentene-1 and 1% (wt) TiO_2 [12]. He taught forming on a cold mold and then fixturing and heating the formed part to crystallize the PET. He thought that the olefin retarded high levels of crystallinity and therefore the product was tougher and less brittle. In 1978, Dempsey et al patented a single step forming method that used up to 0.5% (wt) talc as a nucleant [13]. The sheet was rapidly heated using radiant heaters with surface temperatures up to 1400°F or 760°C until the sheet had reached a crystallinity level of 3 to 10%, in approximately 10 s for 30 mil, 0.030 in or 0.75 mm thick sheet. It was then rapidly transferred to a mold having a temperature of 280 to 290°F or 138 to 143°C and held there until the sheet had achieved 25 to 30% crystallinity, approximately 10 s for 30 mil, 0.030 in or 0.75 mm sheet. In 1984, Gartland et al [14,15] found that olefins also acted as nucleants and so inorganic nucleants were not needed. They heated the 0.85 to 1.0 IV, 15 mil, 0.015 in or 0.38 mm sheet to 135 to 150°C until the crystalline level reached 10%, then held it against a heated mold for 5 to 7 s, or until the sheet had reached 20 to 35% crystallinity. They recommended against forming sheet thicker than 40 mils, 0.040 in or 1.0 mm.

Characterizing Polyethylene Terephthalate

As detailed below, intrinsic viscosity or IV is a measure of the molecular weight of PET. The IVs for PETs used for tire cord, certain films and many heavy fiber-forming applications are typically in the 0.62 to 0.68 IV range. The IV range for bottle-grade, thin film and some fine fiber-forming PET applications is typically 0.78 to 0.85. PETs with IVs in the range of 0.9 to 1.0 are used in thermoforming, blown films and fine fibers. PETs with IVs in excess of 1.0 are usually very difficult to produce. These PETs are sought for high-tenacity fibers, injection blow molding and foams. Although low-IV PETs were used in the early CPET work, it was evident that higher molecular weight PETs gave improved crystallization rate control and tougher final products. With higher molecular weight, there are indications of finer spherulites and earlier secondary crystallization, leading to slower crystallization rates throughout the forming process and during the long-time, high-temperature use of the final product. Thus the final product has lower crystallinity, less brittleness and greater ductility at the end of the oven cycle.

The recommended solvents for PET IV measurements are usually combinations of either phenol and tetrachloroethane or trifluoroacetic acid and methylene chloride. The relationships between inherent viscosity, [η], intrinsic viscosity, IV, and number-average molecular weight, M_n, for various solvents are given in Table 9.2, as are other relationships, such as IV to inherent viscosity and zero-shear melt viscosity to IV [16]. Since melt viscosity is easier and faster to determine in quality control laboratories than is solution viscosity, the last correlation is commercially important. Intrinsic viscosity is not equal to inherent viscosity. At 1.0 IV, the error is about 7.4%. At 0.7 IV, the error is just less than 5%. The error in using these terms interchangeably is about 10% in the value of the number-average molecular weight at 1.0 IV and somewhat less at lower values of IV.

As noted below, PET crystallization rate is maximum at about 175°C. However, the rate is so rapid at this temperature that laboratory measurements of isothermal crystallization rate, half-time for crystallization and induction time cannot be accu-

Table 9.2 PET Viscosity Relationships [16]

Solvents (30°C)	Relationship[1]
3 pts trifluoroacetic acid 1 pt methylene chloride (DuPont)	$[\eta] = 2.45 \times 10^{-3}\,(M_n)^{0.587}$
1 pt phenol 1 pt tetrachloroethane (3M)	$[\eta] = 7.55 \times 10^{-4}\,(M_n)^{0.685}$
60 pts phenol 40 pts tetrachloroethane (Goodyear)	$[\eta] = 7.50 \times 10^{-4}\,(M_n)^{0.68}$
Other correlations	
Goodyear	$[\eta] = 0.5 \cdot e^{(0.5 \cdot IV - 1)} + 0.75 \cdot IV$
Zero-shear viscosity	$\eta_0(\text{poise}) = 0.033 \cdot (IV)^{5.02} \cdot \exp[15(\text{kcal/mol})/R(T + 273)]$

[1] [η] = Inherent viscosity,
IV = Intrinsic viscosity,
M_n = Number-average molecular weight.

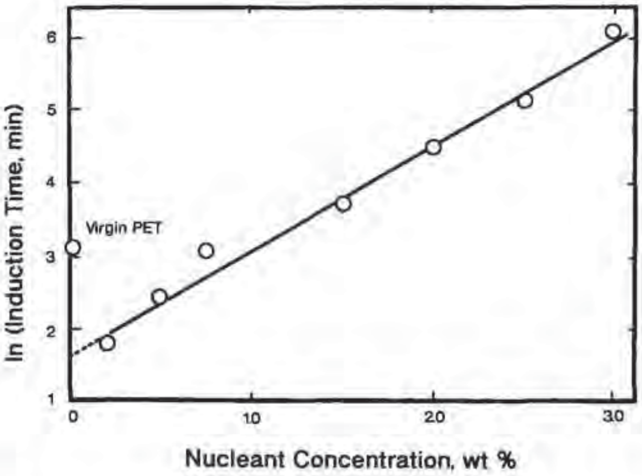

Figure 9.1 Effect of SiO_2 nucleant concentration on isothermal induction time for polyethylene terephthalate, PET. Adapted from [17]

rately determined. As a result, these data are usually obtained at 140°C foramorphous PET initially at room temperature and at 200°C for amorphous PET initially at melt temperature. Many nucleants are used to promote crystallization in high-IV PETs. Figure 9.1 shows the effect of SiO_2 concentration on the isothermal induction time of 1.0 IV PET [17]. The data can be described by:

$$t_i = t_{i,o}\, e^{ac} \tag{9.2}$$

where t_i is the induction time, $t_{i,o}$ is the induction time extrapolated to zero nucleant concentration, c is the nucleant concentration in (wt %), and a is the scale factor. This equation is thought to be reasonably accurate for inorganic nucleant concentrations up to 1% or so. The value for $t_{i,o}$ for inorganic nucleants is about 5 to 10 times less than the actual measured induction time for unadulterated PET. Thus inorganic nucleants in low concentrations act to accelerate the beginning of nucleation. Organic nucleants, on the other hand, show much less influence on induction time, as seen in Table 9.3 for LLDPE nucleant in $[\eta] = 1.04$ PET [14]. The equation describing organic nucleant effect at isothermal conditions is:

$$t_i = t_{i,o}[1 + b\, e^{-ac}] \tag{9.3}$$

where a and b are empirically determined constants for the specific organic nucleant. In addition, nucleants act to accelerate the rate of nucleation. One measure of the rate of nucleation is the half-time of nucleation. This is defined as the time needed to achieve 50% of the final level of crystallinity, as determined by isothermal differential scanning calorimetry or dilatometry [18]. As seen in Table 9.3, the half-time, $t_{1/2}$, for LLDPE in PET decreases with increasing concentration in a fashion similar to that for induction time. Thus Equation 9.3 can be used for both induction time and half-time, if the proper values for a and b are determined. The relative effect of molecular weight on these empirical equations is unknown.

Table 9.3 140°C Isothermal Crystallization Rate Data for LLDPE-Nucleated PET, [η] = 1.04 [14]

Nucleant concentration	Induction time, t_i		Half-time, $t_{1/2}$	
	Experimental (s)	Calculated (s)	Experimental (s)	Calculated (s)
0%	26.5	26.5	22	22.4
1%	22	20.8	15*	15.0
2%	18.5*	18.5	11.5	12.1
3%	17.0	17.6	10.5	10.9
10%	17.6	17.0	12	10.0

* Correlation points

As stated above, PET never achieves 100% crystallinity. The experimental upper limit for nitrogen-crystallized PET appears to be about 50 to 60% [19]. The degree of crystallinity at infinite time, X_∞, is a function of the isothermal crystallization temperature (Fig. 9.2) [20]. A functional relationship for $X_\infty(T)$ to temperatures of 200°C or so is:

$$X_\infty(T) = 0.4[1 - e^{-c(T-d)}] \tag{9.4}$$

where again c and d are experimentally determined coefficients. This expression implies that the highest crystallinity level that can be achieved is 40% and that it is independent of the level of diluent. There is sufficient evidence to indicate that diluents such as LLDPE in PET change the induction time and the rate of crystallization but do not appreciably change the final level of crystallinity.

The room temperature density for amorphous PET is 1.335 g/cm³. The extrapolated room temperature density for 100% crystalline PET is 1.455 g/cm³. The law of mixtures is used to obtain densities at various levels of crystallinity [21]:

$$\frac{1}{\rho} = \frac{X}{\rho_c} + \frac{(1-X)}{\rho_a} \tag{9.5}$$

where X is the crystalline fraction and ρ_c, ρ_a, and ρ are the densities of the crystalline, amorphous and partially crystalline polymers. A linear relationship is sometimes used [13]:

$$\rho = X\rho_c + (1-X)\rho_a \tag{9.6}$$

Although this is not technically correct, it is accurate to within 1% of the law of mixtures to crystallization levels of 40% or so and it is much simpler to use than Equation 9.5.

The relatively slow crystallizing nature of PET and its commercial importance has made PET the polymer of choice for technical studies of crystallization kinetics. The traditional method of observing and measuring crystallization is to watch crystallites grow on an isothermal hot stage of an optical microscope. Again, amorphous room temperature PET film is heated to 170°C or PET melt is cooled to 200°C for examination. The observer records the time when the first crystallites appear as the

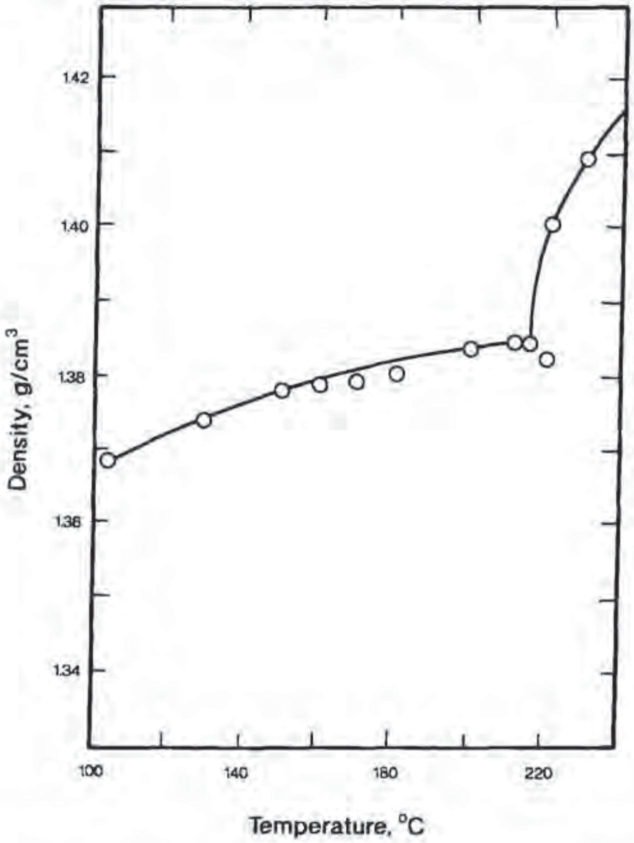

Figure 9.2 Temperature-dependent density of crystallized polyethylene terephthalate, PET, at ten crystallization half-times. Redrawn from [20]

induction time, and the time when crystallization has reached half its final value, $X(t) = X_\infty$, as the half-time. The isothermal crystallization process has been described by the Avrami equation [22-24]:

$$X(t) = X_\infty [1 - \exp (k(T)t^n] \tag{9.7}$$

where k(T), the isothermal Avrami function, is strongly dependent on temperature and n, the Avrami coefficient, is a function of the molecular nature of the crystallizing process. This equation is considered applicable only so long as the crystallites are growing unhindered. This is referred to as the primary crystallization region. In this region, the Avrami coefficient value for PET has a range of 3.0 to 3.5. The Avrami coefficient is a characteristic of the nature of the crystallization and its value does not appear to be influenced by nucleants. The Avrami function, k(T), is directly related to the half-time of crystallization and the value of the Avrami coefficient:

$$(t_{1/2})^n = \ln 2/k(T) \tag{9.8}$$

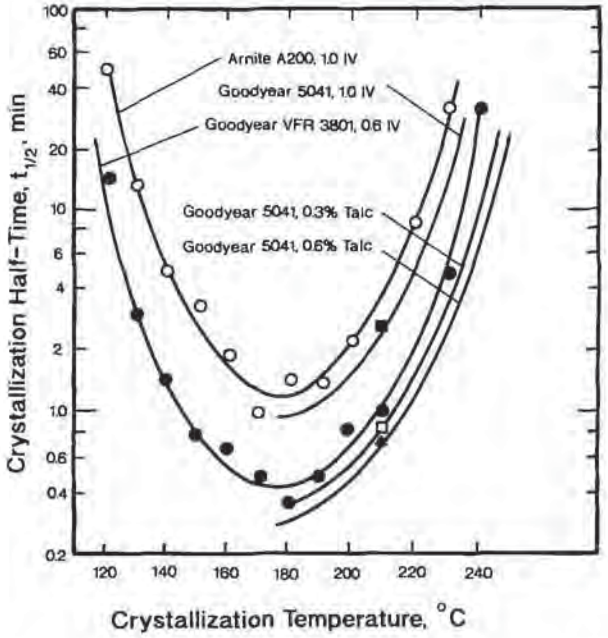

Figure 9.3 Crystallization half-times for various types of polyethylene terephthalate, PET

As shown in Fig. 9.3 [25], the crystallization half-time appears to be symmetric around a specific temperature, the temperature of maximum crystallization rate, T_{max}. One rule of thumb relates this temperature to the glass transition temperature and crystalline melting temperature as:

$$T^*_{max} = \tfrac{1}{2}(T^*_{melt} + T^*_g) \tag{9.9}$$

where the asterisk means absolute temperature. Another rule of thumb gives:

$$T^*_{max} = 0.8\ T^*_{melt} \tag{9.10}$$

For PET, $T_{melt} = 265°C$ and $T_g = 70°C$. These equations yield $T_{max} = 168°C$ and 157°C, respectively. From isothermal half-time determinations, it appears that $T_{max} = 175°C$, experimentally, although values of 165°C to 190°C have been reported. It appears that T_{max} is about 10°C higher when the polymer is cooled from the melt than when it is heated from room temperature. The shape of the half-time crystallization curve appears to be a Gaussian distribution that is symmetric about T_{max} and is given as [26]:

$$t_{1/2}(T) = t_{1/2}(T_{max}) \cdot \exp[4 \ln 2\ (T - T_{max})^2/D^2] \tag{9.11}$$

When $T = T_{max}$, $t_{1/2} = t_{1/2,min}$. D is the half-width of the distribution function. For PET, D = 32°C. The characteristic crystallization data for PET are given in Table 9.4. Figure 9.3 shows the relative effect of PET IV on the isothermal half-time of crystallization [27].

Table 9.4 Characteristic Isothermal Crystallization Kinetic Data on PET

Parameter	Data range	Recommended value
Avrami coefficient, η	3.0–3.5	3.55
T_{melt} (°C)	252–265	255
T_g (°C)	67–70	68
$T_{max,cooling}$ (°C)	174–190	175
$T_{max,heating}$ (°C)	158–165	162
$T_{1/2,min}$ (s) [1.0 IV]	30–60	35
D (°C)	8–32	32

Note that the earliest method of studying crystallization kinetics was the isothermal hot plate, a constant temperature environment. Newer techniques such as the differential scanning calorimeter (DSC) and the differential thermal analyzer (DTA) can examine polymer characteristics in a nonisothermal environment. And of course, the thermoforming process is quite nonisothermal. Although there have been many studies to relate nonisothermal test environments to the isothermal Avrami kinetics discussed above, most require reinterpretation of the initial Avrami assumptions. Ziabicki proposed a simple, empirical model [28]:

$$K(T) = K(T_{max}) \cdot \exp\left[1 - f(T - T_{max})\right] \tag{9.12}$$

where $K(T) = 1/t_{1/2}(T)$ and $K(T_{max}) = 1/t_{1/2 \cdot min}$. The rate of crystallization is then given as:

$$\frac{d}{dt}\left(\frac{X}{X_\infty}\right) = (1 - X)K(T) \tag{9.13}$$

This model is similar to the differentiated form for the Avrami equation if $n \equiv 1$, contains no discrete induction time and so is frequently faulted. It has been noted, however, that "...nonisothermal crystallization kinetics are too complex for meaningful conclusions concerning mechanism and energetics of the nucleation process to be deduced..." [27]. The lack of an identifiable induction time in the nonisothermal process is of concern to others [26,28,30]. In one effort in which crystallization is considered akin to chemical reaction, the nonisothermal crystallization rate equation is replaced with a reaction rate equation in which the reaction rate constant replaces the Avrami-type constant. The nonisothermal induction time is considered a *material function*, and is given as:

$$t_i = t_{i,o} \cdot \exp\left(T/T_o\right) \tag{9.14}$$

where $t_{i,o}$ and T_o are considered material properties that are obtained through standard DSC characterization.

For most rapidly heating or cooling processes such as blown film or thermoforming, the relative effect of nucleants on induction time can probably be ignored as a first approximation. And the overall effect of induction time can probably be folded into the general crystallization kinetics equation as a portion of the half-time value.

The Effect of Temperature on Crystallization During Sheet Extrusion

The general characteristics of extrusion and chill roll cooling were summarized in Chapter 8. Extrusion of PET requires an understanding of the interaction of sheet cooling and crystallization kinetics. This translates into proper chill roll size and careful roll stack temperature control for a given sheet thickness, nucleant concentration and IV value.

There are two general approaches to heat transfer in relatively thin-gage sheet. The first is called the "distributed parameter system" or DP, where the time-dependent temperature is assumed to vary throughout the thickness of the sheet [29]. The second is called the "lumped parameter system" or LP, where time-dependent temperature is assumed to be uniform throughout the thickness of the sheet.

For the distributed parameter or DP system, the operative equation is the one-dimensional transient heat conduction equation [31]:

$$\left(\frac{\partial T}{\partial \theta}\right) = \alpha\left(\frac{\partial^2 T}{\partial x^2}\right) \tag{9.15}$$

where T is the local temperature, x is distance into the sheet and θ is time. For a material, such as water or steel that exhibits a phase change at a very specific temperature, this equation is applied to each side of the liquidus-solidus interface. At the interface, the two equations are coupled through two boundary conditions. One states that the liquid and solid temperatures at the interface are equal and the second states that interfacial energy transfer must include the latent heat of fusion for the material. Methods of solution are given elsewhere [32-34]. Since most polymers exhibit phase change over a substantial temperature range, Equation 9.15 can be applied over the entire structure so long as it is modified to include a heat generation term:

$$\left(\frac{\partial T}{\partial \theta}\right) = \alpha\left(\frac{\partial^2 T}{\partial x^2}\right) + q' \tag{9.16}$$

where q′, the heat generation term, is given as:

$$q' = \rho\,\Delta H\left(\frac{dX}{d\theta}\right) \tag{9.17}$$

where ρ is the density and ΔH is the enthalpy of crystallization in Btu/lb or cal/g. As will be seen below, the boundary conditions include convection and radiation at the free surface and balanced heat flux and temperature at some internal plane for sheets heated or cooled on both sides. There are many ways of solving Equation 9.16 with appropriate boundary conditions. The standard method uses finite difference equations or FDE, the simplest version of which is the explicit or backward-time form. The equations in the x-direction or spatial gradient and θ-direction or temporal gradient are:

$$k\frac{\Delta^2 T_i}{\Delta x^2}(\theta + \Delta\theta) = k\left[\frac{T_{i-1}(\theta) - 2T_i(\theta) + T_{i+1}(\theta)}{(\Delta x)^2}\right] \tag{9.18}$$

$$\rho c_p \frac{\Delta T_i}{\Delta\theta}(\theta + \Delta\theta) = \rho c_p\left[\frac{T_i(\theta + \Delta\theta) - T_i(\theta)}{\Delta\theta}\right] \tag{9.19}$$

The heat generation term becomes:

$$\rho\, \Delta H \frac{\Delta X_i}{\Delta\theta}(\theta + \Delta\theta) = \rho\, \Delta H\, [1 - X_i(\theta)] \cdot K(T_i(\theta)) \tag{9.20}$$

These equations are combined to yield the forward FDE:

$$\begin{aligned} T_i(\theta + \Delta\theta) = T_i(\theta) \cdot \left[1 - \frac{2\alpha\Delta\theta}{(\Delta x)^2}\right] + \left[\frac{\alpha\Delta\theta}{(\Delta x)^2}\right] \cdot [T_{i-1}(\theta) + T_{i-1}(\theta)] \\ + \left[\frac{\Delta H \Delta\theta}{c_p}\right] \cdot [1 - X_i(\theta)] K(T_i(\theta)) \end{aligned} \tag{9.21}$$

The stability of this equation is given by:

$$\Delta\theta \leq \frac{(\Delta x)^2}{2\alpha} \tag{9.22}$$

The time step can be quite small, as seen in Example 9.1.

Example 9.1 Time Step for Explicit FDE for Thin-Gage PET

Consider 0.040-in thick PET sheet with a thermal diffusivity of 0.001 in²/s. If the heating time for this PET is 30 s and the sheet is heated from both sides, determine the time step and number of iterations needed if $\Delta x = 0.002$ in.

The time step is given as:

$$\Delta\theta \leq (0.002)^2/2 \cdot 0.001 = 0.002 \text{ s}$$

Therefore $30/0.002 = 15{,}000$ steps are required.

There are three general types of boundary conditions to be considered here. The first is a *conduction* boundary condition such as direct contact of the extruded sheet against the chill roll. This boundary condition is given as:

$$T_i(\theta) = T_o(\theta) \tag{9.23}$$

where T_o is the surface temperature of the chill roll, for example. The second is a *convection* boundary condition such as contact of the extrudate with the cooler environment. This boundary condition is written as:

$$-k\left.\frac{\partial T(\theta)}{\partial x}\right|_{surf} = h[T_{surf}(\theta) - T_a(\theta)] \tag{9.24}$$

where T_{surf} is the surface temperature of the polymer, T_a is the air temperature and h is a proportionality constant called the "heat transfer coefficient". The third is a *radiation* boundary condition such as the radiant heating of the sheet during thermoforming. The boundary condition in this case is given as:

$$-k\left.\frac{\partial T(\theta)}{\partial x}\right|_{surf} = F^*[T_R^{*4}(\theta) - T_{surf}^{*4}(\theta)] \tag{9.25}$$

where T_R^* is the absolute radiant heater temperature and T_{surf}^* is the absolute sheet surface temperature. Each of these equations can be developed into FDE forms [32,33]. Additional details are given in Chapter 3.

For very thin sheet, the temperature across the sheet thickness is uniform and a lumped parameter or LP, time-dependent energy balance is used. For combined convection and radiation:

$$\rho c_p V \frac{dT}{d\theta} = hA_{s,1}(T_a - T) + F^* A_{s,2}(T_R^{*4} - T^{*4}) \tag{9.26}$$

where $A_{s,1}$ and $A_{s,2}$ are the surface areas for convection and radiation, respectively, and V is the volume of the sheet. Consider the simple case where the sheet is cooled or heated uniformly on both sides. Then $A_{s,1} = A_{s,2} = A$, and $V = AL$ where L is the sheet thickness. Then the equation is written as:

$$\frac{dT}{d\theta} = \left(\frac{h}{\rho c_p L}\right)(T_a - T) + \left(\frac{F^*}{\rho c_p L}\right)(T_R^{*4} - T^{*4}) \tag{9.27}$$

If $Fo = \alpha \cdot d\theta/L^2$, the differential Fourier number, $Bi = hL/k$, the Biot number and $R'' = F^* L/k$, a radiation term, then the equation is written as:

$$dT = Fo \cdot Bi(T_a - T) + Fo \cdot R''(T_R^{*4} - T^{*4}) \tag{9.28}$$

One way[1] of defining a radiation heat transfer coefficient, h_r is:

$$h_r = F^* \frac{(T_R^{*4} - T^{*4})}{(T_a - T)} \tag{9.29}$$

As a result, the Biot number is redefined as $Bi_{c+r} = (h + h_r)L/k$ and Equation 9.29 is written as:

$$dT = Fo \cdot Bi_{c+r} \cdot (T_a - T) \tag{9.30}$$

Note that Bi_{c+r} can be positive if the air temperature is greater than the sheet temperature and negative if the sheet temperature is greater than the air temperature. This equation can be solved analytically to yield:

$$\frac{T - T_o}{T_a - T_o} = 1 - \exp\left[-Fo \cdot Bi_{c+r} \cdot \theta\right] \tag{9.31}$$

This represents a first-order response to a step change in environmental conditions. The first-order time constant is given as:

$$\tau = \frac{1}{Fo \cdot Bi_{c+r}} = \frac{\rho c_p L}{(h + h_r)} \tag{9.32}$$

As is apparent, the time constant is larger and the plastic sheet cools or heats more slowly for thick sheet or low values of heat transfer coefficient. Other examples are given in Chapter 3.

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[1] See Chapter 3 for another way of defining an effective heattransfer coefficient.

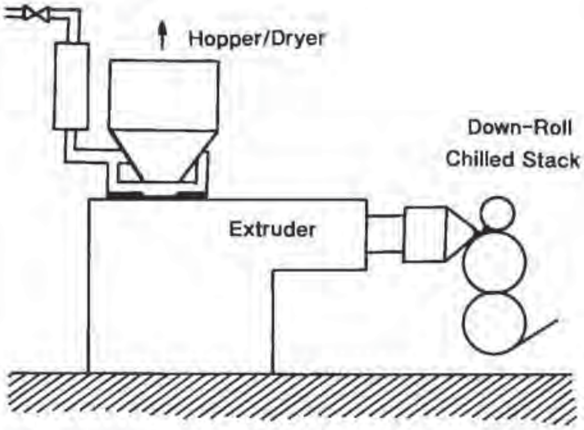

Figure 9.4 Sheet extruder schematic for 60 mil, 0.060 in or 1.5 mm amorphous nucleated polyethylene terephthalate, PET

Cooling CPET on Chill Rolls

Even though PET is extruded in a melt condition and quenched as quickly as possible, crystallizing PET sheet for thermoforming applications is rarely absolutely amorphous. Several conditions contribute to this. The sheet has a finite thickness, low thermal conductivity and thermal diffusivity, and is usually cooled one side at a time. Even though the PET is doped with nucleants to enhance crystallization rate during the heating phase of thermoforming, they act to enhance crystallization rate during quenching of the extruded sheet. Consider a simple three-roll down-stack (Fig. 9.4) [34]. Although the Figure shows a bead or bank between the caliper roll and the first chill roll or polish roll, this bead must be maintained as small as possible. Flow in the nip between the first two rolls, the complex nature of flow in the bank, and the nature of viscoelastic swell of polymer as it exits the pressure zone of the nip are quite complex and are addressed elsewhere [35-37]. The heat transfer analysis of the crystallizing, cooling sheet has been carried out recently [38]. Typical assumptions are:

- Flat velocity profile through the sheet,
- Constant chill roll temperature,
- Sheet thin when compared with roll diameter,
- Heat loss to the environment is accounted for with a single heat transfer coefficient,
- Differential bead thickness relative to sheet thickness can be easily accounted for, and
- The sheet does not move relative to the roll surface.

The easiest way of visualizing the cooling of CPET sheet is by unwrapping the sheet from the roll surfaces, as shown in Fig. 9.5 [39]. This schematic also shows the

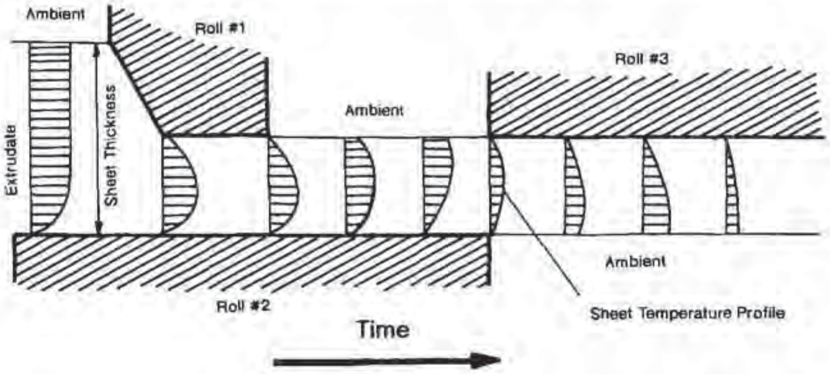

Figure 9.5 Time-dependent temperature profile for extruded 60 mil, 0.060 in or 1.5 mm amorphous nucleated polyethylene terephthalate, PET [39]

expected time-dependent temperature profiles through the sheet. Note that sheet thickness, roll diameter and take-off speed will alter these temperature profiles. The base case is given in Table 9.5 for one example. As seen, the sheet thickness is 60 mil, 0.060 in or 1.5 mm, being extruded at 30-in or 760 mm at 1000 lb/h or 450 kg/h onto 36-in or 915 mm diameter chill rolls that are at 50°C surface temperature. The ambient air heat transfer coefficient is assumed to be 5 Btu/ft^2 · h · °F[1]. The non-

Table 9.5 Crystallizing PET on Chill Roll Stack Basic Design Information [40]

Initial polymer melt temperature	285°C
Roll 1 surface temperature	20°C
Roll 2 surface temperature	50°C
Roll 3 surface temperature	50°C
Contact time on roll 1	2 s
Contact time on roll 2, total	15 s
Contact time on roll 3	20 s
Ambient air temperature	30 s
Ambient air heat transfer coefficient	5 Btu/ft · h · °F
Initial sheet thickness, extruded	0.120 in
Sheet thickness on rolls 2 and 3	0.060 in
Polymer IV	0.9
Nucleant concentration	1.0%
Minimum half-time of crystallization	35 s
Temperature at minimum half-time	176°C
The following data are for computation of temperature profile	
Number of elements	8
Finite difference time step	0.1 s

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[1] See Section 5.4 for other information on convection heat transfer coefficients.

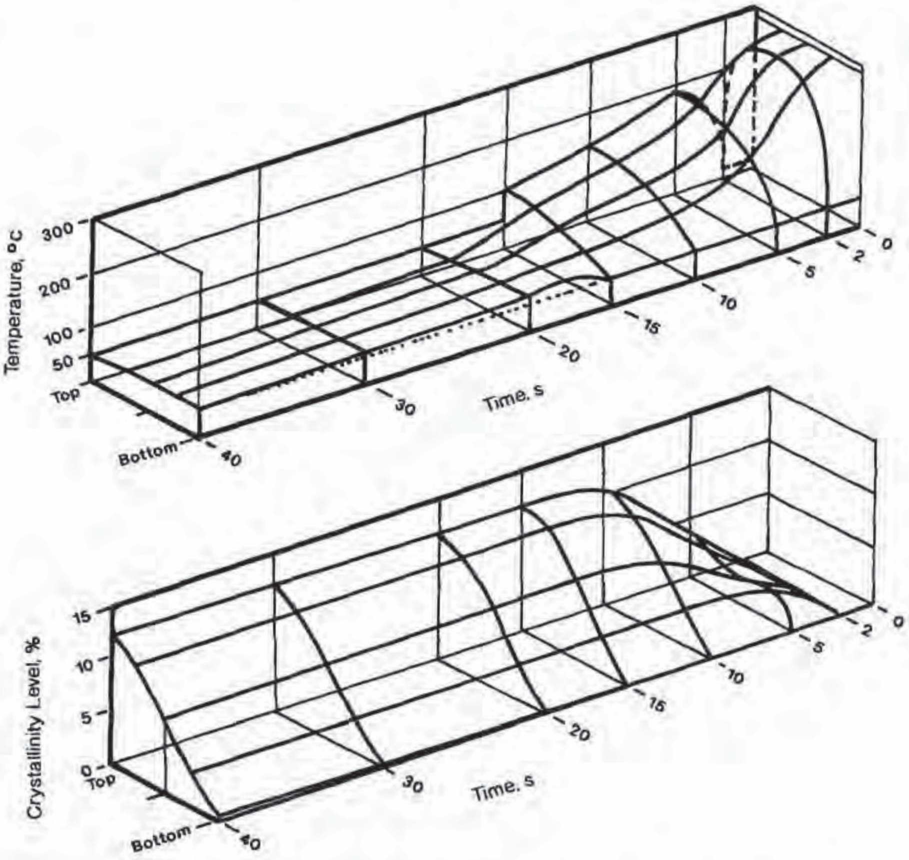

Figure 9.6 Computed time-dependent temperature and crystallinity level profiles for 60 mil, 0.060 in or 1.5 mm amorphous nucleated polyethylene terephthalate, PET on chill roll stack

isothermal crystallization kinetics are assumed to be Ziabickian for 0.9 IV and 1.0% inorganic nucleation. Figure 9.6 (top) shows the temperature profile through the sheet beginning with the bead at the back and moving forward to the sheet exiting the second chill roll [41]. Figure 9.6 (bottom) shows the crystallinity through the sheet for the temperature profiles of Fig. 9.6 (top). As is apparent from the arithmetic and as is clearly observed in actual practice, the crystallinity level of the surface of the sheet in immediate contact with the first chill roll shows essentially no crystallinity, while the surface that does not contact the chill roll for some time shows the highest level of crystallinity, 12% in this case. This is used to advantage in coextruded PET sheet where the low-IV layer containing the nucleant is extruded against the first chill roll and the high-IV layer containing no nucleant is exposed first to ambient air.

An important insight into laboratory simulation of the quenching process is gathered from this example. The thermal gradient at one-fourth the distance into the

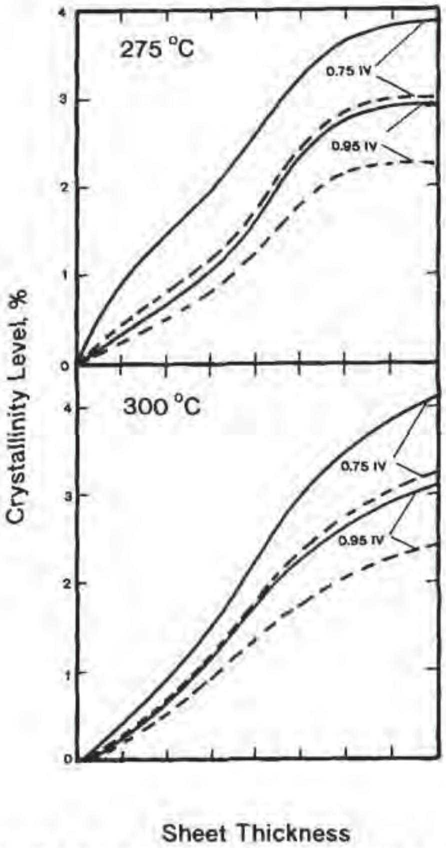

Figure 9.7 Parametric study of chill roll parameter effect on 30 mil, 0.030 in or 0.76 mm nucleated polyethylene terephthalate, PET for two intrinsic viscosities [IV]. (Top) 275°C PET melt temperature. (Bottom) 300°C PET melt temperature. Solid lines are 1% [wt] nucleant level. Broken lines are 0% nucleant level. Adapted from [42]

sheet from the initially free surface is as much as 30°C/s through the crystallizing region above 120°C or so. The final sheet crystallinity at this point is only 3%. Free surface cooling at this condition is only about 10°C/s and so yields a sheet having more than 11% crystallinity. In order to determine crystallization kinetics using differential scanning calorimetry, the DSC must be able to cool at rates of 10°C/s or less to rates of 30°C/s or more. The effects of polymer molecular weight and nucleant concentration on the final crystallinity levels of 30 mil, 0.030 in or 0.76 mm sheet extruded at two temperatures are shown in Fig. 9.7 [42]. As expected, lower IV PET crystallizes to a higher level than higher IV PET and nucleated PET crystallizes to a higher level than unnucleated PET. It is further apparent that the reduction in maximum crystallinity level between this 30 mil sheet and the 60 mil sheet of Fig. 9.6 is the result of sheet thickness.

Heating CPET in Roll-Fed Thermoformers

Thermoforming equipment used for CPET forming is similar to but not identical to equipment used for APET, PVC or PS. Specific details of the equipment are discussed later. The general concepts of thermoforming, detailed in Chapters 3 and 4, applied to CPET forming, are considered here. Recall that crystallization is highly time- and temperature-dependent. Thus, the key to forming CPET parts beginning with nearly amorphous crystallizing PET sheet is to raise the sheet temperature to the forming range before substantial crystallization can occur. If the sheet is thin enough, rapid heating is controlled by the heater temperature. For relatively thick CPET sheet, care must be taken to prevent overheating and scorching the sheet surface before the sheet centerline is in the forming temperature range. Typically, residence time of the sheet in the oven should be about 2 to 5 times the residence time of the sheet on the heated mold. For example, if the residence time on the mold is 5 to 10 s, the residence time in the oven should be in the range of 10 to 50 s. Longer residence times in the oven imply low heater temperatures or exiting sheet having very high crystallinity levels. The exiting sheet surface temperature should be between 120°C and 160°C and the overall sheet crystallization level should be 3% to 12%. If the sheet crystallinity is too low, the sheet might stick and locally tear on the hot mold. If the sheet crystallinity is too high, the sheet stiffness may prevent complete draw-down into the mold or may require excessive forming pressure.

As with most organics, PET absorbs at 3.5 μm wavelength or a peak monochromatic temperature of about 600°C. There is also an absorption peak at about 5.9 μm or about 230°C. For one type of oven [43], the effects of radiant heater temperature and residence time on the average sheet temperature and level of crystallinity are shown for a 0.9 IV, 60 mil, 0.060 in or 1.5 mm thick sheet with 1% inorganic nucleant using the lumped parameter heat transfer and a Ziabickian crystalline kinetic model (Fig. 9.8). As is apparent, crystallization levels are low if the radiant heater temperatures are low. It is also interesting to note that the crystallinity level plateaus if the heating rate is too high. A comparison of the distributed parameter method using FDE and the lumped parameter method using Equation 9.32 for 60 mil, 0.060 in or 1.5 mm 0.9 IV PET with 1% inorganic nucleant is shown in Fig. 9.9 [44]. Note the good agreement between the average temperature and average crystallinity level predicted by the DP and the value from LP.

Forming the Sheet

The sheet that is presented to the mold should have an average temperature of 120°C to 160°C, about 3% to 12% crystallinity and should be rapidly crystallizing. For transparent PET, the sheet is exhibiting whitening as it is transported into the mold/platen area. The sheet may also be tightening between the chain rails. Excessive crystallization may result in the sheet tearing out of the pins. The mold temperature should be 150°C to 190°C or within a few degrees of T_{max}, the temperature for maximum crystallization rate. The exact mold temperature will depend on:

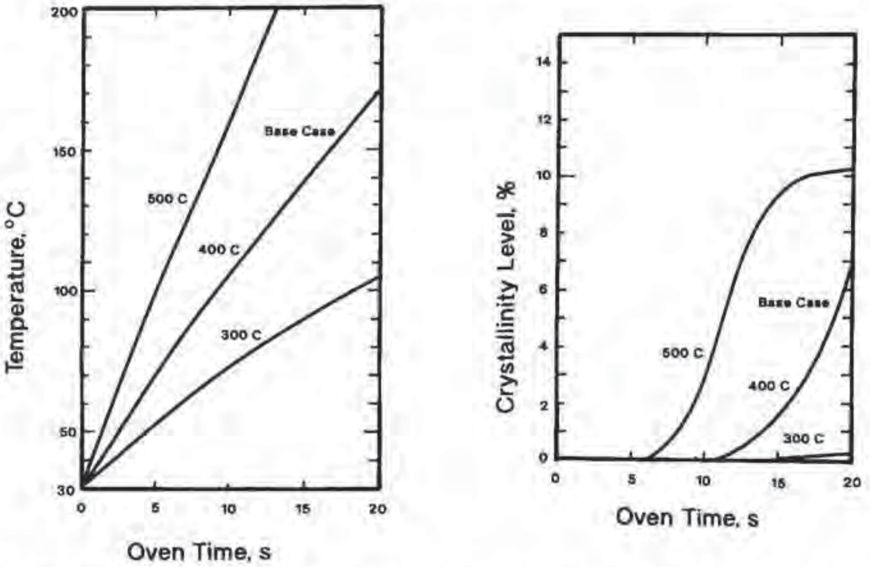

Figure 9.8 Parametric effect of radiant heater temperature for 60 mil, 0.060 in or 1.5 mm nucleated polyethylene terephthalate, PET, using lumped parameter model. (Left) Time-dependent sheet temperature with radiant heater temperature as parameter. (Right) Time-dependent crystallinity level at same conditions

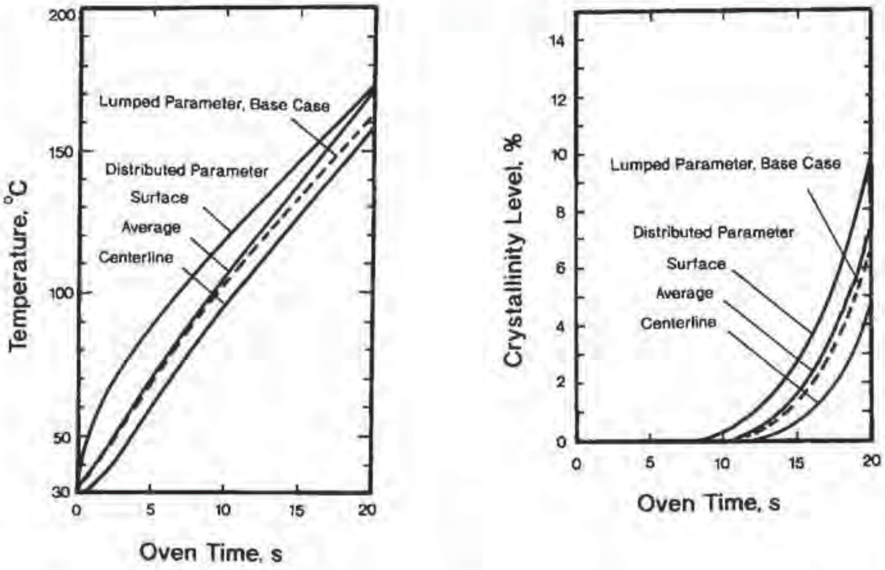

Figure 9.9 Comparison of lumped parameter model and distributed parameter model for 60 mil, 0.060 in or 1.5 mm amorphous nucleated polyethylene terephthalate, PET with radiant heater temperature of 400°C [see Fig. 9.8]. (Left) Time-dependent temperature profile through sheet. (Right) Time-dependent crystallinity level through sheet at same conditions

- The temperature and crystallization level of the sheet,
- The sheet thickness,
- The IV of the polymer,
- The depth of draw,
- The amount of detail required in the molded part,
- The role of plug assist,
- The orientation of the mold (male or female),
- Whether pressure is used, and if so,
- The available pressure for forming.

Typically, CPET parts are formed into an up mold. That is, the female mold is mounted above the sheet with plugs advancing from below the sheet. Actively heated aluminum plugs are recommended, with the plug surfaces nylon- or teflon-coated if plug mark-off is a problem. For pressure forming, the pressure box is advanced against the sheet from below. In cases where very thin sheet is being formed into relatively large surface area parts, a cavity isolator or clamping-off grid carries the sagging sheet upward against multiple cavity molds. Keep in mind that as the PET crystallizes, it is rapidly increasing in density. This is manifested as dramatic shrinkage in sheet dimension. Much of this is taking place while the sheet is against the hot mold. As a result, the forming pressure must be sufficient to keep the sheet pressed tightly against the mold surface throughout the crystallizing portion of the cycle. Air pressure of at least 50 lb_f/in^2 or 0.34 MPa is recommended, with the pressure being maintained throughout the molding time. The machine sequence must allow for cavity venting prior to separating the pressure box from the mold base.

The instant the sheet surface touches the hot mold, it attains the mold surface temperature. As with nearly all thermoform molding operations, the sheet surface that is free of the mold surface can interchange energy only with quiescent air. The rate of conduction heating is proportional to the square of the sheet thickness. As a result, the thinnest sections of the sheet, such as the three-dimensional corners, heat much more rapidly than the thickest sections, such as the lip or rim region or the bottom of shallow draw containers. Even though this effect is somewhat tempered by the fact that the thick sections touch the mold first and the thin sections touch last, the crystallization levels in the thin sections are usually substantially greater than those in thick sections. Since excessive crystallization yields brittleness in thermally-induced crystalline PET, thin three-dimensional corners are more likely to fail under impact than the thicker rim areas. As noted, residence times of 5 to 10 s on hot molds are typical for 30 to 60 mil, 0.030 to 0.060 in or 0.76 to 1.5 mm sheet.

Cooling the Formed Part

When the part has been formed and the crystallinity level of the sheet reaches about 20% to 25%, the sheet is stripped from the mold. The hot sheet is then exposed to ambient conditions and the web cools to room temperature or until the parts are ready to be trimmed from the web. The sheet continues to crystallize during cooling. As a result, traditional quenching means such as forced air or water spray mist are

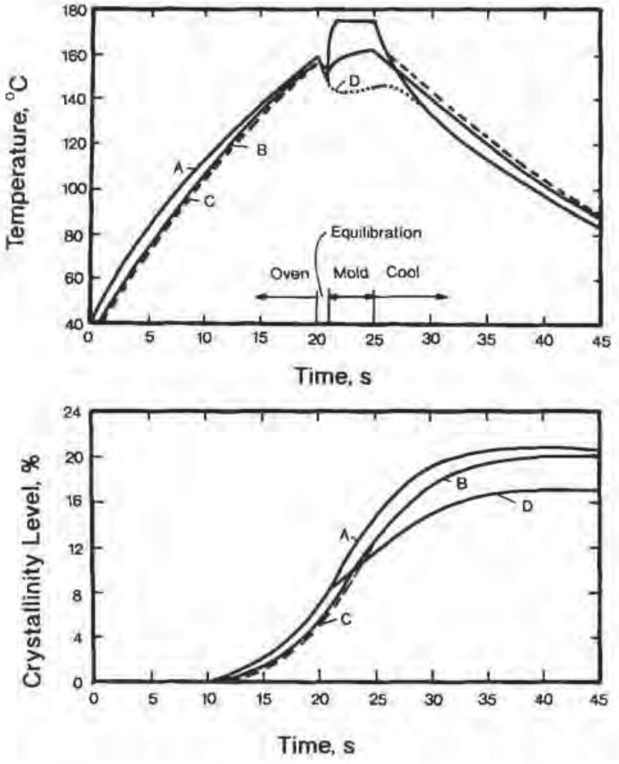

Figure 9.10 Distributed parameter parametric effect of environmental conditions on time-dependent temperature, top, and crystallinity level, bottom. For 40 mil, 0.040 in or 1.0 mm nucleated polyethylene terephthalate, PET. A: Sheet surface temperature during heating for base case. B: Sheet surface temperature during heating with 50% greater air convection heat transfer. C: Centerline temperature for base case. D: Free surface temperature when thermoforming into 140°C mold rather than 175°C base case mold temperature

not recommended. In some machines, a cooling table is provided, This allows the web to cool very slowly and allows the thicker sections of the molded parts to continue to crystallize while the thinner sections usually cease crystallizing relatively quickly. In some machines, a second mold is used to retain the formed part dimension during cooling. In this machine, the second mold temperature is carefully monitored. If it is too high, crystallinity continues and the final part becomes brittle. If it is too low, the formed part has low crystallinity and it will distort at elevated use temperatures. Figure 9.10 [45,46] shows several temperature profiles for 40 mil, 0.040 or 1 mm sheet, beginning with 0% crystallinity and ending with about 20% crystallinity. As is apparent, the sheet first contacts the mold with a crystallinity level of about 5% to 7% and exits the mold with a crystallinity level of about 15%. Crystallinity continues throughout the cooling portion of the process until the formed part reaches a final value of about 20%. The crystallinity level of the free surface is about 3% to 5% below that for the part surface that had contacted the 140°C mold surface.

Trimming Parts from Web

Trimming technology is discussed in detail in Chapter 5. Trimming CPET parts from web offers additional challenges. Since PET exhibits a significant increase in density with crystallinity level, trim die dimensional tolerances are difficult to predict. Since the parts continue to crystallize after release from the mold, trim-in-place is not practical. Spacing between formed parts, trim guides and registration nubs can change, depending on the crystallinity level of the polymer in the web between parts. Furthermore, uneven crystallinity level between webs can cause the structure to warp into a non-flat configuration, leading to feeding problems in the trim press. Greater daylight between platens on hump-back trim presses is required and spring-loaded guide rods are sometimes used to help center the sheet prior to trimming. Conical or deep-drawn wedge-shaped registration nubs and individual cavity locators are recommended.

Room temperature CPET at about 20% crystallinity level is ductile-tough. Therefore, substantial force is needed to trim parts from web. Furthermore, since PET is a fiber-forming polymer, fibers are frequently formed during the trimming. Fibers, also called angel hair or fuzz, are most prevalent when trim dies are dull or blunt. As a result, very sharp trim dies are required and dies must be meticulously honed or sharpened on an hourly or shift basis. To minimize fiber forming, compression cutting is preferred over shear cutting. Even though CPET at elevated temperature is much easier to trim, continuing crystallization and attendant warpage makes elevated temperature trimming difficult, if not impractical. Heated dies can be effective if the sheet is more than 40 mil, 0.040 in or 1 mm thick and if the initial cutting rate is slow.

Troubleshooting CPET Forming

Traditional troubleshooting guidelines of Chapter 10 apply to thermoforming CPET. Additional guidelines are given in Table 9.6. Other extrusion guidelines are given in Chapter 8.

9.3 Pressure Forming

As noted in Chapter 1, in the 1870s, some of the first semi-synthetic plastics were skived into thin sheets that were then steam heated and pressed into detailed molds to produce items such as baby rattles and jewelry cases. Modern-day pressure

Table 9.6 Troubleshooting Guide for CPET Thermoforming

Problem	Probable cause	Suggested course of action
Excessive outgassing of sheet during heating	Fugitive adducts in polymer	Remove volatile adducts Rapidly heat sheet only in last zone of oven
	Organic nucleants such as LLDPE, LDPE in polymer	Change to HDPE, PP nucleants
	Moisture	Check moisture level in PET sheet before forming Use in-line predryer
Sheet splits, pulls from rails	Sheet crystallizing in oven	Shield rails from heaters Water-cool rails Reduce amount of nucleant
	Diverging rails	Use parallel rails
	Pin shape causing notch sensitivity	Use rounded pins Increase (slightly) pin diameter
	Sheet crystallizing between oven and mold	Reduce last zone oven temperature Reduce time in oven Increase transfer rate to mold
Sheet tears during forming	Sheet too hot	Reduce sheet temperature
	Crystallinity level too low	Hold sheet in oven longer Delay applying plug/pressure assist Increase next-to-last zone oven temperature
	PET IV too low	Increase molecular weight of virgin PET Reduce amount of regrind Thoroughly dry PET, PET rolls
	Plug advancing too quickly, too early	Delay plug advance Slow initial plug advance rate
	Incorrect plug shape	Redo plug shape, rounding all radii Reduce plug dimension
Sheet sticks to mold	Mold surface too hot	Reduce mold temperature
	Polymer contains adduct that is diffusing to the sheet surface	Reduce sheet temperature Change to higher temperature adduct Reduce adduct concentration

(Continued)

Table 9.6 (Continued)

Problem	Probable cause	Suggested course of action
	Draft angle too low	Increase draft angle on male mold elements
Webbing	Excessive sheet sag	Reduce sheet temperature Thermoform into up mold Increase crystallinity at molding time Add web catchers at corners
	Low molecular weight	Increase PET molecular weight Check PET sheet IV Check moisture content of PET sheet Reduce regrind amount
	Mold cavities too close	Increase land between cavities Create artificial dam to catch web
	Pattern heating profile wrong	Change pattern heating to reduce temperature in center of sheet
Oily plate-out on mold, plug	Fugitive adducts in polymer	Check for waxes, internal lubricants, colorants and remove
	Organic nucleants such as LLDPE, LDPE in polymer	Chemically analyze for olefin Reduce olefin concentration Change to HDPE, PP nucleant
Excessive part distortion	Part crystallizing after molding	Increase mold temperature Increase time in contact with mold
	Crystallization too high	Reduce nucleant concentration Reduce residence time on mold Decrease (or increase) mold temperature Increase molecular weight
	Part releasing from mold prematurely	Increase cavity pressure during forming Reduce crystallization rate
	Nonuniform wall thickness	Change plug shape Change pattern heating profile
Nipples on formed part	Sheet too hot	Reduce sheet temperature
	Mold too hot	Reduce mold temperature Increase sheet crystallinity prior to touching mold by delaying oven transfer

Table 9.6 (Continued)

Problem	Probable cause	Suggested course of action
	Excessive pressure	Reduce pressure Delay pressure boost until sheet has cooled slightly
	Vacuum holes too large	Plug/redrill vacuum holes
Transparent areas/bands	Sheet not touching mold locally	Add vacuum holes Increase air pressure Check mold draft angle
	Excessive sheet sag at molding temperature	Reduce sheet temperature locally Employ sag bands
	Sheet temporarily folding	Check sheet transfer rate for nonuniformity Reduce sheet temperature
	Poor mold heat transfer	Check channel flow for blockage
Blotchy or shiny/dull areas on part	Mold surface temperature nonuniform	Check mold temperature with IR monitor Check flow paths through mold Check all fluid lines
	Sheet temperature nonuniform	Readjust heating pattern Check for excessive sag away from top heaters
	Poor regrind mixing	Measure IV of sheet in blotchy areas Add backpressure to extrusion process
	Poor vacuum	Check all vacuum holes for plugging Increase vacuum in critical areas Check vacuum at mold cavity
	Poor air pressure	Make certain air pressure is adequate for sheet temperature, mold temperature, and crystallinity level
	Mold surface too smooth	Roughen mold surface locally
Microscopic surface bubbles in parts	Moisture	Thoroughly dry PET before extruding Store PET rolls in silica gel/PE wrap Employ preheater to pre-dry sheet
	Fugitive adducts in PET	Replace with stable adducts If accompanied by mold plate-out, replace low melting olefin nucleant with higher melting one

(Continued)

Table 9.6 (Continued)

Problem	Probable cause	Suggested course of action
Poor bottom logo definition	Crystallinity too high	Increase sheet temperature Increase forming rate Increase number of vacuum holes Increase air pressure
	Mold too cold	Increase mold temperature
Yellowing	Excessive regrind	Reduce regrind amount
	Overheating	Reduce temperature Reduce regrind amount Increase thermal stabilizer package
Parts splitting during trimming	Crystallinity level too high	Reduce time on mold Cool finished parts more rapidly Reduce nucleant level Increase molecular weight
	Edges have sharp radii	Increase radii
	Excessive orientation at edges	Use moats, dams Use cavity isolators to minimize sheet pull-down into cavity
	Excessive thickness differential between edges and mold flats	Use more generous radii
Fuzz or angel hair on parts	Dull trim dies	Sharpen trim dies on regular schedule Change to hardened dies, self-sharpening dies
	Shear cutting	Compression cutting

forming began in earnest in the late-1970s when designs in electronic cabinets, automotive interiors and other consumer products moved away from generously-rounded contours and relatively smooth surfaces toward crisp, sharp corners and distinct textures such as pebble finish, wood grain and simulated leather [47,48].

In traditional vacuum forming, crisp texture and sharp radii can only be achieved with very hot sheet and heated molds. In the discussion on vacuum hole size, a clear relationship was developed between the amount of plastic drawn into a depression and (P/E), the ratio of applied pressure to temperature-dependent modulus:

$$\frac{D}{t} = a\left(\frac{\alpha E}{P}\right)^{1/4} \tag{9.33}$$

where D is the characteristic lateral dimension of the depression, α is the characteristic depth of the depression, a is a geometric constant with a value between 1 and 2, and t is the local sheet thickness. D is usually very small and α is very large for most surface textures. A temperature-dependent material parameter, $\phi(T)$, essentially the temperature-dependent secant tensile modulus, was defined in Chapter 4 to characterize the polymer resistance to applied pressure. As noted in Table 4.8, the value of $\phi(T)$ should be less than about 10 times the applied pressure value in order to achieve draw-down. For vacuum forming, the differential pressure never exceeds 14.7 lb_f/in^2 or 0.1 MPa and is usually about 10 lb_f/in^2 or 0.07 MPa. As a result, for vacuum forming, $\phi(T)$ is usually less than about 147 lb_f/in^2 or 1 MPa. To get crisp detail, P/E or $P/\phi(T)$ must be as large as possible. And as details become finer, P/E or $P/\phi(T)$ must increase. It is therefore apparent that applied pressure must be increased if increased surface detail cannot be achieved by further increasing sheet temperature. Vacuum forming is truly pressure forming with the differential pressure on the sheet being 1 atmosphere, 14.7 lb_f/in^2 or 0.1 MPa or less. Pressure forming as understood today is the application of additional pneumatic or air pressure, with pressures to 100 lb_f/in^2 or 0.7 MPa common and pressures to 200 lb_f/in^2 or 1.4 MPa used for reinforced and highly filled polymers and certain difficult-to-form neat polymers such as polycarbonate.

Safety is of paramount importance when pressure forming. When the pneumatic pressure exceeds about 100 lb_f/in^2 or 0.7 MPa, special attention must be paid to the machinery and controls. The platen clamping system needs to be sufficiently robust to withstand the air pressure. The mold must be capable of tolerating high pressures without distortion, metal fatigue, surface microcracking or catastrophic collapse. Bolsters or support posts are needed throughout the vacuum box. The pressure box, and in some instances the mold and pressure box combination, may need certification as unfired pressure vessels. The method of closing and clamping the pressure box against the mold and the method of gasketing against the air pressure must be carefully reviewed with regard to safety. Safeguards for venting the pressure box prior to opening the mold must be in place and regularly inspected. If it is determined that pneumatic pressure in excess of 100 lb_f/in^2 or 0.7 MPa is required to thermoform the hot sheet to the desired level of detail, a careful cost, engineering and safety comparison of pressure forming on special machines, matched die molding, and sheet stamping or compression molding is warranted [49-53].

Thin Gage

Pressure forming is used with thin-gage and heavy-gage sheet. In the 1970s, pressure was used to form 30 mil, 0.030 in or 0.76 mm polypropylene homopolymer below its melt temperature [54]. The technique is called "solid phase pressure forming" or SSPF (Fig. 9.11) [55]. The melt viscosity of homopolymer polypropylene at its melt forming temperature is about one-tenth that of polystyrene at its forming temperature. As a result, this type of polypropylene exhibited excessive sag and was considered unformable. The apparent viscosity of this polypropylene about 160°C or about 2° to 5°C below its melt temperature was about 100 times that of polystyrene.

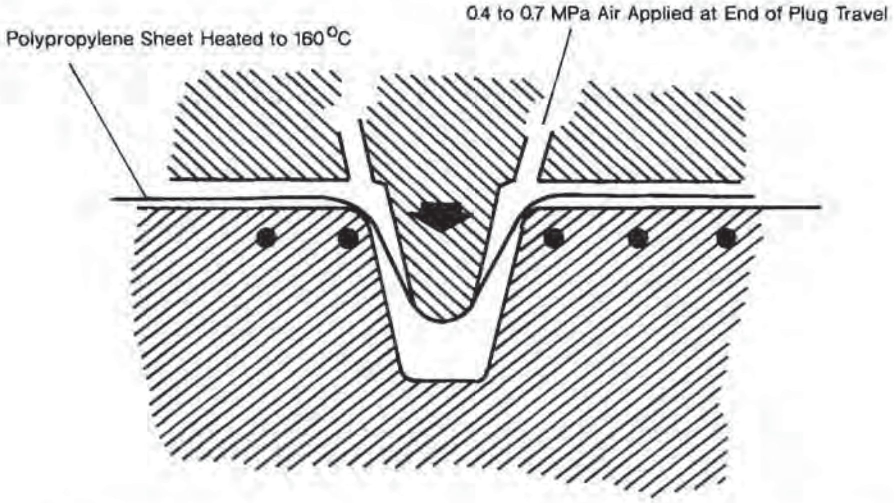

Figure 9.11 Schematic of plug-assisted pressure forming of polypropylene, PP, also called solid-phase pressure forming or SSPF

In order to form this polypropylene at this temperature in the solid phase, the sheet required plug assist and air pressure of 80 to 100 lb_f/in^2 or 0.55 to 0.7 MPa. The characteristic stress-strain curves for homopolymer polypropylene to 160°C are given in Fig. 9.12 [56]. Note that this polypropylene shows relatively little strain-rate hardening at 160°C.

In the past decade or so, improvements to polypropylene melt strength have enabled thermoformers to melt form polypropylene in much the same way as low-density polyethylene. Improvements include copolymer polypropylene, high molecular-weight polypropylene and high crystallinity polypropylene [57-59]. The nature of polypropylene forming is discussed in more detail below.

The development of crystallizing polyethylene terephthalate (CPET) thermoforming has also required applied pressure during the forming and crystallizing step. As noted above, air pressure helps prevent the formed part from shrinking away from the mold as it crystallizes. Pressures to 100 lb_f/in^2 or 0.7 MPa are used in CPET forming. Recently, pressure has been used during plug-assisted deep draw forming of APET or amorphous polyethylene terephthalate into thin-wall drink cups. The combination of pressure and controlled plug rate is used to minimize necking or banding[1] in the sidewall and rim region of axisymmetric parts such as cups.

---

[1] Necking is an obvious change in the thickness of the part wall, usually in a band perpendicular to the axis of the part. As discussed in the section on stress-strain-rate of strain behavior of polymers, necking is the result of localized drawing during forming. Necking is a temperature-dependent material property and so is distinguished from chill marks or mold marks that are related to localized drawing on the mold surface, and plug marks that are related to the region where the cooler plug touches the hot sheet.

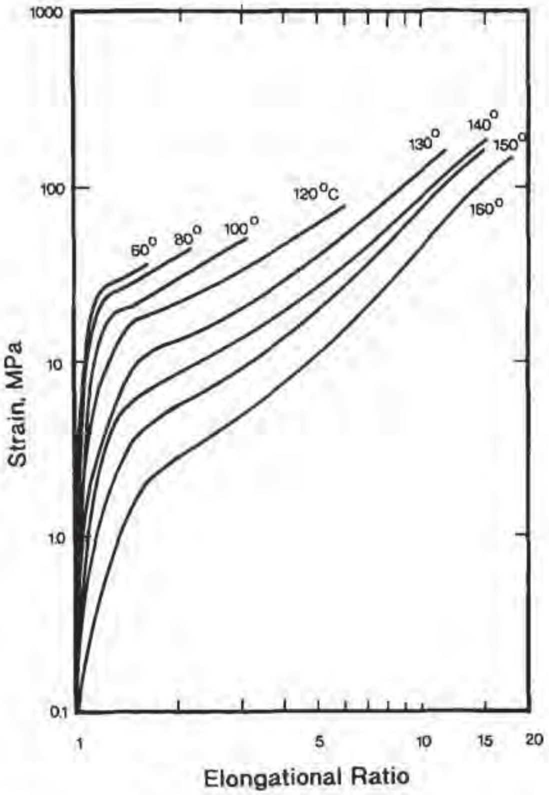

Figure 9.12 Temperature-dependent tensile stress-strain curves for polypropylene, PP, homopolymer. Redrawn from [56] and used with permission of copyright owner

Heavy Gage

Pressure formed heavy-gage products were first produced in 1959 [50]. Heavy-gage pressure forming focuses on surface texture and contour crispness. Pressure forming is sometimes used to compensate for extraordinarily long pre-stretching time. For example, when the product requires deep forming onto a male mold, the sheet is usually stretched first into a bubble either by inflation or by stretching into a vacuum box. Then the mold is immersed in the stretched sheet. In order to achieve good bubble stability, most polymers must be relatively cool during inflation. This is also true if the mold also acts as a plug to stretch the sheet during initial contact. A pressure box or bell is placed over the mold near the end of or just after the mold immersion. Pressure is then used to press the cool sheet against the mold in two- and three-dimensional corners. Pressure is used with female molds for the following reasons:

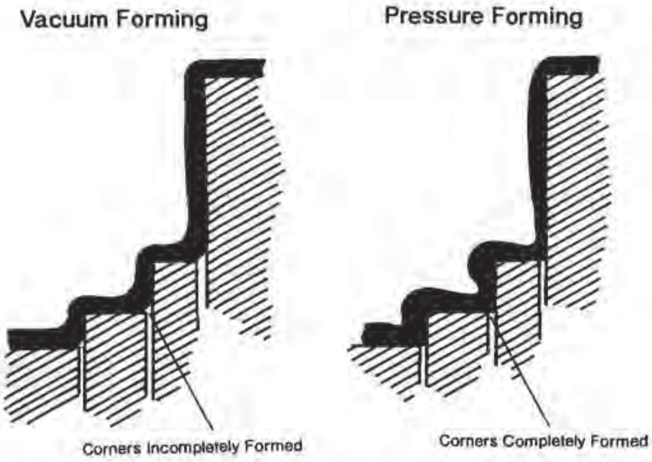

Figure 9.13 Pressure forming (right) yields details on female portions of the mold surface that have greater sharpness than those produced by vacuum forming (left)

- The part requires crisp texture and sharp corners,
- There must be a sharp demarcation between textured and non-textured surface areas,
- The draw is deep,
- A cool plug or a very large surface area plug is used,
- The sheet does not have good hot strength, and/or
- The modulus is very temperature-dependent, requiring that the sheet be formed very rapidly [60].

Typical air pressures are 20 to 50 lb_f/in^2 or 0.14 to 0.34 MPa. Corner radii to 0.005 in or 0.13 mm have been pressure formed from PMMA and polycarbonate into transparent fresnel lenses and light fixtures [61]. This is shown schematically in Fig. 9.13 [62]. Texture surface dimensions of 100 microinches, 0.0001 in or 2.5 μm and depths to 0.010 in or 0.25 mm with ABS have been achieved using pressures to 100 lb_f/in^2 or 0.7 MPa. Draft angles of 1° plus 1° per mil, 0.001 in or 25 μm of texture depth are recommended for vertical sides of female molds and 5° plus 1° per mil, 0.001 in or 25 μm of texture depth for vertical sides of male molds are recommended [61]. Forming tolerances for cast aluminum molds of ±0.020 in or ±0.5 mm for the first 12 in or 305 mm of mold length and an additional ±0.001 in per inch of length or ±0.001 mm per mm beyond are expected. For machined aluminum molds, forming tolerances of ±0.001 in per inch or ±0.001 mm per mm are expected [63]. For ribs and louvers, the height of the rib and the distance between ribs should be equal. Some additional design information is given in Table 9.7.

In addition to the safety and engineering aspects of pneumatic pressure, molds must be sufficiently robust to withstand forces of at least twice that expected. Water lines, for example, must be sufficiently far from the mold surface to prevent mold collapse into them. The high pressure that is sought to press plastic into highly

Table 9.7 Recommended Radius Dimensions for Pressure Thermoformed Equipment Cabinet Applications [63]

Depth of draw		Radius	
(in)	(mm)	(in)	(mm)
0–3	0–76	≥0.030	≥0.76
3–6	76–152	0.030–0.090	0.76–2.3
6–12	152–305	0.090–0.125	2.3–3.2
>12	>305	≥0.125	≥3.2

detailed textures also forces plastic into vent holes, machining marks, scratches, ejector pins and rings and other elements on the mold surface. Molds are usually cast or machined aluminum. Sprayed metal/epoxy molds are used for very short runs of less than 100 parts at reasonably low pressures, less than 50 lb_f/in^2 or 0.34 MPa.

For production runs of less than about 10,000, large-part, heavy-gage pressure forming is economically competitive with injection molding, reaction injection molding and foam injection molding [64].

Pressure forming is also combined with other processing elements to achieve unique products [65-67]. For example, the pressure box can contain hydraulic or pneumatic elements that allow secondary stamping or coining on the still-hot free surface of the sheet. In this way, part numbers or other identification codes can be placed in non-appearance portions of the part. These elements can also press inserts into the hot free surface of the sheet.

9.4 Forming Filled and Reinforced Polymers

Fillers are usually inorganic particulates such as talc, calcium carbonate or chalk, mineral wool, glass or quartz powder, graphite, carbon black and metal oxides. Most fillers are spherical or platy. Some such as asbestos and TiO_2 are acicular or fiberlike. Long fibers and continuous fibers provide substantial reinforcement to the polymer. Figure 9.14 [68] shows the various types of textile glass fiber products. Carbon, organic fibers such as polyaramides and polyamides, silicon carbide and boron fibers are also used to reinforce thermoplastics. The characteristic effects of fibers and reinforcements on polymer properties are illustrated in Table 9.8 [69]. Fillers and fibers are usually added to improve polymer stiffness. They can dramatically change the polymer load-bearing characteristics as shown for polystyrene in Fig. 9.15 [70]. As is apparent, below the polymer glass transition temperature, polymer stiffness increases with increasing filler loading. Although there appears to be a slight increase in polymer stiffness with filler loading at T_g, the shapes of

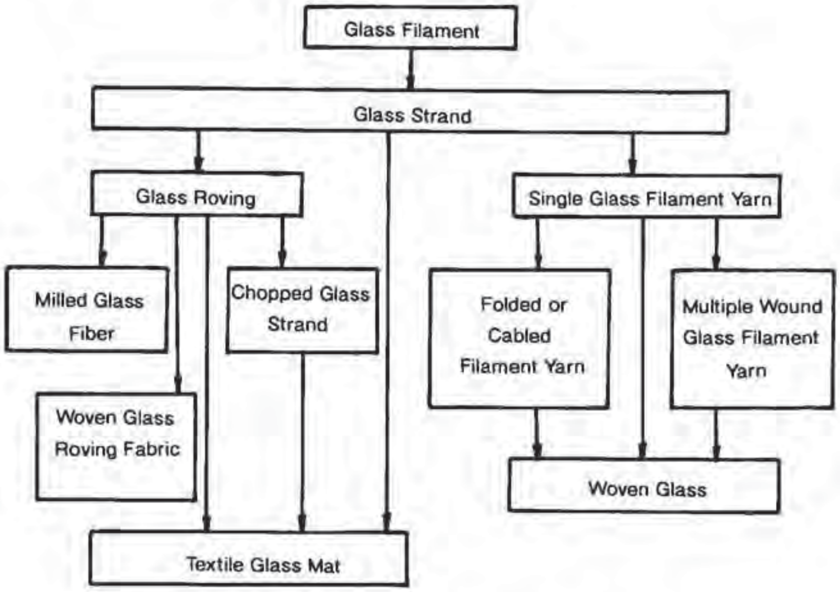

Figure 9.14 Various types of fibrous products used in thermoplastics [68]

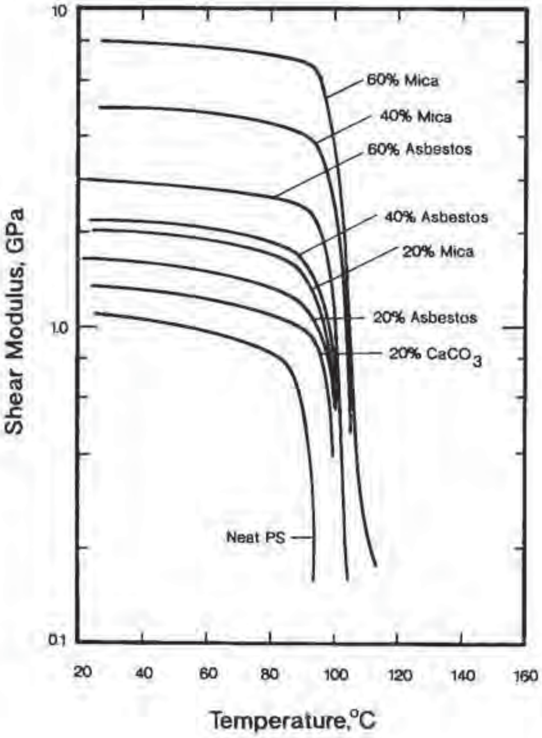

Figure 9.15 Effect of fillers and fibers on temperature-dependent shear modulus of polystyrene, PS. Redrawn from [70]

Table 9.8 Effect of Fillers and Reinforcements on Polymer Properties [69]

Key to fillers and fibers

A = Glass fibers
B = Asbestos
C = Wollastonite
D = Carbon fibers
E = Whiskers
F = Synthetic fibers
G = Cellulose
H = Mica
I = Talc
J = Graphite
K = Sand or quartz powder
L = Silica
M = Kaolin or clay
N = Glass spheres
O = Calcium carbonate
P = Metal oxides
Q = Carbon black

Polymer property	Fibrous fillers and reinforcements							Platelet-like types			Spherical fillers						
	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q
Price reduction	+	+	+				+	+	+	+	++	+	+	+	++		
Extrusion rate	−+	+						+					+		+		
Tensile strength	++	+		+	+−			+	0					+			
Compressive strength	+								+		+			+	+		
Elastic modulus	++	++	++	++	+			++	+		+	+		+	+	+	+
Impact strength	−+	−	−	−		++	+	−+	−		−	−	−	−	−+	−	+
Reduced thermal expansion	+	+			+			+	+		+	+	+			+	
Reduced shrinkage	+	+	+	+				+	+	+	+	+	+	+	+	+	+
Heat conductivity		+	+	+					+	+	+	+			+		+
Heat resistance	++	+	+	++				+	+				+		+	+	
Electrical conductivity				+						+							+
Electrical resistance			+					++	+			+	++			+	
Chemical resistance		+	+					+	0	+			+	+			
Abrasion performance				+				+	+	+			+				
Abrasion in equipment	−	0			0	0	0		0	0	−			0	0		0

+ + = Strong effect
+ = Mild effect
0 = No effect
− = Negative effect
− + or + − = Variable effect

the curves are quite similar. Increased forming pressure is needed to overcome the increased stiffness at temperatures just above the glass transition temperature. Filled thermoplastics are usually clamped solidly during forming.

Under tensile load, randomly oriented short fibers, whether natural such as asbestos and TiO_2, or prepared from continuous glass and mineral wool, behave much like particulate fillers. The thermoforming biaxial stretching mechanism acts to separate the short fibers and filler particles. If the fiber concentration is relatively low, less than 20% wt or so, there is little initial entanglement in the extruded sheet. As a result, fiber resistance does not add greatly to the tensile resistance of the matrix or polymer around the fiber during the forming portion of the process. If continuous fibers are used or if the discontinuous fiber concentration is increased to 40% wt or more, the composite becomes greatly resistant to tensile loading. Consider continuous uniaxial fiber reinforcement of a polymer matrix. The stress-strain equation in the fiber direction is given as:

$$\sigma = \phi_f \cdot \sigma_f + (1 - \phi_f) \cdot \sigma_m \tag{9.34}$$

where σ is the applied stress, ϕ_f is the volume fraction of fiber, σ_f is the stress on the fiber and σ_m is the stress on the matrix or polymer. If both the fiber and polymer are Hookean, or have linear stress-strain curves, this equation is written as:

$$\sigma = \phi_f \cdot E_f \epsilon_f + (1 - \phi_f) \cdot E_m \epsilon_m \tag{9.35}$$

where E_f and E_m are the moduli and ϵ_f and ϵ_m are the elongations of the fiber and matrix, respectively. The composite modulus is:

$$E_c = \phi_f \cdot E_f + (1 - \phi_f) \cdot E_m \tag{9.36}$$

where E_c is the modulus of the composite. For most reinforcing fibers at matrix thermoforming temperatures, $E_f \gg E_m$. For reasonable values of ϕ_f, this equation is approximated as:

$$E_c \approx \phi_f \cdot E_f \tag{9.37}$$

It has been noted that the "...polymer matrix is ... simply acting as a glue..." [71]. As noted above, good formability depends on the value of applied pressure being at least one-tenth the value of the sheet modulus. As a result, as the fiber concentration increases, the applied pressure must increase in proportion.

For randomly placed continuous fibers, the following moduli apply:

$$E_{2D,c} \approx \frac{3}{8} E_c \tag{9.38}$$

$$E_{3D,c} \approx \frac{1}{5} E_c \tag{9.39}$$

where E_c is the value obtained from Equation 9.37.

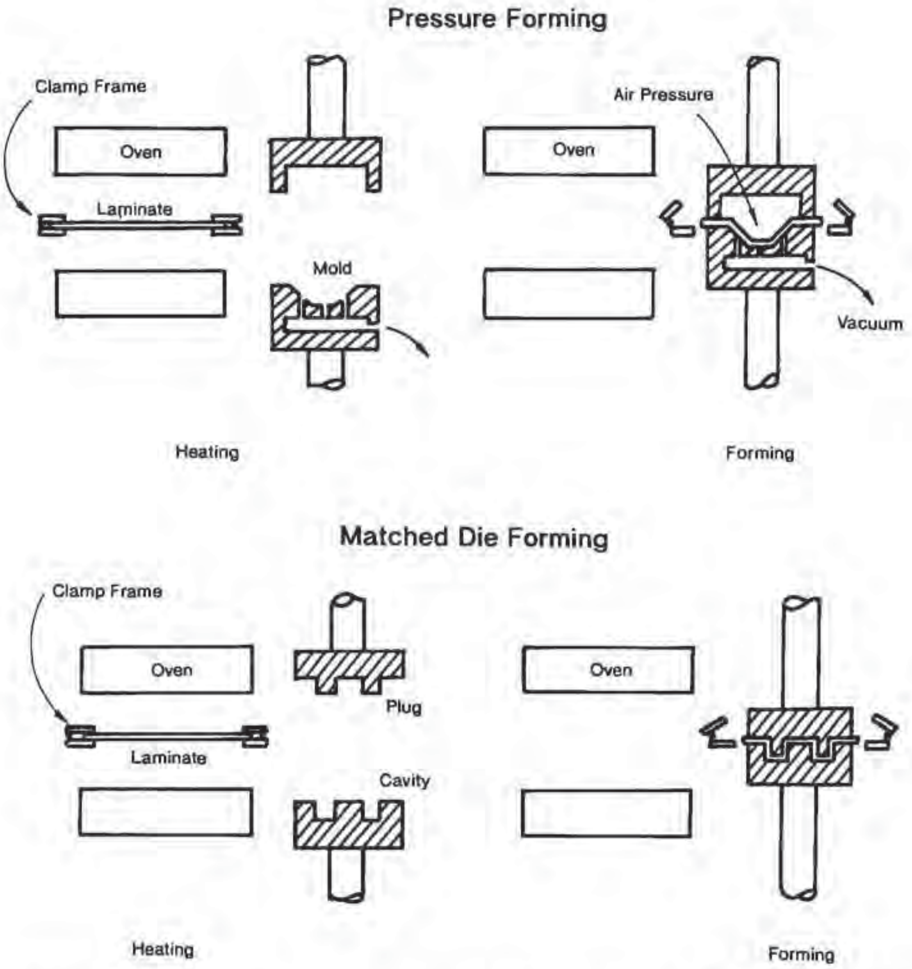

Figure 9.16 Illustrations of (top) pressure forming and (bottom) matched die molding of reinforced or stiffened laminate or composite. Redrawn from [72,73]

Continuous fibers are considered to be inextensible. As a result, thermoforming focuses on slip forming or changing the shape of the sheet without substantially increasing its surface area (Fig. 9.16) [72,73]. Products are restricted to shallow draws and very simple shapes. Example 9.2 clearly illustrates this. It is now believed that the standard method of deformation is interply slip, much like the way in which individual playing cards slide over one another in a bending mode. The proliferation of technical developments dealing with shaping continuous fiber-reinforced high-performance thermoplastics attests to the growing economic importance of this area [74-88].

Example 9.2 Approximation of Pressure Required to Thermoform Reinforced Sheet

Consider that an unreinforced polymer is vacuum formed with 10 lb_f/in^2 *or 0.07 MPa. The polymer modulus at the forming temperature is 100* lb_f/in^2 *or 0.7 MPa. The polymer is random-in-plane reinforced with glass having a modulus of 100,000 MPa. Determine the approximate pressure required to stretch/form the sheet containing 10% (vol) continuous glass fibers and 10% (vol) discontinuous glass fibers with na = 2. Can this sheet be thermoformed?*

For vacuum forming, the modulus-to-pressure ratio, E/P = 10. The one-dimensional modulus of the continuous fiber composite is:

$$E_c = 0.1 \cdot 100{,}000 \text{ MPa} = 10{,}000 \text{ MPa}$$

For two-dimensional mat, the modulus is:

$$E_{2D,c} = 0.375 \cdot 10{,}000 = 3{,}750 \text{ MPa}$$

The pressure required to stretch and deform this sheet is then:

$$P_c \approx 0.1 \cdot 3750 = 375 \text{ MPa} = 54{,}000 \text{ lb}_f/\text{in}^2$$

For discontinuous fiber, From Fig. 9.17, $\eta \approx 0.2$. As a result, the pressure required to stretch and deform the continuous fiber-reinforced sheet is:

$$P_d = 0.2 \cdot P_c = 10{,}900 \text{ lb}_f/\text{in}^2$$

It is apparent that this sheet must be compression molded or slip formed.

For long, discontinuous fibers, Equation 9.36 is modified to account for the stress concentrations at the fiber tips:

$$E_{c,d} = \eta \cdot \phi_f \cdot E_f + (1 - \phi_f) \cdot E_m \tag{9.40}$$

where η is a correction factor that depends on the product, na, where n is a function of the ratio of polymer to fiber moduli and of the ratio of interfiber spacing to fiber diameter, and a is the fiber aspect ratio or length-to-diameter ratio. The value of η is extremely dependent on the value of na as seen in Fig. 9.17 [89]. Typically n is on the order of 0.1 to 0.4 and a should be greater than 50. Equations 9.36 and 9.37 are used for random two- and three-dimensional structures, with E_c being replaced with $E_{c,d}$. Discontinuous fiber reinforced thermoplastics are also frequently slip formed as shown in Fig. 1.19. Matched metal molds are usually used with applied pressures to 200 lb_f/in^2 or 1.38 MPa (Fig. 9.18) [90]. If pressure forming is used, a flexible membrane or diaphragm is placed over the sheet prior to forming to provide an air seal at the pressure box edges (Fig. 9.19) [91,92]. Straight diaphragm forming is also used in an autoclave, with the superplastic aluminum membrane being inflated with differential air pressure (Fig. 9.20) [93].

In addition to the increased stiffness of the polymer at the forming temperature, other practical forming problems include:

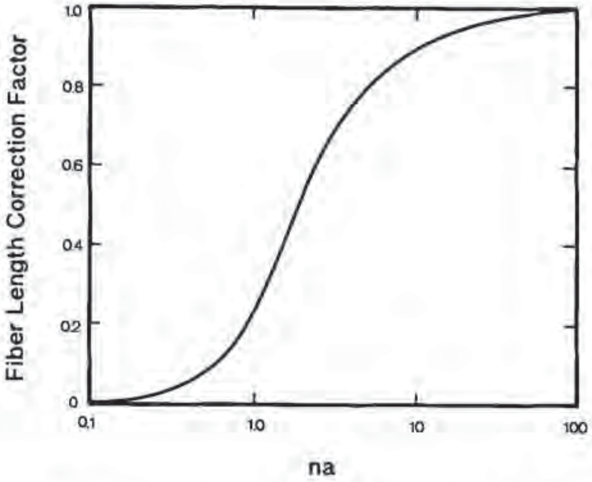

Figure 9.17 The effect of fiber length, given as na, on the reinforcing effect or fiber length correction factor, for fiber reinforcement of thermoplastics [89]

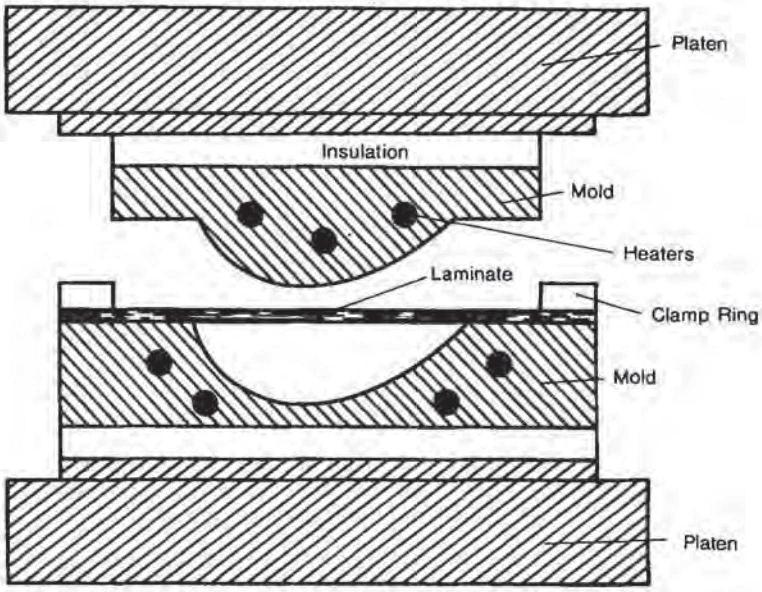

Figure 9.18 Matched die forming of high-performance composite. Redrawn from [90]

- "Lofting" during heating. The fiber network is flattened into the polymer matrix during the fabrication of the composite sheet. This locks in fiber stresses. When the sheet is reheated, the stresses relieve and the composite grows in thickness and

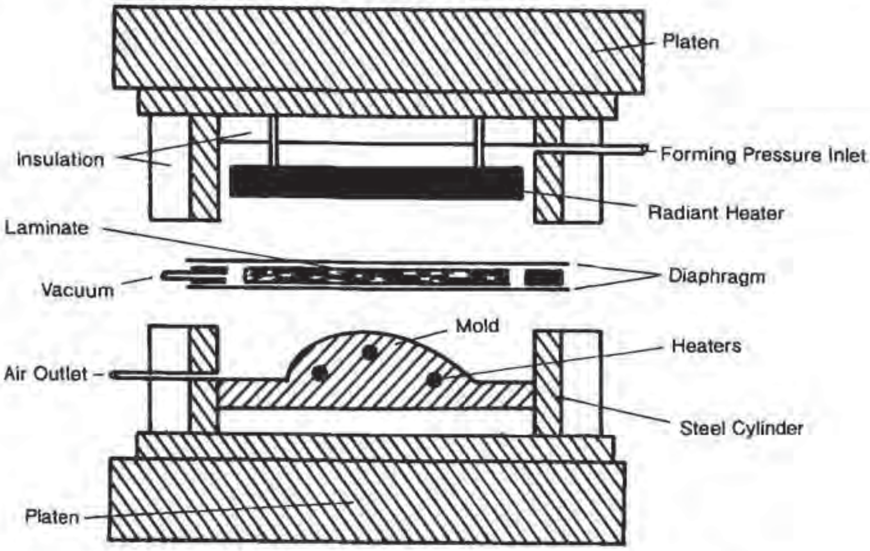

Figure 9.19 Pressure forming of high-performance composite. Redrawn from [91]

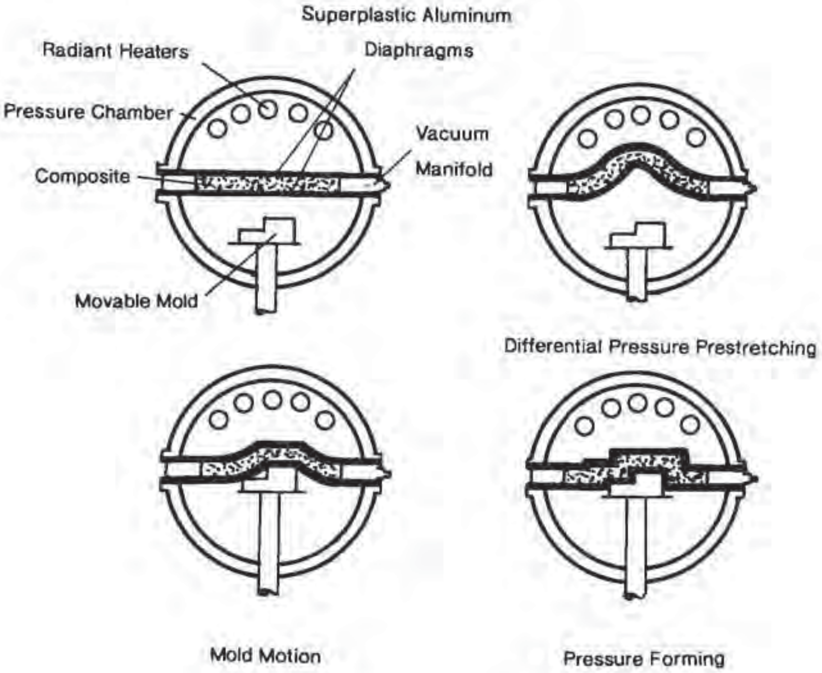

Figure 9.20 Plug-assisted pressure forming of high-performance composite. Redrawn from [93]

increases in porosity. Lofting is a serious problem with all but the shortest fibers. Acicular fillers such as TiO_2 and platy fillers such as talc exhibit mild lofting as well. In the mildest case of lofting, the free surface of the sheet shows "fiber prominence". In severe cases, the formed surface shows fiber prominence and the free surface is bristled.

- Moderate to severe trimming difficulties. Most fiber-reinforced composites cannot be trimmed with steel rule dies. The method of trimming depends on the type of fiber and the toughness of the matrix. Typically, for filled and short-fiber reinforced composites where the polymer matrix has a relatively low elastic modulus, such as talc-filled polypropylene, forged steel dies are used. For high-performance composites such as carbon-fiber reinforced PEEK, diamond-coated toothed saws and routers are used [94]. Diamond-coated abrasive wheels are usually used to finish the cut surfaces. The major problems are delamination of the matrix from the fibers, shedding, and the formation of splinters. Internal delamination results in stress concentration at edges and cut-outs, which in turn results in premature failure. To minimize heat build-up on saws and drills, water- or air-cooling the cutting area is strongly recommended. Despite precautions, splintering remains a major processing problem with high-performance composites.

9.5 Laminated Sheet Thermoforming

There are many applications for thermoformed laminated products. Heavy-gage applications include PMMA/ABS and PMMA/PVC for pools, spas, soaking tubs and shower stalls, and cap-sheet acrylic on ABS or HIPS for exterior products. Thin-gage applications include rigid barrier containers of PS/EVOH/PP and PS/PVDC/PE. The heating and forming philosophies of multilayer sheet rely entirely on the heating and forming philosophies of monolithic sheet. There are some important exceptions that are documented here.

Heating Multilayer Sheet

Heating the multilayer structure is the primary focus of the few studies of thermoforming conditions [95-98]. If all the layers are infrared-opaque, the sheet behavior is similar to the behavior of a monolithic sheet. Radiant and convective energy is absorbed on the sheet surface and conducted through the various layers. The arithmetic of Section 3.15 is used for each layer. For the ith layer:

$$\rho_i \cdot c_{p,i} \left(\frac{\partial T}{\partial \theta}\right) = \frac{\partial}{\partial x}\left(k_i \frac{\partial T}{\partial x}\right) \tag{9.41}$$

The boundary conditions at the sheet surface and centerline remain as before. In addition, there are interlayer boundary conditions:

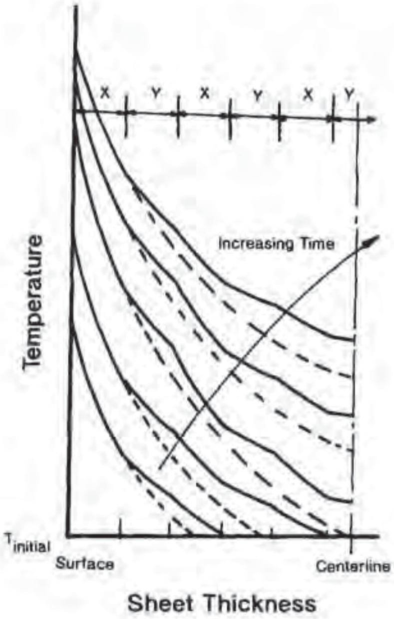

Figure 9.21 Sheet thickness- and time-dependent temperature profile through XYXY-type laminate. Variation in thermal conductivity and/or thermal diffusivity causes differential change in temperature from broken lines to solid lines

$$T_i = T_{i+1} \tag{9.42}$$

$$q_i = k_i\left(\frac{\partial T}{\partial x}\right) = k_{i+1}\left(\frac{\partial T}{\partial x}\right) = q_{i+1} \tag{9.43}$$

For N layers, the N heat conduction equations are simultaneously solved to yield the temperature profile through the laminate. Figure 9.21 shows a typical temperature profile for a constant heat flux input to the sheet surface [99].

In addition to the infrared-opaque sheet, there are several other variations:

- A multilayer sheet where a semitransparent layer is in the interior of the laminate. One example is PS/PVDC/PP where EVA is the tie-layer between the plies. For this example, the heating profile is essentially the same as that for infrared-opaque sheet [98].
- A multilayer sheet where an outside layer is semitransparent. An example is the PMMA cap-sheet on ABS for outdoor applications. The energy transmitted to the inner layer is wavelength-dependent. Beer's law is frequently used to describe the extent of energy absorption by the semitransparent layer:

$$I(x,\lambda) = I_o\, e^{-\alpha(\lambda)x} \tag{9.44}$$

where I_o is the energy intensity on the sheet surface ($x = 0$) and $\alpha(\lambda)$ is the wavelength-dependent absorptivity, Chapter 2. If the surface layer is physically thick or has a large absorption value, essentially all the incident energy is absorbed before reaching the interface. The arithmetic becomes considerably more complex if the surface layer is physically or radiantly thin [95]. The interface between the first two layers acts to reflect a portion of the incident energy back

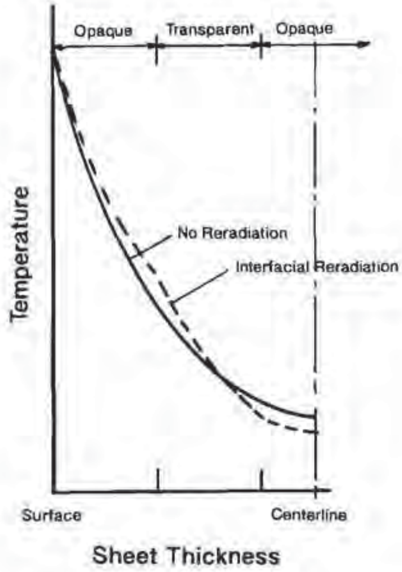

Figure 9.22 Effect of internal reradiation on temperature profile through transparent-opaque-transparent laminate

through the first layer, and the analysis requires an integral technique known as the "two-flux method" [100]. Figure 9.21 is a schematic of the relative effect of internal reradiation on the thickness-dependent temperature profile [101]. For heavy-gage sheet where a thin layer is used as a protective layer, the reradiation effect is small enough to ignore. The effect usually cannot be ignored for roll-fed multilayer sheet. However, another simplification is possible. Figures 9.23 and

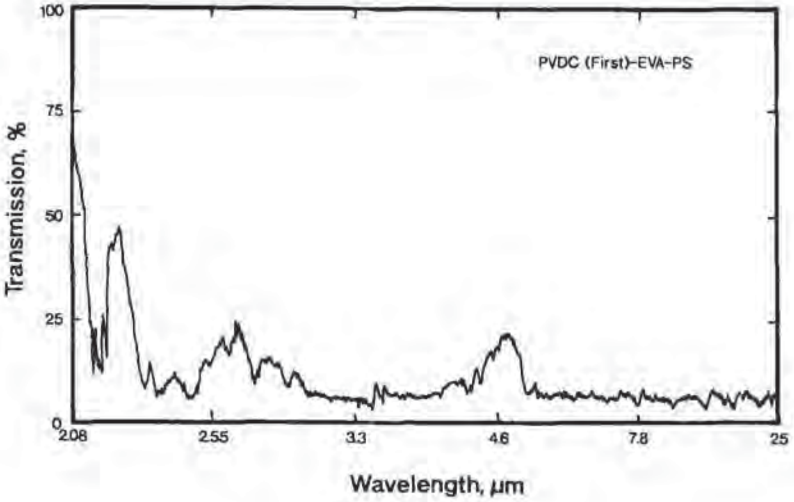

Figure 9.23 Infrared transmission through PVDC-EVA-PS laminate with PVDC as first layer

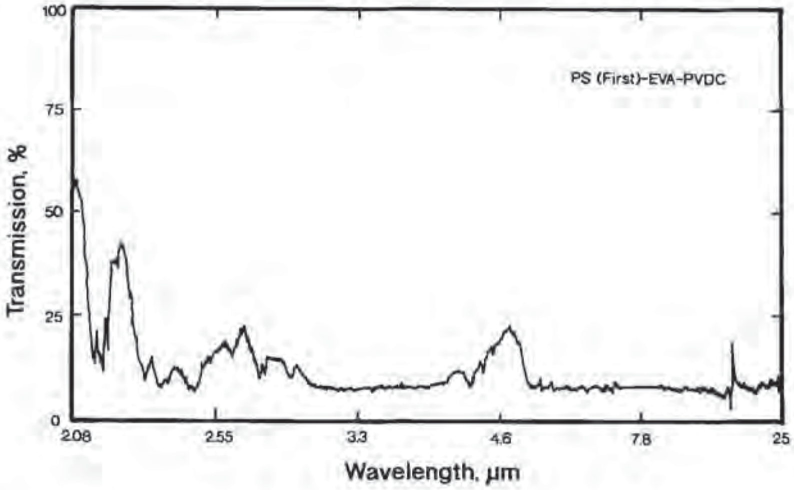

Figure 9.24 Infrared transmission through PS-EVA-PVDC laminate with PS as first layer

9.24 are infrared absorption spectra of PS-EVA-PVDC [102]. The first figure shows PVDC first and the second shows PS first. As is apparent, the through-ply absorption spectra are essentially the same. From Fig. 9.25 [103], it is apparent that Beer's law, Equation 9.44, will yield the extent of wavelength-dependent volumetric absorption, regardless of which ply is the first surface to receive infrared radiation. This means that when analyzing the heating characteristics of thin-gage

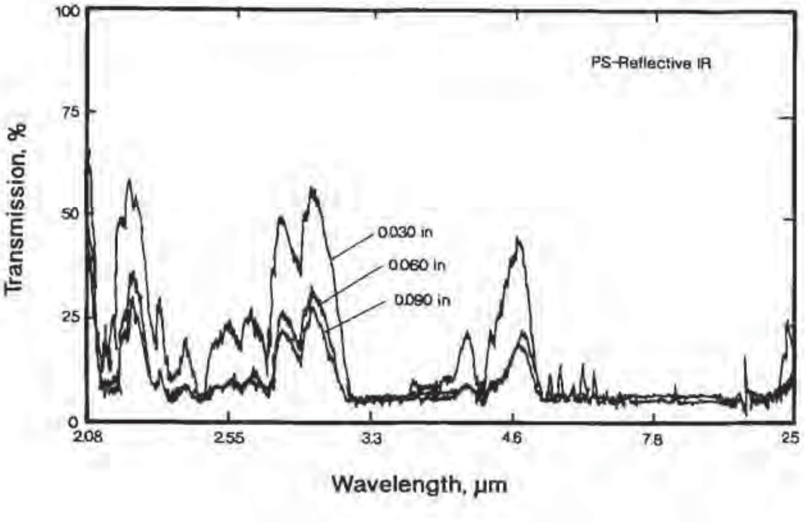

Figure 9.25 Thickness-dependent reflective infrared transmission through polystyrene, PS

multilayer structures, as a first approximation, they can be treated as simple monolithic polymers albeit with unique sets of energy absorption characteristics.

Forming Multilayer Sheet

The polymers that make up a multilayer sheet usually have quite different temperature-dependent stress-strain curves. The objective is to determine the appropriate forming temperature range for the laminate. Obviously, the polymers in all layers must be at or above their individual minimum forming temperatures, as given by Table 2.5. And, no polymer should be above its maximum forming temperature. The forming window for a laminate is usually narrower than that for any of its individual layers (Fig. 9.26). It is apparent that the breadth of the forming window is also important in the way in which the laminate is heated. If one of the layers is very thick, the formability of that layer will dominate that of the other layers. As a first approximation, then, the formability characteristics of the dominant polymer dictate the forming parameters of the laminate. If no layer dominates the strength of the laminate at the forming temperature, the laminate resistance to applied load is obtained from the rule of equivalent moduli. That is, the ratio of local stresses at a given strain is:

$$\frac{\sigma_i}{\sigma_o} = \frac{E_i}{E_o} \tag{9.45}$$

where σ_i is the stress and E_i is the modulus in the ith beam and σ_o is the stress and E_o is the modulus in a reference beam. For simple beam bending (Fig. 9.27) [104], the effective widths of the beam sections change in inverse proportion to their moduli:

$$\frac{b_i}{b_o} = \frac{E_o}{E_i} \tag{9.46}$$

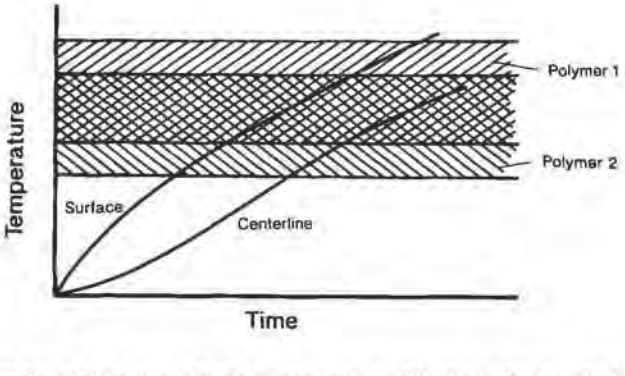

Figure 9.26 Schematic of time-dependent temperature profile through two-ply laminate where the ply forming windows overlap

Figure 9.27 Equivalent stiffness concept for three-ply laminate. (Left) Actual thicknesses of laminate. (Right) Effective thicknesses when plies vary in modulus

As a result, the deflection of a simple beam, δ, under uniform load is given as:

$$\delta_{max} = \frac{5 \cdot w_o L^4}{384 \cdot E_o I^*} \tag{9.47}$$

where w_o is the weight per unit length, L is the span of the beam, and I^* is the sum of the moments of inertia of the various elements that make up the effective beam structure of Fig. 9.27. This analysis is appropriate so long as the neutral axis remains in the beam structure. Once the entire beam is in tension, the appropriate property is the composite tensile strength. The amount of force required to stretch the laminate, F_{lam}, is simply the sum of the forces required to stretch the individual layers to the same extent. This is given as:

$$F_{lam} = \sum \frac{T_i}{A_i} \tag{9.48}$$

where T_i is the tensile strength of the ith layer and A_i is its cross sectional area. For a constant-width laminate, A_i is proportional to the thickness of the ith layer. Example 9.3 illustrates this.

Example 9.3 Strength and Deflection of Laminates

Currently, 0.400-in thick PMMA sheet is being thermoformed into a female mold for a spa. At the lowest forming, temperature, the 1.05 g/cm³ PMMA sheet has a modulus of 1000 lb$_f$/in². A portion of the PMMA sheet is to be replaced with fire retardant PVC at 1.4 g/cm³. The PVC chosen has a modulus of 500 lb$_f$/in² at the forming temperature. Use Equations 9.46 and 9.47 to determine the effect of polymer replacement on sheet sag for a 10-in wide section having an 18-in span. For the first case, assume that 50% of the PMMA is replaced with PVC. In the second case, assume that 75% is replaced with PVC.

The moment of inertia of the monolithic PMMA sheet is given as[1]:

$$I_{PMMA} = \frac{bh^3}{12} = \frac{10 \times 0.4^3}{12} = 0.0533 \text{ in}^3$$

where b is the width of the sheet and h is its thickness, 0.400 in.

The unit weight of the sheet is given as:

$$w_o = \frac{1.05 \times 62.4 \times 0.4 \times 10}{1728} = 0.152 \text{ lb per inch of span}$$

The deflection is given as:

$$\delta_{PMMA} = \frac{5w_oL^4}{384EI} = \frac{5 \times 0.152 \times 18^4}{384 \times 1000 \times 0.0533} = 3.90 \text{ in}$$

For the replacement where the modulus is 50% of that being replaced:

$$b' = b\left(\frac{E'}{E}\right) = 0.5b$$

As a result, the beam is replaced with a T-beam, with the top section 10 in wide and 0.2 in thick and the lower section 5 in wide and 0.2 in thick. The moment of inertia of this T-beam is determined by first obtaining the distance from the top surface of the T-beam of the centroid:

$$\bar{y} = \frac{\int y\,da}{A} = \frac{5 \times 0.2 \times 0.1 + 5 \times 0.4 \times 0.2}{5 \times 0.2 + 5 \times 0.4} = 0.1667 \text{ in}$$

The combined moment of inertia for the two elements of the T-beam about the top surface is:

$$I_x = \frac{5 \times 0.2^3}{3} + \frac{5 \times 0.4^3}{3} = 0.120 \text{ in}^4$$

The moment of inertia about the centroid is then given as:

$$I_{centroid} = I_x - A\bar{y}^2 = 0.120 - (5 \times 0.2 + 5 \times 0.4) \times 0.1667^2 = 0.0366 \text{ in}^4$$

The new weight per inch of span is given as:

$$w_o = \left(\frac{1.05 + 1.4}{2}\right) \times \frac{62.4 \times 0.4 \times 10}{1728} = 0.177 \text{ lb per inch of span}$$

The new deflection is:

$$\delta_{PMMA+PVC} = \frac{0.177 \times 0.5 \times 18^4}{384 \times 1000 \times 0.0366} = 6.614 \text{ in}$$

This is nearly 70% increase in deflection.

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[1] Again note that the neutral axis is outside the dimensions of the part. Correctly, this equation does not yield the correct answers in this case. However, the relative effects are considered to be about right.

For the 25-75 PMMA-PVC, the following obtains:

$$\bar{y} = 0.17 \text{ in}, \ I_{\text{centroid}} = 0.1083 - 2.5 \times 0.17^2 = 0.0361 \text{ in}^4$$

$$w_o = \left(\frac{3 \times 1.4 + 1.05}{4}\right) \times \frac{62.4 \times 0.4 \times 10}{1728} = 0.190 \text{ lb per inch of span}$$

$$\text{and } \delta_{\text{PMMA}+3\text{PVC}} = 7.20 \text{ in}$$

or an increase in deflection of nearly 85% from the monolithic PMMA. For this case, note that 25% of the increase in deflection is due to the increased weight of the sheet when PVC is substituted for PMMA. The rest is the result of the lower PVC modulus.

Wall thickness variation in the formed laminate is independent of the make-up of the laminate of or the strength of adhesion between the layers [103]. Figure 9.28 illustrates the draw-down of components of a PVDC-EVA-PS multilayer into a 60° cone. As is apparent, the wall thickness along the cone is essentially independent of the nature of the laminate. For the analyses above, the plies are considered to be firmly laminated. That is, the forces required to bend and stretch a laminate are substantially less than the forces required to delaminate the plies. Three general cases are:

- Interlayer sliding without interlayer shear. This is equivalent to thermoforming a set of stacked cards with the coefficient of friction between the cards being zero. Each layer or ply is considered as isolated from the others. The amount of force required to thermoform each layer is given by the temperature-dependent stress-strain characteristics of that polymer. The total force required to form the laminate is therefore the sum of the forces required to form the individual layers. If one of the layers is prone to forming pinholes or ruptures beyond a given strain level, it will also do so in the laminate. The draw ratio of each layer is identical to the draw ratio of the laminate.
- No interlayer sliding or shear. In this case, the laminate is behaving as a monolayer. Regardless of the difficulty in the draw, the interfacial adhesion is far greater than the interfacial shear.
- Interlayer shear without interlayer sliding. In this case, the bending forces create shearing stresses that vary from zero at the neutral axis to maximum at the outer fiber stress. The local shearing stress, τ, is given as:

$$\tau = \frac{VA\bar{y}}{Ib} \tag{9.49}$$

where V is the vertical shear on the beam, I is the moment of inertia of the beam, A is the area of the section between the horizontal plane where the stress is to be determined and the bottom or top surface of the beam, $\bar{y}$ is the distance from the centroid of the area to the neutral axis of the beam and b is the width of the

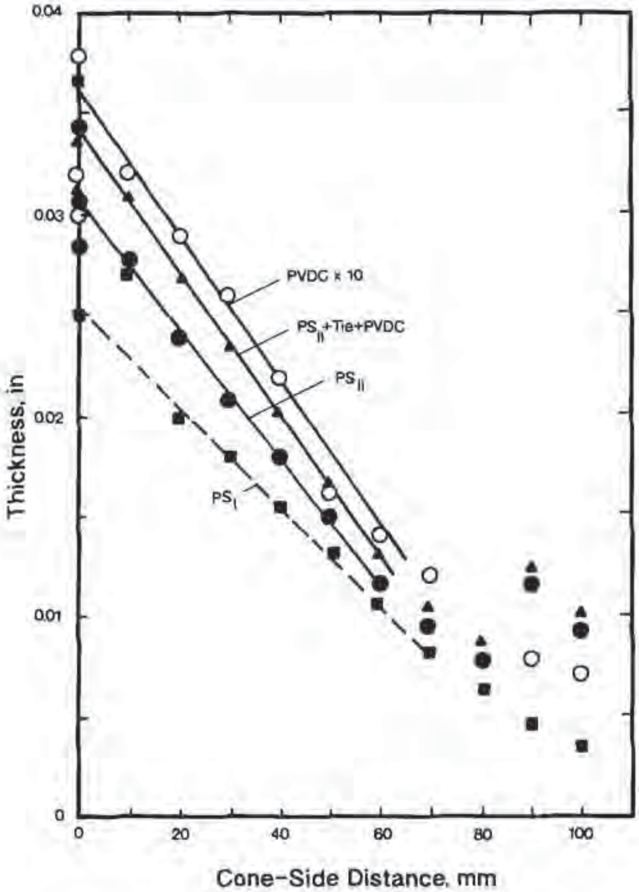

Figure 9.28 Measured wall thickness for draw-down of several elements of laminate into 60-degree cone [103]

beam.[1] Example 9.4 illustrates the method of calculating the local shearing stress. If the local shearing stress exceeds the interlayer shear strength of the laminate at any point, the plies may delaminate. As an example, when a laminate having a very thin protective outer layer is stretched over a male mold, the delaminated thin layer can tear at concave 3D corners and compressively buckle at convex corners.

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[1] Again, this expression is strictly valid only when the neutral axis remains within the physical dimensions of the beam.

Example 9.4 Interply Shear Strength

Consider a 9 in wide, 0.400-in laminated beam having a 0.050-in cap-sheet being stretched with 15 lb vertical shear. The adhesive strength of the interface is 1200 lb_f/in^2. Determine whether the laminate will delaminate.

Equation 9.49 gives the interfacial shear strength for this laminate. The moment of inertia is given as $I = bh^3/12$:

$$\tau = 12 \cdot \frac{Va}{h^3} = 12 \cdot \frac{V\bar{y}}{bh^2}$$

$\bar{y} = (0.400 - 0.050)/2 = 0.1875$ in. $V = 15$ lb. Therefore the shear strength is:

$$\tau = \frac{12 \cdot 15 \cdot 0.1875}{9 \cdot 0.05^2} = 1500\ \text{lb}_f/\text{in}^2$$

the interply shear strength exceeds the adhesive strength and the plies may delaminate.

Differences in thermal expansion coefficients between the plies will acerbate the delamination problem, as well [97].

9.6 Twin-Sheet Thermoforming

Twin-sheet thermoforming is the process of producing an initially hollow container beginning with two sheets of plastic [105-107]. Rotational molding, blow molding, thermoforming double-walled extruded sheet and seam welding two thermoformed sheets are some of the many competitive ways of making an initially hollow container. For many products such as garage doors, equipment cabinet sides, marine dock floats, components for voting booths, gurneys, food serving carts, refrigeration and freezer doors, cargo compartment doors, transit and mass seating, truck bedliners, pallets and tote boxes, the containers are in reality hollow flat panels that can be foam filled for added stiffness or thermal insulation[1]. Foam reaction injection molding, rotational molding, laminated honeycomb, gas-assisted injection molding and foam injection molding of thermoplastics produce competitive products. Table 9.9 gives a comparison of competitive ways of fabricating rigid flat panels [109].

There are two general ways of producing two-sided or double-walled structures. Sequential thermoforming produces one formed surface after the other, with assembly taking place either on the forming press or in a secondary fixture removed from

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[1] Although nearly all of the twin-sheet applications are currently in heavy gage sheet, it is reported that the earliest twin-sheet thermoformed products were ping-pong balls, in 1935 [108].

Table 9.9 Comparison of Several Process for the Fabrication of a Rigid Flat Panel [109]

Item	Thermoplastic structural foam [low-pressure]	Rotational molding	Twin-sheet thermoforming	Industrial blow molding	Gas-injection molding
Resin form	Pellets	Powder	Sheet	Pellets	Pellets
Availability of polymers	Excellent	Fair	Good	Limited	Excellent
Polymer cost	Standard	Price includes grinding	Price includes sheet extrusion	Above average	Standard
Breadth of polymers	All	Restricted-olefin dominated	Amorphous polymers preferred	Restricted - olefin dominated	Most
Nonproduct produced per shot	<5%	5%	30–50%	30%	<5%
Nonproduct reuse	Immediate	No thermally sensitive polymers	Must be re-extruded	No thermally sensitive polymers	Immediate
Color	Colored pellets or masterbatch[1]	Dry blend	Colored sheet	Colored pellets or masterbatch	Colored pellets or masterbatch
Processibility of thermally sensitive polymers	Moderate	Very difficult	Controllable but color can change	Difficult to impossible	Moderate
Melt viscosity control	Moderate	Easy flow polymers	Requires good hot strength	Requires excellent melt strength	Moderate
Variety of mold materials	Aluminum of steel	Sheet metal, aluminum, steel	Wood, plaster aluminum	Aluminum	Steel but aluminum ok

(Continued)

Table 9.9 (Continued)

Item	Thermoplastic structural foam [low-pressure]	Rotational molding	Twin-sheet thermoforming	Industrial blow molding	Gas-injection molding
Cost of molds	Moderate	Low	Low to moderate	Moderate	Moderate to high
Mold maker reliability, quality	Good	Poor to good	Fair	Fair to good	Good
Mold closure	Butt	Tongue/groove	Butt, tongue/groove	Butt	Butt
Method of holding mold closed	Platen hydraulics	Mechanical toggle	Pneumatic, hydraulic	Hydraulic	Platen hydraulic
Thermal cycle	Moderate to long	Long	Long	Moderate to long	Moderate to short
Major trial/ error problems	Part density, minimum cooling time, blowing agent conc.	Ratio of arm speeds, warpage	3D corner thickness, thickness, parting line integrity	Pinchoff, wall uniformity	Gas injection rate, time
Cooling method	Mold core	Water spray	Mold, one-side	Mold core, one-side	Mold core
Part release	Ejector pins	Manual	Manual	Manual, air	Ejector pins
Operating pressure	Relatively low	Low	Low	Moderate	Moderate to moderately high
Operating temperature	Polymer melt temperature	Above polymer melt temperature	Below polymer melt temperature	Polymer melt temperature	Polymer melt temperature
Life of molds	Moderate to high	Low to high	Low to high	High	Moderate to high
Controlling part of cycle	Cooling	Heating	Heating[2]	Cooling	Cooling

Skill of operator	High	Low	Moderate	High	High
Man/machine interaction	Moderate	Very high	High	Moderate	Moderate
Filling method	Automatic hopper load	Manual	Manual to semi-automatic	Automatic hopper load	Automatic hopper load
Part removal method	Automatic to manual[3]	Manual	Manual	Automatic to manual[3]	Automatic to manual[3]
Part wall uniformity	Good to excellent	Fair	Fair to good	Fair to good	Good
"Skin" thickness Uniformity	Fair	Fair	Fair to good	Fair to good	Fair
Molding characteristics requiring attention	Gate region	Parting line	Weld line/ tackoff	Parting line, blow pin hole	Gate region
"Skin" thickness control	Poor	Fair to poor	Fair to good	Fair to good	Fair
Method of skin thickness control	Injection rate, blowing agent concentration	Ratio of arm speeds	Temperature, mechanical assists	Parison programming	Gas injection rate, time
Method of increasing part stiffness	Part design Ribs, bosses	Foam filling	Tackoff, foam filling	Tackoff, foam filling	Mold design Ribs, bosses
Inserts	Feasible	Special design only	Post-molding inserts only	Feasible	Feasible
Polymer orientation	Low to moderate[4]	Unoriented	Highly biaxial	Biaxial and uniaxial	Biaxial and uniaxial
Stress retention	Low to moderate[4]	Little	High	Moderate to high	High

(Continued)

Table 9.9 (Continued)

Item	Thermoplastic structural foam [low-pressure]	Rotational molding	Twin-sheet thermoforming	Industrial blow molding	Gas-injection molding
Method of controlling warpage, distortion	Cooling, fixturing, mold temperature	Internal air during cooling	High mold temperature	Internal air pressure, mold temperature	Time in cooling, fixturing
Primary mechanical part failure	Weldline, low density region	Low tensile strength, poor fusion	Thin corners, poor weld at parting line	Thin corners, poor weld at parting line	Thin skins
Surface finish-typical	Poor	Fair	Good to excellent	Excellent	Excellent
Processing problems that causes poor surface	Swirls, bubbles	Pock marks	Poor replication of mold surface	Air bubbles	Break-through
Part cost					
1,000	Very high	Low/very low	Moderate	High/very high	Very high
10,000	High	Moderate	Moderate	Moderate	High
100,000	Moderate	High	Moderate/high	Moderate	Moderate
1,000,000	Moderate/low	Very high	High/very high	Moderate/low	Moderate/low
Production of small parts (brush handle)	Excellent	Impractical	Impractical	Probable	Good
Production of very large parts (pallets)	Very expensive	Excellent	Excellent	Good, expensive	Very expensive

[1] Owing to swirl pattern, color matching is very difficult, particularly with dark colors

[2] For single heater shuttle, heating dominates. For dual heater shuttle, forming and cooling dominate

[3] Depends on the part size and weight

[4] Orientation increases substantially with decreasing part wall thickness and relative flow length

the forming press. Simultaneous thermoforming produces both surfaces at the same time, with assembly taking place within the forming press.

Simultaneous Twin-Sheet Forming

Two general approaches are used here. The first, primarily for heavy-gage parts, employs two thermoforming machines that interact at the assembly station (Fig. 9.29) [110]. Either shuttle or rotary presses are used. The loading and unloading sequence for a dual shuttle press is more difficult than that for rotary presses owing to the complexity of the twin-sheet mold and assembly machinery. The objective is to simultaneously heat and form the two sheets in separate machines, then move the formed, hot sides in their molds into an assembly press to produce the double-walled part. The second technique uses a single thermoforming machine, with the two sheets clamped in a single frame although separated with spacers (Fig. 9.30). The clamping frame is equipped with air nozzles and air is injected between the sheets to keep them separated throughout the heating and forming process. A single robust forming press is used. During forming, the mold cavities are evacuated and additional warm air may be injected through hypodermic needles that pierce the sheet. Air pressures to 50 lb_f/in^2 or 0.34 MPa are typical. Other mold characteristics are described in Chapter 6 on mold design.

Although simultaneous thin-gage twin-sheet thermoforming is technically feasible, it has few major commercial successes. Blow molding dominates the thin-wall hollow container applications and single-ply thermoformed low-density foam dominates the flat panel and tray applications.

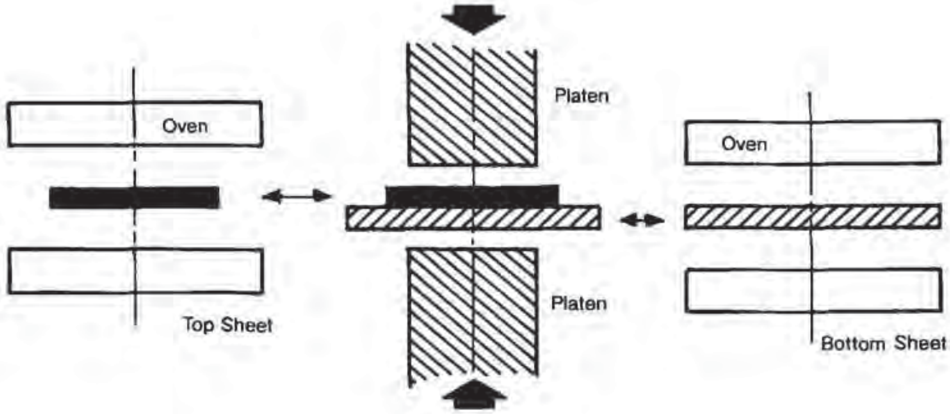

Figure 9.29 Schematic of dual shuttle machine for simultaneous or sequential twin-sheet forming

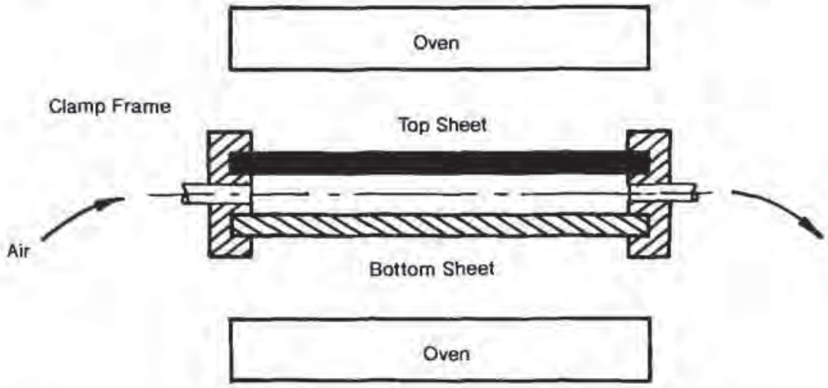

Figure 9.30 Schematic of simultaneous twin-sheet forming using a single clamp frame

Sequential Twin-Sheet Forming

This technique is reserved for heavy-gage forming. There are several ways of producing two-sided structures using sequential thermoforming. The simplest uses a single forming press. The press can be either a shuttle press or a rotary press. The objective is to install the mold for the first side and to form a quantity. This mold is then replaced with the mold for the second side and a quantity of the second side is formed. The two sides are then assembled away from the press by solvent or thermal welding. This technique is shown in schematic in Fig. 9.31. A more automated but more complicated method also employs a single press but has the two female molds installed in the press at the same time. The first sheet is heated and

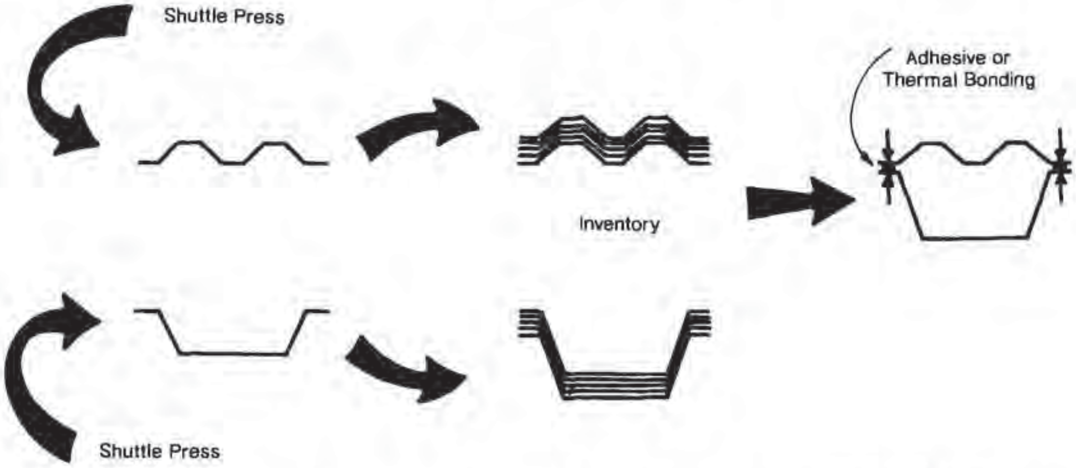

Figure 9.31 Schematic of twin-sheet production where mating parts are inventoried prior to fabrication

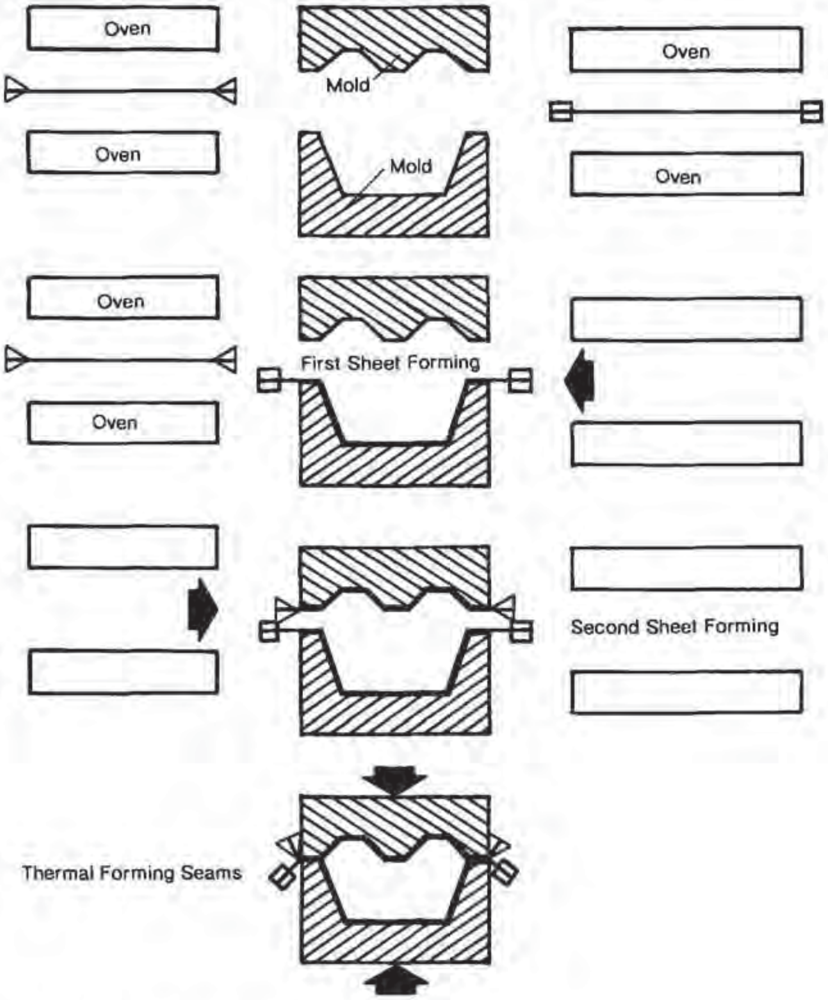

Figure 9.32 Sequential twin-sheet forming schematic

formed into the first mold, in the down position, for example. The second sheet is heated and formed into the second mold, in the up position. The press then closes to form the double-walled product. So long as the region to be welded on the first sheet is kept hot, no secondary welding is required. This is shown in schematic in Fig. 9.32. If one or both of the molds are male molds, the formed sheet is usually transferred from the male mold to a holding frame prior to forming the double-walled product.

Sequential twin-sheet thermoforming also uses the two-machine twin-sheet forming concept (Fig. 9.29). For sequential forming, the first sheet is heated and formed several seconds to a minute ahead of the second one. Usually the most difficult draw is done first. The delay allows for inspection of the formed part as well as for

Table 9.10 Adhesion Temperature [170]

Polymer	T_m, Melt temperature (°C)	T_g, Glass transition temperature (°C)	T_t, Tack temperature (°C)
Low-density polyethylene	120 ± 1	—	115 ± 5
High-density polyethylene	130 ± 2	—	130 ± 5
General-purpose polystyrene	—	105	110 ± 5
Medium-impact polystyrene	—	105	110 ± 5
ABS	—	105	125 ± 5
Polymethyl methacrylate	—	105	105 ± 5
Polycarbonate	—	155	160 ± 5

Obtained by blowing −35 mesh polymer powder against a linear temperature melting point apparatus held in the vertical position

insertion of reinforcing elements or insulating pads, as examples. In reality, most two-machine forming operations that begin as simultaneous forming usually operate as sequential forming. Some increase in the speed of forming and in the efficiency of welding, the seam is achieved by using a four-station rotary with two ovens. The first sheet is rotated to the second oven and the second is immediately rotated to the first. When the first sheet is hot, it is rotated to the forming station and formed. The second sheet remains in the second oven until the first is formed. It is then rotated to the forming station for forming and mating with the first. Quartz or rapid response ceramic ovens are required for this form of twin-sheet forming. Table 9.11 compares the advantages and disadvantages of these twin-sheet forming techniques.

Seal Area—Adhesion

Successful twin-sheet forming depends on the success of the peripheral seal or weld between the two sheets. The seal must be 100% liquid-tight if the hollow cavity is to be subsequently filled with polyurethane foam. In simultaneous forming, the mating surfaces of the two separately formed sheet are usually quite hot and adhesion is usually not a significant problem. In sequential forming, on the other hand, the first sheet formed is cooling while the second sheet is being formed. In certain cases the time delay between the formation of the first sheet and the mating is so long that good adhesion is not possible. Auxiliary heaters are then required. Usually high-intensity quartz tube heaters are indexed into the mold cavity over the first sheet just prior to moving the molds together. To achieve good adhesion, both sheet surfaces

Table 9.11 Advantages and Disadvantages of Various Types of Twin-Sheet Thermoforming

Method	Advantage	Disadvantage
Simultaneous two-machine (Fig. 9.29)	Very high productivity. Both sheet free surfaces very hot, so welds very good.	Sheet thicknesses need to be similar. Imperfection in one sheet requires scrapping entire formed part. Difficult to insert reinforcing elements.
Sequential two-machine (Fig. 9.29)	High productivity. Insert reinforcement possible. Plug assist possible only if assembly station separate from forming stations.	Capital intensive compared with other sequential methods.
Simultaneous one-machine (Fig. 9.30)	Good productivity. Capital cost less than two-machine. Pressure-formed surface textures possible.	Load/unload difficult with shuttle press. Long cycle times since each sheet heated only on one side. Careful air control to keep sheets from touching when hot. Sheet thicknesses need to be similar or identical. No means of inserting reinforcements. Special purpose machines with very heavy clamps needed for pressure forming.
Sequential one-machine, one mold at a time (Fig. 9.31)	Sheet of different thicknesses, colors possible. Very low capital, mold cost. Ideal for prototyping. Reinforcement insert easy. Solvent, thermal welding possible. Can be done on conventional thermoforming machine. Plug-assist possible.	High manual labor, particularly in assembly area. Plastics must be thermal or solvent weldable. Welds may not be as strong as with other techniques.
Sequential one-machine, two molds at a time (Fig. 9.32)	More automated than one-machine, one-mold.	First sheet weld area must be kept hot. Welds may not be as strong as with other techniques. More robust press required. Plug-assist very difficult, even with assists that shuttle into and out of press.

must be above the glass transition temperature of the polymer. The desired temperature is the "tack" temperature or the temperature where the polymer begins to feel sticky. Tack temperatures for several polymers are given in Table 9.10 [170]. Typically the tack temperature is just above the melt temperature of a crystalline polymer and about 0°C to 20°C above the glass transition temperature of an amorphous polymer. It is always better to err on the side of high polymer temperatures in the seal area. In addition to sufficiently high polymer temperature, the seal region must be free of contaminants such as:

- External lubricants and waxes,
- Low-molecular weight carriers for pigments,
- Antistatic agents,
- Processing aids, particularly stearates and titanates, and
- Dispersing agents.

Seal Area—Compressive Force

Care must be taken to ensure proper registry without shear during the mating of the two surfaces. Because the seal area is usually not planar, the mating halves must seat uniformly along the seal line. Otherwise, uniform seal compression is impossible. For very large molds or for mold halves operating at different temperatures, the difference in thermal expansion between the mold halves may cause the mating to be out of registry. This is particularly important if one or both sheets are relatively thin. The seal is simply a thermal weld. In structural blow molding [111], the parison halves are compressed to half their total thickness. The same level of compression is recommended for twin-sheet thermoforming. Owing to mold-to-mold tolerances, typical compression levels are 25% to 50% of the total sheet thickness. Consider a simple butt-weld (Fig. 9.33). Consider squeezing the polymer at a constant squeezing rate [112]:

$$h = h_o(1 - a\theta) \tag{9.50}$$

where h_o is the initial double-sheet thickness. The rate of compression is:

$$\frac{dh}{d\theta} = -a \tag{9.51}$$

where a is the squeezing rate constant. The squeezing force, F, is given as:

$$F_N = \frac{3\eta V^2}{32\pi h^5} \cdot \left(-\frac{dh}{d\theta}\right) = \frac{3a\eta V^2}{32\pi h^5} \tag{9.52}$$

where η is the Newtonian viscosity and V is the volume of the seal area. The initial force, F_o is obtained when $h = h_o$. The final thickness, h_f, is given as:

$$h_f = \beta \cdot h_o \tag{9.53}$$

And the final force is given as:

$$F_f = F_o/\beta^5 \tag{9.54}$$

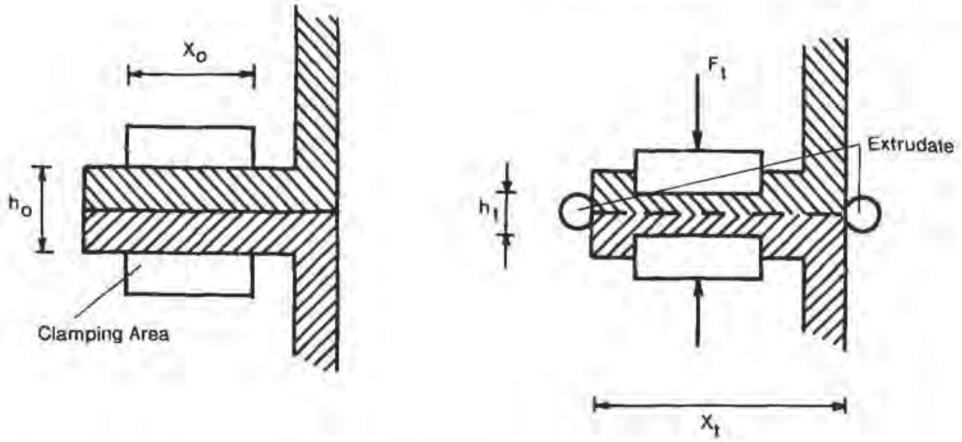

Figure 9.33 Characteristics of squeezing at twin-sheet mating seal

Because the seal area is assumed to have a constant volume, the spreading width, X, is simply given as:

$$X_f = X_o/\beta \tag{9.55}$$

Figure 9.34 shows the force ratio, F_f/F_o and the spreading width, X_f/X_o, as functions of the compression, h_f/h_o. Note that the force required to compress the seal area to 50% is 32 times that required to just mate the surfaces. This force must come from the clamping system on the press. The mating tolerance along the seal area should be no more than 25% of the total sheet thickness in the seal. In quality molds, the seal areas are constructed separately from the mold body. This allows fine tuning and adjustments of the seal areas with shims. It also allows the seal area to be constructed of hardened steel for better wear resistance. In addition to traditional guide pins, secondary guides and lockups are sometimes used to provide the necessary close tolerances. Increasing press clamping force usually does not solve any seal area tolerance problem and can result in damaging the mold or the press.

Seal Area—Design

In addition to sheet temperature and clamping forces, the design of the seal area is important. Figure 9.35 shows several seal area schemes. The most common are the butt-weld, the channel and the vee seal. No vent holes are provided in the seal area. The seal area should be designed with some relief on both sides of the seal. In blow molding, this is known as a gutter-dam design. This allows the compressed plastic to shear-flow from the compression zone at right angles to the seal.

Blow pins are usually required in all twin-sheet molds, regardless of whether fabricated simultaneously or sequentially. For heavy-gage sheet, the blow pins are

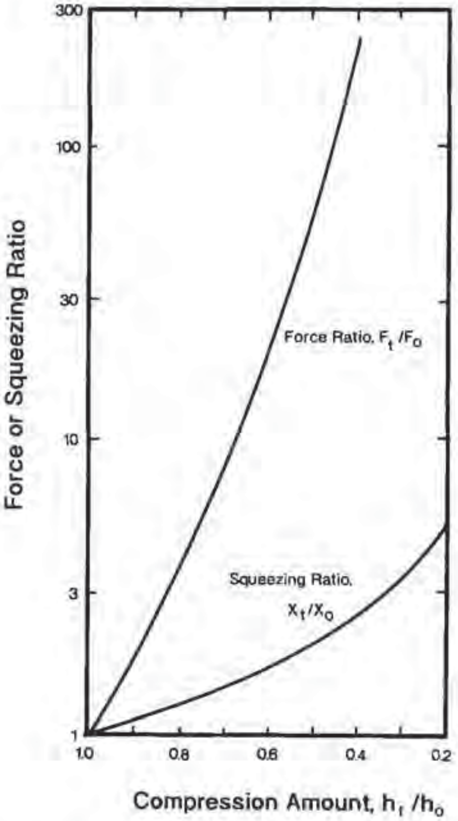

Figure 9.34 Compression level-dependent squeezing or force ratio. See Fig. 9.33

typically 3/16-in to 1/4-in in outside diameter, with 1/8-in inside diameter. Hypodermic needles are sometimes used if blowing through a finished surface is required. Typically blow pins are used in pairs, with one acting as the exhaust pin. With appropriate air line valving, the exhaust pin can also act as a blow pin, if needed. It is recommended that one blow pin be used for every 1 ft^3 or 0.03 m^3 of internal volume in the part. The actual number of blow pins depends on the extent of internal constrictions in the part. The objective of the blow air is to keep the sheets separated. As seen in Table 7.9, the required level of air pressure is very low. Air flow is important as a means of supplemental cooling of the free sheet surfaces. Blow pins are either fixed in the mold surface or driven through the formed sheet just after the part half has been formed. Air cylinders are usually adequate to push the pin through the sheet. Functional blow pins require the plastic to seal the internal air pressure around the blow pin itself. Peripheral blow pins are usually mechanically extended into place just before the two sheets are brought together. The seal area must be designed to accommodate and pinch off the sheet around the blow pin.

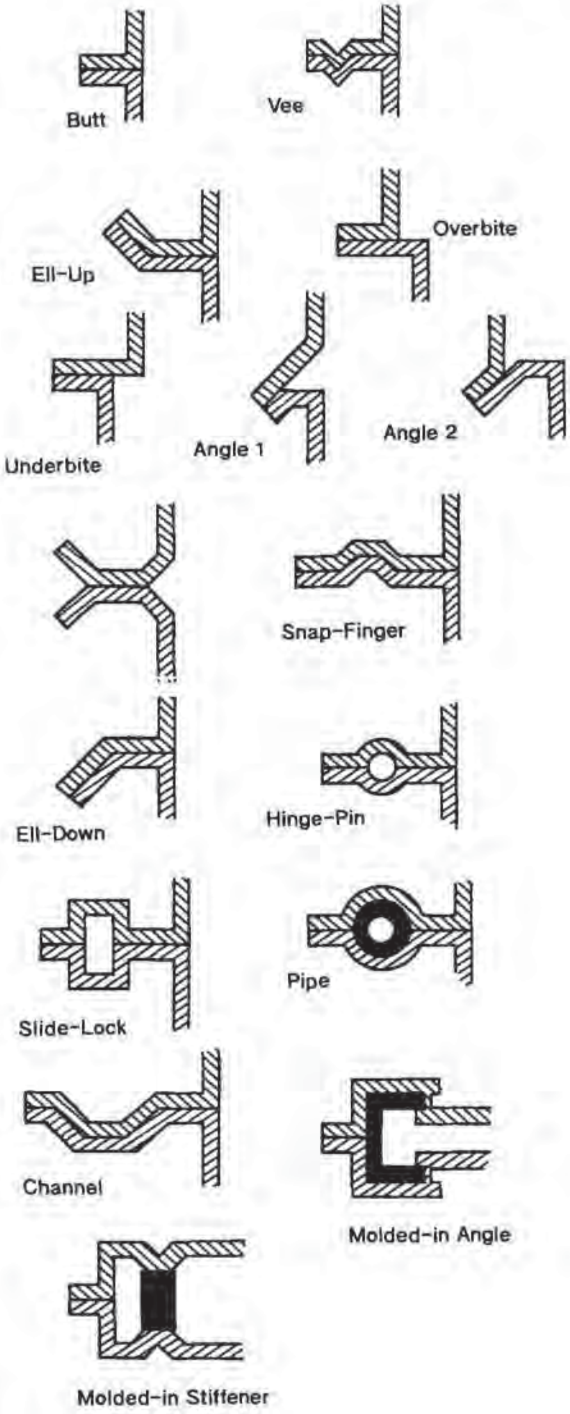

Figure 9.35 Examples of seal area methods

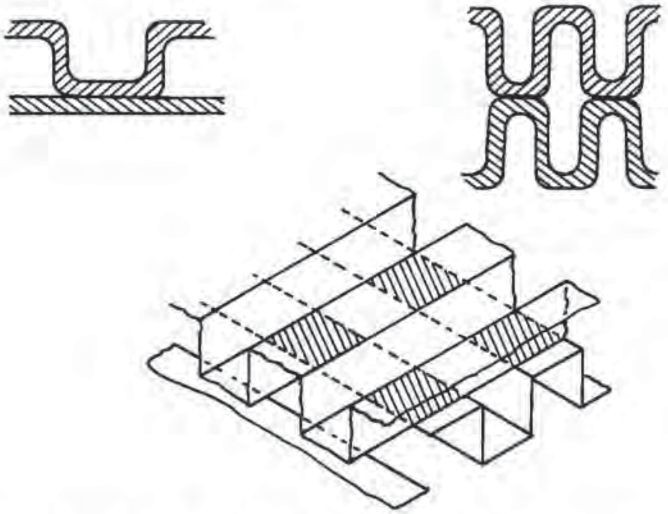

Figure 9.36 Examples of internal tack-off or kiss-off configurations. Lower example shows right-angle tack-offs

Twin sheet designs frequently include "kiss-offs" or "tack-offs" (Fig. 9.36) [113]. These tack-offs greatly improve the stiffness of the hollow shape. Unlike structural blow molding, thermoforming tack-offs do not usually mark or strike through to the exterior sheet surface. This is because the sheet is rubbery rather than fluid at the tacking temperature.

The molding protocol depends on the mold characteristics [114] . If one portion of the mold is predominantly male, it should be placed on the top platen to take advantage of sheet sag. If one portion is predominantly female, it should be placed on the bottom platen, again to take advantage of sheet sag. The first sheet is usually formed into the bottom mold. This allows the clamp to release the sheet without having the sheet experience substantial distortion or warpage. The bottom mold is then run hotter to ensure minimum distortion and warpage[1].

9.7 Polypropylene Thermoforming

Polypropylene epitomizes the best and worst aspects of thermoformable crystalline polymers. For decades, polypropylene has been considered an inexpensive commodity polymer. It has the highest melt temperature of all commodity polyolefins and its

---

[1] Note, however, that if the bottom mold temperature is substantially higher than the upper mold temperature, the sheet will shrink more on the bottom mold. This may change the nature of the sheet in the seal area.

good chemical resistance makes it attractive for autoclavable and microwavable containers. Owing to its relatively high crystallinity level, unpigmented and unfilled PP is usually translucent or "contact transparent". The size of the crystallite determines the level of haze or translucency. Crystallites having dimensions 0.1 μm to 10 μm affect visible light transmission as haze.

Polypropylene has a relatively narrow melting point range of 160° to 165°C. As seen in Fig. 9.37 [55], the apparent viscosity of homopolymer polypropylene changes by a factor of 1000 or more in this melting point range. As is apparent, PP is a solid below its melt temperature and the temperature-dependent strain or elongational response to applied stress is appropriate (Fig. 9.12) [115]. PP is a liquid above its melt temperature and the temperature-dependent strain rate response to applied stress or elongational viscosity is important [116]. Figure 9.38 shows time-dependent nature of PP extensional or elongational viscosity. Shear viscosity is also considered a measure of PP resistance to applied stress, as seen for modified and unmodified PP at 170°C (Fig. 9.39) [117]. The very tight helical structure of the PP molecule provides for relatively good stiffness and chemical resistance but does not allow for a high degree of intermolecular entanglement. Intermolecular and side chain entanglements are major contributors to melt elasticity or "melt strength". Without these effects, PP elongational and shear viscosities are relatively low and the transition between the solid polymer modulus and the elastic strength of the melt is quite abrupt, as seen in schematic in Fig. 9.40 [118]. And as noted shortly, the initially low value for elongational viscosity means that the polymer can quickly sag during heating.

The morphology or crystalline architecture of PP has been studied for decades. The crystalline structure consists of a super-lattice containing large hexagonal β-crystallites and small monoclinic α-crystallites [119-121]. β-crystallites begin to melt at about 147°C and some remain recognizable at 155°C. α-crystallites begin to melt around 152°C and may persist to 162°C. The way in which the PP sheet is extruded and cooled alters the balance between α- and β-crystallites and the propensity for one type to dominate the super-lattice. The crystallites melt relatively slowly during heating and polypropylene crystallizes relatively slowly from the melt to a crystallinity level of approximately 70%, as seen in Table 2.4.

Sag Test

There is no single agreed-upon test for sheet formability [117,118]. Nor is there an agreed-upon way to determine whether a polymer can be heated to the forming temperature without excessive sagging. As discussed in Chapter 4, initial sheet sag can be determined from:

$$y = -\alpha \cdot \frac{qb^4}{Eh^3} \tag{9.56}$$

where y is the extent of sag, α is a Roark-Young scale factor, b is the sheet width, q is the weight of the sheet, h is the sheet thickness and E is the temperature-depen-

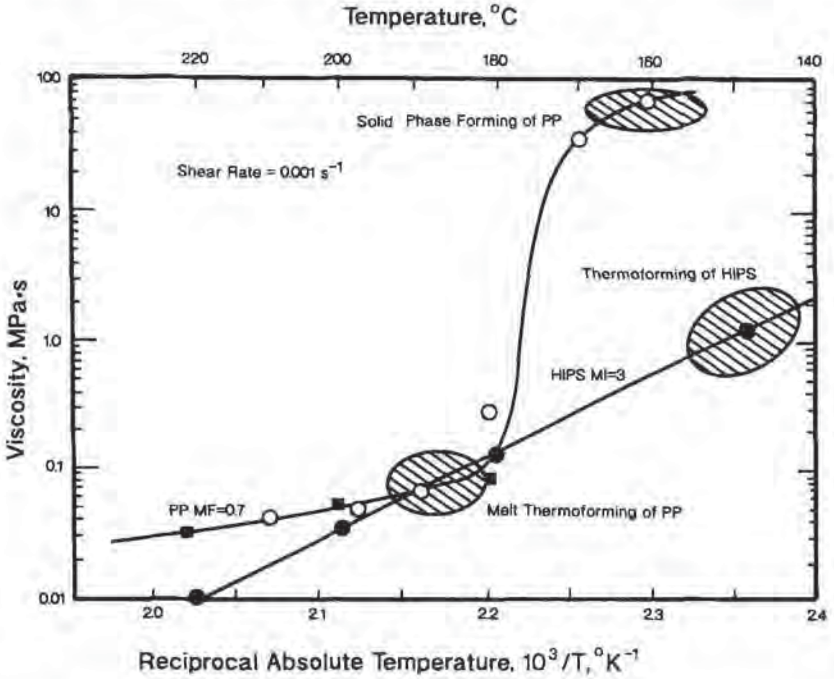

Figure 9.37 Temperature-dependent viscosity for polypropylene, PP, homopolymer and high-impact polystyrene, HIPS. Redrawn from [55]

dent tensile modulus. As is apparent, sag increases with decreasing modulus and increasing temperature. Heavy-gage sheet shows much greater initial sheet sag and wide sheet sags much more than narrow sheet. Once the top portion of the sheet has passed the neutral axis, sheet sag is determined from flexible cable or catenary theory. As shown in Fig. 9.41 [122], if the sheet initially b units wide has sagged y units, the arc length, s, at distance x from the clamp is given as:

$$s = \frac{T_o}{q'} \sinh \frac{q'x}{T_o} \tag{9.57}$$

where q′ is the sheet weight per unit width, $= q/b$ and T_o is the tensile load at the clamp. The amount of sag is given as:

$$y = \frac{T_o}{q'} \left(\cosh \frac{q'x}{T_o} - 1 \right) \tag{9.58}$$

The maximum amount of sag occurs at $x = L/2$, as:

$$y_{max} = \frac{T_o}{q'} \left(\cosh \frac{q'L}{2T_o} - 1 \right) \tag{9.59}$$

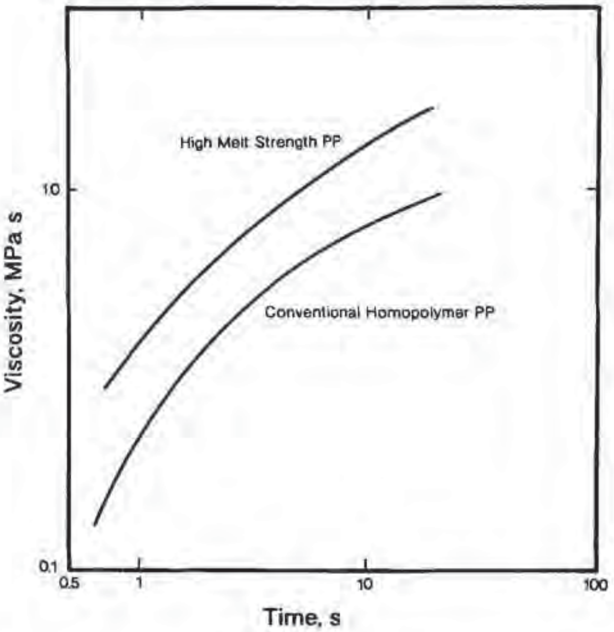

Figure 9.38 Relative time-dependent viscosities for conventional and high melt strength polypropylenes, PP

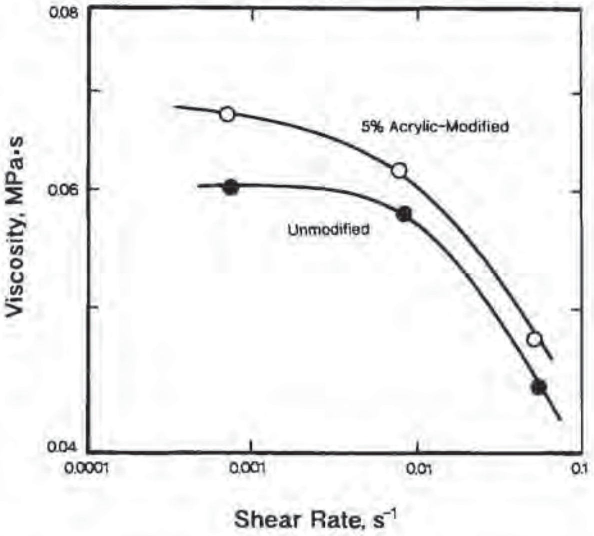

Figure 9.39 Viscosities of unmodified and 5% acrylic-modified polypropylene, PP. Redrawn from [117]

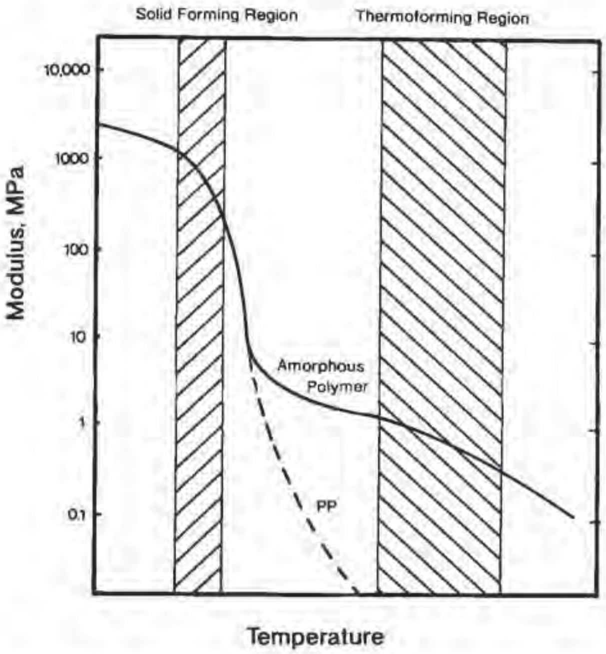

Figure 9.40 Temperature-dependent modulus of polypropylene, compared with an amorphous polymer with same room temperature modulus

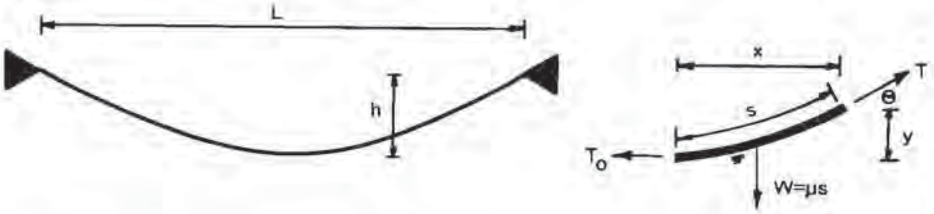

Figure 9.41 Geometric characteristics for catenary sag

The tensile load at any point x from the clamp is given as:

$$T = T_o \cosh\left[\frac{q'x}{T_o}\right] \tag{9.60}$$

Or with substitution:

$$T = T_o + q'y \tag{9.61}$$

The maximum tensile load occurs when $y = y_{max}$. Typically, the amount of sag, y_{max}, is measured as a function of temperature. As is apparent, if the sheet weight is

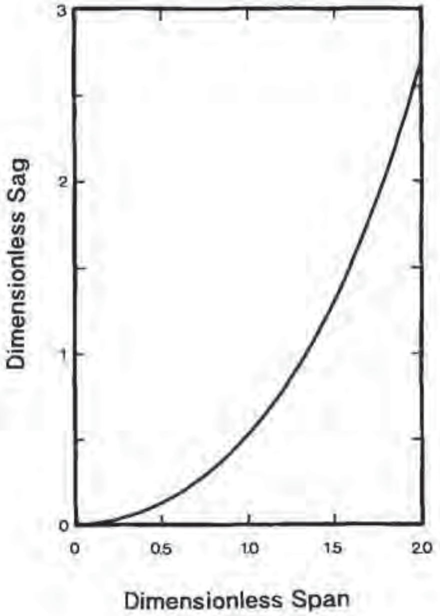

Figure 9.42 Effect of span, as $\rho \cdot y/t_o$, on extent of sag, as $\rho \cdot x/t_o$

known, the tensile strength of the polymer at that amount of sag is obtained from Equation 9.60. The equations are derived for one-dimensional sag. Thermoforming considers planar two-dimensional sag. As a result, Equation 9.59 is written in terms of polymer density, ρ, lb/in^3 or g/cm^3 and tensile strength, t_o, lb$_f$/in^2 or Pa. The relationship is rewritten as:

$$(\rho y/t_o) = \cosh(\rho x/t_o) - 1 \tag{9.62}$$

Since the equation is transcendental, it is best solved graphically. Figure 9.42 shows the relationship between $\rho y/t_o$ and $\rho x/t_o$. Since it is usually the case that the span value, $x = b/2$, is fixed and y, the extent of sag, is measured, Fig. 9.42 is also the relationship between y/x and $(\rho x/t_o)$. Example 9.5 illustrates how these functions are related. Keep in mind that these equations may not yield entirely practical results. For example:

- The arithmetic assumes that the sheet is initially uniform in temperature,
- The arithmetic assumes that the sheet is isothermal during sag,
- The arithmetic assumes that the sheet is only clamped along two edges. Although this approximates sagging conditions in roll-fed thermoforming, this is not the way most sag experiments are conducted [116,117],
- The sheet thickness decreases as the sheet stretches. This means that the sheet weight decreases as the sheet stretches. Although this can be accounted for, it further assumes that the sheet is stretching uniformly,
- The arithmetic assumes elastic deformation of the sheet. As a result, the predicted amount of sag is time-independent,

- The effect of sheet thickness on the extent of sag is not a factor. According to Equation 9.62, the only material parameters are the sheet tensile strength and the polymer density,
- The arithmetic assumes a catenary shape to the sheet, and
- The arithmetic assumes that the sheet simply pivots in the clamp and does not account for any reinforcement by the clamp during sagging.

Example 9.5 Correlation Between Catenary Sag and Hot Strength

A 36-in span of HDPE cannot sag more than 4 inches. Determine its sag if its hot tensile strength is 100 lb_f/in^3, *10* lb_f/in^2, *and 1.0* lb_f/in^2. *Then determine its sag if a sag band is used.*

The density of HDPE is 0.96 $g/cm^3 = 0.0347\ lb/in^3$. Equation 9.62 becomes:

$$y_{\text{deflection}} = \frac{t_o}{0.0347} = \left[\cosh\left(\frac{0.0347 \cdot L}{2 \cdot t_o}\right) - 1\right]$$

The following table obtains:

t_o, lb_f/in^2	$y_{\text{deflection}}$, in L = 36 in	L = 18 in
100	0.056	0.014
10	0.56	0.14
1	5.8	1.4

As seen in Fig. 9.43 [123], isothermal sag is time-dependent. Elongational stretching force is related to elongational viscosity [96]. Elongational viscosity, η_e, is the ratio of applied extensional stress, τ_e, to strain rate or rate of deformation, $\dot{\epsilon}$:

$$\tau_e = \eta_e \dot{\epsilon} \tag{9.63}$$

If the amount of sag increases linearly with time, as shown in Fig. 9.44, the extensional viscosity is constant. If the rate of sag increases with time, the extensional viscosity is decreasing. And if the rate of sag decreases with time, the extensional

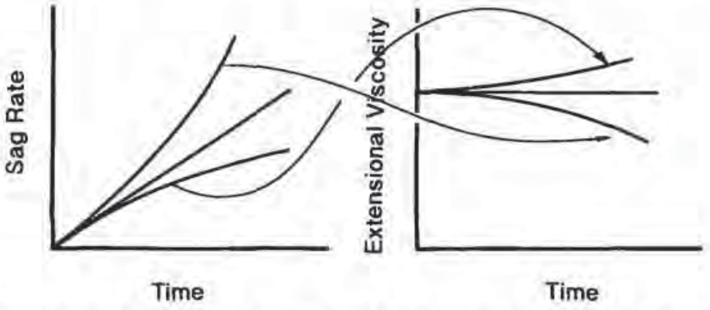

Figure 9.43 Conceptual relationship between time-dependent isothermal sag and time-dependent extensional viscosity for polypropylene, PP

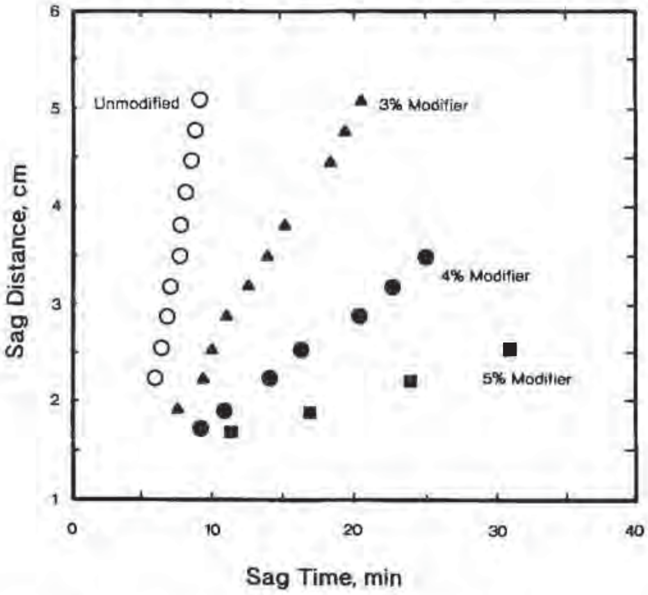

Figure 9.44 Experimental time-dependent sag for polypropylene, PP having various levels of acrylic modifier added. redrawn from [124]

viscosity is increasing. This is seen in schematic in Fig. 9.44 [124]. An extensional strain growth function, M:

$$\tau_e = \tau_{e,o} \exp (M\dot{\varepsilon}t) \tag{9.64}$$

is a measure of strain-hardening or -softening. If $M \geq 1$, the polymer strain-hardens and the rate of sag decreases with time. If $M < 1$, the polymer strain-thins and the rate of sag increases with time. As seen in Fig. 9.45 [125], neat and mineral-filled homopolymer polypropylene show increasing sag rates with time, indicating $M < 1$ or strain softening. On the other hand, the modified PP shows decreasing sag rate, indicating $M > 1$, or strain hardening.

Sag occurs in parison blow molding [126]. Technically, parison sag is not predicted using either an elastic approach using linear creep compliance or elastic modulus [127], or the viscous approach that relates the sag rate to elongational viscosity [128]. As with sag in thermoforming ovens, parison sag is neither a constant stress process nor a constant strain rate process. In other words, the correct material approach is to consider the polymer as a viscoelastic liquid.

Additional tests for formability are given in Chapter 10.

Modified Polypropylenes

As noted above, the addition of fillers does not necessarily change the ability of a crystalline polymer to be thermoformed in the melt state. Filled polypropylene,

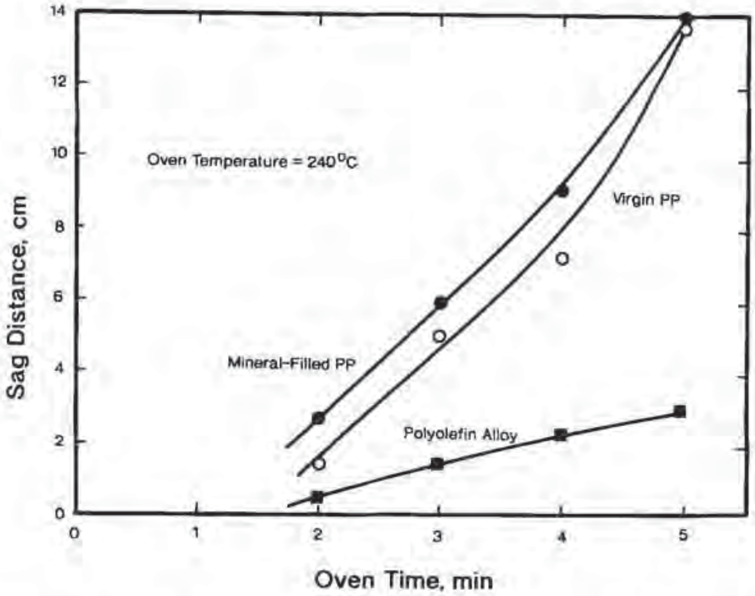

Figure 9.45 Comparison of time-dependent sag characteristics of neat and mineral-filled polypropylene, PP, homopolymer with polyolefin alloy. Redrawn from [125] and used with permission of copyright owner

usually filled with about 20% (wt) talc, has been thermoformed on conventional equipment since the 1970s. The filler adds stiffness to the melt and provides nucleating sites for crystallization as the sheet cools on the mold surface. The finished parts are opaque, have a semi-gloss finish, exhibit lowered impact strength and split resistance, and are difficult to rim roll. Care is required in heating to keep the sheet temperature below about 170°C. These low forming temperatures imply more difficult forming, very short transfer and forming times, shallow draw and a lack of sharp detail in the formed parts. Excessive heating will result in sag characteristics of the unfilled polymer.

The complex morphology and low melt strength of the neat homopolymer combine to cause uncontrollable sagging and to prevent traditional commercial thermoforming. As a result, PP was first commercially formed in the solid state using high air pressure. Currently there are two ways of altering PP to make it melt formable:

- *High molecular weight or high melt strength polypropylene* [129]. Although increasing the molecular weight increases the polymer resistance to tensile load, it also makes traditional extrusion more difficult [118]. Increasing the molecular weight distribution increases the melt strength of the polymer without substantially increasing its viscosity at normal extrusion shear rates [130]. Increasing the dispersity index, a measure of molecular weight distribution, from 5 or 6 to 10 or

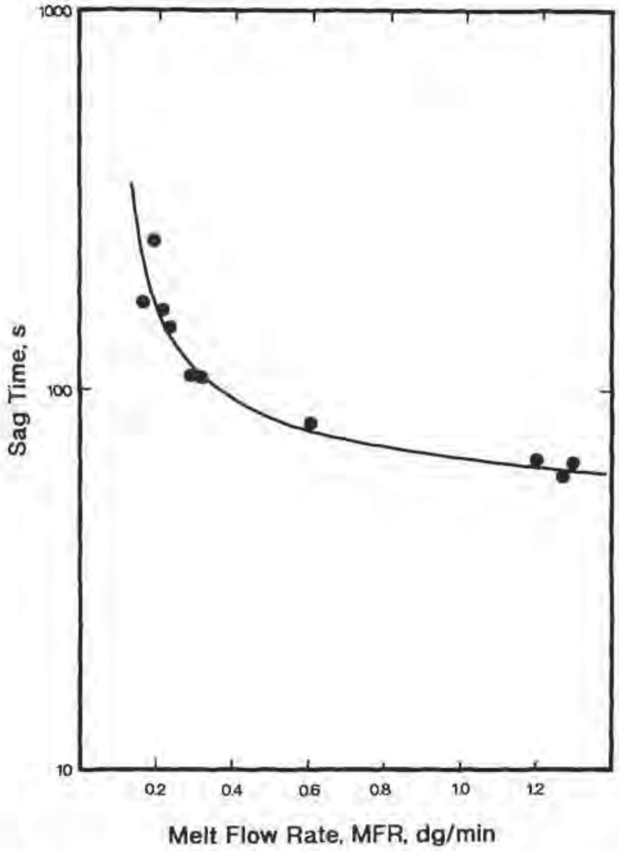

Figure 9.46 Effect of molecular weight, as melt flow rate, MFR, on sag time for polypropylene, PP, homopolymer. Redrawn from [131] and used with permission of copyright owner

more dramatically increases the formability window for PP. Figure 9.46 shows the effects of increased molecular weight or reduced melt flow index on the time required to sag PP a fixed amount [131]. Figure 9.47 shows the effects of increased molecular weight distribution on this same time [132]. The results are asymptotic for both cases. Figure 9.48 shows that increased molecular weight distribution is effective for both homopolymer and copolymer grades of PP [133].

- *Copolymer or modified polypropylene* [117,134,135]. The primary objective of copolymerization is to increase molecular entanglements by altering the polymer backbone stiffness or by adding end-groups or bulky side chain branches. This increases the melt viscosity of the polymer. Acrylic acid graft copolymer to 5% (wt) is one example, as shown in Fig. 9.39. The effect of copolymer concentration on sag resistance is shown in Fig. 9.44 [136]. As another example, a proprietary blend of olefins reduces the extent of sag when compared with homopolymer and mineral-filled homopolymer (Fig. 9.45) [137].

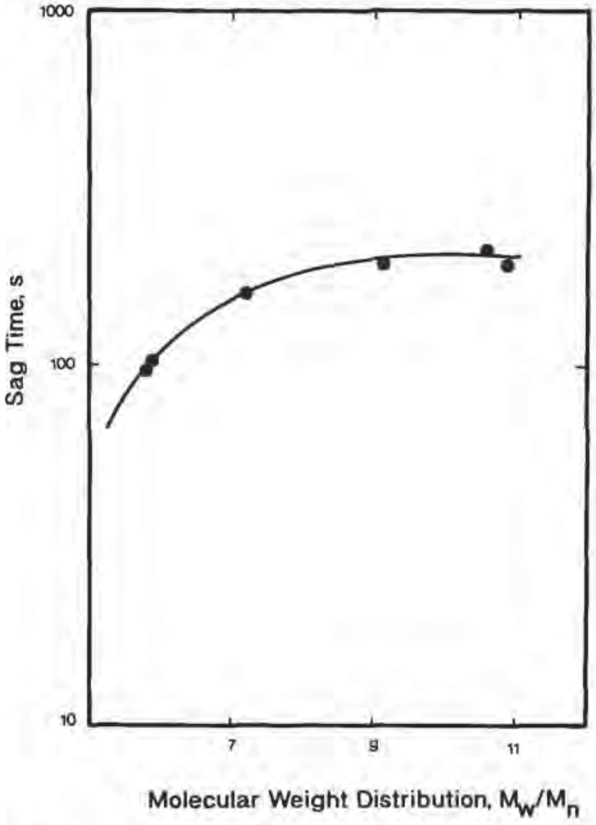

Figure 9.47 Effect of molecular weight distribution on sag time for polypropylene, PP, homopolymer, melt flow rate held constant. Redrawn from [131] and used with permission of copyright owner

Most of the work with modified PP has been with thin-gage sheet, in the thickness range of 20 to 60 mil, 0.020 to 0.060 in or 0.5 to 1.5 mm. As is apparent from Equations 9.59 and 9.62, increased sheet thickness and increased sheet width exacerbates sheet sag. However, work with viscosity-modified PP indicates that most of the formability improvements with thin-gage sheet are translatable to heavy-gage sheet. All of the methods being promoted to improve polypropylene thermoformability add substantial cost, in reduced extrusion rate or increased material cost, to the base polymer. In certain cases [117], some of this cost is recovered in reduced cycle times (Fig. 9.49) [138]. As with any diluent, there is concern that the modifiers may alter the chemical resistance, microwavability, oil resistance, autoclavability, moisture resistance, FDA status, taste and odor acceptability and recyclability of polypropylene. Other information is given in [139,140].

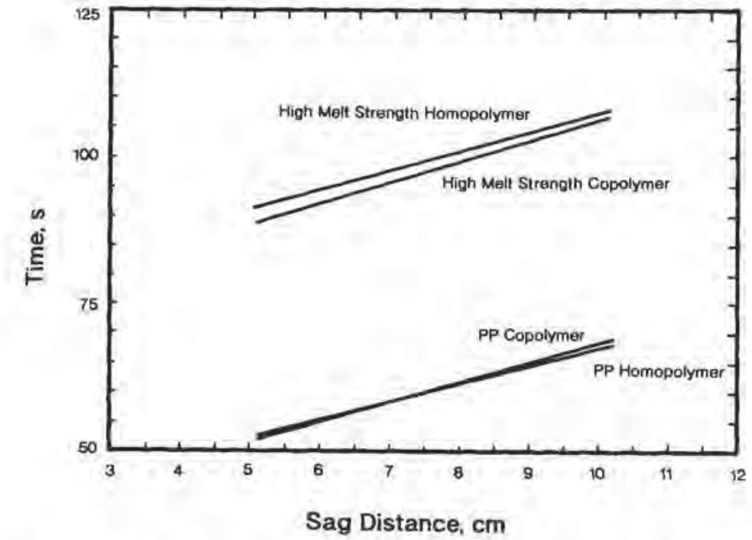

Figure 9.48 Comparison of time-dependent sag distance for traditional polypropylene, PP, and high melt strength polypropylene, PP, for both homopolymer and copolymer grades. Redrawn from [133] and used with permission of copyright owner

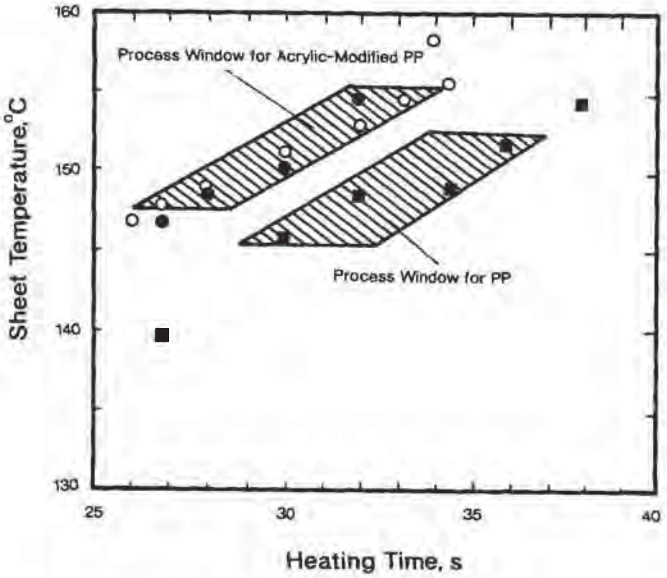

Figure 9.49 Comparison of process windows of neat and acrylic modified polypropylene, PP, homopolymers. Redrawn from [138] and used with permission of copyright owner

9.8 Thermoforming Foam Sheet

Flat low-density foam sheet is produced by mixing polymers with appropriate foaming agents and extruding through special sheet dies. Although polystyrene and polyethylene are the most common polymers processed into foam sheet, other polymers such as polypropylene, styrene-maleic acid or SMA, polyethylene terephthalate or PET and modified polyphenylene oxide or mPPO are also available as foam sheet. The technical details of making fine-celled, dimensionally stable extruded low-density foam sheet are covered in detail elsewhere [141,142]. Polystyrene-based foam sheet is shaped into products such as automotive headliners, disposable meat trays, burger and pizza boxes, egg cartons, hot drink cups and other disposable products. Polyolefin foam sheet is shaped into automotive trunk liners and shaped underlayment for carpeting. US polystyrene low-density foam thermoforming is estimated at 500 Mlb or 225 Mkg, nearly all for packaging and automotive applications [2]. US polyolefin low-density foam thermoforming is estimated at 100 Mlb or 45 Mkg. Much of the discussion will focus on forming polystyrene foam. Forming of polyolefin foams follows the same general concepts.

Cell Architecture—Actual v. Ideal

When pressurized gas-laden melt is extruded through die lips, the rapid drop in melt pressure allows the dissolved gas to come from solution, nucleate and form bubbles. Very early bubble growth is inertia-controlled. That is, bubble growth rate decreases with increasing polymer viscosity. Relatively quickly, bubble growth rate decreases as the polymer melt in the region around the bubble is depleted of gas and the bubble growth becomes diffusion-controlled. For low-density foams, as the bubbles continue to grow, the regions between bubbles thin to form membranes. The final bubble growth stage is controlled by elongational viscosity or melt elasticity of the polymer in the membrane. Foam cell size is affected by nucleant concentration, gas concentration, melt elasticity, and diffusivity of gas in polymer, among other parameters. Typically, foam cells are quite uniform in dimension, as shown in Fig. 9.50. Foams are usually discussed in terms of their architectural elements. Nearly all thermoplastic foams are closed-cell foams. Nearly all thermoplastic foams have membranes that are uniformly thick across their surfaces. And nearly all thermoplastic foams have membrane intersections that are not much thicker than the neighboring membranes. Foam architecture is usually considered as either regular dodecahedrons with five-edged membranes, Fig. 9.51A, or regular tetrakidecahedrons, 14-edged structures having six four-edged membranes and eight six-edged membranes, Fig. 9.51B. Simpler architectural models include three-dimensional cube-in-cube and two-dimensional square-in-square models, Figures 9.51C and 9.51D, respectively [143]. It is apparent from Fig. 9.50 that although real foam cells are relatively uniform in shape, it is only by chance that they achieve one of the several regular architectural models. Figure 9.52 shows the theoretical relationship between polystyrene foam density, cell

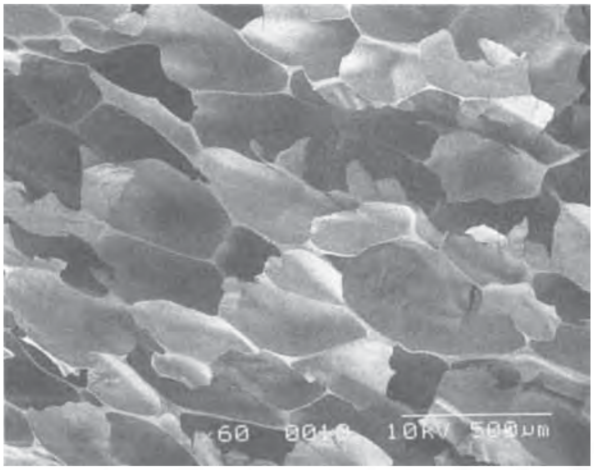

Figure 9.50 Scanning electron micrograph of low-density polystyrene foam. Scale bar is 500 µm or 0.020 in

size and cell wall thickness [145]. Table 9.12 shows other relationships for low-density polystyrene foam. Example 9.6 shows these relationships for a typical polystyrene foam used for meat trays. Note that the thickness of polymer is very small, on the order of 50 µm or so, compared with the thickness of the foam sheet, on the order of 5 mm or so. Even more important, the experimental end-to-end dimension of a randomly coiled 60,000 molecular weight polystyrene molecule is about 1×10^{-6} in or 0.025 µm. For the foam of Example 9.6, the cell wall thickness is 80 microinches

Table 9.12 Cell Architectural Dimensions for Polystyrene [145]

Foam density (lb_f/in^2)	Cell size ($\times 10^{-3}$ in)	Cell wall thickness ($\times 10^{-6}$ in)	Volume percent of solid (%)	Number of cells per ft^3 ($\times 10^9$)	Ratio of cell size to cell wall thickness
16.0	10	974	24.3	1.3	10.3
8.0	20	880	12.1	0.19	22.7
8.0	40	1760	12.1	0.024	22.7
4.0	40	834	6.0	0.025	48.0
2.0	40	400	2.94	0.027	100
2.0	32	320	2.94	0.051	100
2.0	16	160	2.94	0.41	100
2.0	8	80	2.94	3.3	100
2.0	4	40	2.94	26.0	100
2.0	2	20	2.94	210	100
2.0	1	10	2.94	1700	100
1.0	40	190	1.41	0.027	210
0.5	40	87.1	0.651	0.027	459

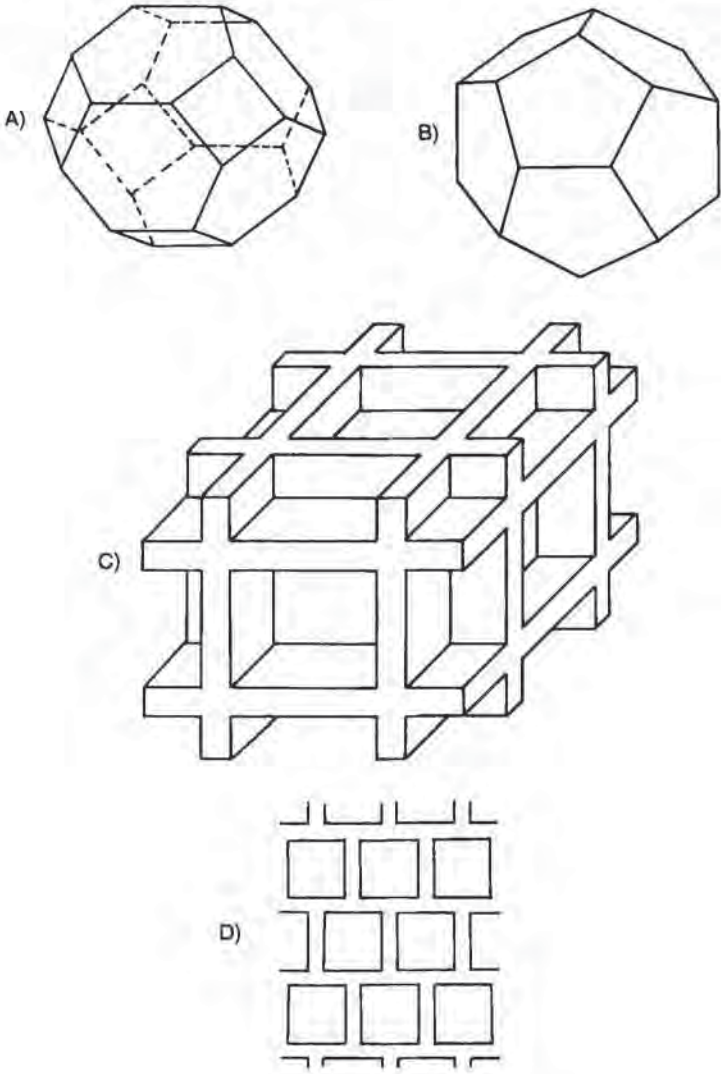

Figure 9.51 Various classical foam architectural shapes

or 2 μm. Thus if the polymer in the cell wall has no orientation, the cell wall is only about 80 molecules thick. Even with substantial orientation, typical cell walls are on the order of a few hundred molecules thick.

Example 9.6 Cell Dimensions for a Meat Tray Polystyrene Foam

Consider a 2 lb/ft^3, 0.200 in thick polystyrene foam used in meat tray applications. If the typical cell dimension is 200 μm, determine the typical cell wall thickness, the number of cells per unit volume, the number of cells in the foam thickness direction, *the thickness of polymer in the sheet thickness direction and the volume fraction of solid.*

The cell dimension is 0.008 in. From Fig. 9.52, the cell wall thickness is 80 microinches or 2 μm. From Table 9.12, the volume of foam contains less than 3% polystyrene. The rest, 97%, is cell gas. There are 3.3×10^9 cells/ft^3. For 0.200 in thick of foam sheet, there are:

$$3.3 \times 10^9 \times \frac{1}{1728} \times 0.200 = 3.8 \times 10^5 \text{ cells/in}^2$$

The number of cells in the sheet thickness direction is given as:

$$\frac{0.200}{0.008} = 25$$

The number of cell membranes is thus $25 + 1 = 26$. The thickness of plastic in the sheet thickness direction is:

$$26 \times 80 \times 10^{-6} = 2.0 \text{ mil, } 0.002 \text{ in or } 50\ \mu\text{m}$$

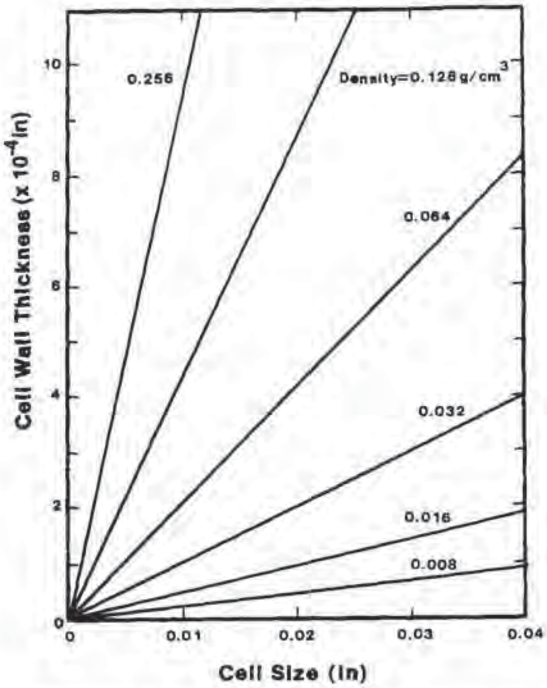

Figure 9.52 Classical relationship between polystyrene, PS foam density, cell size and cell wall thickness. Redrawn from [145] and used with permission of copyright owner

These models are used primarily to predict mechanical and thermal performance of thermoplastic foams. As is shown below, the square-in-square model is used to determine how a foam responds to conduction and radiant energy transmission.

Radiant Energy Transmission

The three primary modes of energy transmission, conduction, convection and radiation, are applied to heating foam sheet. Convection involves energy transfer between the foam sheet and the air in the oven as well as microcirculation of cell gases during heating. As with heating of most plastic sheet, sheet surface convection is considered small when compared with conduction and radiation. Low-density foam is a good thermal insulator or a poor thermal conductor. The thermal conductivity of low-density foam is calculated from:

$$k_{foam} \approx k_g + (2/3)(1 - \phi)k_p \tag{9.65}$$

where k_{foam} is the thermal conductivity of the foam, k_g is the thermal conductivity of the gas, k_p is the thermal conductivity of the polymer and ϕ is the volume fraction of the gas phase. The thermal conductivity of gas is always less than that for the polymer, as seen in Table 9.13. As a result, thermal conductivity of foam decreases with decreasing foam density, as illustrated in Example 9.7. As noted in Chapter 3, on heating the sheet, the material property for transient heat conduction is thermal diffusivity:

$$\alpha_f = k_f/\rho \cdot c_{p,f} \tag{9.66}$$

where ρ is the foam density and $c_{p,f}$ is the heat capacity of the foam. Density-dependent thermal diffusivity values for polystyrene and PVC foams are shown in Fig. 9.53 [146]. The thermal diffusivity for most thermoformable foams is about the same as that for the unfoamed polymer. As noted many times herein, the rate of conduction energy transfer is a function of the Fourier number:

$$Fo = \alpha\theta/L^2 \tag{9.67}$$

The time to heat to a specific forming condition is then proportional to the square of the thickness. Foams cannot be heated efficiently to their forming temperature with conduction alone.

Example 9.7 Effect of Foam Density on Room Temperature Thermal Conductivity

Determine the thermal conductivity of fresh 2 lb/ft³ or 32 kg/m³ polystyrene foam blown with R-11. What is the value if the foam is blown with n-butane? What is the value if the foam is blown with CO_2? What is the value if the foam cells contain only air? What is the value if the foam is 4 lb/ft³ or 64 kg/m³ and the cells contain air?

The thermal conductivity of low-density foam is calculated from:

$$k_{foam} \approx k_g + (2/3)(1 - \phi)k_p$$

From Table 9.13, the volume percent of polymer in 2 $\mathrm{lb/ft^3}$ foam is 2.94%. Thus $\phi = 1 - 0.0294 = 0.9706$. Similarly, ϕ for 4 $\mathrm{lb/ft^3}$ foam is 0.94. The R-value is given as the reciprocal of the British unit thermal conductivity per inch of foam thickness:

$$\text{R-value} = 1/k_{\text{Btu-in}} = 0.1443/k_W$$

From Table 9.13, the thermal conductivities (in W/m · k) of the various gases and the polystyrene are:

Trichlorofluoromethane (R-11)	0.0074
n-Butane	0.0159
Carbon Dioxide	0.0166
Air	0.0260
Polystyrene (PS)	0.16

The calculated thermal conductivities (W/m · K) and R-values for the foams are:

	Foam thermal conductivity [W/m · K]	R-value
2 $\mathrm{lb/ft^3}$ PS/R-11	0.0105	13.7
2 $\mathrm{lb/ft^3}$PS/n-Butane	0.0190	7.6
2 $\mathrm{lb/ft^3/CO_2}$	0.0197	7.3
2 $\mathrm{lb/ft^3}$/Air	0.0291	5.0
4 $\mathrm{lb/ft^3}$ PS/R-11	0.0138	10.5
4 $\mathrm{lb/ft^3}$ PS/n-Butane	0.0223	6.5
4 $\mathrm{lb/ft^3/CO_2}$	0.0230	6.3
4 $\mathrm{lb/ft^3}$/air	0.0324	4.5

Radiation transfer through very thin membranes is the key to efficient and uniform heating of low-density foams. Energy uptake during radiant heating of foams has not been measured. However, extensive studies of radiant energy transmission through foams have been done in conjunction with insulation. For this area, energy transfer is considered in terms of effective thermal conductivities:

$$k_{f,\text{eff}} = k_{\text{cond}} + k_{\text{rad}} + k_{\text{conv}} \tag{9.68}$$

The last two are artificial conductivities. The overall effect of cell gas convection energy transfer is considered small for all but very low density foams having very large cells [149].

There have been many attempts to predict k_{rad}, the artificial effective radiative thermal conductivity [150-154]. The Rosseland approximation solves the general equation for radiation through optically thick media [155]. For low-density foams, the equation is written as:

$$q_r = \frac{4}{3K}\frac{de_b}{dx} \tag{9.69}$$

Table 9.13 Room Temperature Thermal Conductivities of Foaming Agent Gas and Plastic [146,147]

Gas	Thermal conductivity	
	(Btu/ft · h · °F)	(W/m · K)
Air	0.0150	0.0260
Nitrogen	0.0151	0.0261
Carbon dioxide	0.0096	0.0166
Water vapor	0.0103	0.0178
Propane	0.0103	0.0178
n-Butane	0.0092	0.0159
i-Butane	0.0094	0.0163
n-Pentane	0.0078	0.0135
Methanol	0.0117	0.0203
Ethanol	0.0091	0.0157
Dichloromethane (methylene chloride)	0.0070	0.0122
Trichloromethane (chloroform)	0.0070	0.0121
Trichlorofluoromethane (R-11)	0.0043	0.0074
Dichlorodifluoromethane (R-12)	0.0055	0.0095
Dichlorofluoromethane (R-21)	0.0057	0.0099
Chlorodifluoromethane (R-22)	0.0068	0.0118
Trichlorotrifluoroethane (R-113)	0.0065	0.0112
Dichlorotrifluoroethane (R-123)	0.0060	0.0104
Dichlorofluoroethane (R-141b)	0.0058	0.0100
Difluoroethane (R-152a)	0.0054	0.0094
Tetrafluoroethane (R-134a)	0.0081	0.0141
Chlorodifluoroethane (R-142b)	0.0054	0.0094

Plastic	Thermal conductivity	
	(Btu/ft · h · °F)	(W/m · K)
Cellulose acetate (CA)	0.156	0.27
Cellulose acetate butyrate (CAB)	0.179	0.31
Cellulose propionate (CAP)	0.116	0.20
Polyoxymethylene (Acetal or POM)	0.173	0.30
Polycaprolactam (Nylon 6 or PA 6)	0.168	0.29
Polyhexamethylene adipamide (Nylon 66 or PA 66)	0.133	0.23
Polycarbonate (PC)	0.121	0.21
Low-density polyethylene (LDPE)	0.185	0.32
High-Density polyethlene (HDPE)	0.231	0.40
Polymethyl methacrylate (PMMA)	0.104	0.18
Modified polyethylene oxide (mPPO)	0.133	0.23
Polypropylene (PP)	0.127	0.22
Polystyrene (PS)	0.092	0.16
SAN	0.104	0.18
High-impact polystyrene (HIPS)	0.104	0.18
ABS	0.104	0.18
Polyethylene terephthalate (PET)	0.144	0.25
Rigid polyvinyl chloride (RPVC)	0.092	0.16
Polyvinylidene fluoride	0.075	0.13
Polytetrafluoroethylene (PTFE)	0.133	0.23
Fluoroethylene copolymer (FEP)	0.150	0.26

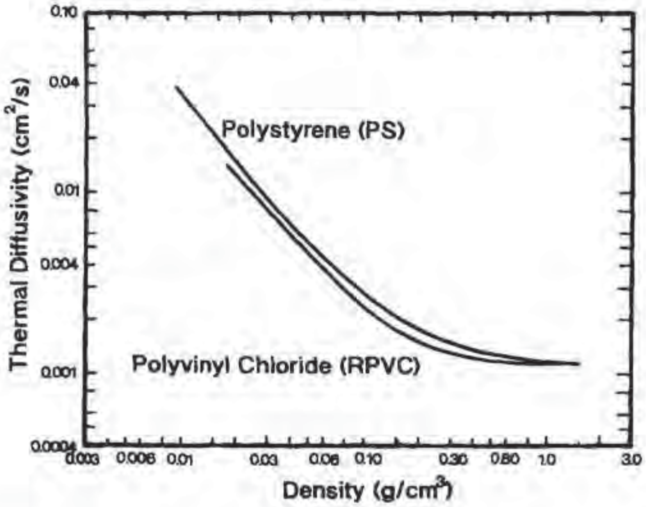

Figure 9.53 Density-dependent thermal diffusivity for polystyrene, PS, and rigid polyvinyl chloride, RPVC, foams. Redrawn from [146] and used with permission of copyright owner

where q_r is the radiant flux into the foam, x is the distance into the foam, K is the extinction coefficient and e_b is the radiative emissive power, given as:

$$e_b = \sigma T_s^4 \tag{9.70}$$

where σ is the Stefan-Boltzmann constant and T_s is temperature of the source, in absolute degrees. With substitution, Equation 9.54 becomes:

$$q_r = \frac{16}{3K}\sigma T_s^3 \frac{dT}{dx} = k_{rad}\frac{dT}{dx} \tag{9.71}$$

When this is combined with the conduction equation, the result is an energy uptake equation for low-density foams:

$$q_t \approx \left[k_g + (2/3)(1-\phi)k_p + \frac{16}{3K}\sigma T_s^3\right]\frac{dT}{dx} \tag{9.72}$$

Measured values of the extinction coefficient, K, range from about 15 cm^{-1} to 45 cm^{-1} [156,157]. Example 9.8 demonstrates that the radiation effect is many times greater than that by conduction. Since the effective radiative conductivity is so great, the energy transmission into the foam is very rapid. As a result, the temperature gradient through radiantly heated low-density foam is on the order of a few degrees, as seen in Fig. 9.54 [158]. This figure also shows that the foam heats in a manner similar to nonwoven matte, indicating that membrane effects such as internal reflections and absorption and reradiation are small.

Example 9.8 Relative Effects of Conduction and Radiation Energy Transmission

Determine the relative values for conduction and radiation conductivities of a 2 lb/ft^3 or 32 kg/^{3} polystyrene foam containing air in the cells. $K = 15\ cm^{-1}$. The heater temperature is 400°F.

The absolute heater temperature is 477 K. σ, the Stefan-Boltzmann constant value, is $0.5674 \times 10^{-10}\ kW/m^2\ K^4$. The value for the effective radiation thermal conductivity is:

$$k_{rad} = \frac{16}{K}\sigma T_s^3 = \frac{16 \cdot 0.5674 \times 10^{-10}}{1.5 \times 10^3} \cdot (477)^3$$

$$k_{rad} = 0.0657\ W/m \cdot K$$

The conduction thermal conductivity of this foam is given in Example 9.7 as:

$$k_{cond} = 0.0291\ W/m \cdot K$$

The total rate of energy transfer through the foam is:

$$k_{total} = 0.0657 + 0.0291 = 0.0948\ W/m \cdot K$$

The total energy transfer is 226% greater than that predicted from simple conduction heat transfer. Radiation accounts for nearly 70% of the total energy transfer.

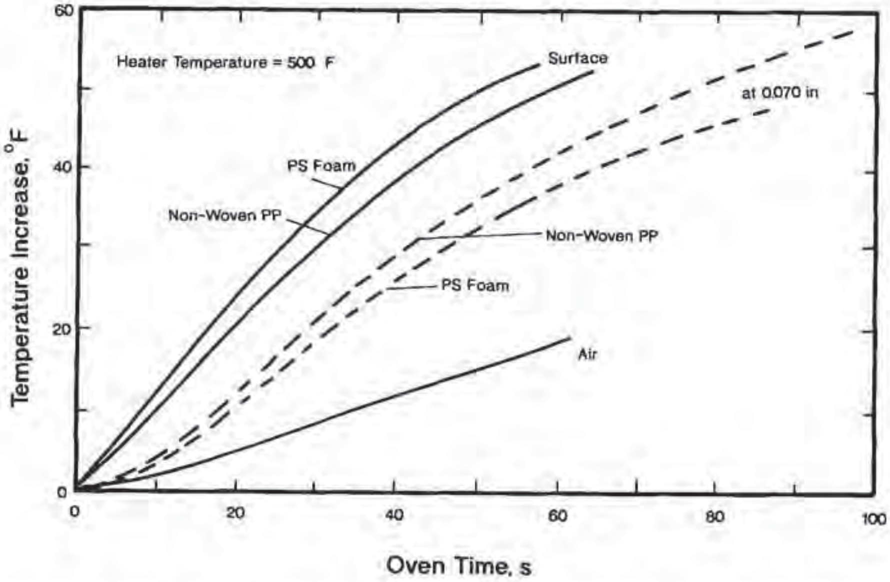

Figure 9.54 Measured time-dependent surface and inner temperatures for polystyrene, PS foam and non-woven polypropylene, PP mat

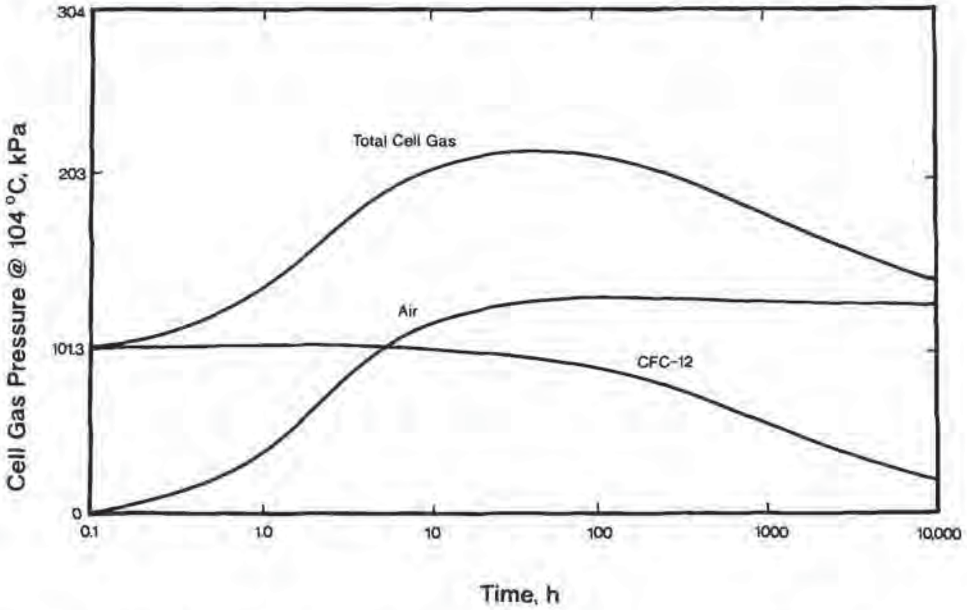

Figure 9.55 Time-dependent internal cell gas pressure showing air pressure, CFC-12 pressure and total cell gas pressure. Redrawn from [159]

Internal Cell Gas Pressure

As gas-laden melt issues from the extruder die, bubbles form and grow and the foam cools until the increasing polymer strength and decreasing gas pressure balance. This is shown in schematic in Fig. 9.55 [159]. At that point, the internal cell gas pressure is slightly greater than one atmosphere absolute. As the foam cools to room temperature, internal cell gas pressure drops to 0.2 to 0.5 atmospheres absolute (Fig. 9.56) [160]. With time, air diffuses into the cells and the foaming gas diffuses out. The rate of foaming gas diffusion depends on its diffusivity. Diffusivity depends on the size of the gas molecule and the type of polymers. For polystyrene, certain classes of gases such as the HCFCs have very low diffusivity values and so remain in the foam for years. Others, such as butane and CO_2, diffuse very quickly. For polyolefins, hydrocarbons and HCFCs diffuse very quickly whereas water vapor does not. Internal cell gas pressure therefore is quite time-dependent in the weeks following extrusion. It is important to know what the initial cell gas pressure is prior to heating since cell gases are rapidly expanded during reheating of the foam for the thermoforming step.

In addition to cell gas pressure, some foaming gas always remains dissolved in the cell walls (Fig. 9.57) [161]. This residual gas affects foam reheating in two ways:

- The glass transition temperature of polystyrene is affected by blowing agents that act as small molecule lubricants. The typical effect is a linear decrease in T_g with blowing agent concentration:

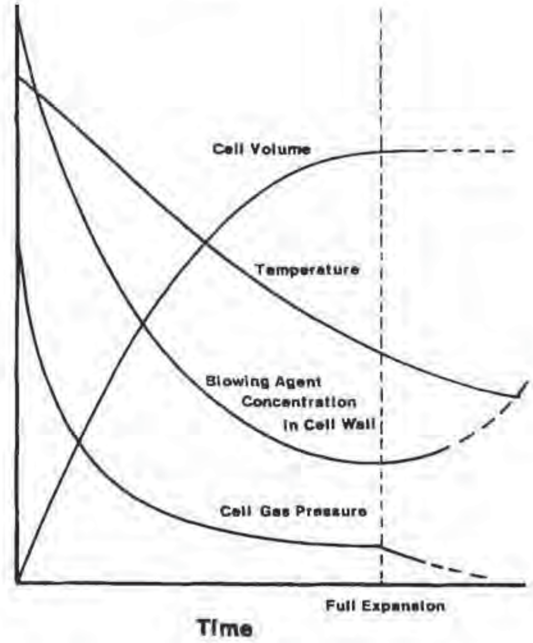

Figure 9.56 Schematic time-dependent foam characteristics. Adapted from [159]

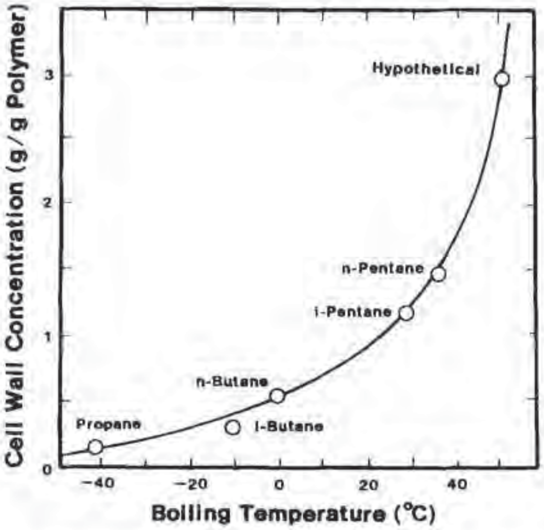

Figure 9.57 Relationship between cell wall concentration and boiling point of foaming agent for polystyrene, PS. Adapted from [159]

$$T_g = T_{g,o} - a \cdot C \tag{9.73}$$

where C is blowing agent concentration (g/g), and a is an empirical coefficient having a range of about 400 to 1000°C. From Fig. 9.57, the residual concentration of n-pentane in polystyrene is 0.017. For $a = 800$, T_g of the foam is 13.5°C below that of the unfoamed polymer. This means that the foam has a lower forming temperature than the unfoamed polymer.

- The blowing agent gas in the cell wall will diffuse into the cell as the foam is reheated. While the partial pressure of this small amount of gas is low, it does contribute to the total cell gas pressure during "secondary foaming" or sheet expansion.

Forming Window for Foam

As foam sheet is heated, the internal cell gas pressure increases and the cell walls soften. Gas pressure at fixed volume is related to absolute temperature as:

$$P/P_o = T/T_o \tag{9.74}$$

where T_o is initial or room temperature and P_o is the cell gas pressure at initial temperature. Example 9.9 demonstrates this effect. Secondary foaming or oven expansion occurs because the polymer cannot resist internal cell gas pressure at the temperature. As seen in Fig. 9.58 for 4 lb/ft^3 or 64 kg/m^3, the experimental expansion ratios lie in a broad band between 1 and 2 over the sheet surface temperature range of 50°C to 120°C [162]. As shown in Example 9.9, variation in room temperature internal cell gas pressure from sample to sample can dramatically affect the temperature where measurable secondary expansion begins. The nature of the heating source also changes the temperature-dependent secondary expansion curve, as seen in Fig. 9.59 [163]. The downward-turning curves indicate that excessive cell collapse or burn is occurring. This is an indication that energy transfer into the foam is strongly dependent on the source temperature, as seen in Equation 9.72. Note also in this figure that secondary expansion is very small with traditional convection oven heat transfer. Since convection energy can only be thermally conducted into the foam, this illustrates the relative importance of radiant heating of foams. The temperature-dependent expansion ratio can be predicted with substantial arithmetic and assumptions. In Fig. 9.60 [164], the predicted value envelope compares favorably with the experimental data.

Example 9.9 Temperature Effect on Cell Gas Pressure

Fresh foam has a room temperature (25°C) cell gas pressure of 0.5 atmospheres absolute. What is the cell gas pressure at 85°C? What is the cell gas pressure at this temperature for aged foam having a cell gas pressure of 1.5 atmosphere absolute at room temperature?

Using Equation 9.59, the fresh foam cell gas pressure at 85°C is:

$$P = 0.5 \cdot (273 + 85)/(273 + 25) = 0.60 \text{ atmospheres absolute}$$

The aged foam cell gas pressure at 85°C is:

$$P = 1.5 \cdot (273 + 85)/(273 + 25) = 1.8 \text{ atmospheres absolute}$$

If the polymer in the aged foam is sufficiently soft at 85°C, the foam will expand. The maximum amount of expansion is given by:

$$P^* v = P_o v_o$$

where P^* is atmospheric pressure, or:

$$v/v_o = P_o/P^* = 1.8/1 = 1.80$$

As seen in Fig. 9.58 [162], the measured expansion ratio is between about 1.25 and 1.6. This implies that the polymer offers some resistance to expansion.

The lower forming temperature for polystyrene foam is the glass transition temperature of the blowing agent-impregnated sheet. The exact value depends on the blowing agent concentration but is probably 10°C to 20°C below the glass transition temperature for the unfoamed polymer. Secondary expansion can occur a few degrees below this temperature if initial internal cell gas pressure is high and the polymer has

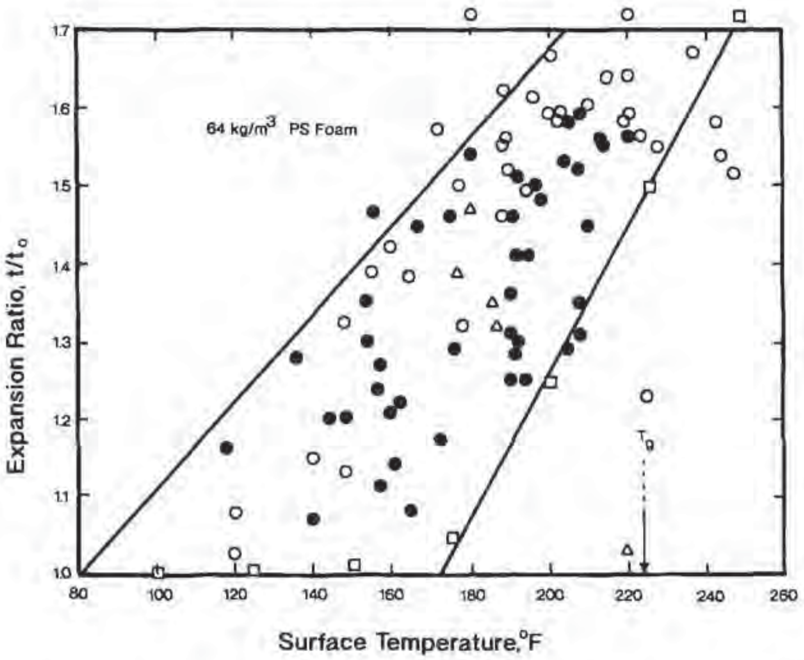

Figure 9.58 Experimental surface temperature-dependent secondary expansion ratio for 4 lb/ft^3 or 64 kg/m^3 polystyrene, PS foam. Open circles are heater temperature = 800°F. Closed circles are heater temperature = 900°F. Open triangles are heater temperature = 1000°F. Open squares are 250°F hot air convection oven temperature. Lines represent 95% confidence limits

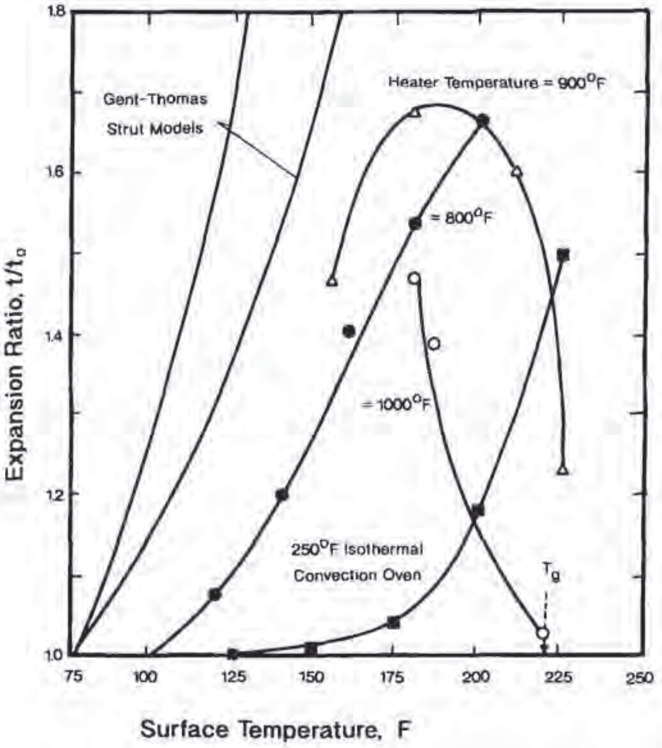

Figure 9.59 Experimental secondary expansion ratio for 4 lb/ft^3 or 64 kg/m^3 polystyrene, PS foam with heater temperature as parameter. Gent-Thomas expansion models represent closed and open celled foam responses [163]

a relatively gradual drop in tensile modulus just below the unfoamed polymer glass transition temperature. The upper forming temperature is the temperature where surface cell collapse or "burn" occurs. As seen in Fig. 9.59, this temperature is greatly dependent on the radiant heater temperature. It appears that at radiant heater temperatures of approximately 260°C, the upper forming temperature is 120°C or so. At radiant heater temperatures of 480°C, the upper forming temperature is 95°C or so. Thus the forming window can range from nearly 0°C to as much as 40°C.

The low value for the upper forming temperature directly affects the drawability of foam sheet. Figure 9.61 [165] shows the very narrow forming range and low values for areal draw ratio for polystyrene foam as compared with those for unfoamed polystyrene. Table 9.14 compares draw ratios for laminated and unlaminated 4 lb/ft^3 or 64 kg/m^3 polystyrene sheet of several thicknesses [166]. Keep in mind that polystyrene is quite brittle near its glass transition temperature. Furthermore, draw-down is restricted by internal cell gas pressure which tends to support the cell walls against deformation. These factors combine with the low forming temperature to limit vacuum-formed foam products in depth of draw and detail. If excessive force is applied, as with plug assist, the sheet will tear.

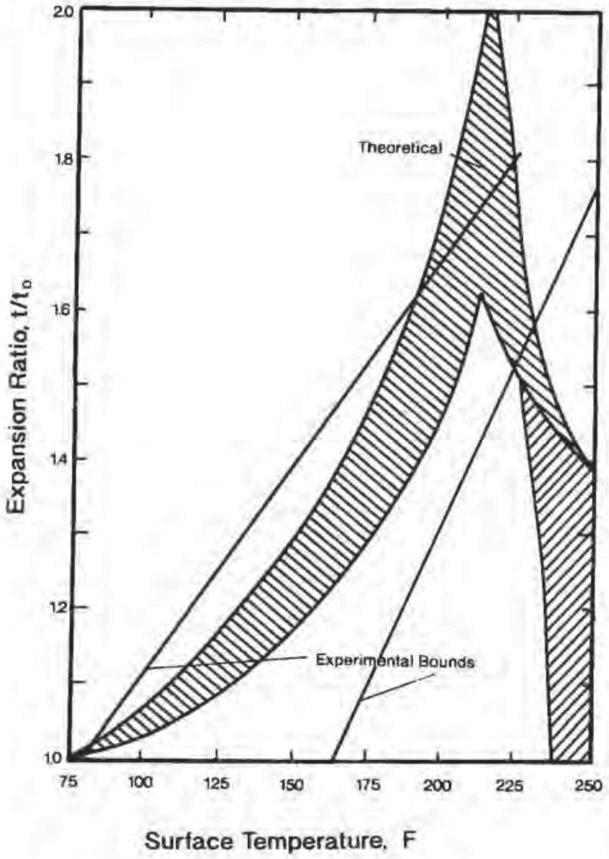

Figure 9.60 Comparison of experimental and theoretical secondary expansion ratios for 4 lb/ft^3 or 64 kg/m^3 polystyrene, PS foam. Shaded area represents heater temperature range of 500°F to 1000°F

Matched die molds are used to achieve deeper draws and finer detail. Typically, the molded part wall thickness is less than the expanded sheet thickness. This allows the foam to compress while stretching. This helps stabilize the stretching process by minimizing cell wall collapse and membrane tearing. This stabilization allows for relatively deep draws. Nevertheless, cell wall rupture is apparent when matched die molding is used. Molding pressures are less than 100 lb_f/in^2 or 0.7 MPa and usually 40 to 50 lb_f/in^2 or 0.28 to 0.34 MPa.

The Forming Equipment

Traditional roll-fed thermoforming equipment is used to form low-density polystyrene foam even though sheet thickness can exceed 0.200 in or 5 mm. Since sheet heating is critical, ovens are designed to handle as many as five shots. This

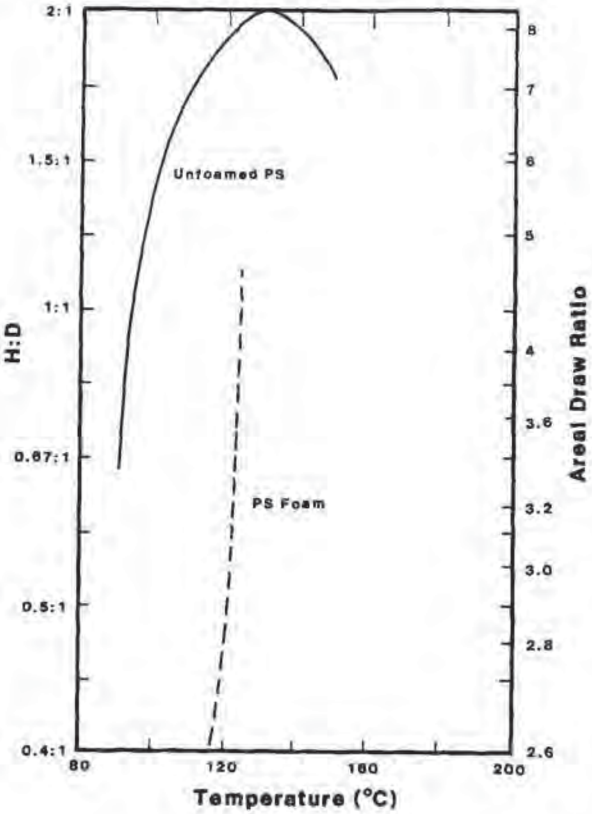

Figure 9.61 Temperature-dependent areal draw ratio or H:D for foamed and unfoamed polystyrene

Table 9.14 Maximum H:D Draw Ratio for Laminated and Unlaminated Polystyrene Foam [166]

(Note: 4 lb/ft³ or 64 kg/m³ polystyrene foam with 0.010 in or 0.25 mm polystyrene sheet lamination)

Thickness of foam		H:D, Unlaminated	H:D, Laminated
(in)	(mm)		
0.010	0.25	0.3:1	0.4:1
0.030	0.76	0.5:1	0.7:1
0.050	1.27	0.7:1	0.9:1
0.080	2.03	0.9:1	1.1:1
0.100	2.54	1.2:1	1.5:1

allows for extended preheating and careful final heating of the sheet to prevent catastrophic cell collapse. Although traditional pin-chains are common, pins that are longer and larger in diameter are sometimes used with thicker sheet. Owing to the relatively low sheet temperatures, there is very little sheet sag although the sheet increases in thickness as discussed above. And the mold clamping section should be more robust in order to handle the weight of the matched dies. Foam sheet is usually not pattern- or zone-heated. As a result, metal rod heaters are sufficient for foam thermoforming. In-press and in-line trimming are common methods of separating the formed parts from the non-product web. Polystyrene foam processing experiences many of the problems encountered with unfoamed polystyrene. If the foam is blown with a volatile hydrocarbon, static charge can be a source of ignition as the sheet exits the extruder. Trim dust and fibers are always quite tenacious. The web is frequently passed through a two-roll nip to densify it prior to shredding or regrinding for recycling.

Since cell collapse is catastrophic, overheated sheet can drop very quickly into the lower heaters. Rapidly opening or withdrawing heater sections are important modifications to any forming press. Shutters have been used over lower heaters. Carbon dioxide is sometimes injected into the heater section in the case of polystyrene foam fire. This polymer generates soot particles that hang in the ambient air and can contaminate product for hours or days after the fire.

A thin sheet of unfoamed polymer is usually hot laminated to foam to improve cut resistance and drawability (Table 9.14). If the laminated sheet or capsheet is sufficiently thick, the sheet, not the foam, dominates the drawing characteristic of the laminate. However, the laminate cannot be overheated without catastrophic cell collapse.

9.9 Other Forming Technologies

The term *thermoforming* correctly encompasses any technology that involves heating and forming of thermoplastic sheet goods. As a result, many processes that are not identified as thermoforming incorporate thermoforming essentials. This section highlights some of these.

Interdigitation

In the 1970s, a technique for mechanically deforming heated thermoplastic sheet was patented [167]. The basic concept involves impaling hot plastic sheet on cold mechanical "fingers". Two aspects of the technique have been commercialized. *Interdigitation*, or the "joining of fingers", produces a three-dimensional honeycomb-like structure by simultaneously impinging digits or fingers perpendicularly in two directions into hot sheet (Fig. 9.62). These interdigitated thermoplastic polymers

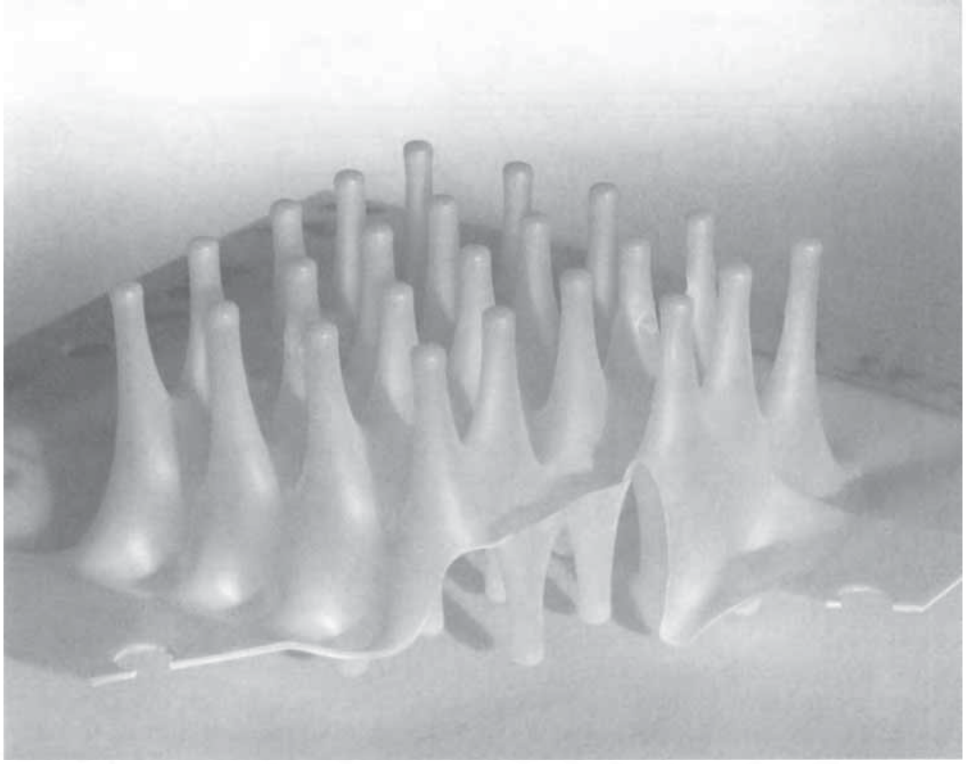

Figure 9.62 Example of interdigitated structure, high-impact polystyrene, HIPS

compete with traditional honeycomb structures, are considerably less costly to produce, but appear to have only about 30% of the crush strength of honeycomb structures of the same density. The primary mode of failure for an interdigitated structure is buckling of the fingers. Thin-gage interdigitated products are produced either on special machines, where the heated sheet is passed at constant rate between two mating double belts that contain the opposing steel fingers as shown in Fig. 9.63, or on conventional jog-stop thermoforming equipment. Heavy-gage interdigitated products are produced on conventional shuttle presses. Applications include carpet underlayment that does not have the wicking and water absorption of foam and core structures for laminated decking and shaped dunnage where strength is needed at low cost.

Mechanical shaping can be combined with traditional thermoforming to produce straight sidewall containers. The technique is called "cuspation-dilation" or "C-D" (Fig. 6.40) [168]. The key is articulation of the plug or finger to form the sidewall ribs and bottom of the container. Vacuum- or pressure-forming can follow to ensure adequate contact of the sheet with the mold surface during cooling, thus minimizing shrinkage effects and maintaining sharpness of detail.

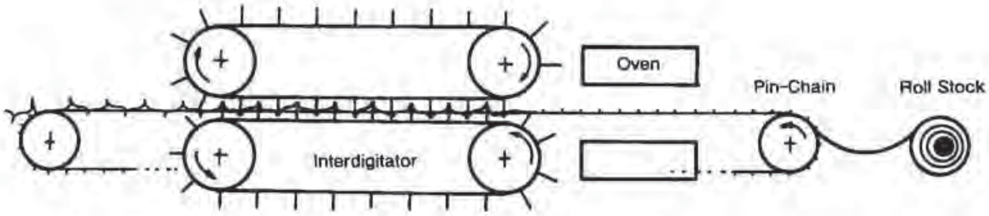

Figure 9.63 Schematic of interdigitation for the production of three-dimensional planar thermoformed structures

Sealed Air Cushion/Dunnage

A thin-gage version of twin sheet thermoforming competes with low-density polyolefin foams in shock mitigating applications. The product is known generically as trapped air wrap, sealed air film or "bubble pack". The last is also a trade name. Four to 8 mil, 0.004 to 0.008 in or 0.1 to 0.2 mm cast or uniform biaxially blown polyethylene film is radiantly heated at a constant throughput rate and formed against a dimpled vacuum roll (Fig. 9.64) [169]. A second film is then heat-sealed against the first. This is done either on the vacuum roll by pressing the second film against the first using a heated mating roll or in a separate in-line step. Air is trapped in the dimples between the two films, thus providing shock mitigation. The energy absorption characteristics depend almost entirely on the compressibility of the air in the dimple. The primary mode of failure is microscopic tearing at the heat sealed edge.

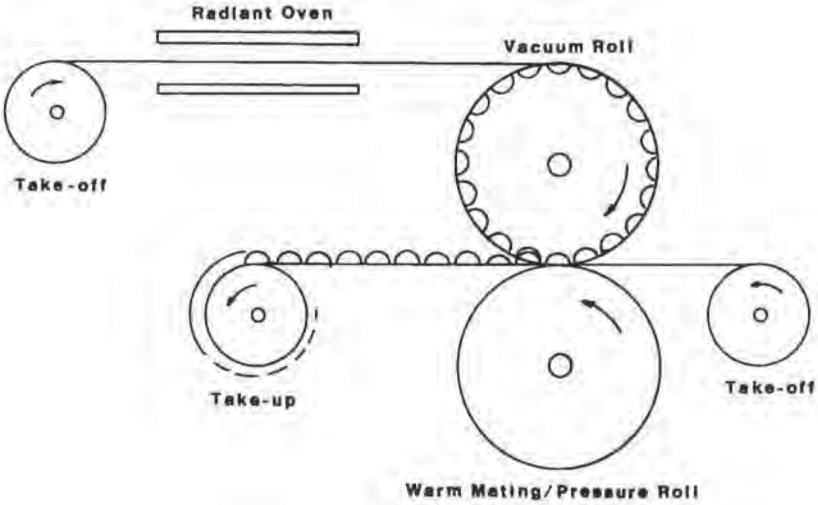

Figure 9.64 Schematic of trapped air wrap for shock mitigation

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10 Set-Up Protocols, Troubleshooting, and the Economics of Thermoforming

10.1 Introduction
10.2 Setting Up a Thermoforming Machine—Protocols
  A New Polymer
  Setting Up a New Mold
  Setting the Mold Stops
  Dry-Cycling the Mold
  Checking the Vacuum
  Attaching Cooling to the Mold
  The Sheet Delivery System
  Setting the Oven Conditions
  Forming Step—Simple Vacuum Forming
  Changing Temperature Conditions
  Activating the Assists
  Pressure Boxes
  General Objectives
10.3 Troubleshooting the Forming Process
10.4 Energy and Materials Cost
  The Energy Audit
  Cost of Extrusion
  Cost of Regrind
  Competitive Costs of Polymers
10.5 General Processing Economics
  Rules of Thumb
  Global Production Costs
  Manufacturing Efficiencies
  The Learning Curve
10.6 Isolated Venture Costs
10.7 New Venture Economics
  Entrepreneurial Risks
10.8 The Incremental Operation
10.9 Comparative Process Economics
10.10 References

10.1 Introduction

The business of thermoforming depends on several fundamental concepts. Modern machines are designed to produce parts, repetitively, day in and day out, with relatively little maintenance or attention. Businesses require that these machines make money. Profitable businesses require that the machine make quality parts that can be sold at values greater than their total manufacturing costs. Profit is the expected return on investment for taking the risk of being in business. The keys to business success are quality and accountability. To make products from sheet, the interaction of the sheet with the process parameters should be thoroughly understood. The quality of the product depends on:

- The skill of the operator,
- The selection of quality raw materials, and
- An adequate quality control of all incoming and outgoing materials.

This is shown in schematic in Fig. 10.1. Since energy consumption is an important factor in thermoforming, energy audits are necessary, as shown in Fig. 10.2. Money, as cash flow, is also treated in this fashion in Fig. 10.3.

In previous chapters, the technical and marketing aspects of thermoforming have been analyzed in detail. In this chapter, the focus is on the business aspects of thermoforming. Good finished parts cannot be made from imperfect sheet material. Incoming materials quality and the condition of regrind materials for reprocessing into additional sheet require management awareness and dedication. In order to become and remain competitive, an understanding of current processing practices in other, non-thermoforming areas such as extrusion, calendering, milling and casting, must be understood. This understanding allows the thermoformer to establish meaningful quality standards for his/her products. Accountability has become immeasurably easier with the successful development of small, inexpensive computers

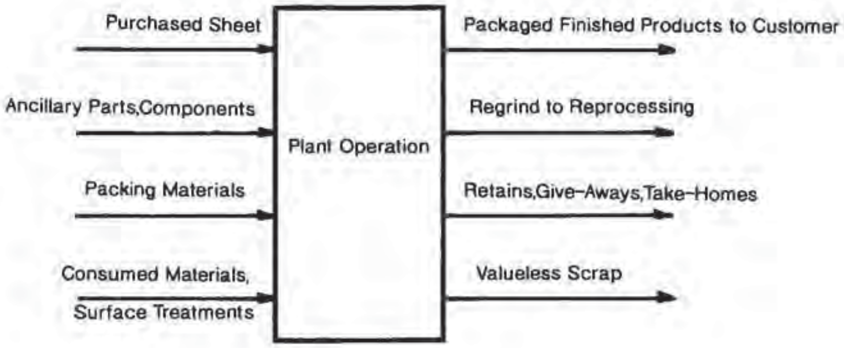

Figure 10.1 Steady-state material balance in thermoforming

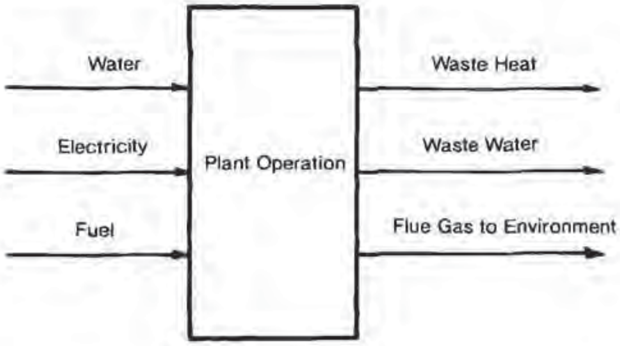

Figure 10.2 Steady-state energy balance in thermoforming

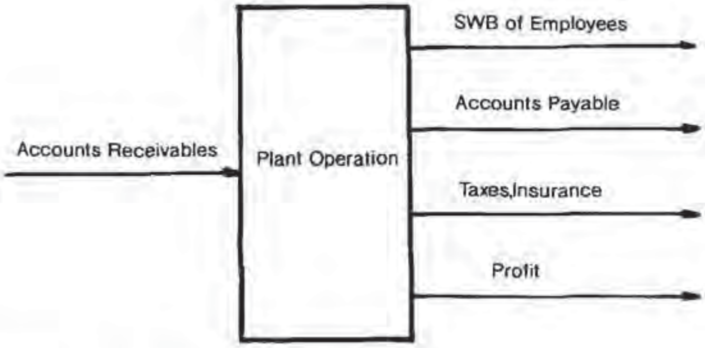

Figure 10.3 Steady-state cash flow in thermoforming

and attendant accounting and storage software. Even the smallest business now has the capability of keeping detailed records on:

- Payroll,
- Incoming materials inventory,
- Outgoing materials inventory,
- Work in progress,
- Regrind,
- Accounts receivables,
- Accounts payables, and
- Many other accounting techniques [1].

The rapid development of barcoding[1] has opened new opportunities for keeping track of things such as:

- Incoming materials, including delivery dates, warehouse location, and any receivable materials tests,
- Outgoing product, including day and time of production, machine, shift, operator(s), storage location and all inspection information,
- All work in progress and all rework, including reasons for delays and reasons for reworking,
- All regrind, whether rolled web or reground cut-sheet chip,
- All molds, including original manufacturing date, reworking dates, total production information, storage procedures, and warehouse location,
- All incoming machinery spare parts and warehouse locations.

Despite these aids, the thermoform business person must still have a basic understanding of the various elements of his/her specific business that make up cash balances and annual operating costs. The thermoform business person is usually concerned with at least one of three general categories of business:

- *Existing business*, where the costs required to produce a product are similar to the already-known costs to produce a similar product. Existing product business is usually considered as fitting into an on-going thermoforming effort whose costs are essentially time-independent or steady-state,
- *Isolated new business*, where a new business is begun in a location that is remote from the current business area and/or where the existing business is not thermoforming. Classic examples of isolated new business ventures include:
  - Manufacture of thermoformed parts that replace nonthermoformed products such as sheet metal or fiber-glass-reinforced thermosets with thermoformed products, and
  - Incorporation of thermoforming as part of a forward- or backward integration, such as adding thermoforming containers to a manufacturing operation or thermoforming an assembly component that was previously purchased, and
- *Incremental business*, where a new product line is added to an existing business. The incremental venture combines certain aspects of steady-state production costs and new venture costs.

The isolated new business venture requires the most analysis, since not only is the value of the product initially unknown, but long-term effects of energy costs, money

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[1] PC-based software enables customized barcodes to be created and printed directly on PSA-backed labels. This allows any size company to create its own data-logging scheme using barcodes and laser scanners. Some suppliers are:
Bear Rock Technologies, 4140 Mother Lode Dr., Suite 100, Shingle Springs CA 95682, 916-672-0244
River City Grafix, 11765 West Avenue, Suite 321, San Antonio TX 78216, 210-496-5109
Riversedge, 10902 Forest Summit, San Antonio TX, 78233, 210-590-9528
T.A.L. Enterprises, 2022 Wallace St., Philadelphia PA 19130, 215-763-5096.

Table 10.1 Nature of the New Thermoforming Product on Business Structure

Nature of the new product/business	Existing	Incremental	Isolated new venture
Nature of business	Existing	New product on existing business	New
Effect on general operation	None, steady state	Existing, expansion	New expansion
Effect on equipment	None	New or modification	New
Effect on site	None	Existing expansion	New expansion
Effect on labor	None	Expansion	New hires
Effect on sales/service	None	Expansion, retraining	New hires
Effect on management	None	None	New, training
Effect on R&D	Little	Moderate	Significant
Effect on facilities	None	Expansion	New, ground-up
Nature of polymers	New or well-known	New	New
Debugging of			
Machine	None	Some	Significant
Polymers	Some	Some	Significant
Facilities	None	Moderate	Significant
Molds	Moderate	Moderate	Significant
Debugging time	Immediate to week	Week to month	Months to year
Start-up costs	None to slight	Moderate	Significant
Accuracy of cost analysis	±5%	±15%	±25% or more

costs and inflation are also unknown. Isolated ventures require careful analysis of competitive processes as well. For these reasons, major emphasis is placed on understanding the elements of the isolated venture.

Some important elements of each of these business strategies are given in Table 10.1.

Businesses also depend on the ability to convert new ideas to income in minimum time at minimum cost. Most of the early discussion focused on the technical aspects of how plastic sheet responds to its environment. However, there are many times when theory and sound reasoning must be replaced with traditional check-lists accumulated through hands-on experience. Two general "fix-it" sections are included here:

- Setting up the thermoforming system with a new polymer and/or a new mold, and
- Finding out why the product is not forming correctly.

Many quality control tests have been discussed throughout the technical sections of this book. Some of these are summarized in this chapter as well.

10.2 Setting Up a Thermoforming Machine—Protocols

There are many occasions when it is necessary to rapidly spiral in on operating conditions for a new plastic or a new mold. Certain protocols are possible to help speed this process[1].

A New Polymer

The most important first step when considering thermoforming a new polymer is to collect as much information about the polymer as possible. This is true whether the sheet is cut heavy-gage for shuttle or rotary presses or is thin-gage for roll-fed operations. For example, the morphological nature of the polymer is needed:

- A polymer that is *amorphous* has no melting temperature. Typically, amorphous polymers such as styrenics, vinyls, acrylics, amorphous polyesters and polycarbonates have similar forming characteristics:
  - The polymer softens over a wide temperature range,
  - The polymer generally has good to excellent melt strength,
  - The polymer usually has controllable sag, and in some cases, no sag at all, and
  - The polymer has a wide forming window.
- *Crystalline* polymers have finite melting temperature ranges. Some melt over a relatively broad temperature range usually greater than 10°C. Low-density polyethylene is an example. Others melt over a very narrow temperature range usually less than 1°C. Nylon 66 or PA 66 is an example. Others, such as polypropylene and high-density polyethylene, have melting temperatures in the 1 to 10°C range. Crystalline polymers have similar forming characteristics:
  - The polymer softens and melts over a narrow temperature range,
  - The polymer may exhibit excessive sag and poor melt strength,
  - The polymer may exhibit high shrink and warping characteristics, and
  - The polymer usually has a narrow forming window.

In addition to general forming characteristics, certain polymers may exhibit other undesirable characteristics such as:

- Color change, particularly yellowing. PVC and PET are polymers that show this tendency,
- Loss in molecular weight with the resulting loss in physical properties. PET, PVC and PA 6 are polymers that show this tendency,
- Outgassing, odor and excessive smoke. ABS, PVC and mPPO are polymers that show these tendencies, and
- Loss of embossing or surface gloss. ABS and RPVC are polymers that show these tendencies.

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[1] Portions of this section are abstracted from notes provided by Don Carroll, Consultant, with permission [2].

Filled and reinforced polymers offer additional general characteristics that must be addressed prior to thermoforming. For example:

- Filled polymers usually require higher forming pressures but the forming temperature usually is restricted by the forming temperature of the neat polymer. Excessive sag occurs if the filled polymer temperature is raised substantially above that for forming the neat polymer,
- Reinforced polymers usually require higher forming pressures and probably matched dies for molding. The forming temperature is usually substantially higher than the forming temperature for the neat matrix. The fiber reinforcement keeps the sheet from sagging substantially even at very high sheet temperatures.
- Colorants and pigments may change the way in which the polymer absorbs radiant energy. Typically, polymers colored with metallic oxide pigments and carbon will heat much more rapidly than the natural polymers. Even though the forming window is not dramatically changed by pigmenting, the time to achieve the forming window is.

Some of the inherent forming characteristics of a polymer can be deduced by observing how the homologous series of polymers form. For example, the forming window for a new impact polystyrene is not expected to be substantially different than the forming window for other, well-known impact polystyrenes. The same is true for polyethylenes and cellulosics. On the other hand, not all polyvinyl chlorides form the same. Polyvinyl chloride formability depends on the adducts that are compounded into the polyvinyl chloride resin. Certain adducts improve the extrusion characteristics but are detrimental to the thermoforming hot strength. Other adducts improve the forming range but shorten the high-temperature exposure time.

In addition to the general characteristics of the polymer, information regarding the polymer mechanical properties should be obtained. Information that is useful to the designer includes:

- Impact strength, including
  Notched and
  Drop weight,
- Heat distortion temperature,
- Continuous service temperature,
- Coefficient of linear expansion,
- Shrinkage,
- Thermal conductivity and thermal diffusivity, and
- Chemical resistance.

No new polymer can be offered to the thermoformer without having been extruded. For initial trials, only virgin sheet is used, unless the customer requires 100% regrind only. The first-hand knowledge of the extruder in dealing with extrusion aspects of the polymer is important in determining proper handling protocol. The extruder should be able to provide the thermoformer with the following information:

- Sheet preparation conditions, including drying, storage, and unusual sheet orientation problems,

- Unusual sag conditions,
- Extrusion time and temperature conditions,
- Unusual handling conditions, such as splittiness or brittleness,
- Potential maximum regrind level, and
- Safety precautions, including obnoxious gases or odors, discoloration, and the like.

Concern about the sheet quality is usually less critical with prototype set-up operations than with manufacturing operations. Nevertheless, the extruder and thermoformer should agree on acceptable standards for the initial prototyping, process and product trials. Standards should include:

- Gage, width and length dimensional tolerances,
- Sheet flatness and squareness,
- Sheet orientation, across the sheet, in the sheet direction, sheet to sheet and pallet to pallet (or roll to roll),
- General appearance including surface defects and moisture level,
- The nature of the trimming and whether dust or slivers are apparent, and
- Molecular weight or IV for PET, melt index for polyethylenes and melt flow rate for polypropylenes.

Then some simple tests are needed. Sheet orientation should be checked on several sheets.

The orientation of the sheet is determined with the test described in Section 8.11 [4]. The formability of the sheet and its forming range are determined with the funnel test described in Appendix 7.I. The technique is used in the following way:

- A heating protocol is defined. One such protocol is given in [3]. This protocol is used throughout the test.
- Sheet is heated to a fixed temperature, then formed into a 60° metal funnel.
- The formed cone is removed and the thickness of the bottom center of the shape is measured.
- The process is repeated at a slightly higher sheet temperature, say, 5°C.
- As noted in Chapter 7, the local thickness ratio is the reciprocal of the local areal draw ratio. The temperature-dependent formability of the sheet can be easily determined, as shown in Fig. 10.4 for PVC.

The equipment needed for this technique is very inexpensive. A 4-in to 6-in diameter metal funnel can be obtained at any feed store. A toaster oven will suffice for the heating source and a shop vacuum system will work for the vacuum source. The funnel is connected to the vacuum system with a section of heavy rubber hose. The sheet is clamped in a simple book mold using vise grips.

Another test uses the draw-down into a two-dimensional radius as a measure of the formability. As noted in Chapter 7, the relationship between local sheet thickness and drawn radius is:

$$\left(\frac{h}{h_o}\right) = \left(\frac{R}{R_o}\right)^{4/\pi - 1} = \left(\frac{R}{R_o}\right)^{0.273} \tag{10.1}$$

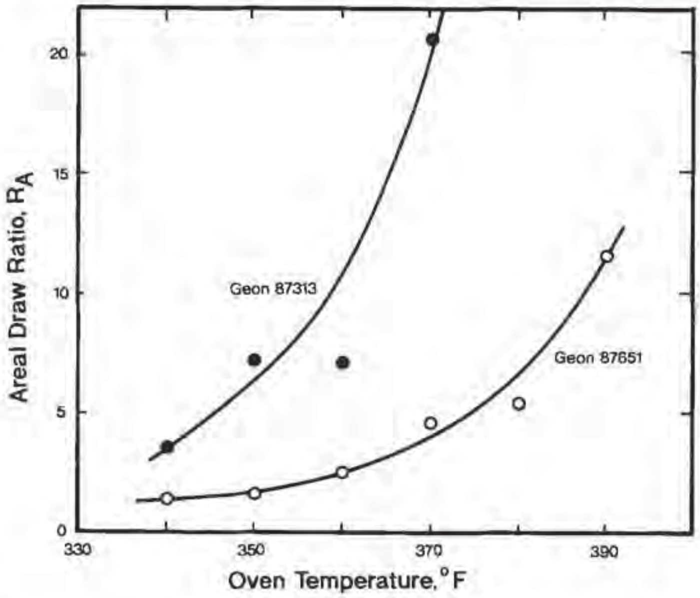

Figure 10.4 Temperature-dependent maximum areal draw ratio for two types of polyvinyl chloride, PVC. Data obtained using 60° cone

Figure 10.5 shows the relationship between R/h_o and sheet temperature. The temperature-dependency of h/h_o is obtained from Equation 10.1.

The circle-grid technique is used in many ways. For example, it is routinely used in trouble-shooting to determine whether zonal heaters are functioning properly. It is also helpful in determining the relative effect of plugs and billow prestretching on material reallocation[1]. The technique is very simple. The sheet surface is scribed with a standard cross-hatch of, say, 1 in or 25 mm squares. A circle is drawn at the axis of each set of crossing lines (Fig. 10.6). After forming, the circles are examined and measured, as follows:

- If the final shape is still a circle, the local areal draw ratio is:

$$R_a = \frac{A_f}{A_o} = \left(\frac{R_f}{R_i}\right)^2 \tag{10.2}$$

---

[1] The standard method of applying the circle-grid pattern to the sheet is to use indelible ink. A rubber stamp is useful for small parts. A silk screen is used for larger surfaces. For trouble-shooting, the entire surface does not need to be circle-gridded. Frequently, a template is placed over the critical area through which the pattern is marked. This technique must be used with care when the sheet is very thin or is transparent. High carbon- or iron-content ink will preferentially absorb radiant energy, leading to sheet wrinkling and questionable localized drawing. Dye-based inks are more acceptable.

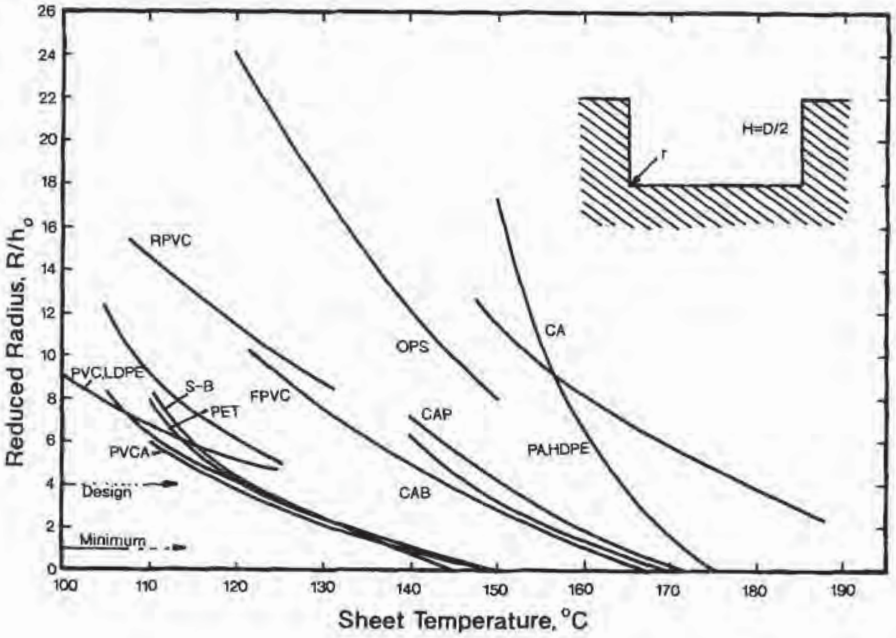

Figure 10.5 Temperature-dependent corner radius for several polymers

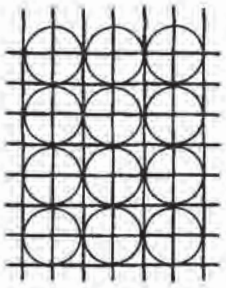

Figure 10.6 Circle-grid pattern for stretching characteristics of thermoformed shapes

The local thickness ratio is again the reciprocal of the areal draw ratio:

$$\frac{h_f}{h_o} = \left(\frac{R_o}{R_f}\right)^2 \tag{10.3}$$

More importantly, the sheet has been *uniformly biaxially oriented* in the local area.

- If the final shape is an ellipse, Fig. 10.8, the local areal draw ratio is:

$$\frac{R_a}{R_o} = \frac{A_f}{A_o} = \left(\frac{ab}{R^2}\right) \tag{10.4}$$

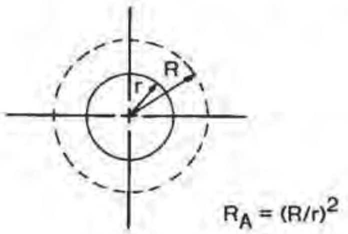

Figure 10.7 Uniform biaxial stretching with circle-grid pattern

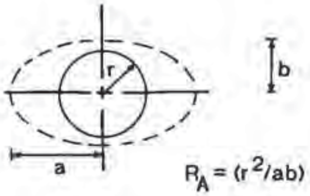

Figure 10.8 Nonuniform biaxial or uniaxial stretching with circle-grid pattern

where a is the major half-axis and b is the minor half-axis of the ellipse. The local thickness ratio is the reciprocal of this local areal draw ratio. The sheet has been *nonuniformly biaxially oriented* in the local area.

- If the final shape is an ellipse where b, the minor half-axis, equals the initial radius, R, the local areal draw ratio is:

$$\frac{R_f}{R_o} = \frac{A_f}{A_o} = \left(\frac{a}{R}\right) \tag{10.5}$$

  The sheet has been *uniaxially oriented* in the local area.
- If the final shape is tear-drop in shape, Fig. 10.9, no inference can be drawn about the local extent of orientation. It is suggested that the test be rerun using smaller circles in this area.

If the polymer is found to be satisfactory for the application, the thermoformer and extruder must negotiate the standards and guidelines for production quality sheet product. The correct procedure for this negotiation is described in Chapter 8.

Setting Up a New Mold

The thermoformer should work with the mold maker throughout the manufacture of the mold to ensure that the mold meets the required specifications. A typical checklist is given as Table 10.2. Any standard checklist should include:

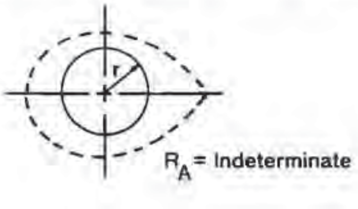

Figure 10.9 Tear-drop or nonuniform elongation with circle-grid pattern

Table 10.2 Setting up a Thermoformer—The Check List

Prior to the Mold Leaving the Mold Maker

- Check surface texture, polish
- Look for oil, grease leaks
- Check all mechanical actions
    - Cams
    - Slides
    - Hinges
    - Plugs
- Review aspects of coolant lines
    - Proper layout
    - Chip-free
- Check vacuum lines
    - Chip-free
- Check vacuum holes
    - All open
- Dry-cycle mold action
- Pressurize coolant lines
- If possible:
    - Place rubber sheet over mold cavity
    - Apply vacuum and observe draw-down

Put Mold on Platen

- Center
- Align
- Level
- Set stops
- Set platen movement rate
    - Check platen velocity
- Realign at top of stop
- Relevel at top of stop
- Dry-cycle mold on platen
- Align and time each ancillary element
- Install vacuum line
    - Smooth interior line
    - Minimum number of L's and T's
- Test vacuum seal
    - Place gasketed metal plate with pressure gage, petcock over cavity
    - Measure rate of evacuation
- Test the vacuum hole configuration
    - LDPE film or rubber sheet over mold cavity
    - Measure rate of evacuation
- Install coolant hoses
    - Manifolds
    - Insulate hoses
    - Use oversize quick-disconnects
- Apply coolant to mold
    - 10–20°F below HDT of polymer
    - Allow steady-state, hour(s)
    - Check for leaks
- Check mold temperature
    - Surface thermocouple
    - Infrared probe
    - Thermography
- Look for regions of differential temperature
    - Slides
    - Hinges
    - Plugs
    - Ribs, bosses, gussets
- Recheck platen/mold level
- Dry-cycle hot mold
    - Check all alignments
    - Check for metal-to-metal interference, binding
    - Remachine rather than lubricate

Set Sheet Delivery System

- Coordinate/time sheet delivery with mold dry-cycle
- Set sheet delivery sequence first, then set load/unload sequence

Set Oven Conditions

- Set top heater bank to fixed, constant temperature across all heaters
- Wait for steady-state heater cycling—minutes
- Measure individual heater temperature
    - Thermocouple
    - Infrared
    - Thermography
- Shut off top heater bank, allow to cool
- Repeat with bottom heater bank
- Clean, reposition photo-eye for sag limit
- Adjust lower over to accomodate expected sheet sag
- Clean, reposition in-oven infrared
    - Calibrate infrared if possible
    - Check, clean air/water coolant to infrared detector

Reset Safeguards

- Close all mechanical, light beam gates
- Secure all pinch-point protectors
- Secure all hot zone protectors
- Position required fire equipment
- Check emergenecy fire equipment
- Check and set in-operation warning lights

Set the Forming Process—Simple Vacuum Forming

- Circle-grid several sheets
- Begin with mold, oven at fixed temperature
    - Placed ungridded sheet in rail, clamp
    - Move into oven
    - Observe time-dependent sag, surface texture

(Continued)

Table 10.2 (Continued)

  - Observe time-dependent temperature, color, smoke, odor
  - Remove from oven when sag, temperature indicates sheet is formable
  - Allow sheet to cool without forming
  - Measure sheet time-dependent temperature as sheet cools in ambient air
  - Repeat with circle-gridded sheet
  - Look for abnormal orientation during heating, cooling
- Repeat with circle-gridded sheet but now engage mold action without ancillary elements
  - Check to see if sheet covers mold periphery
  - Watch drape into mold to observe initial contact points
- Repeat but now apply vacuum
  - Observe the nature of draw-down, particularly around male portions of female mold
  - Measure temperature of free surface if possible

Set Forming process Temperature
- Repeat but now adjust temperature zones to achieve better stretch profile
- Continue temperature zone adjustment until it appears that no additional benefit can be obtained.

Setting Forming Process Assists
- If billow prestretching is to be used—
  - Use circle-gridded sheet to initially stretch without molding
  - Check extent of stretch to see if sheet forms aneurysm, blow-out
  - Change zonal temperature profile to accomodate prestretching
- If plug assist is to be used—
  - Make certain that every other means of material reallocation has been tried first
  - Activate plug slowly at first to ensure stretching is occurring where it is needed
  - Measure final part wall thickness to ensure sheet is stretching correctly
  - Measure sheet temperature to ensure sheet is at proper temperature
  - Examine final part to ensure sheet is not against mold or plug surface during stretching
- If pressure forming is to be used—
  - Make certain that all other molding aspects— temperature, prestretching, mold element actuation—are completely understood and functional before using pressure box

- Mold surface texture and/or polish. This is most important if the polymer is crystalline, if the part is transparent or is used as an optical part, or if the part is to be pressure-formed. Any imperfection, including machining and polishing marks, burrs, dents or local deglossed areas may make the product unacceptable.
- Mechanical action. Cams, ejection mechanisms, slides, hinged areas, and plug assists, if part of the mold design, should work flawlessly *while on the mold maker's work table*. The thermoformer may wish to "dry cycle" these mechanical devices while the mold is still at the mold maker, to ensure that the actions will work flawlessly over many cycles. Usually such actions are pneumatically driven. A simple pneumatic system with proper valves and timers will usually suffice for this type of testing. During this cycling, the thermoformer should check for oil or grease leaks.
- Coolant lines. The lines should be chip-free and properly threaded for large-diameter fittings. Manifolds should be provided where multiple coolant lines are used. These should be mounted directly to the mold base. Lines should be pressurized to at least twice expected maximum coolant line pressure and the

pressure should be kept on the lines and monitored for at least 72 hours to ensure that there are no internal cracks or leaks.

- Other connections. Vacuum lines should be chip-free and large enough to accommodate adequate vacuum lines. Vacuum holes should be chip-free and all should be demonstrated to be open between the mold cavity and the vacuum box.
- Surface preservatives, conditioners. Sometimes *blueing* or other surface coatings are applied during machining. These, any other surface coatings such as shipping greases, rust or oxide inhibitors, and all oils and greases should be removed prior to starting the mold in service.

When the mold is ready to be installed in the thermoforming machine, all the above elements should be carefully checked again to ensure that there has been no damage during shipping. The mold should be carefully mounted to the top or bottom platen, taking care to center the mold on the platen. A heavy off-center mold can rapidly wear guide-pins or guide-rods flat on one side. The mold should be carefully leveled to the rails or sheet frame. For small molds and/or platens, this can be done manually. For large molds and/or platens, this is usually done with optical devices such as a surveyor's laser. The leveling tolerance is usually established by the machinery builder but should not exceed 0.005 in (125 μm) in any direction on platens that are less than 48 in (1.2 m) on a side.

Setting the Mold Stops

Once the mold is positioned on the platen, the hydraulic/pneumatic action of the machine should be started. At this point, the mold should not be plumbed for cooling or auxiliary actions such as cams or ejection bars. The mold should be raised or lowered to the final position and the level again checked against the sheet frame or rails. The tolerance should be *exactly* the same as before. If not, the mold guide rails and the mold lifting mechanism must be checked for out-of-tolerance conditions. The mold should then be stopped at the half-way point and the level check repeated. The mold stops should be set to move to this position at the slowest rate. The mold motion is then observed during its movement from one stop to another. A laser leveler or bubble spirit level is used. If an electronic position indicator is used, the local mold velocity is charted. If there is any hesitation or racking, it is necessary to pinpoint the region and correct the problem before continuing. If the platen velocity can be controlled along the path between stops, its initial speed should be relatively high but should decrease rapidly as the platen approaches its maximum position. This minimizes hydraulic valve hammer or pneumatic piston wear.

Dry-Cycling the Mold

Once all the stops are in place, the mold is "dry cycled" for some time to ensure that all stops are locked in and all sliding surfaces are fully lubricated. The ancillary mold elements are then connected to their appropriate power supplies but only after it

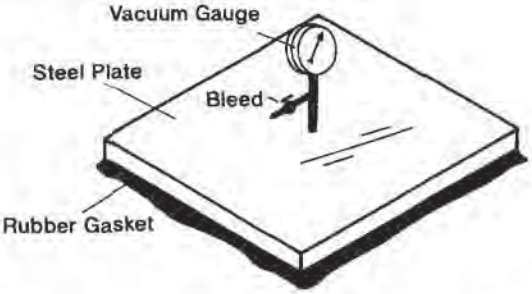

Figure 10.10 Apparatus for determining effectiveness of applied vacuum for given mold cavity design

appears that the mold and platen are functioning nominally. The positioning and timing of each of the slides, unscrewing devices, cams and plug assists must be treated separately. Once each of these devices has been properly tuned and the entire mold is functioning as expected, the vacuum line is installed. Again the vacuum line should have a smooth interior, should be of minimum length with as few elbows and tees as possible and there should be no constriction between the vacuum box and the vacuum surge tank, Chapter 6. A metal plate containing a vacuum gauge and a petcock valve to atmosphere is then placed on the mold surface and gasketed or sealed with metal tape (Fig. 10.10). Vacuum is then applied to the mold and the rate of evacuation is measured. The time needed to get to 50%, 75%, 90% and 95% of the maximum vacuum supplied by the vacuum system is recorded. This is shown in schematic in Fig. 10.11. As discussed in detail in Chapter 6, the ideal maximum vacuum is $28\frac{1}{2}$ in Hg or 35 Torr. Vacuum of 25 in Hg or 125 Torr is barely adequate. With proper arithmetic, the evacuation rate, in in^3/s or cm^3/s, can be determined. The evacuation rate should be constant with time. If the evacuation rate decreases rapidly with time, the surge tank is too small. If the time required to evacuate the cavity is long, there are insufficient vacuum holes or there is serious constrictions in the vacuum system, Chapter 6. As soon as the vacuum in the cavity has reached 95% of the maximum vacuum supplied by the vacuum system, the petcock is opened and the valve to the vacuum surge tank closed. The time it takes for the surge tank to achieve the original vacuum value is the *vacuum recovery time*. This value should be less than the time required to evacuate the cavity. If not, the vacuum pump is too small. If the system is run at this rate, the vacuum pump will run continuously and the vacuum in the mold cavity will never achieve maximum value.

Checking the Vacuum

A piece of flexible PVC or LDPE film or rubber sheet is now placed in the clamp frame and the press cycle is activated. The sheet should cover the mold surface. It must be clamped tightly *before* the vacuum system engages. If the sheet does not seal

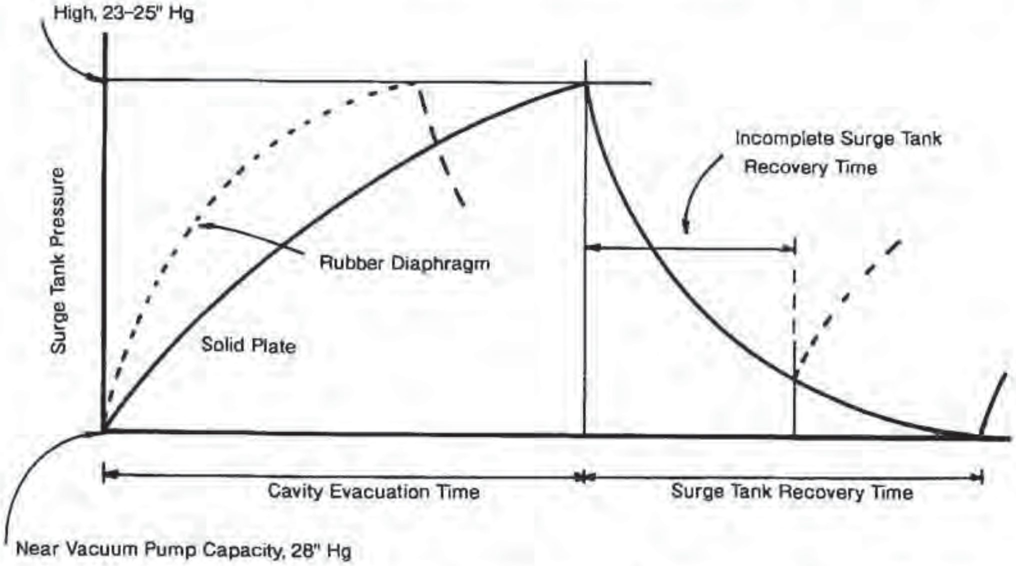

Figure 10.11 Time-dependent vacuum in mold cavity, using solid plate of Fig. 10.10 or rubber sheet. Figure also shows time-dependent nature of surge tank vacuum recovery

the cavity, air will leak under it and the effect of the vacuum will be compromised. One way of achieving good initial seal is to bring the mold deeper into the sheet during platen travel. Other ways include cavity isolators, peripheral clamping frames and cavity dams. The rate at which the flexible sheet is drawn into the mold cavity should be compared with the rate at which air was evacuated from the cavity when the rigid plate was used. Since the initial volume of air is the same, the initial evacuation rate should be the same. However, the film acts as a flexible bladder, keeping the pressure on the mold cavity side of the vacuum holes at or close to atmospheric. As a result, the overall evacuation rate should be greater than that with the metal plate (Fig. 10.11). If not, air may be leaking around the film/mold interface. Another cause is that the sheet may be covering too many vacuum holes early in the draw. Additional vacuum holes are then required and these must be placed in two- and three-dimensional regions last covered by the sheet.

Attaching Cooling to the Mold

If the system is satisfactory to this point, coolant hoses are installed. Again, large diameter lines are required everywhere. If quick-disconnect fittings are used, they must be oversized so that the flow channel through the body of the fitting is the same diameter as that in the hoses. Since the temperature rise in any coolant line should not exceed 5°F or 3°C, for large molds, coolant lines should be manifolded to achieve this. Again, pressure drops into and out of manifolds should be minimized by using the largest possible fittings. The manifolds should be mounted directly on the mold base. Platen motion should not drag coolant hoses. If hot water, steam or oil is used as coolant, all hoses must be of appropriate design and should be insulated. If chilled water or glycol-water mixture is used as coolant, all hoses should be oversized and again should be insulated. After all lines are pressure-tested, the coolant system is turned on and the mold allowed to achieve constant temperature. This may take an hour or more. The mold is considered to be at constant temperature when the coolant lines show no change in temperature over several minutes. The practical beginning mold temperature should be 10°F to 20°F or 6°C to 11°C below the polymer 66 lb_f/in^2 or 0.455 MPa heat distortion temperature. It is now necessary to determine the uniformity in mold surface temperature. This is done in one of three ways:

- Surface thermocouple. A thermocouple is pressed against the mold surface and held until the reading stabilizes. The temperature at that point is recorded. This technique is repeated at many places on the mold surface, particularly on vertical surfaces and thin mold sections.
- Infrared pyrometer. The infrared temperature is measured without direct contact with the mold. The probe emissivity should be adjusted to accommodate reflective mold materials rather than non-reflective plastics. Again the temperature is monitored at many places on the mold surface.
- Infrared thermal imaging. This new technique takes a video scan of the entire two-dimensional surface at one time. Only one reading is needed and the results are displayed on a video screen for all to see and comment on.

Particular attention must be paid to male portions of female molds, such as ribs, bosses or gussets, and to any element that undergoes mechanical action, such as hinged sections, cams or slides. Active cooling of these elements is usually limited by the mold design. If any portion of the mold seems cool, a major decision must be made whether to run the mold knowing of this limitation. If the part is critical, this decision must be made on a high level and must include the mold maker and the customer. This decision is particularly important if chill marks are typically a problem with the particular polymer. When the mold reaches constant temperature, the platen should be dry cycled to ensure that the thermal expansion has not interfered with the platen travel or rate of travel. All slides, cams and plugs should function without binding or squealing. If an element binds, it must be removed and machined to tolerance. Simply lubricating the element will ultimately lead to oil contamination of the product and binding or squealing some time in the future. In addition, the level of the platen should not have changed with increased mold temperature. If it has, the platen will need to be re-leveled.

The Sheet Delivery System

Once the isothermally hot press and mold system are functioning, the sheet delivery system is interfaced with it. This is usually a simple matter of adjusting the speed of rotation for a rotary machine or the speed of the chain drive for a roll-fed machine. However, in some cases, automatic load and unload stations must be properly sequenced as well. The delivery system is brought into sync first. Then the loading and unloading stations are attended to.

Setting the Oven Conditions

The heating portion of the process is now addressed. At this point, the platen motion and all mold element actuation efforts are stopped, although the heat to the mold remains on. The top elements on the primary oven are switched on and allowed to achieve an equilibrium or steady state condition, as indicated by cyclical on-off control[1]. The elements should be set at a flat temperature profile across the heater surface. As with mold temperature measurement, heater measurement is made with a direct contact thermocouple, an infrared pyrometer or by thermal imaging. As with mold temperature measurement, the thermal imaging gives the most rapid and easily interpreted result. Although it is possible to detect a burned-out metal wire or rod heater by current flow means, it is difficult to detect a defective heater that is showing an intermittent short or hot spot. Ceramic heaters with liquid crystal temperature indicating coatings are now available to help maintain fully functional heaters.

The recorded temperatures are then calibrated against the power input to the individual element. The top heaters should be switched off and the unit allowed to cool before the bottom heaters are tested. The bottom heaters are tested in the same fashion as the top heaters. Once this exercise is completed, the lower heater spacing from the clamp frame or the pin-chain is adjusted to accommodate sheet sag. At that time, the photoelectric eye should be cleaned and positioned to detect critical sag conditions. If through-the-oven-wall infrared sheet temperature monitoring is used, the quartz lens should be removed and cleaned, the water or air line to the cooling collar around the sensor should be cleaned and the sensor should be recalibrated at this time. The outboard lip of the oven is then positioned to prevent the sagging sheet from touching it as it exits the oven.

At this point, proper safeguards that were removed for calibration are now replaced. Pinch-points and hot zones must be isolated. Electronic barriers and mechanical cages must be closed properly. Personnel must don protective equipment such as gloves, ear plugs, and sleeve protectors. Fire protection must be in place and emergency exits and warning lights actuated.

[1] Note that the set-up described here is strictly valid only for ceramic and rod heaters. Quartz and the new halogen heaters operate on an entirely different principle, Chapter 3, and as a result, cannot be calibrated in this fashion. To ensure that all the quartz elements are functional, the quartz heaters are turned on in zones and the incandescence from each quartz element observed. If a quartz tube is burned out, the element will be black. Since the quartz heater has essentially no thermal feedback control, it must be switched off as soon as it has been found to be functional. Gas-fired burners and catalytic surface burners are easily monitored with a simple thermocouple in the middle of the burner. The natural-gas supply safety system requires the thermocouple to sense whether the burner is on. As a result, the system is either on or off and its status is clearly indicated.

Forming Step—Simple Vacuum Forming

The sheet is now readied for forming. For cut sheet forming, several sheets are marked with the circle-grid pattern. For roll-fed sheet, a strip of sheet that could form eight to ten shots is cut from the roll. The circle-grid pattern is marked along the entire length of the sheet. For cut sheet forming, an ungridded sheet is placed in the clamp frame and rotated into the primary oven. Observers record the time, a temperature somewhere on the sheet, and the extent of sag. When the sheet sag is great, the sheet temperature is high, or the sheet is smoking, the sheet is then rotated over the stationary mold. The mold motion is not activated however. The hot sheet is observed for warping, discoloration, and abnormal stretching as it cools in free space. The sheet surface temperature is recorded as a function of time in the ambient air. If sheet sag and the forming temperature window appear satisfactory, a second sheet that has been circle-grid marked is clamped and heated to about the desired time and temperature. As with the first sheet, the second sheet is allowed to cool in ambient air. The extent of stretch and any abnormal stretching areas are determined by observing the changes in circle characteristics, as discussed earlier. At this point, no adjustments should be made to the temperature field. This is very important.

Another circle-gridded sheet is then clamped and heated. This time, the platen and mold are allowed to penetrate the sheet but all ancillary actions such as cams, cavity isolators, peripheral seals, pre-blowing or plug assist stretching, and slides are locked out. In addition, vacuum is not applied to the sheet. Instead the sheet is allowed to drape into the mold. This allows the operator to see and verify the first points of contact of the sheet with the mold. This step is repeated but now maximum vacuum is applied. This simple vacuum forming step forms the basis for all additional manipulations of the sheet. At this point, free sheet surface temperature is measured as a function of time, using an infrared pyrometer. Thermal labels, tabs or crayon-type sticks can also be used to determine local sheet temperature. These data give baseline values for the cooling rate of the sheet. This step should be repeated several times to ensure that the sheet is in fact forming the same way every time. What is sought is uniformity in draw-down into three-dimensional corners, stretching over male portions of the mold, draw-down uniformity into multicavity molds, and regions of thinness and potential tearing. It is understood that it may be necessary to activate some of the ancillary aspects of the mold, such as hinged sections, in order to get the part out of the mold cavity.

Note that this exercise may not yield manufacturing data. When a single sheet is loaded in a rotary press and rotated through the complete cycle, the thermal duty on the oven is frequently substantially less than when every frame contains a sheet. As a result, the actual cycle time for a one-at-a-time trial will usually be different than that for steady-state production. This is true for roll-fed units as well. In particular, if a sheet of 10 to 12 shots is fed continuously to ensure that the sheet is forming the same each time, the last sheets of the short roll will assuredly form differently than the first.

Changing Temperature Conditions

At this point, the forming press is acting as a simple flat plate heater and vacuum former. The next series of steps depends on the confidence and experience of the operator. Recall that raising overall heater temperature simply shortens cycle time. If the sheet is thinning in one specific region, the heater temperature in that region must be lowered or equivalently, the heater temperatures everywhere else increased. Webbing is the result of high heater temperature and so the temperatures in the web region must be lowered. Increasing heater temperature on heavy-gage sheet can result in surface burn or blister. Increasing heater temperature on saggy materials can result in dropping the sheet onto the lower heater.

Although the temperature profile change seems to give the most rapid effect on forming conditions, temperature effects do not take place instantaneously. Heaters require time to achieve new steady-state values and the air in the oven takes even longer to steady out. Circle-gridded sheets are very functional when determining the somewhat subtle effects of differential energy input on material reallocation on the mold surface.

Activating the Assists

Once it is apparent that the sheet is being vacuum formed in the best manner possible using only temperature as a means of reallocating plastic, the assists can now be activated. Consider simple billow prestretching. This can be done by pneumatically inflating the sheet prior to insertion of a male mole or by everting the inflation into a female mold. Or it can be done by drawing the sheet with vacuum. Billow prestretching is the simplest means of prestretching the sheet. A photoelectric eye is usually employed to stop the inflation pressure. The interactive timing of inflation and mold motion is important as well. If prestretching is used with zone or pattern heating, some adjustment in the heating profile is usually needed in order to minimize bubble blow-out or aneurysm. The prestretching rate is controlled by simple air-flow valves. As a result, initial prestretching can be very rapid and final prestretching can be very slow.

Plug assists are very difficult to install and operate correctly. As a result, they should be the last elements to be employed during mold start-up. The plug process control variables include:

- Plug temperature,
- Surface texture of the plug,
- Rate of plug travel,
- The time when plug travel is initiated, and
- The differential pressure across the stretching sheet.

All the variables but plug temperature and surface texture can be time-dependent. Articulated plugs offer yet another dimension of plug motion. It is important to remember that the action of a plug is quite localized. The majority of sheet thickness distribution and redistribution should be accomplished, without plug assist, by other means such as temperature and pre-inflation. All too often, plug assists are only used when the operators and engineers cannot find any other way of forming the part.

Pressure Boxes

There must be adequate justification to add more than one atmosphere of pressure to the forming process. Pressure forming requires the addition of a pressure vessel that must be correctly interactively sequenced along with the other mold and press activities. Pressure is usually not applied prematurely, simply because other mold activities usually take precedence. Typically pressure is applied late in the forming process. If the pressure application is delayed too long, the polymer may cool so much that the extra pressure to deform is insufficient. As with plug assist, pressure forming should be one of the last features to add to a start-up process.

General Objectives

The primary objective of new mold or new plastic start-up is molding consistent parts having relatively uniform wall thicknesses without degradation or deterioration of the polymer. Initially, effort is focused on just getting the polymer to stretch reasonably well. Once this is achieved, effort moves toward optimization of the forming process. Usually the sheet heating time dominates the total cycle and so is the first part of the process to undergo optimization. Depending on the length of the production run and the cost and complexity of the part being formed, this may be the only process effect to be optimized. This is particularly true if sheet make-up is also changed. For example, start-up usually uses only virgin sheet. Once the product is forming well, regrind is added to the virgin sheet. The nuances of the forming character of the sheet now change and fine tuning progresses at the expense of further process optimization.

Custom molders are faced with the added burden of needing to remove and reinstall molds at frequent intervals. The protocol described above for new molds and new polymers must necessarily be shortened to enable production in the shortest time interval. Computer storage of vital information about machine settings, including mold positions, stops, timing sequences, temperatures at various zones and transfer rates aids the progress in rapid mold change. Nevertheless, the experienced operator is always on the lookout for excessive mold element wear, over-zealous coatings of corrosion inhibitor, worn hoses, loose connections, out-of-level platens, heaters that are losing efficiency and mold coolant lines that are plugging with scale. These long-term effects can substantially increase the time needed to get an old mold back into production.

10.3 Troubleshooting the Forming Process

Good quality parts begin with good quality sheet. The interface between the thermoformer and the sheet producer is in many respects similar to that between the thermoformer and the customer of his formed parts. The sheet producer needs to sell product to the thermoformer at a profit and the thermoformer needs to buy quality product from the sheet producer at the best price. In addition to agreeing on price and delivery, the thermoformer and the sheet producer must agree on quality, in writing. An example of a typical purchasing specification check list was given as Table 8.12.

As discussed in Chapter 8, extrusion is the common way of producing thermoplastic sheet for thermoforming. The overview of extrusion was included to help the thermoformer understand the various aspects of the conversion process that most affect the quality of the thermoformer's raw material. The thermoformer does not need to be able to troubleshoot the extrusion process. Nevertheless, he/she should generally know what aspects of the conversion process are most apt to generate less-than-acceptable sheet goods. More importantly, the thermoformer must understand that writing very stringent specifications may cause the sheet converter to use very expensive procedures and that these very expensive procedures will undoubtedly be reflected in the final sheet unit cost. Table 10.3 gives a brief troubleshooting guide for extruded sheet product. Sheet is also produced by calendering and compression molding.

Table 10.3 Troubleshooting the Extrusion Process—A Brief Guide

Problem	Probable cause	Suggested course of action
Die lines in sheet	Plate-out buildup	Remove and clean die Determine nature of plate-out, review polymer recipe with resin supplier, extruder
Erratic gauge control	Non-uniform thermal environment around die	Check for draft sources around die and correct Insulate die with fiberglass baffles
Surging in extruder	Uneven melt conditions in extruder Erratic polymer feed	Raise heat in first zones of extruder Check feed throat for bridging Make certain hopper level is constant
Die pressure fluctuation	Clogged screen or disk pack	Replace screen and clean out plugged one Go to slide plate screen changer Go to continuous screen changer
Orange peel surface	Surface viscosity in die too high	Raise die temperature Raise heat in last zones of extruder

(Continued)

Table 10.3 (Continued)

Problem	Probable cause	Suggested course of action
	Surface shrinking unevenly during cooling	Raise chill roll temperature Raise die temperature
Dark specks and streaks	Polymer degrading	Lower melt temperature Reduced screw speed Modify screw to decrease flight clearance Modify screw to decrease compression ratio
	Contaminants in melt	Clean die lips Pull screw and examine for pitted chrome Check die design and streamline if necessary Clean hopper and securely cover Pull screw and examine screw shank for oily or carbonaceous buildup If using regrind, examine regrind for contamination Examine virgin polymer pellets for black speck contamination
Lines in machine direction	Damage or corruption on die lips	Disassemble die and clean thoroughly; examine with 30X loupe for corrosion Take scrapings of build-up, chemically analyze and determine if build-up is from polymer
	Surface scratches on chill roll	Clean and optically examine chill rolls. Resurface if necessary
	Polymer hang-up between die lip and die body	Check mating surfaces for misalignment, damaged areas Check die design and streamline if necessary
Curved lines in cross-machine direction	Melt bank too large	Reduce melt bank to pencil-thick diameter
	Melt folding	Check extruder output to determine if surging is occurring. If so, add melt pump
Gels in sheet	Melt has cold spots	Increase heat in last zone of extruder Increase die temperature
	Polymer crosslinking	Reduce heat in first zone of extruder Reduce screw speed to minimize shear heating Reduce regrind level Examine regrind for contamination Increase antioxidant package in polymer

Table 10.3 (Continued)

Problem	Probable cause	Suggested course of action
Dull spots on sheet surface	Sheet picking plate-out off chill roll	Increase first chill roll temperature Discuss alternate adduct packages with resin supplier
	Nonuniform cooling in chill roll	Clean flow channels in chill roll
	Sheet intermittently lifting from chill roll	Use air knife to hold hot sheet against first chill roll
Brittle sheet	For certain polymers such as ABS, PET, polymer is too wet	Thoroughly dry polymer Thoroughly dry regrind
Hazy sheet	Polymer crystallizing — typical of PET, PP	Thoroughly dry polymer Increase melt temperature Reduce first chill roll temperature Reduce melt bank Increase extrusion rate
	Adduct package wrong	Review adduct package with polymer supplier Increase or decrease melt temperature to determine general effect Increase or decrease first chill roll temperature to determine general effect
	Microscopic bubbles inside sheet	Polymer wet; thoroughly dry polymer Polymer degrading; lower melt temperature, reduce residence time Adduct decomposition; review adduct package with polymer supplier
Internal holes in sheet	Moisture	Dry polymer Dry regrind Seal hopper or use inert gas layer
	Air	Increase heat in first zones of extruder Decrease heat in last zones of extruder Increase back pressure on melt pump
	Degrading polymer	Decrease screw speed Decrease temperature profile throughout extruder Decrease back pressure on melt pump Reduce regrind concentration
	Decomposing adducts	Review adduct package with resin supplier

(Continued)

Table 10.3 (Continued)

Problem	Probable cause	Suggested course of action
Melt freeze off	Melt temperature too low	Increase die temperature Increase heat in last zone of extruder Check for burned-out heater bands
	Screen too cold	Intermittent when screens are changed; preheat screens
Surface roughness in sheet	Contamination	Check incoming virgin resin for contamination Check regrind for contamination
	Unmelted pellets	Increase heats on first zones of extruder Decrease extruder throughput rate Increase gear pump back pressure Change screw to higher compression ratio screw Switch to barrier screw
	Moisture	Dry polymer thoroughly
	Trapped air	Move extruder die closer to chill roll Use air knife to hold sheet against chill roll Lay sheet on roll at 300° to 330° angle Increase melt bank diameter slightly Check vertical alignment of chill roll and die
	Unpolished low spots	Increase melt bank diameter Adjust vertical alignment of chill roll and die Adjust die lips to increase flow in low spots
	Insufficient roll stack polish	Increase roll stack temperature Decrease roll gap Increase bottom roll speed slightly

Even if all apparent sheet imperfections are absent, and even if great care has been taken to design out polymer and process elements that interfere with the production of acceptable and quality parts, process problems still occur during start-up and during any normal process run. Many reoccurring processing problems are grouped in Table 10.4 [17]. The probable causes of each of these problem classes are assessed in Table 10.5 [17] along with some suggested methods to correct or eliminate them. Most of these problem classes are characteristic of heavy-gage sheet although some pertain to thin-gage sheet or film as well. Many pertain to all forming

Table 10.4 Categories of Thermoformed Part Process/Product Problems—I [17]

- Bubbles or blisters
- Incomplete forming or poor detail
- Sheet scorching
- Blushing or change in color intensity
- Sheet whitening

- Webbing, bridging, wrinkling
- Nipples or nibs on mold side of formed part
- Excessive sag
- Sag variation between sheet blanks
- Chill marks or "mark-off" lines on part

- Bad surface markings
- Shiny streaks
- Excessive post shrinkage or distortion after part removal from mold
- Warpage
- Poor wall thickness distribution, excessive local thinning

- Nonuniform or bulging prestretch bubble
- Shrink marks on part, particularly in corners or inside radius of molds
- Deep draw corners too thin
- Part sticking to mold
- Sheet sticking to plug assist

- Part tears during forming
- Cracking in corners during use

operations. Recently, another grouping of process problems, primarily for thin-gage forming, has been published (Table 10.6) [5]. Many of the problem areas are similar or identical to those of the earlier list. The probable causes of each of these problem classes are given in Table 10.7, where the causes are also grouped as the result of problems in:

- Production,
- Tool,
- Forming machine,
- Polymer material, and
- Design.

Although no suggested courses of action are recommended, it is apparent that the appropriate response is to negate or neutralize the probable cause.

Certain classes of polymers such as CPET, PP and foams, require specialized forming procedures. Specialized troubleshooting techniques are usually required when processing these polymers. For example, Table 9.6 gives a troubleshooting guide for CPET.

Table 10.5 Trouble-Shooting Guide to Thermoforming—Primarily Heavy-Gage[1]

Problem	Probable cause	Suggested course of action
Blisters	Heating too rapidly	Lower heater temperature Use slower heating Increase distance between heaters and sheet Blow air across sheet surface during heating
	Excess moisture	Pre-dry sheet Preheat sheet Heat from both sides Do not remove moisture barrier film until ready to use Require sheet supplier to provide dry sheet
	Uneven heating	Check heater output, power consumption Use pattern heating
	Wrong sheet type or formulation	Order correct formulation
Incomplete forming, poor detail	Sheet too cold	Heat sheet longer Raise heater temperatures Use more heaters Change to more efficient heater design If problem localized, check heater bank for problems
	Clamp frame cold prior to sheet insetion	Preheat frame
	Insufficient vacuum	Check vacuum holes for obstruction Increase number of vacuum holes Increase diameter of vacuum holes
	Vacuum not applied rapidly enough	Use vacuum slots rather than holes Surge tank/pump too small Vacuum line/valves too small Too many bends in vacuum line Corrugated vacuum line used Vacuum leaks
	Applied pressure too low	Increase air pressure Use plug, silicone slab rubber, or bladder as pressure assist

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[1] Adapted from [17], by permission of the copyright owner

Scorched sheet	Sheet surface too hot	Shorten heat cycle Use slower, soaking heat Consider convection heating
Blushing or color intensity change	Insufficient heating	Lengthen heating cycle Raise heater temperature Change to more efficient heaters
	Excessive heating	Reduce heater temperature Shorten heating cycle If localized, check heater efficiencies Consider convection heating/surface cooling
	Mold too cold	Warm mold
	Assist too cold	Heat assist
	Sheet is stretched too far	Try heavier gage sheet Try more elastic formulation Change mold design
	Sheet cools before fully formed	Transfer sheet faster Increase forming rate Increase mold, plug temperature
	Poor mold design	Reduce draw ratio Increase draft angles Increase corner radius
	Polymer not suitable	Change sheet formulation Change polymers
	Excessive, poor use of regrind	Retest regrind for problems Check percentage of regrind
Whitening	Stretching below forming temperature	Increase sheet temperature Increase forming speed
	Sheet dry-colored	Poor extrusion Polymer unsuitable for pigmentation Local blemishes removed with hot air gun
Webbing, bridging, wrinkling	Sheet too hot, drape into forming area	Shorten heating cycle Increase heater distance Lower heater temperature Air-cool just before forming

(Continued)

Table 10.5 (Continued)

Problem	Probable cause	Suggested course of action
Webbing, bridging, wrinkling (continued)	Resin melt strength too low, sheet sag	Change to lower MI olefin Increase orientation Use very low heater temperature
	Orientation mismatch	Increase or decrease TD-to-MD orientation ratio
	Insufficient vacuum	Check vacuum system Add more vacuum holes
	Preferential bridging	Rotate sheet 90°
	Excess draw ratio, poor mold design/layout	Redesign mold Use plug/ring assist Use female mold rather than male mold Use assist blocks to pull out wrinkles Increase radii/draft angles For many parts on a mold, move them apart For multi-part molds, use part isolators, grids Speed up assist and/or mold travel Redesign grid/plug/ring assists
Nibs or nipples on formed parts	Sheet too long	Reduce heating cycle Reduce heater temperature
	Vacuum holes too large	Plug holes, redrill
Excessive sag	Sheet too hot	Reduce heating cycle Reduce heater temperature
	Melt index too high	Use lower MI olefin Change resins Increase sheet orientation
	Sheet area excessive	Pattern heat to reduce sheet center temperature Add sag bands
Chill marks, striations	Plug assist temperature too low	Increase plug temperature Use wood, synthetic plug Cover plug with wool, felt, fabric
	Mold temperature too low	Increase mold temperature

	Poor mold temperature control	Reconfigure cooling, heating channels Add more coolant channels Increase coolant flow rate Increase coolant channel diameter Inspect flow path for debris, plugging, rust
	Sheet too hot	Reduce heating cycle Cool sheet surface with air prior to forming
	Wrong forming technique	Change forming rate Change forming technique
	Wrong polymer	Change to higher tensile strength resin, lower MI olefin polymer
	Ghosts in details, rim on roll-fed	Matched die mold misaligned Mold hesitates in travel—check guides, alignment
Surface blemishes	Indentations	Mold surface too smooth—roughen Increase vacuum hole area Sheet cast against smooth roll, air trapping
	Poor vacuum	Increase vacuum hole area If localized, check for plugged vacuum holes
	Plasticizer accumulation	Clean mold periodically Reduce mold temperature Regulate mold temperature Do not allow mold to "see" heaters Shorten heating cycle
	Mold too hot	Reduce mold temperature
	Mold too cold	Increase mold temperature
	Improper mold composition	Change mold materials Try machined aluminum molds
	Rough mold surface	Polish mold Use aluminum molds
	Dirt	Clean mold, sheet
	Atmospheric dust	Clean thermoforming area Enclose former Use filtered air for blow-off
	Contaminated polymers	Check regrind for dirt Check resin, sheet supplier

(Continued)

Table 10.5 (Continued)

Problem	Probable cause	Suggested course of action
Surface blemishes (continued)	Scratched sheet	Review sheet handling procedures Use surface paper protection Polish sheet prior to forming
	Drag marks on roll-fed sheet	Use sag bands to keep sheet from touching mold edge Increase mold daylight
Shiny streaks	Local overheating	Check heater temperature Check heating pattern, zones Air-cool locally Reduce heating cycle Increase heater-to-sheet distance
Post-forming shrinkage, distortion	Time on mold too short	Increase cooling time Decrease coolant temperature Use free-surface cooling Change free-surface cooling to water mist Check for restricted coolant flow Use cooling fixtures
	Mold too hot	Reduce mold temperature Increase coolant flow rate
Warped parts	Uneven part cooling	Change coolant channel configuration Check for blocked coolant channels Direct free-surface cooling to warped area
	Poor polymer distribution in part wall	Use prestretching or plug assist Poor temperature uniformity Out-of-spec sheet thickness Vacuum holes in wrong place
	Poor mold design	Increase vacuum hole area Redesign rim area to stiffen Add moat to mold at trim line Unplug vacuum holes

Poor material allocation	Poor part design	Large flat areas should include ribs, corrugations Crown large radius areas
	Mold temperature too low	Increase mold temperature to just below polymer set temperature
	Part removed too early	Part must be below set temperature
	Part cold formed	Increase sheet temperature Increase hold-down pressure Increase vacuum hole area Increase forming rate
	Improper sheet sag	Try mounting mold on top platen Try vacuum snap-back Try sag bands Use sheet with higher orientation Increase speed of forming Use resin with higher MI
	Sheet thickness variation	Gauge all sheet, contact sheet supplier Set guidelines with sheet supplier
	Hot, cold spots	Check heater elements Go to pattern heating
	Periodic drafts	Enclose oven, forming area
	Excessive sag	Increase sheet orientation Reduce sheet temperature Use more elastic resin Use sag bands Go to pattern heating
	Cold mold	Increase mold temperature Change coolant channel configuration Check for channel plugging
	Sheet pulls from rails	Air-cool rails prior to heater Move rails in to grasp more sheet Use drag bands at rail edge Increase rail tooth bite, e.g., longer teeth
	Sheet slips from frame	Adjust frame alignment Increase frame clamp pressure Sheet gage variation Heat frames prior to inserting sheet

(Continued)

Table 10.5 (Continued)

Problem	Probable cause	Suggested course of action
Poor material allocation (continued)	Sheet slips from frame (continued)	If retainer springs are used, change to higher temper springs
Nonuniform prestretch bubble	Uneven sheet thickness	Check with sheet supplier Tighten quality control on extrusion Heat sheet slowly, in hot air
	Uneven heating	Check heater efficiency Change to more efficient heaters Improve heater temperature control Change to pattern heating
	Periodic drafts	Enclose oven, forming area
	Non-uniform air inflation	Check air flow Install baffles if necessary Preheat blow air
Shrink marks	Inadequate vacuum	Vacuum leaks Vacuum surge tank, pump inadequate Plugged vacuum holes Vacuum hole area inadequate
	Mold surface too smooth	Roughen mold surface Change to lower conductivity mold material
	Part shrinking during forming	Increase forming pressure Increase mold temperature Change to less elastic polymer Reduce free-surface cooling
	Inadequate air pressure	Increase air flow rate Increase air pressure Increase cycle time under pressure
Very thin corners	Incorrect forming technique	Try plug assist
	Sheet too thin	Increase sheet thickness
	Sheet temperature variation	Check material allocation Switch to pattern heating Increase forming rate

	Variation in mold temperature	Change coolant line configuration Check free-surface cooling
	Incorrect polymer	Use stiffer polymer Use more elastic polymer
Parts stick in mold	Part temperature too high	Increase cooling time Lower mold temperature Reduce heating cycle time
	Inadequate draft	Rework mold for more draft Use female mold
	Mold undercuts	Remove part early, then fixture until cool Consider more sophisticated ejection system Use pulling cores, breakaway frame Decrease depth of texture
	Sticking in one spot	Uneven mold temperature Uneven sheet temperature prior to forming Vacuum break inadequate Check for local mold damage
	Wooden mold	Lubricate with dry mold release
	Rough mold surface	Polish, especially corners Use dry mold release
	Very smooth surface-olefins	Add antiblock to polymer Roughen mold surface slightly Inadequate vacuum break Try female mold if excessive shrinkage
Sheet sticks to plug	Plug temperature too high	Reduce plug temperature Use dry mold release Use permanent mold coating Use felt/cloth/wool/fabric covering
	Wooden plug	Coat with lubricant Use felt/cloth/wool/fabric covering Switch to temperature-controlled plug material
	Plug speed too high	Reduce plug penetration rate Increase air pressure behind plug Decrease air pressure ahead of plug

(Continued)

Table 10.5 (Continued)

Problem	Probable cause	Suggested course of action
Sheet tears while forming	Mold design	Increase corner radius
	Sheet too hot	Decrease sheet temperature
		Preheat sheet, then bring to forming temperature slowly
		Sheet thickness may not be uniform
	Sheet too cold	Increase heating time
		Preheat sheet
	Improper polymer	Depth of draw excessive for polymer, see resin supplier
		Change forming technique
	Forming conditions improper	Decrease plug penetration rate
		Increase inflation rate
		Increase draw-down rate
Corner cracking in service	Stress concentration	Increase radii
		Corner too cold during forming
		Increase mold temperature
		Increase sheet temperature
		Increase forming rate
		Prestretch sheet
		Decrease free-surface cooling
		Decrease plug rate of penetration
		Change to ESCR resin
	Under-designed	Reevaluate design

Table 10.6 Categories of Thermoformed Part Process/Product Problems—II [5]

- Blisters or bubbles
- Poor forming and bad detail
- Product surface distorted
- Color changes
- White marks

- Webbing, bridging or wrinkling
- Mold side bumps
- Chill marks
- Surface marks
- Surface shiny

- Excessive post-forming shrinkage or distortion
- Warped or twisted part

- Thin corners
- Thin surfaces
- Thin sides

- Poor wall thickness distribution
- Post-forming cracking
- Shrink marks
- Too much sag
- Pre-blow/vacuum bubble variation
- Material sticks to plug assist
- Material tears during forming
- Demolding problems

10.4 Energy and Materials Cost

Every business, regardless of size, should operate on micro-economics. That is, an economics balance should be made on every part produced[1]. With some modifications, the global concepts of Figs. 10.1 through 10.3 are directly applicable to every part produced. There is a general tendency to lump production costs into a "machine hour cost". Although this is acceptable for a "Class C" estimate, it should never be the norm for day-to-day price forecasting. This is discussed in more detail below.

The Energy Audit

Thermoforming is an energy-intensive business. Recently, the re-emergence of gas-fired heaters has sparked another round of economic focus on power consumption. As discussed in detail in Chapter 3, there are many ways of heating a plastic sheet. The nature of the energy source is strongly dependent on the nature of the polymer and the sheet thickness. In other words, the optimum energy source is usually not the most economic energy source [6]. Care must be taken when considering a simple substitution, since other non-energy cost factors such as maintenance, time-dependent energy efficiency of the heating unit, and installation costs can temper an otherwise obvious selection. The decision to replace current heaters with more efficient units should be made only *after* a thorough energy audit is made on each

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[1] It is apparent that if the forming shop is producing a few hundred outdoor signs or swimming pool, the cost associated with each part can be carefully monitored. It is not apparent that this same philosophy holds if the forming shop is molding unit dose cups or margarine tubs. Nevertheless, the general approach is valid if applied to, say, each 1000 units or each hour of production.

Table 10.7 Thermoforming Troubleshooting Guide—Primarily Thin-Gage[1]

		Possible causes			
Problem	Production	Tooling	Machine	Material	Design
Blisters or bubbles	Material too hot Material heated too quickly Forming vacuum/pressure too slow Forming vacuum/pressure not turned off Forming vacuum/pressure too short Cooling too soon	Too hot Too smooth—not grit blasted No venting Not enough vacuum holes or holes too small Missing vacuum holes Incorrect vacuum hole placement Vacuum channels clogged Wrong air supply	Heating intensity too high Incorrect heating pattern Insufficient screening of heater bank	High moisture content Too much release agent Incorrect formulation	
Poor forming, bad detail	Material too cold Draft over the material Grid absorbs too much heat, not polished Forming vacuum/pressure too slow Forming vacuum/pressure too short Cooling too soon Demolded while too warm Operational sequence too slow	No venting Insufficient sealing Hollow, suction volume too large Not enough vacuum holes or holes too small Missing vacuum holes Incorrect vacuum hole placement Drawing edge too small Vacuum channels clogged Wrong air supply	Area within clamp frame too small Clamping frame too cold Clamping frame not sealed Clamping frame not polished Insufficient seal Dirty vacuum filter Incorrect heating pattern Insufficient screening of heater bank	Hard to form Poor heat retention	
Product surface distorted		Too rough Mold dirty		Material not cleaned, static Contains impurities Too much release agent	

[1] Courtsey of [15]

Color changes	Material too cold Plug advances too fast Plug assist too cold Mold advances too slow Forming vacuum/pressure too late Forming vacuum/pressure too slow	Too cold Not enough draft Edges, corners too sharp	Incorrect heating	Incorrect formulation Too much or inconsistent regrind content	Incorrect draw ratio Insufficient draft Corners too sharp
White marks	Material too cold Plug advances too fast Plug assist too cold Mold advances too slowly Forming vacuum/pressure too late Forming vacuum/pressure too slow Cooling too long Demolded while too cold	Too hot Not enough draft Eges, corners too sharp No venting	Table jerks or moves too slowly Incorrect heating	Too thin Incorrect formulation Too much or inconsistent regrind content	Incorrect draw ratio Insufficient draft Corners too sharp
Webbing, bridging or wrinkling	Material too hot No or incorrect form assist grid Assist grid advances too slowly No plug assist Plug advances too slowly Forming vacuum/pressure too fast Not enough forming vacuum/pressure Forming vacuum/pressure not turned off	Too cold Too hot Not enough draft Edges, corners too sharp Spacing too small	Incorrect heating Incorrect heating pattern Insufficient screening of heater bank	Wrong sheet orientation Incorrect formulation	Incorrect draw ratio Insufficient draft Corners too sharp
Mold side bumps	Insufficient preblow Forming vacuum/pressure too slow Not enough forming vacuum/pressure Operational sequence too slow	Too hot Too smooth, not grit blasted Drawing edge too small Spacing too small	Incorrect heating pattern Insufficient screening of heater bank	Thickness variations	

(Continued)

Table 10.7 (Continued)

Problem	Possible causes				
	Production	Tooling	Machine	Material	Design
Chill marks	Material too hot Insufficient preblow Plug assist too cold Forming vacuum/pressure too early Forming vacuum/pressure too slow Not enough forming vacuum/pressure Operational sequence too slow	Too cold	Table jerks or moves too slowly Incorrect heating pattern Insufficient screening of heater bank		
Surface marks		Too hot Too smooth, not grit blasted Too rough Missing vacuum holes Incorrect vacuum hole placement Vacuum holes too large Mold dirty Vacuum channels clogged Plug assist too rough	Scratched surface Material not cleaned, static Contains impurities Incorrect formulation Too much release agent		
Shiny surface	Material too hot Insufficient cooling	Too hot	Heating intensity too high Incorrect heating Incorrect heating pattern Insufficient screening of heater bank		
Excessive post-forming or distortion	Material too cold Demolded while too warm	Too hot	Incorrect heating Incorrect heating pattern		

Warped or twisted part	Grid absorbs too much heat, not polished Cooling too soon Uneven cooling Demolded while too warm Clamping edge not immediately removed Products placed crooked after removal	Too cold Too hot Too smooth, not grit blasted Missing vacuum holes Incorrect vacuum hole placement Vacuum channels clogged	Clamping frame not polished Inconsistent heating Incorrect heating pattern	Thickness variations High shrinkage	Incorrect draw ratio Insufficient ribbing
Thin corners	Grid absorbs too much heat, not polished Insufficient preblow No plug assist Forming vacuum/pressure too late Forming vacuum/pressure too fast Operational sequence too slow	Plug assist too small Plug assist too rough Plug assist not centered	Incorrect heating pattern Insufficient screening of heater bank	Too thin Thickness variations	Incorrect draw ratio
Thin surfaces	Material too cold Too much preblow No plug assist	Plug assist too small Plug assist too rough	Incorrect heating pattern Insufficient screening of heater bank		Incorrect draw ratio
Thin sides	Material too cold Insufficient preblow Plug assist too early Plug assist too cold Mold advances too fast Forming vacuum/pressure too late Forming vacuum/pressure too slow	Too rough Edges, corners too sharp Drawing edge too small Spacing too small Plug assist too big	Area within clamping frame too small Incorrect heating pattern Insufficient screening of heater bank		Incorrect draw ratio

(Continued)

Table 10.7 (Continued)

		Possible causes			
Problem	Production	Tooling	Machine	Material	Design
Poor wall thickness distribution	Material too cold Draft over material Material touches mold during heating Material sag during heating No or incorrect form assist grid Insufficient preblow Too much preblow No plug assist Plug assist too early Plug assist too cold Forming vacuum/pressure too early Forming vacuum/pressure too late Forming vacuum/pressure too slow Uneven cooling Operational sequence too slow	Too cold Too hot Edges and corners too sharp Inconsistent spacing Plug assist too small Plug assist too big Plug assist too rough Plug assist not centered	Area within clamping frame too large Area within clamping frame too small Clamping frame too small Clamping frame not polished Inconsistent heating Table jerks or moves too slow Incorrect heating pattern Insufficient screening of heater bank	Thickness variation Wrong sheet orientation Incorrect formulation	
Post forming cracking	Material too cold Plug assist too cold Mold advances too slowly Cooling too soon Demolded while too cold	Too cold	Clamping frame too cold Incorrect heating		High shrinkage
Shrink marks	Not enough forming vacuum/pressure	Too smooth—not grit blasted Not enough vacuum holes or too small	Insufficient seal		

Too much sag	Material too hot No material support				Wrong sheet orientation Incorrect formulation
Preblow/vacuum bubble variation	Draft over material		Inconsistent heating Incorrect heating pattern Insufficient screening of heater bank	Thickness	
Polymer sticks to plug assist	Plug assist too hot		Improper plug material		
Polymer tears during forming	Material too hot Material heated too quickly Material too cold Insufficient preblow	Too cold Too rough Edges, corners too sharp Drawing edge too small Inconsistent spacing	Area within clamping frame too small Inconsistent heating Heating intensity too high Incorrect heating pattern Insufficient screening of heater bank	Contains impurities Hard to form Narrow forming window Poor heat retention Release agent missing Too much or inconsistent regrind content	Corners too sharp
Demolding problems	Mold returns too fast Cooling too long Incorrect demolding pressure Demolded while too warm	Too cold Too hot Too rough Not tapered enough Too much undercut No venting		High shrinkage Release agent missing	Insufficient taper Corners too sharp

thermoformer. One recommended method is to install electric power meters on each unit. For high-energy heaters, separate units should be installed on both the upper and lower heater banks. Nevertheless, in the US today, natural gas is between 3 and 7 times cheaper than electricity on the same energy unit basis, Table 10.8[1]. The average is about 5.

Table 10.8 Cost of Electricity and Gas to Industrial Users

State	Electricity[1] (cents/kWh)	Natural gas[2] (\$/1000 ft^3)	Natural gas (cents/kWh[3])	Ratio, electricity to natural gas
Alabama	4.46	3.01	0.962	4.6
Alaska	5.96	1.18	0.377	15.8
Arizona	5.67	4.14	1.324	4.3
Arkansas	4.95	3.10	0.991	5.0
California	6.74	3.66	1.170	5.8
Colorado	4.49	2.24	0.716	6.3
Connecticut	7.93	4.79	1.532	5.2
Delaware	4.71	3.20	1.023	4.6
District of Columbia	5.43	NA	—	—
Florida	5.27	3.21	1.027	5.1
Georgia	4.79	3.41	1.091	4.4
Hawaii	7.71	NA	—	—
Idaho	2.59	3.00	0.959	2.7
Illinois	5.50	3.73	1.193	4.6
Indiana	4.33	3.30	1.055	4.1
Iowa	4.00	3.47	1.110	3.6
Kansas	4.90	2.60	0.831	5.9
Kentucky	4.19	3.29	1.052	4.0
Louisiana	4.26	1.83	0.585	7.3
Maine	6.71	4.14	1.324	5.1
Maryland	5.51	3.54	1.132	4.9
Massachussetts	8.50	4.33	1.385	6.1
Michigan	5.72	4.13	1.321	4.3
Minnesota	4.26	3.06	0.979	4.4
Mississippi	4.56	2.53	0.809	5.6
Missouri	4.72	2.92	0.934	5.1
Montana	2.89	3.53	1.129	2.6
Nebraska	4.02	2.78	0.889	4.5
Nevada	4.96	4.02	1.286	3.9
New Hampshire	7.70	4.56	1.458	5.3
New Jersey	7.70	3.43	1.097	7.0
New Mexico	4.84	3.04	0.972	5.0
New York	6.15	5.31	1.698	3.6
North Carolina	5.00	3.35	1.071	4.7
North Dakota	4.64	3.27	1.046	4.4

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[1] This excludes Alaska where cheap gas and expensive electricity make the ratio in excess of 15.

Table 10.8 (Continued)

State	Electricity[1] (cents/kWh)	Natural gas[2] ($/1000 ft^3)	Natural gas (cents/kWh[3])	Ratio, electricity to natural gas
Ohio	4.13	4.15	1.327	3.1
Oklahoma	3.95	1.99	0.636	6.2
Oregon	3.17	3.34	1.068	3.0
Pennsylvania	6.32	3.88	1.241	5.1
Rhode Island	9.11	4.68	1.497	6.1
South Carolina	4.19	2.95	0.943	4.4
South Dakota	4.59	3.37	1.078	4.3
Tennessee	4.66	3.20	1.023	4.6
Texas	4.13	2.07	0.662	6.2
Utah	3.96	3.95	1.263	3.1
Vermont	6.98	3.28	1.049	6.7
Virginia	4.27	4.02	1.286	3.3
Washington	2.38	2.78	0.889	2.7
West Virginia	3.67	2.79	0.892	4.1
Wisconsin	4.04	3.81	1.218	3.3
Wyoming	3.52	2.68	0.857	4.1
Total U.S.	4.85	2.82	0.902	5.4

[1] Data reflect rates in 1991 and were supplied by the Edison Electric Institute, Washington DC

[2] Data for 1992 are from American Gas Association, Arlington VA

[3] These values assume 100% conversion of methane to CO_2 and H_2O. The heat of combustion of CH_4 is 383,036 Btu/lb-mol. There are 359 ft^3/lb-mol at standard conditions. Therefore the energy generated by methane combustion is 1.067×10^6 Btu/1000 ft^3. There are 3413 Btu per kWh. Therefore the energy generated is 312.7 kWh/1000 ft^3. This value was used to convert $/1000 ft^3 to cents/kWh. Again, this assumes 100% combustion. Actual combustion is not 100% efficient

Cost of Extrusion

The thermoformer purchases the extruder's finished product. The thermoformer's initial material cost is the cost of the polymer *plus* the extruder's conversion cost. The thermoformer must understand that thermoforming products are sold by the area, as cost per square foot or square meter. The converter sells his product by the weight, as cost per pound or kilogram. The conversion cost is usually a function of the degree of difficulty of the extrusion and the mass throughput, in lb/h or kg/h. For most commodity polymers such as PE, PP and PS, the conversion cost asymptotically approaches a minimum value of about $0.12/lb in 1992 US dollars (Fig. 10.12) [7]. Typically, for production runs of 1000 lb/h, sheet conversion costs are about $0.20/lb. For higher performance polymers or polymers that require special attention such as PVC, PET and PMMA, conversion costs are approximately double the values shown in Fig. 10.12. If the product is to be used for medical or biomedical applications, regrind may not be allowed. In this case, the material cost in the product, $MC, is:

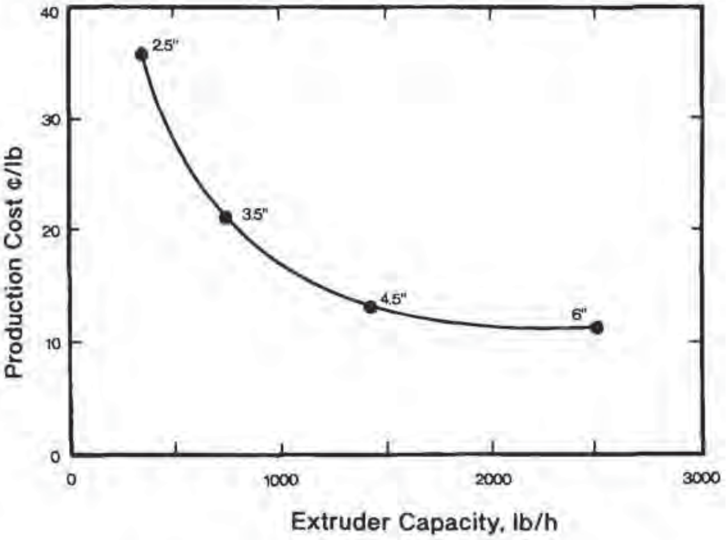

Figure 10.12 Throughput-dependent minimum production cost [1992] for sheet extrusion. Redrawn from [7] and used with permission of copyright owner

Example 10.1 Material Cost for a Polycarbonate Medical Appliance

A 12-in × 12-in medical appliance is to be thermoformed of 0.250-in thick polycarbonate. Polycarbonate costs $1.25/lb and has a density of 1.2 g/cm³. The initial sheet dimension is 18 in square. Determine the material cost if the conversion cost is $0.40/lb and the trim cannot be reused.

The part volume is:

$$\frac{[12 \cdot 12 \cdot 0.25]}{1728} = 0.0208\ \text{ft}^3$$

The part weight is:

$$0.0208 \times 1.2 \cdot 62.4 = 1.56\ \text{lb}$$

The fraction of trim, Y, is:

$$\text{Y} = \frac{18 \times 18 - 12 \times 12}{18 \times 18} = 0.556$$

The cost of the unit weight of the sheet is:

$$\$\text{MC} = \frac{\$1.25 + \$0.40}{1 - 0.556} = \$3.72/\text{lb}$$

The material cost of the part is:

$$\$3.72 \times 1.56 = \$5.80$$

Approximately 66% of the material cost of the part is in conversion and trim that is unusable.

$$\$MC = \frac{\$V + \$C}{1 - Y} \tag{10.6}$$

where \$V is the virgin polymer cost, \$C is the conversion cost, and Y is the fraction of sheet that is trim. Example 10.1 shows the importance of conversion costs.

Cost of Regrind

Regrind was considered in detail in Section 7.2. The steady-state cost of regrind was given as Equation 7.12:

$$F = \$V + \frac{\$C + Y \cdot \$X}{1 - Y} \tag{7.12}$$

where \$X is the cost of reprocessing the trim per unit weight. The cost of reprocessing includes costs such as grinding, drying, re-extrusion into pellets for easier handling but it does not include the cost of re-extruding the trim into sheet. This cost may also include warehouse costs, labor costs in handling the trim, and shipping costs. Example 10.2 illustrates the role regrind costs play on total material costs. Examples 7.5 and 7.6 illustrate other aspects of regrind costs.

Example 10.2 Material Cost for a Polycarbonate Fresnel Lens

A 12-in × 12-in Fresnel lens is to be thermoformed of 0.250-in thick polycarbonate. Polycarbonate costs \$1.25/lb and has a density of 1.2 g/cm³. The initial sheet dimension is 18 in square. Determine the material cost if the conversion cost is \$0.40/lb. The trim can be reused and its reprocessing cost is \$0.30/lb including drying and repelletizing.

The part and sheet weights of Example 10.1 are used here. The part weight is 1.56 lb. Equation 7.12 is the operative expression:

$$F = \$V + \frac{\$C + Y \cdot \$X}{1 - Y} = \$1.25 + \frac{\$0.40 + 0.556 \bullet \$0.30}{0.444} = \$2.53/\text{lb}$$

The total cost for the part is:

$$\$2.53 \cdot 1.56 = \$3.94$$

Note that the use of regrind reduces the part cost from \$5.80 in Example 10.1 to \$3.94, a \$1.86 savings. Nevertheless the cost of reusing the trim is still about half the total material cost.

Competitive Costs of Polymers

Selection of the cheapest polymer that will meet the customer's performance criterion will not always yield the cheapest part. Some of the reasons for this are apparent and others are not:

- The cheaper polymer may be much more difficult to extrude than a more expensive one,
- The cheaper polymer may not have the intrinsic strength or modulus of a more expensive one and so may need to be slightly thicker, resulting in:
  - Longer heating cycles,
  - Longer cooling times, and
  - Greater trimming problems,
- The cheaper polymer may be more difficult to heat,
- The cheaper polymer may sag more, making it more difficult to thermoform uniformly, resulting in:
  - Increased mold costs for gridding,
  - Longer heating cycles, and
  - Maintenance problems with elements such as sag bands,
- The cheaper polymer regrind may need special treatment such as:
  - Extensive drying,
  - Degassing for foams, or
  - Repelletizing,
- The cheaper polymer may have restrictions on the fraction of polymer that can be recycled owing to:
  - Thermal or oxidative degradation,
  - Greater loss in physical properties such as impact strength, and
  - Greater color change.
- If the full amount of cheaper polymer trim generated cannot be recycled, the excess must be discarded and this cost factored into the actual material cost.

Not all these factors are always operative or significant. A recent software guide has been developed that allows side-by-side comparison of several candidate polymers [8]. This package has been reworked and is available through The Society of Plastics Engineers Thermoforming Division. Table 10.9 gives an example of the results of this software program. Side-by-side candidate polymer comparisons can also be made by repeating the single polymer economics described below. Typically, the more expensive the polymer is, the less important the exact economic details of the process become.

10.5 General Processing Economics

Thermoforming competes with many other polymer molding technologies, including FRP, compact injection molding, structural foam injection molding, blow molding and rotational molding. It also competes with non-polymer technologies such as sheet metal and forging. The standard method of cost analysis begins with a quick "Class C" estimate of the cost of the thermoformed plastic part, to determine if the polymer cost is competitive. If so, more advanced analyses are employed to determine more accurate costs.

Table 10.9 Cost Comparison—ABS, HDPE and Modified PP (Adapted from [8][1])

Dimensions of sheet: 33.75 in × 23.25 in × 0.187 in
Materials to be considered: ABS, HDPE and Modified PP
Number of parts: 2000
Number of parts/sheet: 2

	ABS	HDPE	MPP
INPUT			
Production Information			
Set-up time	—	—	—
Cycle time (s)	125	210	127
Percent trim (%)	30	30	30
Percent reject (%)	2	3	3
Finish time/part (s)	30	30	30
Material loss in regrind (%)	2	2	2
Costs			
Cost of sheet ($/lb)	1.50	0.50	0.90
Trim credit (% of CM)[2]	30	30	30
Regrind cost ($/lb)	0.10	0.10	0.10
Line time cost ($/h)[3]	100.00	100.00	100.00
Set-up cost, flat charge ($)[4]	150.00	150.00	150.00
Finishing cost ($/h)	15.00	15.00	15.00
OUTPUT			
Production Information			
Sheet weight (lb)	5.62	5.06	4.77
Total number parts made	2,041	2,062	2,062
Number defective parts	41	62	62
Total number sheets needed	1,021	1,031	1,031
Total weight of sheet needed (lb)	5,734.7	5,217.2	4,916.8
Reject (lb)	114.6	156.5	147.5
Trim (lb)	1,685.0	1,518.1	1,430.7
Sheet to be reground (lb)	1,799.7	1,674.6	1,578.2
Costs per part			
Cost per sheet ($)	8.425	2.530	4.292
Cost per part			
Sheet ($)	4.301	1.304	2.213
Line time ($)	1.736	2.917	1.764
Additional line time ($)	0.035	0.090	0.055
Set-up cost ($)	0.075	0.075	0.075
Finishing ($)	0.125	0.125	0.125
Regrinding ($)	0.090	0.084	0.079
Credit for regrind ($)	(0.397)	(0.123)	(0.209)
Total cost per part ($)	5.966	4.472	4.101
Total Costs			
Cost of sheet ($)	8,602	2,609	4,425
Cost of line time ($)	3,472	5,833	3,528
Cost of additional line time ($)	71	180	109
Cost of set-up ($)	150	150	150

(Continued)

Table 10.9 (Continued)

	ABS	HDPE	MPP
Cost of finishing ($)	250	250	250
Cost of regrinding ($)	180	167	158
Credit for regrind ($)	(794)	(246)	(418)
Total cost	11,931	8,944	8,202
OUTPUT—INITIAL RUN COST			
Total job cost ($)	12,725.10	9,189.25	8,619.80
Total cost per part ($)	6.363	4.595	4.310
Sheet cost per part ($)	4.301	1.304	2.213
Percent of sheet cost per total (%)	67.6	28.4	51.4
Forming cost per part ($)	2.062	3.291	2.097
Percent of form cost per total (%)	32.4	71.6	48.6
OUTPUT—ONGOING RUN COST[5]			
Total job cost ($)	11,931.45	8,943.66	8,202.21
Total cost per part ($)	5.966	4.472	4.101
Sheet cost per part ($)	3.904	1.181	2.004
Percent of sheet cost per total (%)	65.4	26.4	48.9
Forming cost per part ($)	2.062	3.291	2.097
Percent of form cost per total (%)	34.6	73.6	51.1
OUTPUT—PRODUCTIVITY			
Total sheet used (lb)	5,735	5,217	4,917
Total number sheets used	1,021	1,031	1,031
Thermoforming line time (h)	35.4	60.1	36.4
Total parts made	2,041	2,062	2,062

[1] The software used to obtain these values was donated by Rohm & Haas to Society of Plastics Engineers, Inc., Brookfield Center CT. The program has been checked and reformatted by SPE Thermoforming Division

[2] CM is compounded material

[3] The overall line time cost, $/h, is used in the calculation of cost of line time and cost of additional line time. It is not used in the individual values by resin

[4] The flat set-up cost is used in the calculation of cost of set-up but not in line time cost times set-up time

[5] Includes recycle credit

Rules of Thumb

The largest element in the price of any plastic article made of a commodity polymer is the cost of the polymer. It is well-known [9] that injection molded parts are less than about 2.75 times the polymer costs for 98% of the cases studied, and less than 1.8 to 2.1 times for 50% of the cases. The range of 1.5 to 10 includes all polymers and all processes. The "factor of two" rule evolved from this observation:

> **A first approximation of the manufacturing cost is obtained by doubling the polymer cost.**

More expensive resins require more labor to produce a useful product [10]. Although labor costs increase with increasing unit polymer cost, they do not increase in direct proportion to the polymer cost. Therefore the multiplier for more expensive polymers should be less than that for commodity polymers. For thermoforming, the fixed and variable burden should also be less sensitive to polymer costs. One rule of thumb is a power-law [16]:

$$\$L \approx (\$V)^n \tag{10.7}$$

where $0 < n < 1$. When $n = 0$, the cost is independent of polymer cost, or any other cost. When $n = 1$, the cost is directly proportional to resin costs. For most chemical and plastics operations, $0.4 < n < 0.8$. The "six-tenths rule" is frequently quoted:

$$\$L \approx (\$V)^{0.6} \tag{10.8}$$

where \$L is the cost of direct and indirect labor and \$V is the cost of the polymer. The same rule of thumb holds for fixed and variable burden, \$FVB:

$$\$FVB \approx (\$V)^{0.6} \tag{10.9}$$

External costs, on the other hand, increase with the most expensive polymers, as seen in Table 10.10. The ratio here is selling price per unit polymer cost, and so the ratio is substantially greater than 2.

The nature of conversion from polymer to finished goods also has an influence on the selling price range (Table 10.11). Typically, injection molding and blow molding are more highly automated, more energy efficient and less labor intensive than other conversion processes. The thermoforming polymer cost must include a cost to convert the pellets to sheet. The most probable thermoforming ratio of 3 to 4 in this table agrees well with the general ratio range of 2.8 to 4 in Table 10.11. These ratios should be used only to get an approximate cost for a conceptual part and not for comparative process analysis. More detailed comparisons follow.

Table 10.10 Thermoformed Part Selling Price Range

Polymer	Polymer cost	Labor cost	Fixed/variable burden	Manufacturing cost	External charges	Selling price
LDPE, GPS, HDPE, PP, PVC	1	0.65 to 1	1.5	3.15 to 3.5	0.5	3.65 to 4
PET, ABS, PPS, Cellulosics	1	0.4 to 0.75	1.25	2.65 to 3	0.4	3.05 to 3.4
PA 6, PA 66, POM, PC, PMMA	1	0.3 to 0.5	1.0	2.0 to 2.5	0.5	2.8 to 3.0
PI, PESO$_2$, PEEK	1	0.25 to 0.4	1.0	2.25 to 2.4	0.6	2.85 to 3.0

Table 10.11 Comparative Plastics Process Selling Price Range[1] [9]

Process	Range	Average part range
Compression molding	2 to 10	3 to 5
Injection molding	1.5 to 5	2 to 3
Blow molding	1.5 to 5	2 to 3
Extrusion	2 to 5	3 to 4
Thermoforming	2 to 10	3 to 5
Reinforced construction	2 to 5	3 to 4

[1] Polymer cost factor = 1

Global Production Costs

For the simplest case, where an existing business is producing a single product, the unit cost for that product is obtained by dividing the average *global cost* of the business in a given unit of time by the average number of products produced in that time:

$$\text{Global Part Cost} = \frac{\text{Business Expenses}}{\text{Number of Parts}} \tag{10.10}$$

Approximate costs for several products are obtained this way with proper proportioning of business expenses. The items that make up typical manufacturing plant operating costs are given in Table 10.12. Plant operation is considered "steady state" when supplemental orders for currently manufactured goods are quoted. When new products similar to currently manufactured goods are quoted on, the operation can also be considered "steady state", even though additional personnel and/or operating costs are incurred. This is true only so long as the unit manufacturing time to produce

Table 10.12 Manufacturing Plant Operating Costs

Operating labor	Polymers
Maintenance labor	Additives, admixtures and adducts
Supervision	Molds, cutters, jigs, fixtures
Top management	Auxiliary materials—paint, appliques
Overhead employees—guards, cafeteria	Supplies
Technical support	Maintenance materials
Clerical support—secretaries, computers	Overhead materials
Payroll benefits	Local taxes
Utilities	Insurance
Fuel	Contract services—cleaners, consultants
Steam	Demurrage
Electricity	Containers, cartons, pallets
Water cooling and treatment	

Table 10.13 Existing Business Thermoformed Part Balance Sheet

Inventory of raw materials, month X	–	
Additional purchases, month X	–	
Inventory of raw materials, month X – 1	(–)	
Cost of raw materials consumed, month X	–	
Direct wages, month X	–	
Direct utilities, month X	–	
Other direct expenses, month X	–	
Direct manufacturing expense, month X	=	
Payroll overhead, month X	–	
Plant overhead, month X	–	
Other indirect expenses, month X	–	
Indirect manufacturing expense, month X	–	
Depreciation, month X	(–)	
Indirect costs, month X	=	=
Net cost of work in progress, month X		=
Production costs, month X		=
Inventory of finished goods, month X	–	
Inventory of finished goods, month X – 1	(–)	
New inventory cost, month X	=	=
Gross profit, month X		–
Sales, month X		=

the new product is a small faction, 3 to 8% or so, of the typical product manufacturing time.

For a steady-state operation, the unit time global cost is obtained as shown in Table 10.13. Some items need definition:

- *Raw materials* are all elements that go into the final product, such as:
  Polymer sheet,
  Additives and admixtures, such as:
    Surface-applied antistats,
    Finishing and decorating materials,
    Purchased components, such as:
      Inserts and
      Decorations, and so on.
- Direct wages are paid to *Direct laborers*. These are the people who contact the materials during processing. Direct laborers include:
  Thermoform machine operators,
  Trimmers,
  Dock and warehouse workers,
  Quality control inspectors,

Packers, and
Their immediate supervisors.

- Since it is hard to separate direct and indirect *utilities*, to apportion the amount of power required to operate thermoformers from that required to power the buildings and grounds, utilities are usually considered to be *direct utilities.*
- Note that *direct manufacturing cost* simply represents the material and direct labor costs. *Indirect costs* deal specifically with:
  Benefit package to direct laborers,
  Specific cost of the facility to house direct laborers, and
  Depreciation of the processing and ancillary equipment.
- The *plant overhead* specifically *excludes* the cost of indirect labor people such as:
  Management,
  Technical staff,
  Sales,
  Clerical and
  Support staff.

  The cost of their salaries, wages and benefits or SWB, is subtracted from the *gross profit.*
- The net cost of *work in progress* is usually a small but potentially significant fraction of the total manufacturing cost. Work in progress is material that has been moved from inventory to the work stations, already formed, trimmed, inspected, or packed and not yet in finished product inventory. It can be assumed that these goods have values not much greater than raw material value. Occasionally, finished products are awaiting "rework" and so have values only slightly less than finished goods value. Many cost reduction efforts focus on minimizing the net cost of work in progress.

The *gross profit* is the sales revenue less production costs and increases in inventory value, Table 10.14. The *net profit*, before taxes is the gross profit less SAR[1] [11]. Note that *SAR* includes the total cost or SWB of all indirect labor, including top management. For the 1991-1993 period, SAR for the polymer industry was about 20% of the gross revenue [11].

If a single product is produced, the unit production cost and unit net profit is obtained by simply dividing the global production cost and the net profit by the number of *good* or *salable* pieces produced. Further, if all forming machines are the same and produce parts at the same through put rate, for the same number of clock hours, at the same efficiency, then an accurate value for *machine hour cost* or MHC, is obtained from:

$$\text{MHC} = \frac{\text{Production Cost}}{\text{Number Machines} \times \text{Hours per Machine}} \tag{10.11}$$

For example, if four identical machines each operated 500 h/month at a steady state monthly production costs of \$100,000, the average machine hour cost is \$50/h. In

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[1] *SAR*, is sales, adminstration and other costs such as R&D. *SG&A*, being sales, general and administrative costs, is considered to be equivalent.

Table 10.14 Thermoformed Part Balance Sheet for Net Profit

Sales, month X		=
New inventory, month X		(=)
Production costs, month X		(=)
Gross profit, month X		=
Administration	(−)	
Sales, marketing	(−)	
Advertising	(−)	
Technical service	(−)	
R & D	(−)	
SAR, month X	(=)	(=)
Net profiit before taxes, month X		=

general, machine hour cost is the sum of the total annualized cost to operate a given machine, excluding SAR. The total annual production cost, APC_{Total}, is:

$$APC_{Total} = \Sigma\, M_i \cdot h_i \tag{10.12}$$

where M_i is the machine hour cost of the ith machine and h_i is the annual number of hours that machine is run.

Today, computerized accounting procedures allow accurate record-keeping on individual machines, and so such inaccurate estimates are no longer used for final cost analyses.

Manufacturing Efficiencies

Overall *product efficiency* is the actual number of good or salable parts, divided by the ideal number that can be obtained from a given amount of material. *Process efficiency* is the actual number of parts produced in a given period of time, divided by the ideal number that could be produced in that same time period. Individual efficiencies make up these efficiencies. Care must be taken in applying efficiency factors, since they strongly influence part production cost and can penalize it if not applied correctly:

Not all efficiency factors are multiplicative.

Although thermoforming machines are designed to operate continuously, they rarely do so. The industry average is 70% to 80% or 6100 to 7000 hours per year, Table 10.15. Machine efficiency depends on the start-up condition of the thermoformer. Start-up times for forming new products on new molds with new polymers are substantially longer than for momentary shut-downs, at break for example. Start-up procedures and protocols were discussed earlier in this chapter. Table 10.16 gives some ranges for typical start-up times.

Operators are required for all times except during maintenance, mold change-over or lack of business. Industry average is about 75% or 6600 hours per year.

Table 10.15 Thermoforming Machinery Efficiencies

Nature of time	Machine clock time	Percent of total time
Scheduled maintenance		3
Emergency maintenance		1
Shut-down, no business or mold changeover		20
On but idle, not forming	X	2
Running, start-up, set-up, shut-down, no product, see Table 10.16 for specific start-up times	X	2
Running but off-spec parts	X	2
Running quality product	X	70

Table 10.16 Thermoforming Machine Start-up Times[1]

Stock	Start-up condition	Time since last operation	Cycle time
Roll Sheet	Restart after momentary stop	Minutes	4 to 10 cycles 1 to 2 cycles
Roll Sheet	After extended shut-down	Hours	10 cycles to 1 hour 2 to 4 cycles
Both	Cold start, old mold, known polymer	Weeks	1 to 2 hours
Both	Cold start, old mold, new polymer but homologous to old polymers	NA	2 to 4 hours
Both	Cold start, old mold, new polymer	NA	4 to 20 hours
Both	Cold start, new mold, new polymer	NA	20 to 40 hours

[1] Cycle = time on mold
NA = Not applicable

Operator efficiency is about 80%, although it is slightly lower on evening shifts, weekends and for 10 or 12 hour days. Supervision is required to man machines for at least one-half shift per year. This estimate is obtained from:

$$\text{Supervisor Time} = \left[\frac{\text{Machine Time}}{\text{Operator Time} \times \text{Operator Efficiency}}\right] - 1 \qquad (10.13)$$

Example 10.3 illustrates this. Industry standard for direct supervision on forming machines is about 20% to 30%. For those parts where process cycle time controls production cycle time, labor efficiency usually does not affect the number of good parts produced. Instead, it serves to directly affect the production costs on each good part. On the other hand, when the production rate is labor-controlled, as might be the case where extensive finishing and post-forming operations are needed, labor efficiency contributes directly to the overall manufacturing efficiency.

Example 10.3 Direct Supervisory Time on Thermoforming

The thermoforming machine is operated 67% of the time. An operator is used 75% of the time at 80% efficiency. Determine the amount of time supervision is required.

Direct supervision time is given from Equation 10.12:

$$\text{Supervisor Time} = \frac{0.67}{0.75 \cdot 0.8} - 1 = 0.117 \text{ or } 11.7\% \text{ of the year}$$

$0.117 \cdot 8760$ h/y = 1022 h/y or a supervisor is needed approximately 20 hours per week.

Although machine efficiency allows good parts to run about 70% of the year, there are product losses due to the inherent nature of the process (Table 10.17). The most significant of these are forming defects. For certain products, such as transparent goods, surface blemishes and distortion are major reasons for product losses. Thus, product efficiency is usually 80% to 90%, but the nature of rejection of unsalable product depends strongly on its end use.

Example 10.4 is an in-depth review of the costs associated with an on-going or "steady-state" thermoforming operation. The interaction of manufacturing efficiencies used in this example are not always applicable in every case. Machine hour costs should always be calculated from overall material and energy balances and raw materials should always include purchase prices of assembly components.

Example 10.4 Costing a Part in an On-going Forming Operation

Two thousand VCR covers are to be manufactured of smoky PMMA. Determine the manufacturing cost if these covers are part of an ongoing thermoforming operation. The input data are given as needed in the example.

Material Cost

The unit size is 18 in × 12 in × 4 in deep. The average thickness is 0.100 in. The areal draw ratio is given as:

$$\text{Ra} = \left(\frac{18 \cdot 12 + 2 \cdot 4 \cdot 12 + 2 \cdot 4 \cdot 18}{18 \cdot 12}\right) = 2.11$$

Assume initial sheet thickness is given as:

$$h_o \approx 2.11 \cdot 0.100 = 0.211 \text{ in}$$

Material in part:

$$\text{Part volume} = 0.211 \cdot 18 \cdot 12 = 45.6 \text{ in}^3$$

Sheet dimensions are assumed to be 24 in × 16 in × 0.211. Therefore the sheet volume is:

$$\text{Sheet volume} = 0.211 \cdot 24 \cdot 16 = 81.0 \text{ in}^3$$

The percent trim is 43.7%.

PMMA cost is \$1.65/lb plus \$0.35/lb conversion cost or \$2.00/lb. The density of PMMA is 75 lb/ft^3. Therefore, the part and sheet weights and the part and sheet material costs are:

$$\text{Part weight} = \frac{75 \cdot 45.6}{1728} = 1.98 \text{ lb:} \quad \text{Part material cost} = \$2 \cdot 1.98 = \$3.96$$

$$\text{Sheet weight} = \frac{75 \cdot 81.0}{1728} = 3.52 \text{ lb:} \quad \text{Sheet material cost} = \$2 \cdot 3.52 = \$7.03$$

Machine Cost/Efficiency

Machine hour cost is \$100/hour. This assumes labor, overhead, SWB, but excludes profit. Steady-state cycle time is 3 minutes and is based on about 30 s/mm. The process efficiency is 90%. The set-up time is 2 hours plus 10 unsalable parts. The down-time is 10% of the run-time plus 12 unsalable parts. The set-up time and down-time cost is \$100/hour. Quality control retains 100 good parts. The time to produce good parts is:

$$\text{Time} = \frac{(2000 + 100)}{0.9 \cdot 20} = 117 \text{ hours}$$

Material Balance

Good parts shipped:	2000
Good parts retained:	100
Bad parts, 2 × 117:	234
Set-up rejects:	10
Down-time rejects:	12
Total production	2356

Overall Material Costs

Purchased sheet:	2356 · 3.52 = 8293 lb
Purchased sheet cost:	2356 · \$7.03 = \$16,586.24
Salable product:	2000 · 1.98 = 3960 lb
Salable product cost:	2000 · \$3.96 = \$7,920.00

Assume a trim sheet value of \$0.35/lb. The trim credit is then:

Trim:	8293 − 3960 = 4333 lb
Trim credit:	4333 · \$0.35 = \$1,516.55

Net material cost: \$16,586.24 − \$1,516.55 = \$15,069.69

Unit Cost

Net material cost:	\$15,069.69
Machine hour cost: [117 + 2 + 0.1 · 117] · \$100 = 130.7 hours · \$100 =	\$13,070.00
Finishing, including routering, edge polishing, packaging: \$15/hour · 130.7 h	\$1,960.50

Appliques, metallic tape, package materials, $1.95 per good unit	$3,900.00
Manufacturing cost:	$34,000.19
Manufacturing cost per salable unit:	$17.00
Cost per unit weight of salable unit:	$8.59/lb

Material cost efficiency: $\dfrac{\$7920}{\$15{,}069.69} = 52.6\%$

Material weight efficiency: $\dfrac{3960}{8293} = 47.8\%$

Table 10.17 Thermoformed Part Efficiency

Nature of loss	Percent	Comment on types of failure
Sheet damage in shipment	—	Sheet supplier's responsibility, return for credit.
Sheet fails incoming inspection	—	Blemishes, off-color, unacceptable orientation. Same as above.
Damage in warehouse	0 to 1	Corner damage, crushed roll cores.
Damage during drying	1	Handling, blistering, marring of soft surfaces.
Damage in transit to machine	0 to 1	Cracks in edges of brittle materials, scuffing.
Thermal loss	0 to 1	Overheating, grain wash, discoloration. Thermally sensitive polymers such as PVC, ABS.
Poorly formed	3 to 5	Too thin, uneven wall thickness, blisters, webs. Serious if part dimensions are critical, extreme draw-down, low temperature.
Mold stripping damage	1 to 2	Chill marks, blemishes. Low mold, sheet temperature.
Trimming damage	1 to 2	Dull saws, knives, routers cause split, surface melting, produces excessive dust, threads.
Reject by final inspection—polymer, sheet flaws	1	Sheet imperfections such as gels and draw lines become more apparent after heating and forming. Transparent, thin polymers.
Packing damage	0 to 1	Awkward, bulky parts difficult to handle.
Damage in warehouse, miscellaneous causes	1 to 2	Long-term inventory more susceptible. Also, samples, cut-aparts, take-homes, and so on.
Customer returns	2 to 3	
Total	10 to 20	

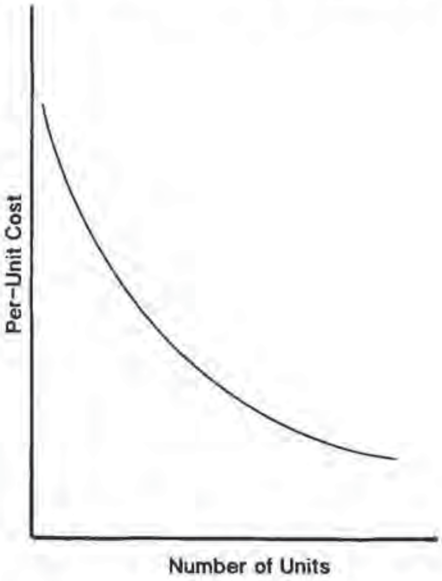

Figure 10.13 An example of the learning curve

The Learning Curve

Efficiencies in the production of new products are lower than those for established products, as seen in Table 10.16. As production continues, learned skills and shortcuts reduce the manufacturing cost per piece. This is usually referred to as the *Learning Curve* (Fig. 10.13). Learning curve arithmetic is used to predict the cost of future parts:

- Let Y be the cumulative average cost per unit. This includes production time, manufacturing cost and so on.
- Let X be the cumulative production, in units. Then:

$$Y = KX^n \tag{10.14}$$

  Where K is the effective cost of the first unit and n is the slope of the learning curve. Typically, $-1 < n < 0$.
- If Y_1 is the cost of the first run of X_1 units, then the average unit cost of the second run is:

$$\bar{Y} = \frac{Y_1[(X_2/X_1)^{n+1} - 1]}{[(X_2/X_1) - 1]} \tag{10.15}$$

  where X_2 is the number of units of the second run. Further, C_X, the cost of the last unit in the production of X units, is:

$$C_X = K[X^{n+1} - (X-1)^{n+1}] \tag{10.16}$$

Example 10.5 illustrates the learning curve. Note that the analysis in this example is global and assumes that a detailed process analysis is well established.

Example 10.5 Determination of the Cost for a Subsequent Run

Consider the "steady state" data of Example 10.4, where 2000 units were produced. Assume that the costs given represent the third order of identical units. The first order was for 1000 units and cost \$24.30 each to manufacture. The second was for 1800 units and cost \$20.30 each to manufacture.

The projected cost of the third order of 2000 is found as follows. $X_1 = 1000$, $Y_1 = \$24.30$, $X_2 = 1800$, $Y_2 = \$20.30$. The first two lots, $1000 + 1800 = 2800$, were manufactured at a cumulative unit cost of:

$$\frac{\$24.30 \cdot 1000 + \$20.30 \cdot 1800}{2800} = \$21.73$$

Thus:

$$\begin{aligned} \ln Y &= \ln K + n \ln X \\ \ln 24.30 &= \ln K + n \ln 1000 \\ \underline{\ln 21.73} &\underline{= \ln K + n \ln 2800} \\ n &= -0.1086 \\ K &= \$51.472, \text{ the unit cost of the first piece sold.} \end{aligned}$$

The average unit cost for each of the next 2000 units is given as:

$$\bar{Y} = \$21.73 \cdot \frac{[(4800/2800)^{0.891} - 1]}{[(4800/2800) - 1]} = \$18.76$$

The cost of the last unit made in the second run, number 2800, is given as:

$$C_X = \$51.472[(2800)^{0.891} - (2799)^{0.891}] = \$19.31$$

The learning curve characteristic is given as:

$$LCC = 100 \ln^{-1} (n \ln 2) = 92.7\%$$

In addition to using the learning curve to predict costs of subsequent products, the slope of the learning curve yields information on production efficiencies. The *Learning Curve Characteristic*, LCC, is defined as:

$$LCC = 100\ e^{(n \ln 2)} \tag{10.17}$$

where n is the slope of the learning curve. If LCC = 100%, learning by experience is not possible and outside influences govern the process. If LCC is less than 60% or so, learning has been expensive, the initial process was very inefficient, or the product was brought to market before the process was fully debugged. Established processing and product schemes have LCCs in the range of about 90% to 95%.

10.6 Isolated Venture Costs

Simple steady-state cost analyses are not recommended when a new business venture is considered. A new venture implies staffing and equipping a new, ground-up facility at a site remote from current operations. All projected manufacturing costs are based on production estimates obtained from accurate market research. Thorough market analysis is mandatory for major installations. Operating expenses, capital costs, and processing costs are far easier to predict than sales and profits. Errors in manufacturing cost projections have much less influence on project profitability than changes in selling price, selling volume, raw material costs, and distribution and transportation costs.

In addition to accurate, detailed market size and price projections, it is important to fully understand the impact of two other elements of the proposed business venture:

- Competition from other thermoformers, and
- Competition from other processors.

Successful business ventures encourage imitators. This effect must be included in long-range sales and profit projections and forecasts. More significant to the early success of the venture is the effect of the potential simultaneous realization of the same or similar new product by two or more businesses. If the venture has a strong likelihood of this event, sales and profit projections must reflect it in lowered expectations of market penetration. Sales projections are frequently time-dependent, showing market penetration to saturation or maturation over a finite number of years. Saturation is followed by a decline in sales as new products replace the now-mature ones. Profits, on the other hand, should continue to increase throughout the growth and maturation time, as production costs follow down the learning curve. Careful market analysis is needed to ascertain the time to maturation and the percent penetration at that time. This value or range in values is the basis for production cost development.

Manufacturing cost, production cost, and fabricating cost are considered here as identical and interchangeable terms. The cost to produce a salable product is partitioned in one of several ways. One way is in terms of direct and indirect costs:

$$\text{Production Costs} = \text{Direct Costs} + \text{Indirect Costs} \tag{10.18}$$

Direct costs are all those elements that are directly related to the production of goods:

$$\text{Direct Costs} = \text{Direct Labor} + \text{Direct Materials} + \text{Other Direct Expenses} \tag{10.19}$$

As noted earlier, *direct labor* is the cost for those people directly connected to or in contact with the product, from receipt of raw materials to loading of finished product. Typically direct laborers are:

- Machine operators,
- Supervisors,

- Foreman,
- Materials handlers,
- Finishers, and
- Inspectors.

Direct labor benefits packages can be included in direct labor costs. Inclusion must be so indicated in any cost analysis, however.

Direct materials are all those materials that are consumed to produce the final product. Direct materials costs should include credits for recovery of trim or unsalable product:

$$\text{Direct Materials Cost} = \text{Incoming Materials Cost} - \text{Returns} + \text{Reclaim Recovery Credit} \tag{10.20}$$

Mold costs are *not* direct materials costs. Other direct costs include:

- The power needed to produce the goods,
- Packaging materials costs, if not already included in the direct materials costs, and
- Outbound freight charges.

All other costs are indirect costs. These include:

- Facility costs,
- Indirect labor and benefits costs,
- Depreciation or amortization of facilities,
- Mold and mold repair costs,
- Repairs and maintenance costs,
- Expendable supplies,
- Rentals and royalties costs,
- Utilities costs except those that are included in direct costs,
- Security, cafeteria and stockroom costs, and so on.

Production costs are also partitioned into those costs that are proportional to production rate and those that are not:

$$\text{Production Costs} = \text{Variable Costs} + \text{Fixed Costs} + \text{Semivariable Costs} \tag{10.21}$$

A *fixed cost* is one that is independent of production rate. Some typical fixed costs are:

- Insurance,
- Property taxes,
- Plant management,
- Engineering personnel,
- Laboratory personnel,
- Maintenance supervision,
- Plant security,
- Maintenance shops such as tool-room and mold repair room,

- Stockroom,
- Depreciation of facility,
- Depreciation of ancillary machinery, laboratory equipment, computers, electrical equipment,
- Depreciation and maintenance of cafeteria, roads, parking lots, sewers, fences,
- Fire protection costs and fees,
- Accounting,
- Purchasing,
- Quality control, all aspects, and
- Traffic dispatching.

Variable costs are those that are proportional to the production rate. These costs include:

- Raw material,
- Operating labor,
- Materials handling,
- Royalties and rentals,
- Supervision, and
- Operating supplies.

Semivariable costs are those that increase with increasing production rate but not necessarily in direct proportion. Some costs plateau or peak with production rate. Examples are:

- Depreciation of equipment,
- Maintenance,
- Repair and replacement,
- Mold costs,
- Utilities, and
- Outbound freight, to some extent.

There are general accounting software programs available for most office computers. None are specific enough to yield production costs for new thermoforming business ventures. Several aspects of production cost projections must be reviewed when developing new business schemes. Some of the concepts that follow are also used in Example 10.9, an illustration of projected costs for a new venture.

As noted, the new production rate is time-dependent. *All* production costs must be clearly accounted for. But no production cost should be counted more than once. *Depreciation* is a measure of the falling value of a piece of equipment. Special purpose equipment should be depreciated at a rate faster than that for general purpose equipment[1]. *Mold costs* should not include installation. Care must be taken

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[1] Federal guidelines dictate the appropriate lifetime of equipment for tax purposes. Business has some option as to rate of depreciation and the practical lifetime of the equipment. Equipment should be replaced when it is apparent that new technologies are making the current equipment too costly to operate. Certainly, no business should keep obsolete or inefficient equipment just because it has not been fully depreciated for tax purposes.

when accounting for the cost of molds. Occasionally, mold costs are amortized over a fixed number of years and so become semivariable costs. Or mold costs are charged against a specific number of sold parts. Current practices set mold costs aside, to be so noted in the projected production cost summary. The costs of mold installation and repair are variable costs and should be included in all projected production cost analyses, however[1].

Once the marketing and early cost incentives indicate a business need for a new thermoforming business venture, determination of the optimum scheme for fabricating the requisite goods follows. Necessary fabrication equipment is researched. If the new product can be fabricated on already-available equipment, specifications are prepared and quotations requested. If available equipment needs to be modified or if specialized equipment is needed, development laboratories of equipment suppliers should be contacted to determine cost and availability to run demonstrations or trials of the to-be-formed parts. Obvious decisions must be made on the capacity of the equipment, given the needed production rate at market maturity. An oversized forming press can be inefficient and costly on a per unit basis, particularly if it sits idle for lengthy periods. An undersized press, on the other hand, may require additional maintenance costs and incremental costs of added shifts to maintain production rate. A table listing all capital cost items and associated installation costs should be made at this time.

When the proposed processing scheme has been accepted by engineering and management and the requisite equipment lists approved by all, production cost analyses follow. In the analysis of Example 10.6 discussed below, the purchase price of the equipment is assumed to be known. Further, it is assumed that the part design is relatively complete and so the unit material cost is known.

Typically, a production layout schematic is prepared (Fig. 10.14). It shows approximate equipment location, floor space, warehouse space, and so on. The process is then "walked through and timed" and manpower allocated. With this information and the estimates of other indirect cost, a quick product cost study, similar to the "steady-state" example, Example 10.4, is done. This will allow a "go-no-go" decision to be made on economic feasibility. Expected manufacturing efficiencies must be carefully thought out at this point and included in this study. Other elements must be included in the projected production costs in addition to standard material and labor costs. *Depreciation* and *profit* are two. Depreciation is usually considered as the tax-free portion of the difference between income and expenditure. The *average annual depreciation* is obtained by dividing some measure of the net cost of an item of fixed capital, by its useful life. There are several ways of *discounting* the item:

- Straight-line depreciation,
- Declining balance,
- Double-declining balance,

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[1] For custom molders, mold costs are usually borne by the customer. However, the custom molder should make certain that mold installation, maintenance, and repair costs are properly accounted for in the unit cost of the part quoted to the customer.

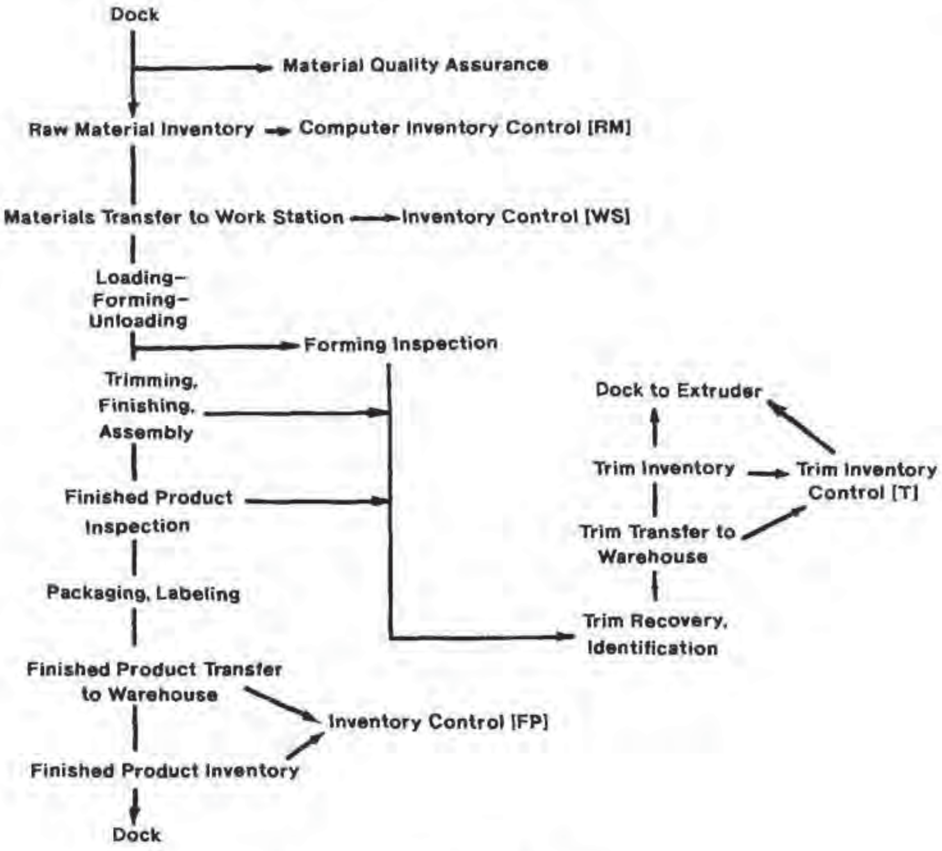

Figure 10.14 Typical thermoforming materials flow layout

- Sum of years digits, and
- Sinking fund.

These methods are compared in standard economics texts [12,13]. Consider the simple straight-line depreciation. If F is the fixed value of the capitalized item, S is its scrap value, and N is its useful life, then the average annual depreciation for any year, D_{SL}, is given as:

$$D_{SL} = \frac{F - S}{N} \tag{10.22}$$

The book value, BV, after n years is:

$$BV = F - nD_{SL} \tag{10.23}$$

For the sum-of-years digits depreciation, D_{SY}:

$$D_{SY} = 2(F - S)\frac{[N - n - 1]}{N(N + 1)} \tag{10.24}$$

The equipment book value after n years is:

$$BV_{SY} = 2(F - S)\frac{[1 + 2 + \cdots + (N - n)]}{N(N + 1)} + S \tag{10.25}$$

The annual depreciation and book value at the nth year for sum-of-years digits and straight-line depreciation schemes are illustrated in Example 10.6.

Example 10.6 Comparison of Depreciation Rates for Thermoforming Equipment

A $100,000 former has a $10,000 scrap value after 10 years. Determine its book value after 5 years using straight-line depreciation. Compare the value with sum-of-years digits depreciation.

Table 10.18 gives a comparison of straight-line and sum-of-years digits depreciation for this example. After 5 years using straight-line depreciation, the former book value is $55,000. For sum-of-years digits depreciation, the former book value is $34,550.

Table 10.18 Annual Depreciation and Book Value Schemes for Thermoform Machinery
(Capital Cost = $100,000, Scrap Value = $10,000, Useful Life = 10 Years)

Year	Sum-of-years digits		Straight line	
	Annual depreciation ($)	Book value ($)	Annual depreciation ($)	Book value ($)
0	18000	100000	9000	100000
1	16360	83640	9000	91000
2	14730	68910	9000	82000
3	13100	57450	9000	73000
4	11450	49270	9000	64000
5	9820	34550	9000	55000
6	8180	26360	9000	46000
7	6550	19820	9000	37000
8	4910	14910	9000	28000
9	3300	11640	9000	19000
10	1640	10000	9000	10000

It is assumed for an isolated venture that external financial sources are to be sought. The *interest* on borrowed monies is the inducement offered to the lender to accept the risk of the venture. Interest rates vary but are usually greater than the prevailing prime lending rate. The *capitalized cost of equipment*, FK, should include the interest on borrowed money. This is given as:

$$FK = \left[F - \frac{S}{(1 + i)^M}\right] \cdot \left[\frac{(1 + i)^M}{(1 + i)^M - 1}\right] \tag{10.26}$$

where M is the number of payment years and i is the interest rate fraction. Example 10.7 shows how the capitalized cost of equipment compares with its purchase price.

Example 10.7 The Cost of Money

The $100,000 piece of equipment described in Example 10.6 is to be financed with an 8-year note at 15% interest. Determine the actual cost of the equipment. Is it cheaper to finance it for 10 years at 12% interest?

The capitalized cost of the equipment, including the interest is given as:

$$FK = \left[F - \frac{S}{(1+i)^M}\right] \cdot \left[\frac{(1+i)^M}{(1+i)^M - 1}\right] = \left[\$100{,}000 - \frac{\$10{,}000}{3.059}\right] \cdot \frac{[3.059]}{[2.059]}$$
$$= \$143{,}710$$

Thus $143,710 − $100,000 = $43,710 is the interest paid on the money over the 8 year period of time.

For M = 10 and i = 0.12, FK = $142,740. Or financing it over 10 years saves $970 or less than 1% of the capital cost.

When a business is begun, monies must be set aside for working capital and start-up capital. *Start-up capital* is the amount of financial resources needed to meet immediate costs to begin the business. In reality, these costs are part of the working capital costs, but usually concentrated at the very beginning of the program. Some of these costs might be:

- Initial interest on borrowed monies for
    - Architect's fees,
    - Site evaluation,
    - Site preparation,
    - Building construction,
- Building permits and operating licenses,
- Equipment installation,
- Equipment start-up costs, including labor,
- Personnel living expenses,
- Initial payment on raw materials,
- Contingency fees and expenses,
- Utilities deposits, and so on.

Working capital is the amount of money needed to meet day-to-day operating expenses (Table 10.19). Initially, nearly all working capital is start-up capital. Within a few months of established production, start-up costs should be small when compared with net costs for materials and accounts (Fig. 10.15).

Projected production costs must ultimately focus on *profit*. For a business to succeed, a reasonable fraction of the selling price of the product must be returned as profit. Two types of profitability are normally considered:

Table 10.19 Working Capital Costs

Inventories	Raw materials Intermediate materials, warehoused Ancillary materials, purchased components, packaging Finished product, unpacked, shipment-ready
Start-up costs	Payrolls Supplies Raw materials Utility deposits
Money	Emergency funds Monies to cover [accounts receivables minus accounts payable]
Running costs	Inventory control Warehousing Transportation Insurance deposits Taxes, prepayments only

- Rate of return on investment, ROI, and
- Discounted cash flow.

Rate of return is a traditional way of measuring profitability:

$$\text{Fractional ROI} = \frac{\text{Annual Profit}}{\text{Invested Capital}} \tag{10.27}$$

Unfortunately, there are many ways of defining profit and invested capital. Profit could be net annual profit before or after taxes. Or it could be annual cash income before or after taxes. Capital can be:

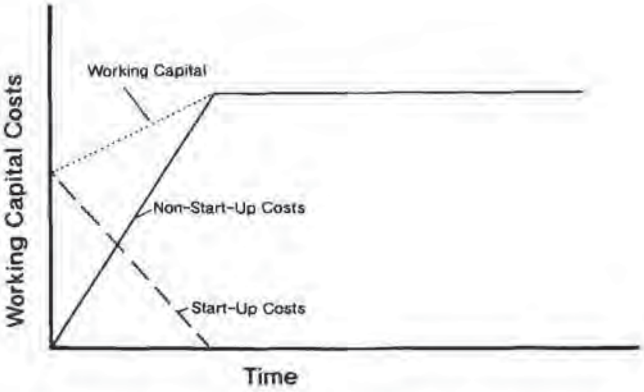

Figure 10.15 Schematic of time-dependent working capital costs. Figure adapted from [16] and used with permission of McGraw-Hill Book Company, copyright owner

- The original invested capital,
- Depreciated investment,
- Current investment, or
- Time-averaged investment.

If the fractional rate of return, ROI, is based on the initial cash investment, F, and the net annual profit after taxes, PAT, the ROI is:

$$\mathrm{ROI} = \frac{\mathrm{PAT}}{\mathrm{F}} \tag{10.28}$$

The net annual cash income after taxes, CIAT, is the sum of the net annual profit after taxes and the average annual depreciation, regardless of the depreciation method:

$$\mathrm{CIAT} = \mathrm{PAT} + \mathrm{D} \tag{10.29}$$

Again, D is obtained from the appropriate depreciation scheme. The effect of depreciation on ROI is shown in Fig. 10.16 [13]. ROI methods have been refined to include more carefully calculated items such as land value appreciation and initial start-up costs. Similarly, there are other traditional techniques as *payback period*, the time needed for net cash flow to recoup original fixed capital costs. Typically, all these techniques lack the flexibility to account for the time-dependent nature of new ventures.

Profitability must be a quantification of the attractiveness of taking a risk, *Discounted cash-flow rate of return*, i, and *net present worth*, NPW, are two such quantifying method. Cash flow, CF, is essentially the transient money supply. Cash-flow value is much greater at the beginning of a project than when the project is fully established. Initially, cash flow is negative. Start-up costs are not balanced by incoming sales revenues. Eventually, start-up costs drop to zero, working capital costs stabilize, and incoming monies exceed expenditures. This produces a positive

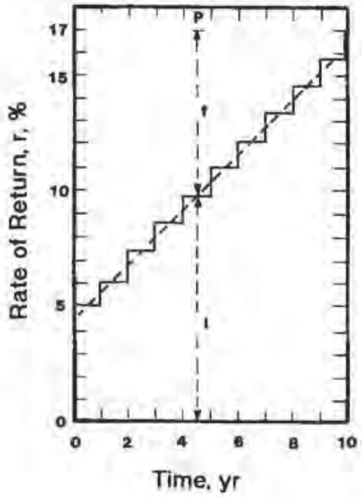

Figure 10.16 Time-dependent rate-of-return for sum-of-years digits depreciation. i is interest rate of return, based on net annual profit after taxes, f is depreciation rate, and P is gross rate of return, ratio of net annual cash income to total capital cost. P = i + f. Figure redrawn from [13] and used with permission of McGraw-Hill Book Company, copyright owner

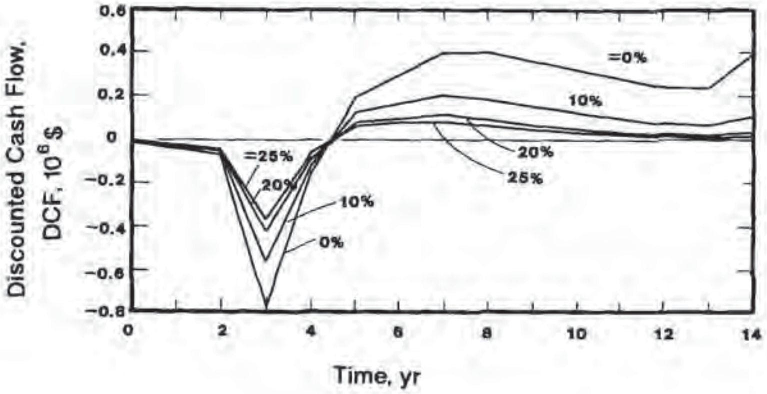

Figure 10.17 Example of time-dependent annual discounted cash flow. Figure redrawn from [13] and used with permission of McGraw-Hill Book Company, copyright owner

cash flow (Fig. 10.17) [13]. *Cumulative cash flow* or CCF is the sum of unit time cash flows. The break-even point is the number of years required to recoup the invested money[1]. The *present value*, P, of a *future sum* of money, f, is given as:

$$P = f \cdot d = \frac{f}{(1+i)^m} \tag{10.30}$$

where d is the discount factor, i is now the *discounted cash-flow rate of return*, and m is the number of years. The discounted cash-flow rate of return is also known as the *profitability index*, PI or the *true rate of return.* IF CF is the annual cash flow, the annual discounted cash flow, DCF, is:

$$DCF = \frac{CF}{(1+i)^m} \tag{10.31}$$

The *net present worth*, NPW, is the running sum of the annual discounted cash flows to the year M:

$$NPW = \sum_{m=1}^{M} DCF_m \tag{10.32}$$

To obtain a suitable value for i, the discounted cash-flow rate of return, the net present work is assumed to go to zero in year M:

$$NPW = \frac{CF_o}{(1+i)^o} + \frac{CF_1}{(1+i)^1} + \frac{CF_2}{(1+i)^2} + \cdots + \frac{CF_M}{(1+i)^M} \equiv 0 \tag{10.33}$$

Since i is implicit in this equation, the appropriate value is obtained by iteration, graphical means or table interpolation. The effective use of NPW to obtain the

---

[1] In the examples that follow, it is assumed that all the capital costs are required at the very beginning of the project. In reality, capital costs are usually ongoing throughout the lifetime of the project, particularly as competitive pressures force manufacturing to become more efficient.

discounted cash-flow rate of return depends on the accuracy of annual cash-flow estimates. Sound venture decisions depend on an accurate interpretation of NPW versus discounted cash-flow rate of return.

Several points are worth noting here. First, depreciation is not considered a separate expense. Instead, it is deducted from the annual cash flow before the net present worth is calculated. The discounted cash-flow rate of return represents the fraction of money returned on the investment *plus* sufficient funds to repay the initial investor, interest on borrowed monies, taxes and expenses. Tables 10.21 and 10.22 illustrate the interactions of cash flow, net present worth and discounted cash-flow rate of return for a made-up example, Example 10.8. Created values for annual sales and expenses are used here. To achieve a zero net present worth value at 10 years, the discounted cash-flow rate of return must be 14.2%. The break-even point, where actual costs are recouped, occurs shortly after 5 years.

Example 10.8 An Example of Discounted Cash Flow and Net Present Worth

A \$1,000,000 forming machine is purchased and installed in a new part of the plant. The new plant cost is \$40,000 and \$160,000 working capital is needed to get the operation going. The annual expenses increase with time according to:

$$\text{Annual expenses} = \$100{,}000 + N \cdot \$10{,}000$$

The depreciation value of the machine is zero after 10 years. The plant and land is worth \$200,000 after 10 years. The output from this machine yields the following annual sales:

Year 0 to 1	*–0–*
Year 2	*\$1,500,000*
Year 3 to 4	*1,000,000*
Year 5 to 7	*800,000*
Year 8 to 10	*400,000*

Determine the discounted cash flow and net present worth after 5 years and after 10 years.

Table 10.20 reviews the data. In Table 10.21, it is seen that the cash flow at 5 years is \$225,000. At 10% discount, the cash flow is \$140,000 and the net present worth is −\$165,000. At 10 years, the cash flow is \$50,000 + the proceeds from the sale of the plant and land. At 10% discount, the cash flow is \$97,000 and the net present worth is \$217,000. The 10 year "break-even" discount rate is about 14.2%.

The *payback period* or PBP is defined in terms of the discounted cash-flow rate of return. Simply, it represents the ratio of capital expenditures to cash flow. For a single capital investment, F, and an annual cash flow, CF, the payback period is just:

$$\text{PBP} = \frac{\text{F}}{\text{CF}} \tag{10.34}$$

Table 10.20 Net Present Worth [NPW] and Discounted Cash-Flow Rate-of-Return [i]

[F]	Capital equipment cost, one-time	$1,000,000
[S]	Scrap value	–0–
[N]	Process NPW = 0 in [N] = 10 years	
[WC]	Working capital cost	160,000
[L]	Cost of land	40,000
[K = F + WC + L]	Total capital cost	1,200,000
[D]	Annual SL depreciation, D = [F − S]/N	100,000
[E]	Annual Expenses = $100,000 + N · $10,000	
[$]	Annual Sales:	
	Year 0 to 1 –0–	
	Year 2 $1,500,000	
	Year 3 to 4 $1,000,000	
	Year 5 to 7 $800,000	
	Year 8 to 10 $400,000	

If the net present worth to the nth year is:

$$\mathrm{NPW} = \mathrm{F} - \mathrm{CF} \cdot \mathrm{d}' \equiv \mathrm{F} - \mathrm{CF} \cdot \Sigma(1 + \mathrm{i})^{-n} \tag{10.35}$$

then $\mathrm{PBP} \equiv \mathrm{d}'$. If $n = \infty$, $\mathrm{PBP} = (1/\mathrm{i})_{\max}$. For example, if the payback period is 5 years, the maximum discounted cash-flow rate of return is just 20%.

The equations presented so far assume no inflation. If a general average *inflation*, I, is included, the net present worth becomes:

$$\mathrm{NPW} = \mathrm{CF}_o + \sum_{n=1}^{M} \frac{\mathrm{CF}_n}{(1 + \mathrm{i})^n (1 + \mathrm{I})^n} \tag{10.36}$$

And the effect on discounted cash-flow rate of return is to generate a new rate of return, called the *effective discounted cash-flow rate of return*, i_e:

$$\mathrm{i}_e = \frac{(1 + \mathrm{i})}{(1 + \mathrm{I})} - 1 \tag{10.37}$$

For example, if i = 20% with an inflation rate of I = 10%, the effective value of i_e would be only 9.1%. Other terms are reduced in similar manners.

10.7 New Venture Economics

The previous sections serve to introduce certain important general accounting terms. Example 10.9 illustrates how these are applied to a new venture, again defined as a stand-alone, remote facility. In this example, the costs are based on buying land and constructing a building to house the production facilities. Further, equipment is purchased as capital equipment, to be depreciated over a reasonable time. Alternate costing methods should include renting facilities and leasing equipment.

Table 10.21 Net Present Worth

Year	Sales (10^3 \$) [S]	Expenses (10^3 \$) [E]	Income (10^3 \$) \$ − E = i	Depreciation [D] (10^3 \$)	Taxable Income I − D = TI (10^3 \$)	50% Tax (10^3 \$) T = 0.5 · TI	Total capital cost (10^3 \$)	Cash flow (10^3 \$) [CF]	Discounted cash flow (10^3 \$) [DCF] = [CF]d		Net present worth, (10^3 \$) [NPW]	
									i = 10%	i = 15%	i = 10%	i = 15%
0	0	0	0	0	0	0	1200	−1200	−1200	−1200	−1200	−1200
1	0	110	−110	100	−210	0	0	−210	−191	−183	−1391	−1383
2	1500	120	1380	100	1280	640	0	640	528	484	−863	−899
3	1000	130	870	100	770	385	0	385	298	253	−565	−646
4	1000	140	860	100	760	380	0	380	260	217	−305	−429
5	800	150	550	100	450	225	0	225	140	119	−165	−317
6	800	160	540	100	440	220	0	220	124	95	−41	−222
7	800	170	530	100	430	215	0	215	110	81	69	−141
8	400	180	220	100	120	60	0	60	28	20	97	−121
9	400	190	210	100	110	55	0	55	23	16	120	−105
10	400	200	200	100	100	50	−200	250	97	62	217	−43
	7100	1550	5550	1000	4550	2330	1000					

[1] Discount factor, d, given in Table 10.22

Table 10.22 Discount Factor, $d = (1 + i)^{-n}$

Year	i = 0	= 10%	= 15%	= 20%	= 30%	= 40%
0	1	1.000	1.000	1.000	1.000	1.000
1	1	0.909	0.870	0.833	0.769	0.714
2	1	0.826	0.756	0.783	0.592	0.510
3	1	0.751	0.658	0.579	0.455	0.364
4	1	0.683	0.572	0.482	0.350	0.260
5	1	0.621	0.497	0.402	0.269	0.186
6	1	0.524	0.432	0.335	0.207	0.133
7	1	0.513	0.376	0.279	0.159	0.0949
8	1	0.467	0.327	0.233	0.123	0.0678
9	1	0.424	0.284	0.194	0.0943	0.0484
10	1	0.386	0.247	0.162	0.0725	0.0346

Example 10.9 New Business Venture—CPET Dinner Trays

A new business is being considered. The product is CPET dinner trays, 8 × 10 × 3/4-in deep. The finished part average wall thickness is 0.030 in, the areal draw ratio is 1.34, the initial sheet thickness is $0.030 \cdot 1.34 \approx 0.040$ *in, and the on-mold cycle time is 12 s. After careful evaluation, engineering selects a special purpose, roll-fed thermoformer with rapid-response high-temperature quartz heaters, sheet temperature monitoring and feed back control, but with essentially standard camel-back trimming equipment. Part layout on its platen yields 4 trays per cycle with 50% trim. The fixed capital cost for the unit is $645,000, as detailed in Table 10.23. The one-time capital costs, including building and land, is estimated to be $2,205,000. The former selected by engineering has a maximum production rate of:*

$$MPR = (24 \cdot 365)\ h/y \cdot (unit/cycle) \cdot (cycle/h) = 10{,}500{,}000\ units/y$$

Through careful discussions with prospective customers, an estimate of the selling price is determined[1]*. In this study, marketing estimates that 4,000,000 units/y can be sold at about $1.75/unit. They estimate that sales will build to this level in 2 years and plan on discontinuing the product line after 5 years. Price elasticity allows discounting to achieve 6,000,000 units/year. One shift, 2000 h/y, produces a maximum of 2,400,000 units/year. Therefore, a three-shift operation without weekends is indicated. The sheet is to be purchased in 1000-lb rolls at $0.90/lb. Owing to loss in IV of PET, it is decided to restrict regrind level to 10%. The rest of the trim is sold at auction for $0.20/lb. Additional data are given in Table 10.24. Management has found capital investment monies at 10%, a semiskilled labor force at $10/h, plus $4/h benefits and no shift differential. Only half the labor force is needed the first year. Management would like NPW = 0 in five years. Therefore the capital equipment is to be internally straight-line depreciated over 5 years. The building and equipment scrap values are given in Table 10.23. The land does not decrease in value during this time. Molds are expected to last at least 1,000,000*

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[1] A good guess of the selling price of the product must be made early in any venture analysis to determine if the effort is worth pursuing. The Class C estimate discussed earlier is a good starting point.

Table 10.23 Fixed Capital Costs and Mold Costs Thermoformed CPET Tray

Fixed capital costs Item	Capital costs (10^3 \$)	Scrap value (10^3 \$)	5 year SL depreciation (10^3 \$)	Installation (10^3 \$)
Thermoformer, roll-fed	450			45
Trim station and web roll-up	75			8
Web regrind	20			4
Ancillary equipment, mold heaters, warehouse equipment	35			5
Contingency	65			10
	645	0	129	72
Building, 40,000 ft^2 @ \$35 (including heated warehouse)	1400	400	200*	
Land, 4 acres @ \$40,000 (fully improved)	160	160	0	
Total capital cost	2205	560	329	72

Mold costs
Steel molds, 4-cavity, channeled for oil heat
Unit cost = \$5000
Lifetime = 1,000,000 units
Contingency = 20%
Cost to produce 2,000,000 good parts: 3.175 × 1.2 = 3.81, say 4 @ \$5000 = \$10,000
Cost to produce 4,000,000 good parts: 6.35 × 1.2 = 7.6, say 8 @ \$5000 = \$20,000

---

* Normally buildings are depreciated over 20 or 30 years. This value is used for this example only.

units and cost \$5,000 each, Table 10.23. Engineering estimates that the special purpose machine will be functional only about 70% of the clock operating time. They expect good parts 90% of the functional machine time. Three shifts, 6000 h/y, will produce:

$$\text{Good parts}/y = 6000\ (h/y) \cdot 4 \cdot (5 \cdot 60) \cdot 0.9 \cdot 0.7 = 4{,}500{,}000$$

Each shift requires the following direct labor force:

2 machine operators,
1 materials handler,
1 supervisor,
1 QC/inspector,

and the following indirect labor:

1 maintenance man per shift,
1 shipping clerk per shift,
1 mold man per shift,
1 handyman per shift, and
1 shop secretary per day.

Table 10.24 Sheet Material Cost Thermoformed CPET Tray

Sheet material cost = $2/kg or $0.90/lb
Sheet contains 10% regrind
Scrap value of regrind = $0.45/kg or $0.20/lb
Density of PET = 1.37 g/cm^3
Material used in single tray:
    $20.3 \cdot 25.4 \cdot 0.1 = 51.6\ \text{cm}^3$ or $32.1\ \text{in}^3$
    $51.6\ \text{cm}^3 \cdot 1.37 = 70.6$ g or 0.156 lb
    Web = 50% sheet = 70.6 g or 0.156 lb
    Total single tray weight = 141.2 g or 0.311 lb

Code	Item	2 × 10^6 trays/y	4 × 10^6 trays/y
N1	Actual number of trays needed, = No./(0.9 · 0.7)	3.175 × 10^6	6.35 × 0^6
MT	Material used	448,000 kg 968,000 lb	895,000 kg 1,975,000 lb
Mt	Material sold as trays	141,000 kg 311,000 lb	282,000 kg 620,000 lb
R	Material reclaimed (MT-Mt)	307,000 kg 676,000 lb	613,000 kg 1,355,000 lb
F′	Fraction recovered in new sheet, 0.1·MT	45,000 kg 99,000 lb	90,000 kg 198,000 lb
S′	Amount sold as scrap (R-F′)	262,000 kg 577,000 lb	577,000 kg 1,157,000 lb
VS	Scrap value*	$118,000	$235,000
G	Gross polymer cost*	$896,000	$1,790,000
MC	Net material cost* (G-VS)	$778,000	$1,555,000

* Values are based on metric values only

Power company costs are estimated to be $5 per machine operating hour. Annual property taxes are $60,000 or about 2.7% of fixed capital cost. The industry range is usually 1.5 to 3%. No local tax abatement is given. Annual insurance is $30,000 or about 1.4% of the fixed capital cost. The industry range is usually 1 to 2%.

Determine the return on investment or profitability index for a range of unit selling prices that bracket marketing's selling price estimate. Then determine price elasticity at 6,000,000 units per year.

Table 10.24 gives the material cost for the CPET tray. Table 10.25 summarizes line item elements that make up the operating expenses, Tables 10.26 and 10.27 list the labor costs and SAR, Table 10.28 itemizes the working capital costs without start-up, and Table 10.29 lists the start-up costs. Direct manufacturing costs represent approximately 67 to 75% of the total operating expenses. Start-up costs and working capital costs represent the rest. When the optimum selling price is unknown, a net present worth table is constructed, with a range in selling price values and several values of the discounted cash-flow rate of return. The net present worth is then determined, Table 10.30. In Table 10.31, price elasticity is also determined by

Table 10.25 Manufacturing Costs, Thermoformed CPET Tray (Values in 10^3 \$)

Costs	Year 1		Year 2–5	
Direct manufacturing costs				
Raw materials, Table 10.24	775		1550	
Operating labor, Table 10.26	160		300	
Utilities	13		26	
Maintenance, Table 10.26				
Labor	48		72	
Supplies	48		72	
	1044	1044	2020	2020
Indirect manufacturing costs (excluding SAR, taxes)				
Labor, Table 10.26	216		312	
Benefits, all labor, Table 10.26	152		248	
Operating supplies, expenses	110		150	
Molds, Table 10.23	20		40	
	488	488	750	750
SAR, Table 10.27	331		405	
Property taxes	60		60	
Insurance	30		30	
	422	422	495	495
Total manufacturing costs		1954		3265
Working capital costs, Table 10.28		515		1029
Start-up expenses, Table 10.29		452		–
Operating expenses		2921		4294

evaluating the net present worth range for 6 million units per year, 50% more than marketing projections[1]. Figure 10.18 and Fig. 10.19 show the effect of discounted cash-flow rate of return on net present worth for 4 and 6 million units/year, respectively. Figure 10.20 shows the effect of selling price as well as the effect of price elasticity on the profitability index.

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[1] Equation 10.7 is also applicable to production costs. Here the expenses are considered to increase according to:

$$\text{Expenses} = A \cdot (\text{Units})^n \tag{10.38}$$

where A is a base value and n has the range $0 < n < 1$. For $n = 0.65$, a 50% increase in production rate should increase production expenses by 30%. This value was used to generate the expense data of Table 10.31.

As is apparent from this example, the selling price of the product is strongly dependent on the cost of money, through the discount rate, and the production rate. Typically, selling price and net present worth are usually plotted against the discount

Table 10.26 Labor Costs, Thermoformed CPET Tray

Item	Year 1	Year 2–5
Number of good trays needed	2,000,000	4,000,000
Minimum hours to produce good trays	1,667	3,333
Actual hours to produce good trays, operating hours	2,646	5,291
Number of shifts at 2000 h/shift year	1.3	2.7
Assumed number of shifts	1*	3
Total labor, DL = 5/shift	8*	15
Minimum DL cost @ $10/h	$132,000	$265,000
DL cost based on shifts	$160,000	$300,000
Maintenance labor, total	2	3
Maintenance cost @ $12/h	$48,000	$72,000
Maintenance supplies, = maintenance cost	$48,000	$72,000
Additional indirect labor, total		
Foreman	2	3
Mold shop	2	3
Shipping clerk	2	2
Shop secretary	1	2
Handyman	2	3
	9	13
Indirect labor cost @ $12/h	$216,000	$312,000
Total labor force	19	31
Benefits @ $4/h, all labor (2000 h/yr)	$152,000	$248,000

* One shift + overtime

rate, as shown in Figs. 10.18 to 10.20, based on the data of Example 10.9. Again, this example is much simpler than reality, since all the equipment is purchased at one time, the production rate is steady-state and money is procured at a fixed interest rate.

Once the basic elements of the process and ancillary costs are well understood, a simple computer program is written to provide more accurate, rapid, and complete price v. capacity v. expense profiles. This program is then used to develop other business scenarios and to compare such effects as overtime pay v. additional shift addition.

Entrepreneurial Risks

Many new ventures are proposed by *entrepreneurs*. Venture capitalists frequently require that entrepreneurial projects pay a *risk factor*, in excess of the discounted cash-flow rate of return. Since, in theory, working capital and for the most part, costs for buildings and grounds are fully recoverable, any added risk factor should be applied only to those costs for items that are lost by premature project termina-

Table 10.27 Sales, Administration, Research [SAR] Costs, Thermoformed CPET Tray

Item	Year 1	Year 2–5
Administration, plant manager	$95,000	$95,000
Operations manager	—	55,000
Sales, marketing	55,000	55,000
Purchasing	40,000	40,000
Technical service, engineering	55,000	55,000
	$245,000	$300,000
Benefits, 35%	$86,000	$105,000
SAR	$331,000	$405,000

Table 10.28 Working Capital Costs Excluding Start-up Costs Thermoformed CPET Tray

Item	Year 1		Year 2–5	
Net accounts (Receivables-Payables) 10% annual product value,	$233,000		$465,000	
3X polymer cost, (net) raw materials inventory, 30 days	$65,000		$129,000	
Finished product inventory, 30 days at 3X polymer cost	$194,000		$388,000	
	$492,000	$492,000	$982,000	$982,000
Contingencies, 20%		$23,000		$47,000
Working capital costs		$515,000		$1,029,000

Table 10.29 Start-Up Costs—First Year Only Thermoformed CPET Tray

Item	Cost (10^3 $)
Installation costs, Table 10.23	72
Permits, utilities deposits	5
Outside equipment rental, start-up	35
Personnel on-site living expenses, personnel hiring costs	50
Initial payment on raw materials	120
Interest on start-up monies	120
Contingency fees, expenses	50
Total start-up expenses	452

tion or business liquidation. If CAC is the cost of allocated capital and RR is the risk rate, the minimum acceptable rate, MAR, is:

$$\mathrm{MAR} = \mathrm{CAC} + \mathrm{RR} \tag{10.39}$$

This is written in terms of the discounted cash-flow rate of return as:

$$1 + \mathrm{i} = (1 + \mathrm{BIR}) \cdot (1 + \mathrm{MAR}) \tag{10.40}$$

where BIR is the best risk-free interest rate, from banks, bonds or treasury notes. The net return on invested capital, i, is:

$$\begin{aligned} \mathrm{i,\ Net\ Return} &= \mathrm{Gross\ Return} - \mathrm{Payback\ of\ Capital} - \mathrm{Interest\ on\ Borrowed\ Capital} \\ &\quad - \mathrm{Taxes} - \mathrm{Other\ Expenses} \end{aligned} \tag{10.41}$$

Therefore, the net return, i represents the entrepreneurial return for *managing* the capital used in the venture. And MAR then becomes the *entrepreneurial risk factor*. Example 10.10 illustrates this.

Example 10.10 The Entrepreneurial Risk Factor

Consider a discounted cash-flow rate of return of i = 20%. If the best risk-free interest rate available from a local bank, BIR is 10%, determine the entrepreneurial risk rate. Determine the risk-free income on $100,000. And then obtain the entrepreneurial effective tax-free income.

From Equation 10.40, the entrepreneurial risk rate, MAR is:

$$\mathrm{MAR} = \frac{1 + \mathrm{i}}{1 + \mathrm{BIR}} - 1 = \frac{1.2}{1.1} - 1 = 0.0909 \text{ or } 9.1\%$$

For $100,000 deposited in a bank at 10%, if half is borrowed at 15%, say, and 50% corporate taxes are paid, the risk-free income is:

$$\$50{,}000 \cdot 0.10 - 0.15 \cdot 0.5 \cdot \$50{,}000 = \$1250$$

The BIR is then $1250/$100,000 = 0.0125 or 1.25%. If the same money is invested in a project with an after-tax return of 10%, the entrepreneurial risk factor is:

$$\mathrm{MAR} = \frac{1.1}{1.0125} - 1 = 0.0864 \quad \text{or} \quad 8.6\%$$

or $8600 on $100,000. If the entrepreneur had invested his own money in the venture, he would have achieved an after-tax return of 50% of 10% or 5% on $50,000 or $2500 on $100,000. Therefore, by managing the venture rather than investing in it, the entrepreneur obtains an effective tax-free income of $8600 – $2500 = $6100 on his $100,000 effort. This is nearly 5 times better than the risk-free income route via banks.

Table 10.30 Net Present Worth (NPW) and Discounted Cash-Flow Rate of Return Thermoformed CPET Tray

4,000,000 units per year selling at $2.00 per unit

Year	Sales (10^3 $)	Expenses (10^3 $)	Income (10^3 $)	Depreciation (10^3 $)	Taxable income (10^3 $)	50% Tax (10^3 $)	Total cap. cost (10^3 $)	Cash flow (10^3 $)	Discounted cash flow			Net present worth		
									i = 10%	20%	30%	i = 10%	20%	30%
0	0	0	0	0	0	0	−2205	−2205	−2205	−2205	−2205	−2205	−2205	−2205
1	4000	2921	1079	329	750	375	0	375	341	312	288	−1864	−1893	−1917
2	8000	4294	3706	329	3198	1599	0	1599	1321	1180	947	−543	−713	−970
3	8000	4294	3706	329	3198	1599	0	1599	1201	926	728	658	213	−242
4	8000	4294	3706	329	3198	1599	0	1599	1092	771	560	1750	948	318
5	8000	4294	3706	329	3198	1599	560	2159	1341	868	581	3091	1852	899

4,000,000 units per year selling at $1.75 per unit

Year	Sales (10^3 $)	Expenses (10^3 $)	Income (10^3 $)	Depreciation (10^3 $)	Taxable income (10^3 $)	50% Tax (10^3 $)	Total cap. cost (10^3 $)	Cash flow (10^3 $)	Discounted cash flow			Net present worth		
									i = 10%	20%	30%	i = 10%	20%	30%
0	0	0	0	0	0	0	−2205	−2205	−2205	−2205	−2205	−2205	−2205	−2205
1	3500	2921	579	329	250	125	0	125	114	104	96	−2091	−2101	−2109
2	7000	4294	2706	329	2370	1185	0	1185	979	875	702	−1112	−1226	−1407
3	7000	4294	2706	329	2370	1185	0	1185	890	686	539	−222	−540	−868
4	7000	4294	2706	329	2370	1185	0	1185	809	571	415	587	31	−453
5	7000	4294	2706	329	2370	1185	560	1745	1084	701	469	1671	732	16

Table 10.31 Net Present Worth (NPW) and Discounted Cash-Flow Rate of Return Thermoformed CPET Tray

6,000,000 units per year selling at $1.60 per unit

Year	Sales (10^3 $)	Expenses* (10^3 $)	Income (10^3 $)	Depreciation (10^3 $)	Taxable income (10^3 $)	50% Tax (10^3 $)	Total cap. cost (10^3 $)	Cash flow (10^3 $)	Discounted cash flow			Net present worth		
									i = 10%	20%	30%	i = 10%	20%	30%
0	0	0	0	0	0	0	−2205	−2205	−2205	−2205	−2205	−2205	−2205	−2205
1	4800	3797	821	329	492	246	0	246	224	205	189	−1981	−2000	−2016
2	9600	5582	4018	329	3689	1844	0	1844	1523	1361	1092	−458	−639	−924
3	9600	5582	4018	329	3689	1844	0	1844	1385	1068	839	927	429	−85
4	9600	5582	4018	329	1844	1599	0	1844	1259	889	645	2186	1318	560
5	9600	5582	4018	329	3689	1844	560	2404	1493	966	647	3679	2284	1207

6,000,000 units per year selling at $1.40 per unit

Year	Sales (10^3 $)	Expenses* (10^3 $)	Income (10^3 $)	Depreciation (10^3 $)	Taxable income (10^3 $)	50% Tax (10^3 $)	Total cap. cost (10^3 $)	Cash flow (10^3 $)	Discounted cash flow			Net present worth		
									i = 10%	20%	30%	i = 10%	20%	30%
0	0	0	0	0	0	0	−2205	−2205	−2205	−2205	−2205	−2205	−2205	−2205
1	4200	3797	403	329	74	37	0	37	34	31	28	−2171	−2174	−2177
2	8400	5582	2818	329	2489	1244	0	1244	1011	918	736	−1160	−1256	−1441
3	8400	5582	2818	329	2489	1244	0	1244	934	720	566	−226	−536	−875
4	8400	5592	2818	329	2489	1244	0	1244	850	600	435	624	44	−440
5	8400	5582	2818	329	2489	1244	560	1804	1120	725	486	1744	769	45

* Expenses increased 30% for increased throughput

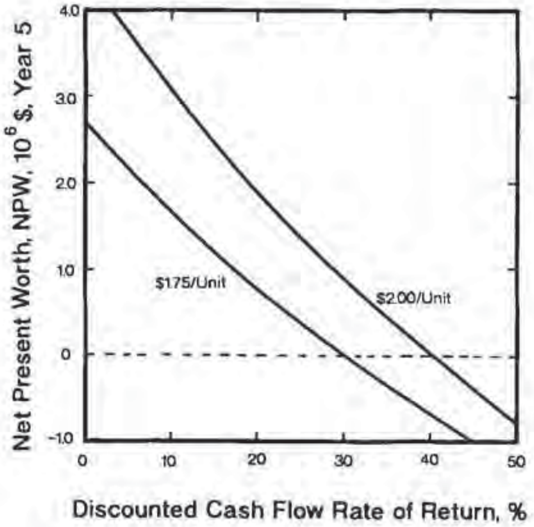

Figure 10.18 Discounted cash-flow rate of return-dependent net present worth for annual thermoform molding of 4,000,000 crystallized polyethylene terephthalate, CPET trays at year 5

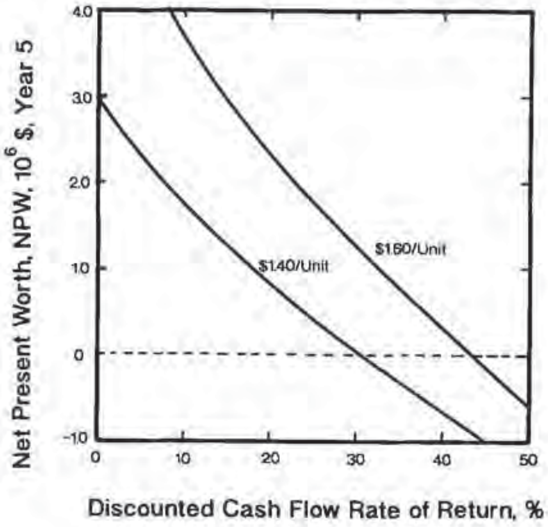

Figure 10.19 Discounted cash-flow rate of return-dependent net present worth for annual thermoform molding of 6,000,000 crystallized polyethylene terephthalate, CPET trays at year 5

Figure 10.20 Price sensitivity analysis for thermoform molding of crystallized polyethylene terephthalate, CPET trays at year 5

10.8 The Incremental Operation

An incremental expansion usually includes addition of a new, dedicated process to an existing plant operation to produce a new product (Table 10.1). If the new process and/or product is very similar to existing operations, the costs are projected from existing business costs. If the new process and/or produce is substantially different from current products, a new business venture plan should be considered. In this case, certain costs such as:

- Start-up costs, and
- Stand-alone ancillary facilities costs including
  - Land,
  - Cafeteria,
  - Power substations, and
  - Parking lots,

are reduced or eliminated. If a modified new venture plan is used, most incremental operating costs are usually much better documented than those for isolated ventures. The information collection procedures are essentially the same however, as shown in Table 10.32. Emphasis is then on determination of the feasibility of expansion at the existing location. In addition to physical location, there are legitimate concerns of adequate space for:

- Materials handling,
- Loading dock,

Table 10.32 Information Collection Procedure, Incremental Operation

Determine market size, share, elasticity
Determine characteristics of product—material, design parameters
Determine cycle times, scrap level
Polymer material specifications, regrind usage, polymer costs
Develop details on process, equipment, cost, delivery
Assess current warehouse, dock, parking, office space utilization
Determine labor requirements
Determine power requirements, costs
Determine cost of plant addition, refurbishing
Obtain management assessment of incremental SAR

- Parking,
- Toilets,
- Traffic control,
- Office space,
- Cafeteria space, and so on.

The adequacy of:

- Sewers,
- Power,
- HVAC, and
- Other utilities,

must also be assessed. If the new process and/or product is technically more advanced than current systems, the availability of a trainable labor supply must be assessed as well. The efficiency of in-plant materials distribution is an important factor in siting any addition. Intrinsically inefficient schemes may require entire plant rehabilitation and this cost *must* be included in the incremental venture cost analysis[1]. The proposed equipment for many systems may be similar or identical to existing equipment. Therefore the initial process efficiencies may be relatively high. For modest incremental systems development, the financial burden is frequently underwritten by the existing business. If this is done, however, management must prudently avoid rate-of-return comparisons between the proposed incremental operation and the current business. The financial status of *all* efforts, including new efforts, must always be assessed against the best available risk-free ventures and not against continuing in-house operations. Example 10.11 illustrates those elements of an isolated venture that are altered to fit an incremental operation.

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[1] The reason for this is apparent. If the new process and/or product had never been conceived, the current functioning of the operation would have continued undisturbed, regardless of how inefficient it was. Therefore the *entire* cost of rehabilitation must be carried by the new venture.

Example 10.11 Thermoformed Camper Top—Incremental Operation

Consider the addition of a camper top production line to an operation currently producing shower stalls, soaking tubs and wading pools. Current ancillary real property is assumed adequate but a 40,000 ft^2 cement block building is needed for the production equipment. The new thermoformer and trimming equipment are identical to existing equipment, although with improved processing controls. The parts formed from PMMA/ABS hot laminated sheet are to be backed with sprayed-up fiberglass-reinforced polyester resin, FRP. This process is new to the corporation. Start-up is assumed to be immediate once equipment delivery and installation are completed. Start-up costs are expected to increase working capital costs by only 10% the first year. Working capital costs are twice net accounts, or receivables minus payables. From experience, the net accounts run about 30% of the annual raw material costs. The final design wall thickness is 0.080 in PMMA/ABS and 0.175 in FRP.

Six good camper tops per hour are to be produced on a two-shift operation. Production efficiency is expected to be 95%. Shift labor is estimated at 20 direct, including maintenance and 20 indirect people. The labor cost is $10/h with $4/h benefits. Determine the unit production cost the first year and every year thereafter, if the operation is designed for a 5 year life and a 10 year life. Determine the approximate selling price per unit.

Table 10.33 gives a review of the fixed capital costs for this incremental addition. Straight-line depreciation is given for both 5 years and 10 years. The building is assumed to have a $400,000 value at the end of the project lifetime. The part dimensions and sheet requirements are given in Table 10.34. The polymer material cost of each good unit is about $215. Additional material costs include window structures and ancillary hardware so that the total product material cost is about $385 per unit. For 24,000 units per year, manufacturing costs are more than $15 million dollars, Table 10.35. Year one includes 10% start-up cost surcharge. The discounted cash-flow rate of return and NPW for both 5 year and 10 year production times are given in Table 10.36. A unit selling price of $725 was used to create this table. At this selling price, for a 5 year neutral NPW, the profitability index, i, is about 15%. For a 10 year neutral NPW, the profitability index, i, is about 28.5%. Price elasticity and the effect of other depreciation schemes are obtained by proper substitution into the arithmetic in Tables 10.33 to 10.36.

10.9 Comparative Process Economics

Thermoforming is a competitive technology. In thin-gage, it competes with:

- Paper,
- Paper-board,

Table 10.33 Fixed Capital Cost Thermoformed Camper Top

(Equipment has zero value after depreciation)

Item	Capital cost (10^3 \$)	SL depreciation 5 y (10^3 \$)	SL depreciation 10 y (10^3 \$)	Salvage ($\times 10^3$ \$)
Shuttle thermoformer—two station	435			
FRP spray-up equipment	210			
Ovens, saws	130			
Ancillary equipment	100			
Contingency	100			
	975	195	98	-0-
Building, 40,000 ft^2 @ \$35	1400	280	140	400
Total	2375	475	238	400

- Paper pulp,
- Plastic-coated paper,
- Expanded polystyrene foam,
- Aluminum, and
- Roll-sheet steel,

and with:

- Plastics extrusion,
- Stretch-blow molding, and
- Injection-blow molding.

In heavy-gage, it competes with:

- Plastics rotational molding,
- Injection molding,
- Blow molding,
- Fiberglass-reinforced polyester resin or FRP as
  spray-up molding, or
  lay-up molding,
- Sheet molding compounds or SMC,
- Bulk molding compounds or BMC,
- Sheet metal forming, and
- Metal die casting.

In certain areas such as equipment cabinets, boxes and containers, thermoforming competes directly with injection molding, blow molding and rotational molding. The comparative characteristics of these processes are outlined in Table 10.37 [10]. Generally when thermoforming is compared with these processes, it is characterized as having higher raw material costs and scrap and lower equipment and mold costs.

Table 10.34 Polymer Material Cost Thermoformed Camper Top

Part dimension = 1270 × 2540 × 508 mm deep
= 50 × 100 × 20 in deep

Part thickness:
PMMA/ABS = 2.03 mm or 0.080 in
FRP = 4.5 mm or 0.175 in

Areal draw ratio:

$$\frac{[1270 \cdot 2540] + 2 \cdot [1270 \cdot 508] + 2 \cdot [2540 \cdot 508]}{[1270 \cdot 2540]} = 2.2$$

Initial thermoplastic sheet thickness = 4.5 mm or 0.175 in

Part weight:

PMMA/ABS	= 1.2 [g/cm³] · 127 · 254 · 0.45	= 17.4 kg or 38.0 lb
FRP	= 1.2 [g/cm³] · 2.2 · 127 · 254 · 0.45	= 38.3 kg or 84.3 lb
		55.7 kg or 122.3 lb

Scrap, zero value:

PMMA/ABS (40%)	17.4 · 0.4 =	7.0 kg or 15.0 lb
FRP (30%)	38.3 · 0.3 =	11.5 kg or 25.3 lb
		18.5 kg or 40.3 lb

Total polymer weight:

PMMA/ABS	24.4 kg or 53.0 lb
FRP	49.8 kg or 109.6 lb
	74.2 kg or 162.6 lb

Sheet material cost:

PMMA/ABS	\$5.00/kg · 24.4 = \$122.00
FRP	\$1.65/kg · 49.8 = \$82.17
	\$204.17

Material cost per good unit: \$204.17/0.95 = \$214.92

Ancillary materials cost: Aluminum trim, metal rails, window assemblies, hardware decoration, decals (purchased) [Assumes all hardware is recoverable]	\$155.00
Shipping crate	\$15.00
Total product material cost	\$384.92

Three decades ago, a major study [14] compared conversion costs for fabricating a 12 in × 12 in × 0.125 in thick five-sided box of LDPE. Four processes were compared:

- Thermoforming,
- Injection molding,

Table 10.35 Manufacturing Costs, 1000 $ Thermoformed Camper Top

Item	Year 1		Year 2+	
Direct manufacturing costs:				
Raw materials	9,238		9,238	
Labor, including maintenance	800		800	
Utilities	40		40	
Other direct costs	200		200	
	10,278	10,278	10,278	10,278
Indirect manufacturing costs:				
Labor	800		800	
Benefits, all labor	640		640	
Operating supplies, expenses	240		240	
Molds	10		10	
	1,690	1,690	1,690	1,690
Incremental SAR, 10% labor	160		160	
Incremental property taxes, insurance	20		20	
	180	180	180	180
Total manufacturing costs		12,148		12,148
Working capital	3,110		3,110	
Start-up costs, 10% working capital	311		—	
	3,411	3,411	3,110	3,110
Expenses		15,559		15,258
Expenses, $ per good unit		$648.29		$635.75

- Blow molding, and
- Rotational molding.

It was anticipated that thermoforming would be the most economical for the production of relatively few units, owing to its low capital and mold costs. And injection molding was expected to be the most economical at high production rates, owing to its lower material and labor costs. The analysis has been redone to 1992 economics using the appropriate machine hour costs and scale factors described earlier and are displayed here in Tables 10.38 and 10.39. The machine hour costs are assumed to be applicable at 100,000 units per year, Table 10.40. Polymer material costs are given in Table 10.41. Process cycle times, scrap percentage, and process efficiencies are estimated from typical processing units [10,15]. Mold, material and finishing costs are representative of the specific processing unit, as well. The comparative manufacturing costs are given in Table 10.42. The thermoforming process yields the lowest unit manufacturing cost for 100,000 parts. Injection molding yields the lowest unit manufacturing cost at one million units. The high machine hour costs for the thermoforming process used in [14] is the primary reason for the relatively flat unit price curve (Fig. 10.21). This is a reflection of the more labor intensive burden carried by thermoforming nearly 30 years ago. However, even at a more-modern machine hour cost scale factor, the inherently higher raw material costs eventually eliminates

Table 10.36 Net Present Worth, Thermoformed Camper Top

Five-year SL depreciation

Year	Sales ($10^3\ \$$)	Expenses ($10^3\ \$$)	Income ($10^3\ \$$)	Deprecia-tion ($10^3\ \$$)	Taxable income ($10^3\ \$$)	50% Tax ($10^3\ \$$)	Total cap. cost*, ($10^3\ \$$)	Cash flow ($10^3\ \$$)	Discounted cash flow		Net present worth	
									i = 10%	20%	i = 10%	20%
0	0	0	0	0	0	0	−2686	−2686	−2686	−2686	−2686	−2686
1	17400	15559	1841	475	1366	683	0	683	621	569	−2065	−2117
2	17400	15258	2142	475	1667	834	0	834	689	653	−1376	−1464
3	17400	15258	2142	475	1667	834	0	834	626	483	−750	−981
4	17400	15258	2142	475	1667	834	0	834	570	402	−180	−579
5	17400	15258	2142	475	1667	834	400	1234	766	496	586	−83

Ten-year SL depreciation

Year	Sales ($10^3\ \$$)	Expenses ($10^3\ \$$)	Income ($10^3\ \$$)	Deprecia-tion ($10^3\ \$$)	Taxable income ($10^3\ \$$)	50% Tax ($10^3\ \$$)	Total cap. cost*, ($10^3\ \$$)	Cash flow ($10^3\ \$$)	Discounted cash flow			Net present worth		
									i = 10%	20%	30%	i = 10%	20%	30%
0	0	0	0	0	0	0	−2686	−2686	−2686	−2686	−2686	−2686	−2686	−2686
1	17400	15559	1841	238	1603	952	0	801	728	667	661	−1958	−2019	−2070
2	17400	15258	2142	238	1904	952	0	952	786	745	564	−1172	−1274	−1506
3	17400	15258	2142	238	1904	952	0	952	715	551	433	−457	−723	−1073
4	17400	15258	2142	238	1904	952	0	952	650	459	333	193	−264	−740
5	17400	15258	2142	238	1904	952	0	952	591	383	256	784	119	−484
6	17400	15258	2142	238	1904	952	0	952	499	319	197	1283	438	−287
7	17400	15258	2142	238	1904	952	0	952	488	266	151	1771	704	−136
8	17400	15258	2142	238	1904	952	0	952	445	222	117	2216	926	−19
9	17400	15258	2142	238	1904	952	0	952	404	185	90	2620	1111	71
10	17400	15258	2142	238	1904	952	400	1352	522	219	98	3142	1330	169

* One-time start-up charge added as depreciation cost in the example, only

Table 10.37 General Characteristics of Comparative Plastics Processes[1]

Characteristic	Thermoforming	Injection molding	Blow molding	Rotational molding
Polymer form	Sheet	Pellets or granules	Pellets	Powder
Variety of polymers	Good	Excellent	Very good	Fair to limited
Raw material cost	Price includes extrusion to sheet	Standard	Standard	Price includes grinding
Types of polymers	Low rubber content	All	Somewhat restricted	No thermally sensitive polymers
Scrap reuse	Economically required	Immediate	Immediate	Usually not practical
Color	Colored sheet	Concentrates	Concentrates	Dry blend
Processability of thermally sensitive polymers	Controllable	Moderate	Difficult	Very difficult
Thermoset polymers	SMC, PUR, foams	Difficult	Not feasible	Possible
Variety of mold materials	Very many	Very limited	Very limited	Many
Mold cost	Moderate to low	Highest	High	Moderate to low
Mold maker reliability	Fair	Excellent	Fair to good	Poor to fair
Mold closure	Rim clamp	Butt	Butt	Tongue and groove
Nonferrous tooling	Excellent	Limited	Limited to good	Good
Method of holding polymer in mold	Mechanical and vacuum	Hydraulic or mechanical	Mechanical	Mechanical
Thermal cycling of mold	Gentle	Moderate	Moderate	Severe
Major trial and error problems	Corner draw-down and wall uniformity	Gating and weld lines	Pinch-off and wall uniformity	Wall uniformity
Cooling method	Air, mold core	Mold core	Mold core and air	Air and water quench
Part release mechanism	Air, stripper plate	Ejector pins	Push pins and air	Manual and air
Life of molds, 10^3	10 to 100	1000 to 100,000	100 to 1000	10

Operating pressure, atm	−1 to 5	100 to 1000	5 to 50	0 to 1
Operating temperature, °C	Room to 200	150 to 300	100 to 250	200 to 350
Controlling portion of cycle	Heating and cooling	Cooling	Blowing	Heating
Skill of operator	Low to moderate	Moderate to high	High	Low
Man to machine interaction	Normally high	Nil to low	Low	Very high
Filling methods	Manual to automatic	Automatic	Automatic	Manual to semi-automatic
Part removal	Manual to semi-automatic	Automatic	Automatic	Manual
Part wall uniformity	Fair	Excellent	Good to very good	Fair
Flash	Highest, trim	Low to very low	Moderate to high	Moderate to low
Inserts	Possible to questionable	Feasible but costly	Feasible	Feasible
Material orientation	Biaxially oriented to uniaxially oriented	Oriented	Uniaxially to biaxially oriented	Unoriented
Stress retention	High	High to moderate	High	Little to none
Method of controlling distortion, warp	Heating	Pressure	Cooling	Air and water cooling
Method of forming hollow part[2]	Welding and twin-sheet forming	Welding	Intrinsic	Intrinsic
Primary mechanical mode of part failure	Thin corners	Weld line	Thin side walls, poor pinch-off	Poor tensile strength
Surface finish	Excellent	Excellent	Very good	Good
Surface Texture	Good to very good	Excellent	Very good	Good

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[1] Adapted from [10] by permission of Marcel Dekker, Inc.
[2] See also Table 9.6

Table 10.38 Plastic Process Scale Factors Updated from [14]

Cost, \$ = A (1000 Units)^n

Process	Manufacturing cost, n	Mold cost, n	Polymer material cost	
			n	A
Thermoforming	0.5 to 0.89*	0.41	−0.14	6.359
Injection molding	0.53	0.45	−0.40	13.29
Blow molding	0.45	0.22	−0.51	23.41
Rotational molding	0.34	0.73	−0.11	4.356

* In [14], the upper value was quoted. Modern thermoforming processes indicate that the lower value is more appropriate

Table 10.39 Typical Machine Hour Costs Plastics Processing—1992[1]

Process	Range (\$/h)	Average (\$/h)
Compression molding, <200 T	75 to 130	80
Injection molding, <150 T	100 to 180	120
Extrusion, 3-in extruder	30 to 65	55
Rotational molding, rotary	30 to 100	50
Thermoforming, shuttle	50 to 105	65
Blow molding, extrusion, gallon bottle	80 to 115	90

[1] Updated and supplemented from [9]

[2] Adapted from [10] by permission of Marcel Dekker, Inc

Table 10.40 Machine Hour Costs for Comparative Process Analysis, Five-Sided Box for 100,000 Units

Process	Cycle Time (min)	Parts (h^{-1})	Total time, 100% efficiency (h)	Overall* efficiency (%)	Actual hours (h)	Machine hour cost (\$/h)	Total machine hour cost, (1000 \$)
TF, 2-up	7	17	5880	85	6920	65	346
IM, 1-up	3	20	5000	90	5560	120	667
BM, 1-up	4	15	6670	85	7850	90	707
RM, 2-up	10	12	8330	75	11110	50	556

* Combined machine and labor efficiencies

Table 10.41 Material Costs for Comparative Plastics Processes, Five-Sided LDPE Box Weighting 3 lb or 1.36 kg

Process	Scrap	Gross material weight		Material form	Material cost		
	(%)	(lb)	(kg)		($/lb)	($/kg)[1]	Total (1000 $)[2]
Thermoforming	25	3.75	1.70	Sheet	0.70	1.54	262
Injection molding	8	3.24	1.47	Pellets	0.45	1.00	146
Blow molding	15	3.45	1.57	Pellets	0.45	1.00	155
Rotational molding	20[3]	3.60	1.64	Powder	0.55	1.21	198

[1] Includes trim recovery value

[2] For 100,000 units

[3] Includes center section of 2-up forming

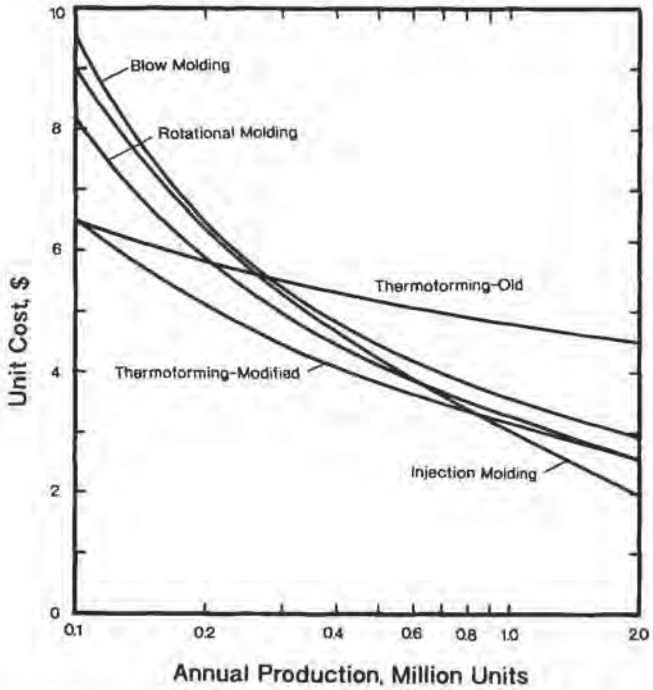

Figure 10.21 Production-dependent unit cost for competitive processes for manufacturing a five-sided box, 12 × 12 × 12 × 0.125 in or 300 × 300 × 300 × 3.2 mm

thermoforming as a competitive economic process as the number of units increases. This is a typical analysis for heavy-gage parts. For thin-gage parts, on the other hand, thermoforming competes quite well with injection molding at any production level.

Table 10.42 Comparative Process Costs, Five-Sided Box

12 in × 12 in × 0.125 in thick
Bold face values indicate minimum unit cost

Process	Machine hour cost*			Material cost*			Material finishing costs*			Mold cost*			Total mfg costs*			Mfg cost/unit ($ unit)		
	100	300	1000	100	300	1000	100	300	1000	100	300	1000	100	300	1000	100	300	1000
TF-Old[1]	346	919	2686	262	674	1898	28	53	110	19	31	50	655	1677	4744	6.55	5.59	4.74
TF-Mod[2]	346	600	1094	262	674	1898	28	53	110	19	31	50	655	1358	3152	**6.55**	**4.53**	3.15
IM	667	1193	2260	146	282	582	–	–	–	81	133	228	894	1608	3070	8.94	5.36	**3.07**
BM	707	1159	1993	155	265	1413	53	104	212	41	52	68	956	1580	3686	9.56	5.27	3.69
RM	556	808	1217	198	527	1824	53	104	212	16	36	87	823	1475	3340	8.23	4.92	3.34

* Global costs are in 1000$ per 1000 units

[1] Machine hour costs are based on a scale factor, n = 0.89

[2] Machine hour costs are based on a scale factor, n = 0.50

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Appendix A
Abbreviations for Thermoformable Polymers Referred to in Text

Abbreviation	Definition
ABA	Poly(acrylonitrile-butadiene acrylate).
ABS	Poly(acrylonitrile-butadiene-styrene).
APET	Amorphous PET.
BOPP	Biaxially oriented polypropylene. Usually thin-gage. Also known as OPP.
CA	Cellulose acetate. One of the family of cellulosics that includes CN, CAP, CAB.
CAB	Cellulose acetate butyrate. Sometimes called cellulose butyrate.
CAP	Cellulose acetate propionate. Also called cellulose propionate or just propionate.
CPET	Crystallized or crystallizing PET. Reserved for high-heat products where PET crystallinity exceeds about 20%.
CN	Cellulose nitrate.
ECTFE	Polyethylene-chlorotrifluoroethylene copolymer. See also FEP.
EPDM	Ethylene-propylene-diene monomer-based thermoplastic elastomer. Also known as a norbornene-based elastomer.
EPM	Ethylene-propylene copolymer. See also TPE.
ETFE	Polyethylene-tetrafluoroethylene copolymer. See also FEP.
EVA	Polyethylene vinyl acetate.
EVOH	Polyethylene vinyl alcohol. Used as a barrier film in packaging applications.
FEP	Fluoroethylene-based polymer. The extrusion and molding grade of PTFE.
FPVC	Flexible PVC. Also called plasticized PVC or soft PVC.
FRP	Glass-fiber reinforced unsaturated polyester resin. Also known as GR-UPE.
GR-UPE	Glass-fiber reinforced unsaturated polyester resin.
HDPE	High density polyethylene (sp.gr. = 0.96 g/cm^3). Also called low-pressure or hard polyethylene.
HIPS	High-impact polystyrene. Also called rubber-modified polystyrene.
LDPE	Low-density polyethylene (sp.gr. = 0.92 g/cm^3). Also called high-pressure or soft polyethylene.

Abbreviation	Definition
MIPS	Medium-impact polystyrene. Also called rubber-modified polystyrene.
mPPO	Modified PPO. A soluble blend of PPO and styrenics.
OPP	Oriented polypropylene. Usually thin-gage.
OPS	Oriented polystyrene. Usually thin-gage.
PS	Polyamide. Also called nylon. Generic unless followed with numbers such as PA 6 for polycaprolactam.
PAI	Polyamide-imide. High-temperature amorphous polymer.
PαMS	Poly-α-methyl styrene. Also known as PAMS.
PAN	Polyacrylonitrile.
PA 6	Polycaprolactam or nylon 6.
PA 66	Poly(hexamethylene diamine/adipic acid) or nylon 66.
PBT	Polybutylene terephthalate.
PCDP	Polydicyclopentadiene.
PEN	Polyethylene naphthanate.
PC	Polycarbonate.
PCTFE	Polychlorotrifluoroethylene. See also FEP.
PE	Polyethylene, generic. See also HDPE and LDPE.
PEEK	Polyetheretherketone.
PEI	Polyetherimide.
PET	Polyethylene terephthalate. Also called thermoplastic polyester or just polyester. Usually the amorphous type of PET or APET.
PETE	Polyethylene terephthalate. The acronym used for recycling PET.
PFEP	Polyfluoroethylene polymer. See FEP.
PI	Polyimide.
PMMA	Polymethyl methacrylate. Also known as "acrylic" although this term can include other types of acrylates as well.
POM	Polyoxymethylene. Also known as polyacetal or just acetal. Can include the copolymer as well.
PP	Polypropylene.
PPA	Polyphthalamide.
PPO	Poly-*p*-phenylene oxide. An intractable polymer unless mixed with other polymers such as styrenics.
PPS	Polyphenylene sulfide.
PS	Polystyrene. Usually refers to the generic family of styrenics, including unmodified or crystal polystyrene and impact grades. See also MIPS and HIPS.
PTFE	Polytetrafluoroethylene.

(Continued)

Abbreviation	Definition
PUR	Polyurethane. Linear or thermoplastic polyurethane is thermoformable. In certain cases, thermoset polyurethane film and low density foam can be thermoformed as well.
PVAc	Polyvinyl acetate. Used as a release agent in mold preparation.
PVB	Polyvinyl butyral.
PSO	Polysulfone. Also given as PSO_2.
PVC	Polyvinyl chloride. See also RPVC and FPVC.
PVDC	Polyvinylidene chloride. Also known as polyvinyl dichloride. Used primarily as a barrier film in packaging applications.
PVF	Polyvinyl fluoride.
PVDF	Polyvinylidene fluoride. Also known as PVF_2. Used as a barrier film in packaging applications.
PVOH	Polyvinyl alcohol. Used as a mold parting agent.
PVK	Polyvinyl carbazole
RPVC	Rigid PVC. Also called unplasticized PVC.
SMA	Polystyrene-maleic anhydride copolymer.
TPE	Thermoplastic elastomer. Although once considered a specific product, now generic designation. Not normally thermoformed.
TPO	Thermoplastic elastomer, usually polyolefinic.
TPX	Polymethylpentene.
UHMWPE	Ultrahigh molecular weight polyethylene.
XLPE	Crosslinked polyethylene. Usually thin-gage or foamed.

Appendix B

Typical Conversion Factors Used in Thermoforming (US Customary to Metric, Metric to US Customary)

European metric	Multiply by	To get US units	Multiply by	To get European Metric
μm	× 39.37×10^{-6}	= inch	× 25.4×10^{3}	= μm
μm	× 0.0394	= mil	× 25.4	= μm
$\mathrm{kg_f}$	× 0.454	= $\mathrm{lb_f}$	× 2.2	= $\mathrm{kg_f}$
Newton (N)	× 0.225	= $\mathrm{lb_f}$	× 4.448	= Newton (N)
cm/s	× 118.1	= ft/h	× 0.00847	= cm/s
$\mathrm{cm^2/s}$	× 3.875	= $\mathrm{ft^2/h}$	× 0.258	= $\mathrm{cm^2/s}$
$\mathrm{gm/cm^3}$	× 62.4	= $\mathrm{lb_m/ft^3}$	× 0.016	= $\mathrm{g/cm^3}$
$\mathrm{kg/m^3}$	× 0.0624	= $\mathrm{lb_m/ft^3}$	× 16.03	= $\mathrm{kg/m^3}$
l/min	× 0.0353	= $\mathrm{ft^3/min}$	× 28.32	= l/min
atm	× 14.696	= $\mathrm{lb_f/in^2}$ (psi)	× 0.068	= atm
Pascal (Pa)	× 0.000145	= $\mathrm{lb_f/in^2}$ (psi)	× 6895	= Pascal
MPa	× 145	= $\mathrm{lb_f/in^2}$ (psi)	× 0.006895	= MPa
GPa	× 145	= 1000 $\mathrm{lb_f/in^2}$	× 0.006895	= GPa
$\mathrm{MN/mm^2}$	× 0.000145	= $\mathrm{lb_f/in^2}$ (psi)	× 6895	= $\mathrm{MN/mm^2}$
$\mathrm{MN/m^2}$	× 145	= $\mathrm{lb_f/in^2}$ (psi)	× 0.006895	= $\mathrm{MN/m^2}$
kW	× 3413	= Btu/h	× 0.000293	= kW

(Continued)

European metric	Multiply by	To get US units	Multiply by	To get European Metric
kW/m^2	× 317.1	= Btu/ft^2 · h	× 0.003154	= kW/m^2
W/cm^2	× 3171	= Btu/ft^2 · h	× 0.0003154	= W/cm^2
cal/cm^2 · s	× 13277	= Btu/ft^2 · h	× 7.54×10^{-5}	= cal/cm^2 · s
cal/g · °C	× 1.00	= Btu/lb · °F	× 1.00	= cal/g · °C
W · s/kg · °C	× 0.000239	= Btu/lb · °F	× 4184	= W · s/kg · °C
J/m	× 0.01875	= ft-lb/in	× 53.34	= J/m
J/m^2	× 4.755×10^{-4}	= ft-lb/in^2	× 2103	= J/m^2
kg/m · s	× 2415	= lb/ft · h	× 4.14×10^{-4}	= kg/m · s
kW/m^2 · μm	× 317.1	= Btu/ft^2 · h · μm	× 0.003154	= kW/m^2 · μm
kW/m · °C	× 578	= Btu/ft · h · °F	× 0.00173	= kW/m · °C
W/cm · °C	× 57.79	= Btu/ft · h · °F	× 0.0173	= W/cm · °C
cal/s · cm · °C	× 241.9	= Btu/ft · h · °F	× 0.004134	= cal/s · cm · °C
cal/s · cm · °C	× 2903	= Btu · in/ft^2 · h · °F	× 3.445×10^{-4}	= cal/s · cm · °C
cal/s · cm · °C	× 7376	= Btu/ft^2 · h · °F	× 1.356×10^{-4}	= cal/s · cm^2 · °C
W/cm^2 · °C	× 1761	= Btu/ft^2 · h · °F	× 5.68×10^{-4}	= W/cm^2 · °C
kW/m^2 · °C	× 176.1	= Btu/ft^2 · h · °F	× 0.00568	= kW/m^2 · °C
Pa · s	× 1.45×10^{-4}	= lb$_f$ · s/in^2	× 6895	= Pa · s

Appendix C
Glossary of Thermoforming Terms

A

Asperities	Microscopic surface roughness.
Amorphous polymers	Polymers that exhibit no melting points.
Absorptance	That fraction of radiant energy that is retained by the sheet.

B

Biaxial deformation	Stretching in two directions.
Billow	Prestretching sheet by inflation with air pressure.
Biot number	A dimensionless ratio of internal to external heat transfer, $Bi = hL/k$.
Black body	A body that emits the maximum amount of radiant energy at a given wavelength.
Blend	Physical mixing of two or more polymers.
Book value	Depreciated value of a machine.
Bursting time	Time to burst a membrane that is biaxially inflated under a known differential pressure.

C

Cauchy strain	Tensor function of the extent of deformation.
Chill mark	A surface blemish on a formed part.
Computer-Aided Design	Computer design of part wall thickness using geometry or FEM. Also shown as CAD.
Computer-Aided Engineering	Computer control of the thermoforming process. Also shown as CAE.
Conduction	Energy transfer by direct solid contact.
Convection	Energy transfer by moving or flowing fluids.
Constrained deformation	Sheet stretching with a portion in contact with the mold.
Copolymer	Polymer with two sets of monomers, such as HIPS.
Creep compliance	A function related to retardation time.
Crystalline polymers	Polymers that exhibit melting points.
Cut sheet	Usually, heavy-gage sheet, fed one at a time to rotary or shuttle thermoformers.

(Continued)

D

Deformation	Stretching.
Depth of draw	Also, draw ratio.
Discounted cash-flow rate of return	Profitability index or true rate of return.
Draw ratio	A gross measure of the extent of sheet stretching. A measure of the area of thickness of the sheet after being formed into a mold to that before forming.

E

Effective discounted cash-flow rate of return	The discounted cash-flow rate of return adjusted for inflation.
Elastic liquid	A polymer that has both fluid and solid characteristics.
Enthalpy	A thermodynamic measure of the intrinsic heat content of a polymer.
Entrepreneurial risk factor	The additional cost of a speculative venture.
Equilibration	Allowing a sheet to reach uniform temperature after the heating source is removed.
Eversion	Transfer of a bubble shape from above a horizontal plane to below it.

F

FEM	Finite Element Method.
Finite Element Method	A computer technique for predicting how a sheet of plastic deforms under load.
Fourier number	A dimensionless time, $Fo = \alpha\theta/L^2$.
Fracture toughness	A measure of the stress intensity at a crack tip needed to propagate a sustained fracture.
Free surface	The sheet surface not in contact with the mold surface.

G

Galerkin weighted residual method	A common numerical method for including boundaries in FEM problems.
Gels	Hard, resinous particles in plastic sheet.
Glass transition temperature	The temperature range above which a brittle or tough polymer becomes rubbery.
Global cost	The overall cost of a business.
Gray body	A body emitting a fixed fraction of the maximum amount of energy, regardless of the wavelength.
Gray body correction	In net radiant energy interchange, the factor that accounts for energy factor interchange that is lower than black body interchange.

H	
Heat flux	The energy incident on a surface element per unit time, in W/in^2, W/m^2, or $Btu/ft^2 \cdot h$.
Heat transfer	A measure of the effectiveness of energy transport between a flowing fluid and coefficient a solid surface. Also known as *convection* heat transfer coefficient.
Heavy-gage	Commonly, sheet having a thickness greater than 3 mm or 0.120 inches.
Homopolymer	A polymer from a single set of monomers such as PS.
Hot creep test	Application of a constant uniaxial load to a tensile strip of plastic that has been heated above its glass transition temperature.
I	
Index	To move a sheet forward a fixed length.
In-situ trimming	In roll-fed technology, trimming that takes place while the formed sheet is still on the mold surface. Also called *in-mold trimming*.
K	
Kirksite	A zinc-based alloy metal used in prototype or short-run tooling.
L	
Learning curve	The cost to produce a given part as a function of the number of parts produced.
Lumped-parameter model	An approximate mathematical heat transfer model that assumes no thermal gradient across the plastic sheet thickness.
M	
Machine hour cost	The cost required to run a machine for one hour, all labor and overhead costs included.
Material allocation	The theory that material on a given spot on a plastic sheet will *always* reside at the same location on the final part.
Maxwell fluid	A model fluid comprised of elastic springs and viscous dashpots in series.
Melt temperature	The temperature range above which a crystalline polymer changes from a rubbery solid to a viscoelastic liquid.
Mode III antiplane pure shear	A technical term describing the nature of nibbling or shear cutting in part trimming.

(Continued)

Mooney rubbery solid	A material that follows a simple linear form for the strain energy function.

N

Newtonian viscosity	A measure of the linear resistance of a molecularly simple fluid to applied shear.
Node	A junction or intersection, used in finite difference equations or FEM.
Non-Newtonian viscosity	A measure of the resistance of a molecularly complex fluid such as a polymer to applied shear.
Nusselt number	A dimensionless ratio of convection to conduction heat transfer for flowing fluids.

O

Orientation	The amount of residual or frozen-in stretch in a plastic sheet, usually in a given direction.

P

Pattern heating	The practice of selectively applying gauze, tissue or welded wire to a sheet, usually heavy-gage, to achieve uniform heating rate.
Peclet number	A dimensionless product of Reynolds number and Prandtl number.
$\phi(T)$	A material design parameter, related to the secant modulus of the polymer and the rate of change of strain energy with the first principal invariant of the Cauchy strain tensor.
Pin-chain	Chains used to accurately feed roll-fed sheet.
Plug	A mechanical device used to aid or assist sheet stretching prior to total contact with the mold.
Poisson's ratio	A measure of the volumetric change in material while it undergoes nonuniform deformation.
Prandtl number	A dimensionless ratio of fluid physical properties.
Pressure forming	Commonly, differential pressure across the sheet in excess of 2 atm or 30 lb_f/in^2.
Price elasticity	The effect of quantity on unit selling price.
Pseudo-convection heat	A measure of the effectiveness of radiant energy interchange between heat source transfer coefficient and sink. Also known as *radiation* heat transfer coefficient.

R

Radiation	Electromagnetic energy transfer or interchange.
Rate of return	Ratio of annual profit to invested capital.
Reflectance	The fraction of radiant energy that is reflected at the surface of a sheet.

Replication	Faithful imaging of the mold surface by the hot formed sheet.
Retardation time	A measure of the ratio of viscous to solid characteristics in a polymer.
Reynolds number	A dimensionless ratio of inertial to viscous forces, for flowing fluids.
Roll-fed	Thin-gage sheet, fed continuously into the thermoformer.
S	
Sag bands	In continuous-sheet thermoformers, metal support bands that run the length of the oven to support the hot sheet and to help minimize sheet sag.
Set temperature	The temperature below which a part can be removed from the mold without appreciable distortion.
Soaking time	Equilibration time.
Sonic velocity	The speed of sound, for air exiting a mold cavity through vent holes.
Steady-state	Income equals outgo, with no accumulation.
Stefan-Boltzmann	A radiation constant, $= 0.5674 \times 10^{-10}$ kW/m$^2 \cdot$ °C^4 or $= 0.1714 \times 10^{-8}$ Btu/ft $\cdot$ h $\cdot$ °R^4.
Strain	Polymer static response to applied stress.
Strain energy function	In solid mechanics, the amount of energy that occurs when a polymer is extended under stress.
Strain rate	The slope of the elongation-time curve for a polymer.
Stress	Externally applied load per projected area of a material.
Surge tank	The tank between the vacuum pump and the mold, to allow near-uniform differential pressure to be applied during forming.
Syntactic foam	A mixture of sintered inorganic foam spheres and plastic foam matrix, used in plugs. The common matrices are epoxy and polyurethane.
T	
Terpolymer	A polymer with three sets of monomers, such as ABS.
Thermal diffusivity	A material property measure of the rate of energy transmission, $\alpha = k/\rho \cdot c_p$.
Thermoplastics	Two-dimensional organic molecules.
Thermosets	Three-dimensional organic molecules.
Thin-gage	Commonly, sheet thickness less than 1.5 mm or 0.060 in.
Transmittance	The fraction of incident energy that is transmitted through a polymer sheet.

(Continued)

Trim	That portion of the sheet that is not part of the final product.
Trouton viscosity	A measure of the resistance of a fluid to applied uniaxial stress, elongational viscosity.

U

Unconstrained deformation	Free-form sheet stretching without mold contact.
Uniaxial deformation	Sheet stretching in one dimension.

V

View factor	A measure of the fraction of radiant interchange that occurs between primary sources and sinks.
Virgin	Unprocessed.

W

Watt density	Heater output rating.
Wavelength	A measure of the nature of incident electromagnetic radiation. Ultraviolet: 0 to 0.38 μm Visible: 0.38 μm to 0.70 μm Near Infrared: 0.70 μm to 3 μm Far Infrared: 3 μm to 20 μm
Wavenumber	Reciprocal of wavelength in radiation.
Web	During draw-down, a fold of plastic that cannot be stretched flat against a mold surface.

Y

Yield point	The polymer stress/strain level below which plastic recovers elastically.
Young's modulus	The initial stress per unit strain of a polymer under uniaxial tensile load.

Author Index

Adkins, J.E. 240, *279*
Ajroldi, G. 717, *745*
Albert, K.A. 719, 720, 721F, *746*
Alfrey, T., Jr. 61, 62F, *103*, 233, *279*
Allard, R. 262, *281*
Alongi, P. 11, *53*, 649, *741*
Arenz, R.J. 216, *278*
Armstrong, R.C. *206f*, 226, 232F, 233, 241, *278-280*
Arpaci, V.S. 168, *195*
Arruda, E.M. 241, *281*
Ashby, M.F. 66, 66F, 67F, *103*
Avrami, M. 655, 656, *741*

Baasel, W.D. 812, *843*
Baer, E. 327, *380*
Bahadur, S. 226, 226T, 247, *278*, *281*
Baird, D.G. 683, 744
Bakker, M. 4, 6F, *52*, 70, 70T, 104, 364, 365T, *380*, 623, 624, *647*
Baldwin, R.L. 73, *104*
Bank, D. 706, *745*
Bartos, O. 241, *279*, *281*, 539, 542F
Basile, P. 547, 549, *579*
Bassani, J.L. 247, *281*
Batterman, S.D. 247, *281*
Beall, G. 4T, 18, *53*, 329, *380*, 567F, 568, 573, *576*, 678, 679, *743*
Belova, E.A. 513, *580*
Benjamin, B.S. 573, *577*
Benjamin, W.P. 387, 390, 392, *467*
Benning, C.J. 503, *574*, 723, 723T, 725F, *746*
Berghmans, H. 658, *742*
Berins, M.L. 584, 586F, *644*
Berns, E.M. 678, 701, *743*, *745*
Bichgalter, V.I. 513, *576*
Bikales, N.M. 72, 72, 92, *104*, 352, 354F, 358T, 380, *583f*
Bird, R.B. *206f*, 226, 232F, 232, 241, *278*, *280*, 294, *379*
Boldt, J.A. 687, *744*
Bongaerts, H. 584, 584T, 590, 593T, 607, 608F, 610, 611, 613, 613F, 618T, 629F, *644*, *645*, *647*
Bongartz, H. 683, *744*
Boyce, M.C. 241, *281*
Brain, R.R. 675, 677, *742*
Brandreth, D.A. 727, *746*
Breuer, H. 607, 608F, 609F, 628, 603F, *646*, *648*
Brinken, F., 76, *104*, 140, 141F, *195*
Brinker, D.M. 794, 795-796T, *843*
Brockschmidt, A. 447, 448F, *468*, 674, 742, 739, *747*
Brown, A.I. 136T, *196*
Bruins, P.F. 4, 6F, 52, 213, 214, 225, 227, 229F, 267T, *277*
Brydson, J.A. 65, 66, 67F, 78, *103*, *206f*, 233, *279*, 587, *644*
Buckley, C.P. 217, 218F, *280*, 682, 684, 685F, *743*, *744*
Bucknell, C.B. 217, 218F, *278*, 682, 684, 685F, *743*, *744*
Burdeinaya, T.A. 513, *580*
Burgess, D. 327, *380*
Burns, M. 395, *468*, 488, *578*
Burt, J.G. 731, 731F, 732F, *747*

Caddell, R.M. 347, *381*
Cakmak, M. 683, *744*
Cammons, R.R. 547, 549, *579*
Carley, J.F. 233, 237, 239T, 249, *279*, *282*, 489, 490, 495, *574*, *583f*, 595, 596, 596F, 597, 598F, 602, 603F, 604, 605F, 628, 630F, *645*, *648*
Carroll, D. 753f, *843*
Chanani, J.P. 687, *744*

Italic = Reference location, F = Figure, f = Footnote, T = Table

Chaney, C. 387, 388T, 389, *467*
Chang, H. 435, *469*, 501, *576*
Charrier, J.-M. 55, 76, *103*, 262, *281*
Chastain, C. 475, *574*
Cheng, C. 711, 719, 719F, *745*, *746*
Childs, E.S. 4, 6F, 6T, 7, 8, *52*
Chudinov, P.B. 513, *577*
Chundury, D. 717, 718F, 719, *745*, *746*
Churchill, S.W. 294, *379*
Coates, J. 83, *104*
Cobbs, W.H., Jr. 657, *742*
Coleman, B.D. 241, *280*
Crawford, R.J. *206f*, 490, 503, 514, 515, *578*, 615E, *646*
Croft, D.R. 188, 192, *196*, 315, *379*, 659, *742*
Cruz, C., Jr. 273, *283*
Cruz, C.A. 719, 720, 721F, *746*
Cummings, D.S. 395, *468*, 488, *574*

Daane, R.A. 435, *469*, 501, *576*
Datta, A. 683, *744*
Dealy, J.M. 215, 216F, 257, *277*, 717, *745*
Deanin, R.D. 58, 70, 70T, *103*, *104*, 622T, *646*, 679, 682F, *743*
Dearborn, J.R. 717, *745*
DeLorenzi, H.G. 241, *281*, 521, 527F, 528F, *575*
Dempsey, R.E. 65, *103*, 652, 655, *741*
Denson, C.D. 207, 207T, 216, 226, 262, 264, *277*
DeSousa, J.P. 683, *744*
Di Pede, S. 683, *743*
Domininghaus, H. 79, 79F, 80, 80F, 81F, *104*, 107, *194*, 199, 210, 211F, 212F, 224, 226, 225F, 227F, 228F, 243, 246F, 247F, 251F, 252F, 254F, 255F, 256F, 257F, 258F, 259, *277–281*, 679, 681T, *743*
Donnell, R. 679, *743*
Dostal, C.A. 374, 376T, *381*, 687, *744*
Drickman, M.R. 718, *745*
Driscoll, S.B. 547, 549, *576*
DuBois, J.H. 2, *52*
Dunning, L.A. 675, *742*
Dusinberre, G.M. 315, *380*, 659, *742*
Dutta, A. 683, *744*

Ehlers, G.L.F. 327, *380*
Elias, H.-G. 650, 650T, *741*
Erwin, L. 226, *278*
Eshbach, O.W. 405, 406, 407T, *467*, *468*

Farnham, S.E. 3, *52*
Fenner, R.T. *583f*
Finney, R.H. 244, *281*
Flecknoe-Brown, A.E. 738, *747*
Fleming, M.F. 683, *743*
Florian, J. 42, *53*, 186, 187, *195*, *196*, 198, *277*, 335F, 340, 355, 363, 364, 367, *380*, 457, *468*
Ford, H. 534, *575*
Foster, J. 675, *743*
Frados, J. 55, *103*, 127, 127F, *194*, 369, *381*
Franey, J. 183, 185, 186F, *195*
Frankenhauser, B. 238T, 239, 240F, *279*
Fredrickson, A.G. *206f*
Friederich, K. 683, *743*
Frisch, K.C. 722, *746*
Fruzzetti, R.E. 655, *741*
Fukase, H. 513, 515, *575*, *577*
Funt, J.M. 226, 234, 236, 237, 238T, 239T, *278*

Galli, E. 696, *744*
Gallo, R.J. 216, 226, 262, *278*
Gartland, R.H. 652, 654, 655, 655T, *741*
Gawrilow, I.K. 513, *577*
Ghafur, M.O. 239, *281*
Gheen, W.L. 490, *576*
Ghosh, A. 262, *281*
Gibson, L.J. 66, 66F, 67F, *103*
Glachter, R. 55, *103*
Glicksman, L.R. 727, *746*
Gogos, C.G. 82, 82F, *104*, 225, *278*, 327, *380*, 654, *741*, 836, *843*
Golike, R.C. 657, *742*
Gonzolez, H. 226, *278*

Italic = Reference location, F = Figure, f = Footnote, T = Table

Goodier, J.N. 504, *574*
Goodman, T.R. 310, *379*
Gornick, G. 658, *742*
Graf, G.L., Jr. 796, 798T, *843*
Green, A.E. 240, *279*
Green, D.W. 812, *843*
Griffin, O.M. 372, 373, *381*
Groeninckx, G. 658, *742*
Gross, H. 168, *195*, 235, *279*, 710, *745*
Gruenwald, G. 52, *53*, 323, 328, 340, 355, 358T, *380*, 425, 426, *468*, 499, *574*, 595, *645*
Gurnee, E.F. 61, 62F, *103*

Haas, T.W. 183, 185, 186F, *195*
Haessly, W.P. 239, *281*
Halldin, G.W. 244, *281*
Han, C.D. *206f*, 226, *278*
Harms, J.F. 675, *742*
Harper, R.C. 684, 685F, 686F, *744*
Harris, R.L. 213, 214, 226, 227, 229F, 267T, *277*
Hartmann, K.-H. 50F, *53*
Hartnett, J.P. 290, 291T, 310, *379*, 444, *469*
Hassager, O. *206f*, 225, 232F, 233, 241, *278*, *279*, *280*
Heil, M. 783, *843*
Heneczkowski, M. 549, 549T, 550T, 551T, *579*
Hensen, F. *583f*, 584, 584T, 590, 593T, 607, 608F, 609F, 610, 611, 613, 613F, 617, 618T, 620, 621, 621F, 622T, 628, 629F, 630F, *644*, *645*, *647*, *648*
Hertzberg, R.W. 348, 349F, 350, 350F, 351, *380*
Hieber, C.A. 290, *379*
Höger, A. 29, 31, 32T, 35, 36T, *53*, 144T, 165, 185, 186F, 187F, *195*, 507, *577*
Holland, F.A. 812, *843*
Holman, J.P. 88, 88F, *104*, 156, 156F, *195*, 300, 359, *379*, *380*
Holt, D.L. 227, 228T, 231, 232T, 240, 249, *279*, 499, 504, 505, 505F, *574*
Hon, M. 683, *744*
Hoover, K.C. 225, 231, 260F, 266, *278*
Howard, J.B. 72, 72F, *104*
Howell, H.G. 501, 541, *576*
Howell, J.R. 662, *742*
Huebner, K.H. 523, *575*
Hylton, D. 227, 229F, 244, *279*, *282*, 711, 715, 717, 717F, 718, 719, 719F, *745*, *746*

Ilenda, C.S. 711, 713F, 715, 716, *745*, *746*
Imada, K. 244, *281*
Ingersoll, H.G. 727, *746*
Irvine, T.F., Jr. 310, *379*
Isayev, A.I. 241, *283*, 521, 527F, *575*
Ito, K. 513, 539, *577*
Iwaaki, A. 513, *577*

Jarma, R.A. 794, 795-796T, *843*
Johnson, R.W. 711, 713F, 715, 716, 719, 720, 721F, *745*, *746*
Jolicoeur, C. 547, 549, *576*
Joye, D.D. 216, 226, 264, *278*

Kamal, M.R. 290, *379*
Kampf, G. 224, *278*
Karynak, G. 674, *742*
Keith, D.G. 738, *747*
Keith, H.D. 710, *745*
Kempthorn, J.T. 210, *279*
Kenig, S. 290, *379*
Kern, D.Q. 289, 289T, *379*
Khorshied, S.A. 541, 556, *576*
Kinloch, A.J. 349, 351, 351T, *380*
Klempner, D. 722, *746*
Kmetz, M. 514, *577*
Kobayashi, A. 334, 336F, 340, 341T, 342, 342F, 343T, 345, 345F, 346T, 368, 368F, 369T, 370-371T, *380*, 501, *576*
Kochar, L.K. 687, 688, 689, 690, 694, 695F, *744*, 755, *843*
Korican, J. 374, 376T, *381*
Kossler, I. 92, *104*
Kothandaraman, C.P. 295, 295T, *379*
Kouba, K. 239, 241, *281*, 523, 539, 542F, *575*

Italic = Reference location, F = Figure, f = Footnote, T = Table

Kovach, G.P. 14, *53*
Kraybill, R.R. 148T, 150, *195*
Kreith, F. 88, *104*, 111, 111F, 122, 132, 133T, 135, 136T, 165, *194*, *195*, 295, 295T, *379*, 659, *742*
Krone, J.R. 683, 683F, *743*
Kumar, A. 244, *281*
Kunio, T. 513, *577*

Lai, M.O. 227, 228T, 231, 232T, 240, 249, *279*, 499, 504, 505, 505F, *574*
Landel, R.F. 216, *278*
Leaversuch, R.D. 720, *746*
Leonard, B.L. 717, 718F, 719, *745*, *746*
Levy, S. *583f*, 595, 596, 596F, 597, 598F, 602, 603F, 604, 605F, 628, 630F, *645*, *648*
Li, C.S. 290, *379*
Liao, M.K. 290, *379*
Lightfoot, E.N. 294, *379*
Lilley, D.G. 188, 192, *196*, 315, *379*, 659, *742*
Lodge, A.S. 251, *280*, 501, 541, *576*
Lodge, C. 679, *743*
Loepp, D. 631, 631T, *648*
Lorntson, J.M. 226, 231, 231F, 233F, *278*
Lui, S.K.L. 490, 503, 514, 515, *574*

Macklin, S.J. 675, *742*
Macosko, C.W. 231, 231F, 233F, *278*
Mallon, P.J. 683, *743*
Malloy, R.A. 573, *576*
Maloney, J.O. 812, *843*
Malpass, V.E. 209, 210, 211, 212, 225, 226, 227, *277*
Manson, J.A. 351, *380*
Mapleston, P. 720, *746*
Marangou, M. 262, *281*
Marco, S.M. 136T, *196*
Markovitz, H. 241, *280*
Martin, E.L. 623, *647*
Martin, T.A. 683, *744*
McConnell, Wm.K., Jr. 4T, 33, *52*, *53*, 81, *104*, 127, 153T, *194*, 308, 308F, 327, *379*, 451, *468*, 633, 634-636T, *648*, 772, 773T, 774-782T, *843*
McCrum, N.G. 217, 218F, *278*, 682, 684, 685F, *743*, *744*
McHugh, K.E. 610, *646*, 718, 719, 721F, *745*, *746*
McKelvey, J.M. 217, 218T, *278*, *281*
McTaggart, L.S. 652, *741*
Meissner, J. 226, *278*
Menges, G. 168, *195*, 235, 239, *279*, *281*, *745*
Menzel, D.H. 689, *744*
Meriam, J.L. 270, 270F, *281*, 712, *745*
Michaeli, W. *583f*, 598, 599F, 600F, 602, 603F, 604F, 616, 626, 628, 629F, *645*, *647*, *648*
Middleman, S. 263, *281*
Miles, M.J. 244, *281*
Miller, R.M. 389, 388T, 453, *467*, *468*
Mills, H.E. 797, *843*
Mills, N.J. 244, *281*
Mills, N.L. 651, *741*
Minagawa, N. 628, *648*
Mintz, S.L. 800, *843*
Mizra, F.A. 241, *281*, 521, *575*
Monks, R. 684, 686F, *744*
Mooney, M. 238T, *279*, 475, *574*
Moskovskii, C.L. 513, *576*
Mucke, W. 617, 618T, 619F, 620F, *647*
Mulcahy, C.M. 678, 701, *743*, *745*
Muller, H. 55, *103*

Naitove, M. 684, 686F, *744*
Nakamura, K. 244, *281*
Narkis, M. 499, 514, 515, *574*, 704T, 706, *747*
Neid, H.F. 521, 527F, 528F, *576*
Neiman, Ya.C. 513, *575*
Nelson, E.D. 547, 549, *576*
Nichols, N. 674, *742*
Nied, H.F. 241, *281*
Nielsen, L.E. 70, 70T, *104*, 347, *380*
Nietzert, W.A. 513, 565, 565F, *576*
Nikitin, Y.V. 513, *577*

Italic = Reference location, F = Figure, f = Footnote, T = Table

Nissel, F.R. 624, 626, 628F, *647*, 791, 792F, *843*
Noll, W. 241, *279*
Norton, F.J. 727, *746*

O'Bradaigh, C.M. 683, *743*
Oelze, H. 513, 567F, 568, *576*
Ogale, K. 610, *646*, 718, 719, 721F, *745*, *746*
Ogden, R.W. 236, 239, *279*
Ogorkiewicz, R.M. 71, 71T, *104*, 227, 234, 240, *278*
Okine, R.K. 683, *744*
Osmers, H.R. 176T, 195, 404, *467*
Overbergh, N. 658, *742*

Padden, F.J. 711, *745*
Palm, J.P. 719, 720, 721F, *746*
Park, J.Y. 226, *278*
Peng, S. 216, *278*
Perry, J.H. 146T, *196*
Perry, R.H. 812, *843*
Peterson, A.C. 460f, *468*, 691, *744*
Petrie, C.J.S. 205, *206f*, 226, 234, 260, 263, *277-281*, *283*, 513, 539, *577*
Pipes, R.B. 683, *743*
Platzer, N. 162F, *195*
Poehlein, G.W. 216, 226, 264, *278*
Pollock, M. 226, *278*
Popper, G. 797, *843*
Potente, H. 76, *104*, 140, 141F, *195*
Powell, P.C. 322, 323F, *380*
Progelhof, R.C. 3, 4T, *52*, 58, 61, 64, 64T, 66, 68F, 74, 74T, 75, 75F, 76, 76T, 77, 77T, 84, *103*, *104*, 181, 181T, 183, 185, 186F, *195*, 199, 202, 203, 203F, 213, 222, 223F, 224, 224F, 225F, 234, 243, 249F, 250F, *277-280*, 322, 326, 348T, *380*, 475, 573, *574*, *576*, 584, 585F, 589, 589F, 590, 591T, 621, 622, 624F, *644*, *647*, 662, 675, 687, 688, 696, 706, 727, *742*, *744*, *745*, *746*
Przygocki, W. 652, *741*
Pye, R.G.W. 404, 442, 454, 456, *467*, *468*

Quintiere, J.G. 183, *195*, 687, 688, 696, *744*

Ragab, A.R. 541, 556, *577*
Raspor, O.C. 683, 743, *744*
Rauwendaal, C. *583f*, 595, 596F, 597, 602, 604, 605T, 606, 616, 616F, 624, 627F, *645*, *647*
Reitz, D.W. 727, *746*
Rhee, B.O. 290, *379*
Richardson, P.N. *583f*
Rivlin, R.S. 236, *279*
Roark, R.J. 267, 268, 268T, *281*, 423, 428, 437, *468*
Rohsenow, W.R. 290, 291T, *379*, 444, *469*
Roller, W.R. 710, *745*
Rosato, D.V. 590, 591, 592T, 594, 594F, 595F, 644, *645*, 717, *745*
Rosen, S.L. *206f*, 377-378T, 379, *381*
Rosenzweig, N. 499, 514, 515, *574*, 704T, 706, *747*
Ruetsch, R.R. 84, *104*, 727, *746*
Ryan, M.E. 262, 263, *281*

Saechtling, H. 65, *103*, 210, 210F, 211F, 242, 242F, 243F, 244F, *277*, *280*, 679, 680F, 728T, *743*, *746*
Sakiadis, B.C. 83, *104*
Salazkin, K.A. 513, 558, 559F, *576*
Saunders, D.W. 236, *281*
Savonuzzi, A. 675, *742*
Scheibelhoffer, A.S. 717, 718F, 719, *745*, *746*
Scheiner, L.L. 675, 711, 712, 712F, *743*
Scherbak, V.V. 513, *577*
Scherer, R. 683, *743*
Scheryschew, M.A. 513, *577*
Schmidt, H.J. 513, *577*
Schmidt, L.R. 233, 235, 237, 238T, 239T, 249, *279*, *282*, 489, 490, 495, 499, 503-505, *574*
Schneider, P.J. 165, 166F, 168, 169F, 172, 174F, 178F, 179, 179F, *195*, 290, 291T, *379*, 444, *469*

Italic = Reference location, F = Figure, f = Footnote, T = Table

Schrage, D.A. 403, 403T, *467*
Schreiber, H.P. 547, 549, *576*
Schrieffer, J. 678, *743*
Schuetz, M.A. 729, *746*
Schuster, A. 689, *744*
Schut, J.H. 333, *380*
Sebastian, D.H. 717, *745*
Semerdjiev, S. 437, 437F, *469*
Shapiro, A.H. 414, *468*
Shea, J.W. 547, 549, *576*
Sheryshev, M.A. 513, 558, 559F, *576*
Shlyakhova, T.G. 513, *577*
Shrivastava, S. 262, *281*
Shutov, F.A. 623, 625T, *647*
Siegel, R. 662, *742*
Siggel, E. 652, *741*
Simonds, H.R. 56, *103*
Singleton, R.W. 142-143T, *196*
Sinofsky, M. 727, *746*
Skee, S. 387, 388T, 389, *467*
Skoblar, S.K. 595, *645*
Skochdopole, R.E. 727, *746*
Smets, G. 658, *742*
Smoluk, G. 595, *645*
Song, W.N. 240, 241, *279*, *281*, 521, 523, 534, 536F, 543, 544F, *575*
Sors, L. 384, *467*
Souders, M. 405, 406, 407T, *467*, *468*
Steinberg, A.H. 3, *52*, 675, *742*
Stephenson, M.J. 263, *281*
Stern, C.H. 729, *746*
Stewart, W.E. 294, *379*
Storr, L.D. 623, *647*
Streeter, V.L. 405, 406, 407T, 414, *467*, *468*
Subramanyan, S. 295, 295T, *379*
Suh, N.P. 436, *468*
Sung, N.H. 436, *468*

Tadmor, Z. 82, 82F, *104*, 226, *278*, 327, *380*, 499, 514, 515, *574*, 654, *741*, 836, *843*
Takayanagi, M. 244, *281*
Tanner, R.I. 241, *280*, 539, *579*
Taylor, C.A. 241, *281*
Taylor, G.A. 527, 529F, *576*
Thorp, M.E. 397, 399T, *467*
Timoshenko, S. 504, *574*
Tock, R.W. 226, 231, 260F, 266, *278*
Treloar, L.R.G. 236, 237, 238T, 239T, 240, 257, *279*, *281*, 527, 529F, *575*
Tsuge, K. 216, *278*
Turner, S. 475, 476f, *574*, *576*

Valenzuela, J.A. 727, *746*
Van Holde, K.E. 73, *104*
Vilyaf, M.A. 513, *576*
Vincent, P.I. 227, 234, 240, *279*, 352, 354F, 358T, *380*
Vlachopoulos, J. 239, 241, *280*, *281*, 521, 523, 539, 542F, *575*
Voigt, H. 82, 82F, *104*, 226, *278*, 355, 356F, 356T, 357F, *380*, 490, 496, 508F, 547, *574*, *576*
Voskresenskii, A.M. 513, *576*

Wagner, M.H. 241, *280*
Walker, J.H. 683, 683F, *743*
Walter, M.M. 711, *745*
Wang, K.K. 290, *379*
Ward, L.G. 675, *742*
Warnecke, H.J. 238T, 239, 240F, *279*
Watson, F.A. 812, *843*
Weinand, D. 94, 95, 95F, 96F, *104*, *105*, 155, 155F, 158, 158F, 184, 185F, 186, *195*, 214, 215F, 239, 243, 248F, 250F, *277*, *280*, *281*, 676, 677F, 709, *743*, *745*
Welty, J.R. 659, *742*
White, C.H. 209, 210, 211, 212, 226, *277*
White, J.L. 226, 233, 234, 236, *278*, *583f*, 604, 605T, 606, 606F, 628, *645*, *648*
Wilkinson, J.K. 812, *843*
Williams, J.G. 237, 238T, 239F, 249, 277F, 278A, *279*, *281*, 504, 533, 534, *575*
Wimolkiatisak, A.S. 717, 718F, 719, *745*, *746*
Wineman, A. 242f, *280*
Wissbrun, K.F. 717, *745*

Italic = Reference location, F = Figure, f = Footnote, T = Table

Wlochowicz, A. 652, *741*
Wood, D.T. 405, *467*
Wood, R. 13, 13F, *53*
Woodhams, R.T. 683, *743*
Wooldridge, J.M. 22, 25T, *53*
Worbye, J. 402, *467*
Wu, R. 262, *281*
Wychoff, H.W. 710, *745*
Wyeth, N.C. 651, *741*
Young, R.L. 349, 351, 351T, *380*
Young, W.C. 267, 268, 268T, *281*, 423, 428, 437, *468*

Zablau, N. 683, *743*
Zerillo, J. 678, 679T, 743
Zhoyolev, I.V. 513, 558, 559F, *576*
Ziabicki, A. 64, 64T, *103*, 657, *741*

Italic = Reference location, F = Figure, f = Footnote, T = Table

Subject Index

ABS 2, 8, 14, 72F, 73, 74, 78, 109, 109-110E, 118, 119-120E, 135, 189-191E, 221E, 235E, 243, 251F, 338, 344, 369, 379, 441, 485E, 486E, 614, 753
ABS/PVC 227
ABS,
  calendering 584
  drying of 618T
  infrared absorption 93F
  moisture in sheet 640
  multilayer sheet 623
  sheet appearance of 642
  static charge on 642
Absorptance 183
Absorption,
  colorant effect on 93, 94, 95F, 96F
  pigment effect on 93, 94, 96F
Absorptivity,
  definition 135
  discussion 92
Absorptivity 112, 136T
Acrylonitrile-butadiene-styrene terpolymer—see *ABS*
Allocation, polymer sheet—see also *Reallocation, polymer sheet, Distribution, polymer sheet*
Allocation, polymer sheet 471, 510, 510F
Allocation, polymer sheet,
  billowing, during start-up 767
  circle-grid test for of 756, 758
  plug assist, during start-up 767
  plug assist effect on 507, 507F, 508F
  preblowing effect on 503, 505F
  prestretching effect on 512
Aluminum, plug material 439, 441, 442, 442F, 443, 443F, 444F
Amorphous polymer 8, 207
Analysis, thermomechanical 224
Angel hair 340, 359, 362F, 364
APET 338, 339, 379, 441, 666, 676
Areal draw ratio—see also *Draw ratio*
Areal elongation—see *Draw ratio, areal*
Arrhenius equation 217, 219, 219E, 221E
  bursting 266
ASA 243, 252F
Avrami equation 656

Barcoding 751, 751f
Barrier polymers 28
Beam bending, discussion 511, 511F
Beer's law 93, 184, 185, 688, 690
Beta gage, sheet thickness 601
Biaxially oriented sheet, discussion 12
Biot number 125E, 165, 168, 169, 169F, 170E, 171E, 174, 174F, 175, 189, 193, 194, 300E, 306F, 308, 661
  definition 125
Birefringence, in orientation 621, 622, 623, 623f, 624F
Blister pack, discussion 12
Blister pack 16
Blocking, effect 643
Blocking, ways of minimizing 643
Blow molding,
  accumulator, competition 11
  competition 28
  competition to thermoforming 835, 836, 838-839T, 840T, 841, 841T, 842F, 842T
  industrial 696, 697-700T
  injection, competition 11
Blown film process 263
Bosses, dimensions 565, 566F
Brittle strength, polymer, discussion 358
Bursting 264
Bursting time 266
Business,
  existing, discussion 751, 752T
  forming, discussion 749

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

  incremental 752T
  incremental, discussion 830, 831, 832E
  isolated, competition 808
  isolated, costs, discussion 808
  isolated, discussion 751, 752T
  isolated, protocol for 811, 812F
  new, discussion 751, 752T
  record keeping 750, 751

CAD—see *Computer-aided design*
CAE—see *Computer-aided engineering*
Calaendering 587
  roll stack configuration 586F
  thin sheet 584
Camel-back trimmer 15, 15F
Capital,
  start-up, discussion 814, 815F
  venture 823
  working, discussion 814, 815T, 815F
Cash flow,
  balance 750F
  cumulative 817
  discounted 816, 817, 817F
  discussion 816, 817
Cauchy strain tensor 248f
  defined 236
Cavity isolator 14, 51
Cell-cast sheet, PMMA 587
Cellulose acetate, infrared absorption 89, 89F
Cellulosic—see also *CA*, *CAB*, *CAP*
Cellulosic 2, 3, 5, 84, 754
  drying of 617, 618T
Chamfer 517E
  design 459, 460, 460F, 460f
Chatter line 557
Chill mark 441f, 543, 676f, 764
  causes of 565
  mold temperature effect on 558
  plug temperature effect on 559
Chill roll—see also *Roll stack*
Chill roll,
  simulation for PET 662, 663, 663F, 663T, 664T
  condition for PET 662
Circle-grid test 756, 756f, 757, 757F, 758, 758F, 766
  during start-up 767
Clamp,
  cavity 449
  edge 463F
  peripheral 448, 449, 449F
  sheet, discussion 448-451
  with coining 449, 450
  with ejection 451
  with trimming 449, 450F
Clamping 383
  sheet, discussion 38, 44
Coefficient of thermal expansion 85-86T, 321T
Coextrusion 586
Coining 449, 450, 450E, 557, 558F
  competition 28
  with pressure forming 679
Compression molding,
  comparison 2
  competition 28
Computer-aided design,
    discussion 508-510
Computer-aided engineering 477F, 509
  multilayer 510
  plug assist 509
  prestretching 509
Computer-aided mold design 477
Computer-aided part design 477
Computer-aided structural analysis 477
Computer prediction,
  boundary condition 192
  heat transfer 188-192
Conduction,
  boundary condition 123
  definition 13, 110, 121, 121F
  into mold 286
  steady-state 121
  transient 121
Cone,
  draw-down into 513, 514, 514E
  truncated, draw ratio, 574A
Constitutive equation of state 205, 241, 521, 523
Convection,
  boundary condition 123
  definition 13, 111
  forced, in ovens 14

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

- free surface 286
- mold coolant 286

Conversion to sheet, discussion 583
Coolant,
- oil as 297E
- water as 296E

Coolant channel, discussion 404
Coolant channel design 404, 404F, 408E-411E
- contraction 406
- expansion 406
- orifice 406, 407

Coolant lines, during start-up 760, 763, 764
Cooling, free surface,
- discussion 303, 304F
- forced convection 303, 307
- natural convection 303, 305
- water mist 303

Cooling, in ambient air 303
Cooling cycle 285, 286, 313, 313-314E
Corner radius,
- start-up protocol 755, 757F
- temperature dependency of 565, 566F

Cost,
- balance sheet at steady state 798, 799, 799T, 800
- capitalized 813
  - SAR 799T, 800, 800f, 826T
- direct, isolated business 808, 809
- direct/indirect labor 797
- fixed, isolated business 809
- fixed/variable burden 797
- fixed capital 822T, 833T
- global production 798
- labor 826T
- machine hour, competitive 840T
- machine hour 800
- manufacturing, isolated business 808
- manufacturing 796, 798, 824T, 835T
- material 823T, 834T
- material, competitive 841T
- mold, accounting for 810, 811, 811f
- mold 822T
  - energy, 783, 790, 790-791T
  - extrusion 791, 792F, 792E, 793, 793E
  - forming, discussion 794, 796, 797
  - forming, general 794, 797, 797T
  - forming, software for 794, 795-796T
- money 813, 814E
  - polymer 793, 794
  - regrind 793, 793E
- operating 798, 798T
- polymer 796
- process, competitive 842T
- production, isolated business 808, 809
  - competitive processes 835, 836, 838-839T, 840T, 841T, 842F, 841, 842T
- semivariable, isolated business 810
- start-up 814, 815F, 816, 817f, 826T
- variable, isolated business 810
- working capital 827T

CPET 3, 5, 7, 13, 37, 38, 285, 339, 340, 441, 545, 650-670, 773
- cooling formed part plug of 668, 669
- crystallization rate, effect of heater temperature on 666, 667F
- crystallization rate, effect of temperature on 666, 667F, 668
- forming 649
- forming conditions 666
- lamination of 643
- mold design for 668
- mold temperature 666
- multilayer sheet 623
- nucleants in 652, 654
- patents on 652
- pressure for forming 668
- pressure forming 676
- thermoforming equipment for 666
- trimming of 670
- troubleshooting forming process of 670, 671-674T

Crack propagation, rate 351, 352T
Creep, hot 226
Creep, isochronous 237
Creep test, hot 213, 214, 215
Crystalline melting temperature 286
- Avrami equation 656, 658T
- crystalline level 651
- transition temperatures 650T
- Ziabicki equation 658

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

Crystallization,
  cold 199f
  on mold 285
  orientation-induced 652
  thermally induced 652
Crystallization rate,
  DSC determination of 658
  DTA determination of 658
  hot-stage microscope determination of 655
CTFE 210
Cut-sheet forming 13
  clamping 13
  shuttle press 33F
Cut-sheet forming—see also *thermoforming* categories
Cutting,
  characteristics, in trimming 341T, 343T
  compression 352
  mechanics 334, 335
  shear 355, 355F, 356F, 356T, 357F, 357T
  steel rule die 352
  thermal 372, 373E
  thermal, melting rate 372
  water jet 374-375, 375F, 376T
Cutting force, defined 354

Dam 558F
  design 459, 459F
Debugging time 752T
Deformation 220
  biaxial, defined 202
  biaxial 241, 250, 260, 260F
  elongational 201, 202
  extensional—see also *Deformation, elongational*
  extensional 207
  solid phase 206
  uniaxial, defined 202
  uniform biaxial, defined 202
Depreciation,
  average annual 811, 816
  discussion 810, 810f
  methods for 811, 812, 813, 813E
Depth-of-draw, discussion 15-16
Design,
  concept feasibility 477
  dimensional tolerance on 472
  environmental effects on 472
  mechanical behavior on 472
  polymer characteristics on 472
Design check list,
  appearance 474T
  application, 473T
  discussion 472
  environmental 474T
  general 473T
  part function 474T
  part limitation 476T
Design criteria, discussion 471
Design philosophy, discussion 476-478
Dewpoint, of air for drying 617, 618
Disperity index 61
Disposables 4
Disposables—see also *thin-gage* categories
Distributed parameter model 659, 669, 669F
  boundary conditions on 660
DMA 224
Double step, design on male mold 459, 459F
Draft angle 558, 561, 562F
  effect on wall thickness 518E
Drape forming 2, 17, 17F
  definition 14
Draw-down—see *Draw ratio*
Draw-down 215, 252E, 253E
Draw-down rate 557
Draw ratio—see also *Depth-of-draw, H:D, Areal draw ratio, Linear draw ratio*
Draw ratio 214
  areal 214, 231, 488, 489, 490, 491, 492E, 493E, 496F 493E, 497, 498
  areal, common shapes 491T
  areal, definition 16
  areal, discussion 471
  areal, practical limit 565
  areal, prestretching effect on 505
  areal, truncated cone, 577, 578
  discussion 471

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

  H:d, definition 16
  linear 488, 494, 495, 495E, 496, 496F, 498, 498E
  linear, definition 16
  linear, discussion 471
  linear, practical limit 565
  linear, truncated cone, 578
  temperature-dependent 503, 504F
Drilling 367-369, 368E, 369T, 370-371T
Drink cups 3, 16
Dryer design 618, 619F
Drying, discussion 617
Dye, infrared effect 185, 186, 186T

Efficiency,
  labor 801, 802, 803E
  manufacturing, discussion 801, 803, 803-805E
  part 805T
  process 801, 803, 803-805E
  product 801
Ejection system 383
Elastic liquid 205, 234, 235E, 260
Elastic liquid—see also *Viscoelastic liquid*
Elastic solid 234
Elongation, ultimate 213
Emissivity 112, 136T
  definition 134
Energy audit, discussion 783, 790
Energy balance 750F
Energy cost, by state 790-791T
Enthalpy 107
  defined 82
Enthalpy—see also *Polymer enthalpy, Polymer heat capacity*
EPDM 239
Epoxy, plug material 439, 441
Equilibration 177F, 285
  definition 176
Equilibration time 177-178, 178F, 178E, 179F, 180E
  computed 180-181
Euler buckling—see *Plate buckling*
EVA 28
Evaculation rate, during start-up 762, 763, 763F
EVOH 28

Extension,
  biaxial, uniform 257, 258E
  biaxial 207, 257
  biaxial—see also *Deformation, biaxal*
Extension, uniaxial 207, 257, 258E
Extension, unaxial—see also *Deformation, uniaxial*
Extruder,
  annular die for 584, 587
  heat buildup owing to shear 597, 597E
  pressure in 596, 597
  screen pack for 591, 594
  single-screw, characteristics 590, 591, 591T, 592T, 593T
  single-screw, compression ratio 589, 589T
  single-screw, melt pumping section of 590
  single-screw, plasticating section of 590, 590F
  single-screw, residence time in 614
  single-screw, screw design for 589, 589F, 590, 594, 594F, 595, 595F
  single-screw, solids conveying section of 589
  single-screw 587, 588, 588T, 588F
  tandem 587
  twin-screw 587
Extrusion 2, 3
  aspects affecting thermoforming 583
  blown film 584, 585F
  cost 508
  CPET 659
  discussion 583
  economic penalty 583
  foam 587
  property penalty 583
  residence time 583
  sheet die, heat buildup owing to shear 601
  sheet die, pressure in 598, 661
  sheet die 587, 598, 599F, 600F
  single-screw 583
  thickness range 584T
  thin sheet 584
  twin-screw, discussion 604, 606, 607
  twin-screw, types 605T, 605F, 606F

Extrusion—see also *Sheet, extrusion*

Failure criteria 472
FEA—see *Finite Element Analysis*
Female forming—see *Vacuum forming*
FEP 243, 255F
  fluoropolymer, infrared absorption 92F
  mold release 457
  mold surface 434
Fiber,
  effect on tensile strength 210
  reinforcing 679, 680F
Fiber-forming polymers, trimming 285
Fiber spinning 263
Filler, effect on tensile strength 210
Film, definition 12
Film resistance,
  coolant 287F
  free surface 287F
Finger strain tensor 241
Finite difference equation model 659
Finite Element Analysis 510, 522, 523, 523F, 524, 525F, 526F, 527, 527F
  comparison with data 522F, 527, 528F, 529F
  computational time, discussion 522
  discussion 521
  Galerkin weighted residual 523
  internal energy function 523
  K-BKZ model 539, 541, 542F, 543, 544
  mesh selection 524
  Newton-Raphson iteraton 523
  node 521
  plug assist 524
  plug design 539-543
  sheet removal from plug 541, 543, 544F
  stability 524
  3-dimension 521
  2-dimension 521
  web prediction 525F, 526
Foam,
  architecture 57f
  bubble growth discussion 722
  cell architecture 722, 723, 723F, 723T, 724, 724F, 724E, 725F
  depth of draw in 735, 736, 737F
  forming equipment 736, 738
  forming pressures for 736
  forming window for 733
  heating of 726
  internal cell gas pressure in 731, 731F, 732F, 733, 733E
  molecular diffusivity in 731
  nucleants for 722
  radiant transmission, Rosseland approximation 727
  radiant transmission through 726, 727, 729, 730E
  secondary expansion in 733, 734, 734F, 735, 735F, 736F
  thermal conductivity of 726, 726E
  thermal diffusivity in 729F
Foam sheet 556
  discussion 12
Food containers 16
  convenience 3, 7, 7T
Forging, competition 28
Form-fill-seal 16
  discussion 12
Forming,
  billow 20, 20F
  billow drape 20F, 20
  billow snap-back 25T
  billow vacuum 20, 21F
  cell architecture, discussion 722
  CPET 649, 651
  diaphragm 26, 27F
  drape 25T, 125
  drape, plug-assisted 22, 23F
  embossed sheet 26
  filled polymer 649, 679, 687
  flocked sheet 25
  foam 649
  foam sheet, discussion 722
  free blow 18F, 18
  immersion 22, 24F
  matched mold 25T
  metallized sheet 25
  multilayer 649, 687
  mulilayer, trapped air 740, 740F

plug-assisted 19-21
plug-assisted reverse draw 22, 24F
polyolefin foam sheet 722
PP, discussion 709, 710
pressure 18F, 18, 671, 674-679
pressure, CPET 676
pressure, discussion 36
pressure, during start-up 768
pressure, effect on detail 674, 675
pressure, heavy-gage 677, 678, 678F
pressure, plug-assisted 19, 22, 23F
pressure, PP 675, 676, 676F
pressure, safety concerns for 675, 678
pressure, thin-gage 675
pressure, with prestretching 677
pressure-bubble immersion 22, 24F
pressure box for 675, 677
printed circuit board sheet 26
printed sheet 26
PS foam sheet 722
PSA-applied sheet 25
reinforced polymer, problems 685, 686, 687
reinforced polymer 26, 649, 679, 683, 683F, 685F, 686F
safety concerns 37
slip 25T
splitty plastic 26
start-up, heavy-gage 766
start-up, thin-gage 766
trapped sheet 127, 127F
twin-sheet 649, 696
twin-sheet, air injection 701, 702F, 707, 708
twin-sheet, competition to 696, 697-700T
twin-sheet, heavy-gage 27, 27F
twin-sheet, historical 696f
twin-sheet, products of 696
twin-sheet, seal area, adhesion 704, 704T
twin-sheet, seal area, compressive force 707, 707F, 708F
twin-sheet, seal area, design 707, 709F
twin-sheet, sequential 702, 702F, 703, 703F, 704, 705T
twin-sheet, simultaneous 701, 701F, 702F, 705T
twin-sheet, tack-off 710, 710F
twin-sheet, thin-gage 28, 28F, 701
vacuum 25T
vacuum, plug-assisted 22, 22F, 25T
vacuum snap-back 21, 21F, 25T
very thin sheet 26

Forming process,
  troubleshooting, discussion 769
  troubleshooting 773T, 783T
Forming station,
  ancillary 31
  discussion 31
  drive 31
  drive units 32T
  pressure 31, 32
Forming temperature, 69T, 230F, 233
  lower 115, 116, 116F, 117F, 118F, 119F, 120F
  normal 115, 116, 116F, 117F, 118F, 119F, 120F
  range 8
  upper 115, 116, 116F, 117F, 118F, 119F, 120F
Forming window 198, 222E
  definition 115, 256
  effect of fillers on 679, 680, 682, 682F
Fouling factor, defined 289, 289T
Fourier number 165, 168, 169F, 170, 170E, 171E, 174, 174F, 188, 306, 306F, 315f, 444E, 445F, 661
FPVC 3, 338, 355, 451, 456, 545
Fracture energy 350E
  defined 348
Fracture mechanics, in trimming 340
Fracture toughness, defined 349
Free surface cooling 285
Friction factor 421F
  defined 294
Funnel test 260-263, 755
  prior to start up 755

Gamma gage, sheet thickness 601
GEA 496F
GEA—see also *Geometric Element Analysis*
Gear pump 594, 595, 595F, 596, 596F

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

Geometric Element Analysis 496F, 513, 513F, 514, 514E, 515, 515F, 516F
  comparison with data 522F
  converging wall 516F, 517, 518
  design protocol 515, 520, 521
  elements of 516F, 517-519
  one-side lay-down 516F, 518, 519
  parallel wall 516F, 517
  plug design 536
  shallow part 519, 519F, 520F
  sheet removal from plug 541, 543F
  three-dimensional corner 516F, 517
  two-dimensional corner 516F, 517
Glass transition temperature 56-57, 69T, 62, 65, 66, 66F, 67F, 78, 83, 199, 199f, 202, 207, 217, 220E, 231, 286, 358
  effect of blowing agent on 731, 733
Gray body correction factor 136-138E
  definition 135
Grooving 367

H:D 488, 496, 496F
  practical limit 565
  truncated cone, 574, 575
HDPE 5, 28, 56, 58, 109, 109-110E, 118, 119-120E, 189-191E, 207, 231F, 246F, 285, 338, 340, 349, 355, 369, 373E, 441, 451, 651
Heat balance, cyclic 302
Heat capacity 107F
  defined 82
Heat capacity—see also *Polymer heat capacity*, *Polymer enthalpy*
Heat conduction,
  equation 305
  mold, cooling 308
Heat distortion temperature, 69T
Heat flux 122
  constant, application 138, 139, 139F, 139, 140E
  constant, approximation 167
  constant 127
  definition 112, 113F
Heat removal from part,
  cyclical transient 287
  steady state 287, 288
Heat transfer, transient,
  computer model 314
  finite difference 315
Heat transfer coefficient 660, 661
  convection 111, 124, 124T, 124E, 145, 146, 146T, 147, 147E, 148E, 148T, 149F, 150, 288f, 294, 298-301E, 300, 305, 309T
  interfacial 290, 291T
  overall 288
  radiation, definition 126
  radiation 126E, 144, 146E, 147E, 661
Heat transfer resistance,
  interfacial 289, 290F
  overall 288, 292-293E
Heater,
  edge loss 154
Heater,
  ceramic 30
  efficiency 140-141, 141F, 142-143T, 144T, 151, 152, 153T
  examples 128
  gas-fired, catalytic 30
  gas-fired, direct 30
  gas-fired, indirect 30
  halogen 30
  heavy-gage formers, discussion 45, 46
  lamps 30
  local energy input 155-160, 155F, 157F, 158F
  metal plate 30
  metal resistance rod 29
  nickel-chrome 29
  pattern, during start-up 767
  quartz 30
  rod 150E, 150F, 151, 151E, 152F
  spacing 162-164, 163F
  start-up conditions for 765
Heating,
  energy efficiency 108T, 110
  heavy-gage, guidelines 193
  heavy-gage 14, 117, 168-175, 171T, 173E, 174E
  pattern, discussion 106
  pattern 160-161E, 161-162, 162F
  thin-gage, guidelines 193
  thin-gage 116, 164-167
  zone, discussion 106

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

- zone—see also *Pattern heating, Zonal heating*
Heating methods, summarized 29
Heating oven, discussion 29
Heating time 149F
Heavy-gage, definition 12
Heavy-gage thermoforming, in-line 13F
Heavy-gage thermoforming—see also *Cut-sheet forming*
HIPS 72*F*, 135, 210, 227, 338, 441
HIPS, sheet appearance of 642
HIPS/PVDC lamination 628
Hooke's law, defined 202
Hookean 202, 203F
Hot-melt adhesive 28
Hot strength, defined 208
Hyatt, J.W. 3
Hyperelastic analysis, defined 235f
Hyperelasticity 205

Impact forming 28
Index of refraction, in orientation 621
Inflation,
- effect on rate of return 819
- sheet 215
- tube 215, 216, 216F

Infrared radiant heating 13
Infrared wavelength range 88, 88T
Injection molding,
- comparison 2
- competition 11
- competition to thermoforming 835, 836, 838-839T, 840T, 841T, 842F, 841, 842T
- foam 696, 697-700T
- gas-assisted 696, 697-700T

Interdigitation, as a forming method 738, 739, 739F, 740F
Interest on money, simple 813
Interfacial resistance, computer model 318, 319T, 319F
IPS 754
IV—see *PET, intrinsic viscosity of*

K-BKZ equation 241
K-BKZ model—see also *Finite Element Analysis*
K-BKZ model 539, 541, 542F, 543
Keratin 3

Lake, causes of 565
Laminar flow, coolant 405
Laminated honeycomb 696
Laminated object manufacturing—see *Rapid prototyping*
Latex, solution casting 585
Law of mixtures,
- linear, defined 547
- linear, property type 548T
- logarithmic, defined 547
- logarithmic, property type 548T

LDPE 7, 25, 51, 55, 56, 58, 71, 168, 232F, 232E, 246F, 352, 456
Learning curve, discussion 806, 806F, 807, 807E
Learning curve characteristic—see *Learning curve*
Linear draw ratio—see also *Draw ratio*
Liquid,
- viscoelastic 205
- viscous 201

LLDPE 25
LLDPE as nucleant in CPET 654
LOM—see also *Rapid prototyping*
LOM 478
Loss factor—see *Loss tangent*
Loss tangent, defined 223
Lumped-parameter, approximation 127, 164, 165T, 166E, 166F, 659
- in cooling 304
- model, boundary conditions on 661

Machinery, innovations in 11
Male forming—see *Drape forming*
Matched die molding 14, 19F, 19, 557
Material balance 749F
Maxwell-Voigt viscoelastic model 223F, 224F
Maxwell viscoelastic model 22, 223F, 233, 234F

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

Melt strength, hot 220
Melting temperature—see also *Melting point*
Melting temperature 66, 67F, 78, 199f, 202
Metal forming, competition 28
Microcrack 352, 359, 364
  formation 339
  generation 285
Moat, 557, 558F,
  design 458, 458F
Mode I fracture 352, 354F
  defined 347, 349F
Mode II fracture, defined 347, 349F
Mode III fracture, defined 347-348, 349F
Modulus,
  creep 267T
  flexural, hot 211F, 212F
  loss 226F, 227F, 228F
  loss, defined 223
  reindorced polymer 680, 682, 683, 684, 685F
  storage, defined 223
Moisture,
  adsorption 617
  effect on sheet quality 640
  equilibrium content 617, 619F
Mold,
  aluminum 383, 401, 402
  aluminum, properties 402T
  cooling on non-metallic 309-311, 311-312E
  discussion 383
  female, draft angle 558, 561, 562F
  fiberboard 386, 387, 387T, 388F
  flipper in 452F
  hinge in 452, 452F, 453, 453F
  male, draft angle 558, 561, 562F
  materials, discussion 383
  metal, other 403
  nickel 400
  non-metallic 309-311, 311-312E
  plaster 383, 384, 387-388, 388T, 389
  plaster, finishing 389
  plaster, reinforcement 389, 389f
  plaster, repair 389
  plastic 383, 384, 389-397
  plastic, coolant channel 397
  plastic, epoxy 394, 395
  plastic, gel-coat, recipe 391T
  plastic, gel-coat 390
  plastic, internal support 392-393, 393F, 394F
  plastic, polyurethane 395, 396T
  plastic, reinforcement 390
  plastic, SMC 400
  plastic, unsaturated polyester resin, recipe 392T
  plastic, unsaturated polyester resin 390-395
  production, discussion 400-401
  prototype 384
  service requirements 383-384
  steel, properties, 403T
Mold, steel 383, 402, 403
  surface finish 433, 434, 434F, 434f, 435, 435F, 436, 436E
  surface texture 436, 437, 438
  swing in 453F
  white metal 397
  white metal, coolant channel 399, 399F
  white metal, properties 399T
  white metal, reinforcement 399
  white metal, spray-up 397, 398, 398F
  wood 383-386
  wood, finishing 386, 386f
  wood, properties 385T
  coolant 384
Mold design,
  cammed section 454
  collapsing core 454
  included hinge 455F
  moving elements, discussion 454
  pressure forming 678, 679, 679T
  reinforcement, encapsultaion of 453
  slide 454
  stripper plate/bar 455, 456, 456F, 457F
  undercut, discussion 452
  unscrewing section 454
Mold mark 676f
Mold materials,
  coefficient of thermal expansion 86T

  - density 86T
  - heat capacity 86T
  - thermal conductivity 86T
  - thermal diffusivity 86T
- Mold protocol, during startup 759-760T
- Mold release,
  - discussion 456, 457
  - permanent 457
  - temporary 457
- Mold surface, discussion 383
- Mold temperature, 69T
- Molecular weight distribution 61F
  - discussion 62
  - effects on 62-63
- Mooney-Rivlin model 205, 237f, 239F, 524f
- Mooney model 237, 238T, 258E, 278A
- Morphology, effect of extrusion on 583
- mPPO 77, 614, 753
  - sheet appearance of 642
  - foam 722
- Multi-cavity forming 14
- Multilayer sheet,
  - delamination, causes of 644
  - delamination of 694, 695, 696, 696E
  - ~~discussion 633~~
  - energy absorption in 688, 689, 689F, 690, 690F
  - forming of 687, 691, 692, 694, 695F
  - forming window for 691, 691F, 692
  - heating of 687, 688, 688F
  - lamination, measurement of 643
  - lamination, quality of 643
  - thin-gage, trapped air 740, 740F
  - tie layers in 623
  - two-flux method 689
  - via coextrusion 624, 626, 626F, 627F, 628, 630, 631
  - via lamination 628, 630, 630F, 631
- Murphy's oil soap 388, 388f

- Neck-down 208
- Necking 230
- Necking—see also *Yield*
  - as localized drawing 676f
  - during forming 676
- Neo-Hookean 249
  - model, defined 236, 238T
  - model 237, 238T, 244, 245, 248f
  - modulus 252E, 253, 253E, 254E, 256, 278A
  - response 206T
- Net Present Worth 816, 817, 818, 818E, 819T, 820T, 828T, 829T, 830F, 833E, 837T
- Newton's law 205
- Newtonian viscosity 205, 217, 233
- Nibbling, defined 355-356
- Nibbling force 356E
- Normal stress difference 233
- Notch sensitivity in formed part 565
- NPW—see *Net Present Worth*
- Nusselt number 373
  - defined 298
- Nylon 58, 63, 78, 81, 92, 352, 369, 451
- Nylon—see also *PA*, *PA 6*, *PA 66*
  - glass-reinforced 2
  - infrared absorption 90F
  - plug material 439, 441
- Nylon-6 243, 256F
- Nylon-66 243, 257F

- Off-gassing,
  - dissolved gases 199
  - lubricant 199
  - moisture 199
  - processing aid 199
- Ogden model 205, 239, 240, 244, 524f, 539
- OPP—see also *Oriented PP*
- OPP 25
- OPS—see also *Oriented PS*
- OPS 25, 352, 441
- Orientation,
  - biaxial 620
  - biaxial, blown film 620
  - biaxial, tentering 620, 621F
  - birefringence in 621
  - cross-direction 620, 621
  - machine-direction 620, 621
  - sheet, cross-direction 583, 608
  - sheet, machine-direction 583, 608

  sheet, start-up 755
  sheet, test for 637, 638, 756, 757, 758
  specification of 637, 638, 639
Oriented
  HDPE, properties 70T
  PET, properties 70T
  PMMA, properties 70T
  PP, properties 70T
  PS, properties 70T
Ovenable containers 3

PA 26, 58, 352, 451
  moisture sensitivity of regrind 545
  notch sensitivity 565
PA-6—see also *Nylon 6*
PA-6 2, 243, 256F, 753
PA-66 243, 257F, 650, 753
PAN 28
Part design,
  dimensional tolerance on 565
  edge, discussion 569
  edge, heavy-gage, adhesive trap 570F
  edge, heavy-gage 569
  edge, twin-sheet 569f
  guidelines, general 555
  guidelines, prestretch 559
  guidelines, process 556
  guidelines 561
  rim, discussion 569
  rim rolling 569, 570, 571F, 572, 572E, 573, 573E
  slot formation 568, 568F, 569F
  source of performance on variability 573, 577
  stiffening elements 566, 567F, 568
Part removal system, discussion 29
Parts design, discussion 471
Pattern heating, screen material 557
Payback period 818, 819
PBT 243, 258
  drying of 617, 618T
PBT 243, 258
PC 58, 127, 182, 224, 226F, 338, 339, 352, 368, 369, 792E
  moisture sensitivity of regrind 545
  stresses in formed 565
PE—see also *HDPE, LDPE*
PE 2, 55, 243, 573, 791
Penetration model, described 310
Performance criteria, discussion 471
PET 26, 28, 51, 58, 64, 65F, 73, 78, 92, 96F, 182, 199, 243, 250F, 349, 352, 573, 614, 753, 755, 791
  drying of 617, 618T, 620F
  infrared absorption 92F
  moisture in sheet 640
  moisture sensitivity of regrind 545
  multilayer sheet 623
  sheet appearance of 642
  static charge on 642
  stresses in formed 565
Pigment, infrared effect 185-187, 187F
Plane strain
  analysis 534, 535F, 536F
  stretching 540F
Plate, definition 12
Plate buckling, discussion 511, 512, 512F
Plug 14
  articulated 383, 447F
  bullet-nosed 446F
  coolant design 441-444, 444E
  effect on textured sheet 560, 560F
  flat 446F
  metal 441
  plastic 441
  prestretch depth 560, 560F
  ring 446F
  syntactic 559
  temperature control on 764
  thin-gage, discussion 51
  wood 386, 441
Plug assist 25
  during start-up 767
Plug assist—see also *Plugs*
Plug characteristic 439
Plug design 445, 446, 446F, 447, 447F, 447T, 448
  blunt-nosed 529, 530, 530F, 531, 532E, 543, 544F
  differential pressure effect 540, 542F
  discussion 439, 527, 530, 530F, 531, 531F
  Finite Element Analysis 539-543

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

  - force balance 533, 534, 534E, 535F, 536F
  - Geometric Element Analysis 536, 537F, 538F, 539F
  - Geometric Element Analysis—see also *Geometric Element Analysis*, *Plug design*
  - shape 507
  - spherical 531F, 533
  - tapered 540, 542F
  - temperature 507
- Plug mark-off 434, 441f, 543
- Plug material 439
  - properties 440T
- Plug temperature 559
- PMMA 2, 3, 7, 8, 58, 70-72, 74, 78, 84, 95F, 96F, 127, 176T, 182, 185F, 218, 219-220E, 227, 239F, 243, 249F, 338, 339, 344, 349, 791
  - biaxially oriented, properties of 622T
  - drying of 618T
  - infrared absorption 91F
  - molecular weight, 62
  - notch sensitivity 565
  - stresses in formed 565
- PMMA/ABS lamination 628
- Poisson's ratio,
  - defined 202
  - in trimming 347, 348T
- Polyamide,
  - biaxially oriented, properties of 622T
  - drying of 617, 618T
  - extrusion 584, 594
  - moisture in sheet 640
- Polyazole, solution casting 585
- Polybutadiene, mold surface 434
- Polycarbonate 58
  - drying of 617, 618T
  - infrared absorption 91F
  - moisture in sheet 640
- Polyethylene 56, 58, 63, 77, 92, 224, 228F, 754, 755
  - biaxially oriented 620
  - extrusion 584
  - infrared absorption 90F
  - low-density, extrusion of 594
  - molecular weight 61, 62F
- Polyethylene terephthalate 58, 63, 610
- Polyethylene terephthalate—see also *PET*, *CPET*
  - extrusion of 594, 596
  - regrind property loss 546T
- Polyimide 78, 243, 259
  - infrared absorption 92F
  - solution casting 585
- Polyisobutylene 65, 66F, 260F, 265, 265F
- Polymer,
  - absorption bands 94T
  - addition, chemical structure, 59T
  - addition 57
  - aliphatic 58
  - amorphous 63, 109, 437f
  - amorphous, modulus 57F
  - amorphous, phase diagram 68F
  - amorphous, start-up on 753
  - amorphous, stress-strain 79F
  - amorphous, thermoforming window 81
  - aromatic 58
  - chain mobility, discussion 70
  - comparative size, 56T
  - condensation 58
  - condensation, chemical structure, 60T
  - crosslinked, discussion 56
  - crosslinked, modulus 57F
  - crystalline 63, 109
  - crystalline, modulus 57F
  - crystalline, phase diagram 68F
  - crystalline, sag 451
  - crystalline, start-up on 753
  - crystalline, stress-strain 80F
  - crystalline, thermoforming window 81
  - definition 55
  - density 110, 82F
  - enthalpy 82F
  - filled, start-up on 754
  - gas permeation resistance, discussion 72-73
  - heat capacity, defined 82
  - heat capacity 83T, 85-86T
  - infrared-transparent 182, 183F
  - infrared absorption 89T
  - infrared spectra 87-96

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

  laminate, discussion 78
  modulus 79F
  molecular weight, definition 58
  molecular weight, discussion 55
  molecular weight, number-average 58
  molecular weight, weight-average 58
  orientation 70T
  orientation, properties 70
  processing characteristics, summary 97-102T
  radiation absorption characteristics 132T
  reinforced, start-up on 754
  specific heat 110
  steric hindrance, 71, 71T
  stress-crack resistance, discussion 72
  thermal conductivity 85-86T, 110
  thermal properties of 110
  thermoplastic, discussion 55
  thermoset, definition 55
  vinyl 58
Polymer adduct 74T
  blowing agent 77
  discussion 74
  fiber reinforcement 77, 77T
  filler 76, 76T
  plasticizer 74-75
Polymer blend, discussion 74
Polymer copolymerization, discussion 73
Polymer crystallinity,
  Avrami 65
  effects on 63-64
Polymer crystallization, half-time 64
Polymer crystallization rate, 64T, 65F
Polymer foams 57f
Polymer morphology, discussion 63
Polymer properties, start-up 754
Polymethyl methacrylate,
  cell-cast 587
  moisture in sheet 640
Polyolefin 84, 229F, 232T, 372, 441, 545
  drying of 617
  foam 12
Polyphenylene oxide—see also *mPPO*
Polyphenylene oxide 74
Polypropylene 58, 63, 71, 73, 227, 273E
Polypropylene—see also *PP*
  extrusion 584, 594
  infrared absorption 90F
Polystyrene 65
Polystyrene—see also *PS*
  drying of 618T
  extrusion 584
  foam, lamination of 628
  infrared absorption 90F
  multilayer sheet 628
Polyurethane,
  crosslinked 57
  mold surface 434
  thermoplastic, infrared absorption 91F
  thermosetting 285
Polyvinyl acetate 74
Polyvinyl chloride—see also *PVC*, *RPVC*, *FPVC*
  calendering 584, 587
  flexible 584
  rigid 584
  rigid, extrusion of 594, 596
POM 352, 441
Poppet valve—see also *Vent, poppet valve*
Poppet valve 429, 430F, 430E, 456, 456F
Porous metal, manufacturer 424T
PP 3, 5, 13, 18, 19, 25, 28, 38, 51, 58, 65, 78, 81, 84, 168, 234, 243, 247F, 248F, 285, 340, 349, 355, 369, 441, 451, 456, 545, 573, 610, 610F, 610f, 614, 755, 773, 791
  biaxially oriented 620
  biaxially oriented, properties of 622T
PP/PVDC lamination 628
PPS 368
Prandtl number 373
  defined 294, 295, 295T
Pressure, effect on surface texture 436, 437, 437F, 438, 438F, 438E
  inflation 249
Pressure forming 555, 557, 565
  discussion 14, 15
  during start-up 768
  textured surface 561
Pressure system, discussion 29
Prestretching 503-507, 505F
  air pressure 506T

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

- discussion 14, 29
- double-bubble 461, 461F
- restraint 461, 461F

Process control, discussion 36, 37

Profit,
- gross 799T, 800
- net 799T, 800, 801T

Profitability, discussion 814, 815

Profitability index—see *Rate of return, discounted cash-flow*

Property value loss 549, 549T, 550T, 551T, 552E
- declining, property type 548T
- offset, property type 548
- offset 548
- power-law, property type 548T
- power-law 548
- proportional, property type 548T
- proportional 547
- protocol for determining 551, 552

Prototyping, objective of 486-488

Prototyping, rapid—see *Rapid prototyping*

Prototyping 478

PS, biaxially oriented, properties of 622T

PS 3, 5, 8, 14, 28, 58, 70, 73, 74, 77, 84, 95F, 96F, 135, 182, 210, 221E, 224, 243, 251F, 338, 339, 344, 349, 355, 368, 369, 379, 573, 791

PS—see also *HIPS*
- biaxially oriented 620
- foam 12, 19, 78
- notch sensitivity 565
- sheet appearance of 642
- static charge on 642
- stresses in formed 565

PTFE 80, 89, 210, 243, 254F, 349, 369
- infrared absorption 93F
- modulus 80F, 81F
- mold release 457
- mold surface 434
- plug material 439, 441
- sag band coating 451

PUR Foam 27

Purchase order, importance of 477

PVC 2, 3, 5, 8, 14, 25, 30, 58, 65, 71, 72, 74, 84, 89, 182, 207, 214, 227, 239, 243, 244F, 245F, 254E, 255E, 262F-265F, 267T, 441, 753, 754, 791

PVC—see also *PFVC, RPVC*
- drying of 617, 618T
- glass transition temperature 75
- infrared absorption 91F
- plasticizer addition 75F
- sheet appearance of 642

PVC/PMMA 176T
- lamination 628
- multilayer sheet 623

PVDC 28, 78

Quality, thin-film 587

Radiation,
- black body, definition 129, 130, 130F, 131, 131E, 131T, 132T, 133T, 133E, 134E
- boundary condition 123
- definition 13, 111, 111F, 128
- gray body, definition 134, 135, 135F
- infrared 111, 128, 129, 129T

Radius, design 459, 460, 460F

Rapeseed oil, drilling 369

Rapid prototyping 395, 487
- layered paper molding 487, 488
- layered sheet molding 487, 489F
- polymer droplet 488
- powder fusion 487, 489F
- stereolithography 395, 487, 489F

Rate of return 816, 824, 825
- discounted cash-flow 816, 817, 818, 818E, 819T, 820T, 821T, 828T, 829T, 830F, 833E, 837T
- effective discounted cash-flow 819
- true—see *Rate of return, discounted cash-flow*

Redistribution,
- polymer sheet, advantages of 512
- polymer sheet 471

Reflectance 183, 184, 184E

Refrigerator liners 3

Regrind 38f, 478, 585

Regrind—see also *Trim*
  cascade, discussion 553, 554, 554F, 554E
  discussion 544
  economics 545
  fiber-reinforced polymer 545
  generation of 461
  material property loss during 545, 546T
  mechanical property loss, theory, 579A, 579FA, 580A
  steady-state 579A, 579FA, 580A
Reprocessing,
  cascade 553, 554, 554F, 554E, 555
  closed-loop 546, 547F
  cost of 508
  economics of 484-485, 485E
  steady-state 484-485, 485E
Residence time,
  extruder 614
  mean 614, 615E, 616, 617E
  plug flow 614, 615E
Residence time distribution 615, 616, 616F
Residual stress 199
Retardation time 234, 235E, 235F
  defined 234
Return on investment 815, 816
Reynolds number 405, 416F, 419
  defined 294, 294E
Rheology, defined 206, 206f
Reometer, strain 214, 215F
Rheometry, extensional 226
Rim material,
  amount, force balance 499F, 500-503, 502E
  effect on draw ratio 499, 500, 500E, 501F, 502E
Rim rolling 450
Risk factor, entrepreneurial 823, 824, 825, 825-826E
Rivlin model 236, 238T, 239, 240, 240F
Rod heater, spacing 556, 556F
ROI—see *Return on investment*
Roll-fed forming—see also *thermoforming* categories
Roll-fed forming 3, 13, 15F
Roll stack,
  bank on 607, 608, 609F
  configuration of 608F
  cooling v. crystallinity 610, 610F
  discussion 607
  function 607
  temperature effect 609F, 610F, 610
Rotary press 42, 43F, 44F
  four-station 42, 44F
  three-station 42, 43F
Rotational molding, competition 11, 28, 835, 836, 838-839T, 840T, 841T, 842F, 841, 842T
RPVC 213, 229F, 243, 344, 352, 355, 369, 545, 614, 753, 756F
Rubbery sheet 201

Safety, during start-up 765
Sag 51, 198, 199, 200, 200F, 201, 201F, 221E
  as determined by photoelectric eye 765
  catenary 199, 269, 269F, 270, 272F, 276, 274E, 277
  discussion 266
  during start-up 765
  initial, definition 267, 267F, 268, 268F, 268T
  initial 273E
  parabolic 270, 270F, 271, 273F, 274E, 276, 277
  polymer sheet 556
  reinforced polymer sheet 556
  temperature effect 275E, 276E
  tensile, definition 268
Sag band, discussion 451
SAN 243, 247F, 344, 368
Schmidt model 237, 238T
Scrap 38f
  definition 478f
Scrapless thermoforming 3
Set temperature 286
Shape factor, cooling 289, 291, 292F, 293F
Shear modulus, in trimming 347
Sheet,
  custom size, economics 483-486

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

  dimensional tolerance on 566
  extrusion 2, 3
  specifications, discussion 633, 634-636T, 637
  standard size, economics 483-486
  virgin, defined 632
  virgin + regrind, defined 633
Sheet appearance,
  color 642
  discrete marks 641
  discussion 641
  effect of process on quality 641
  surface marks 641
  surface protection of 643f
  surface texture 642
Sheet characteristic, start-up 754, 755
Sheet die, coextrusion 624, 627F
Sheet dimension,
  discussion 637
  tolerance on 637, 638E
Sheet flatness, specification of 638E, 639
Sheet handling 29
Sheet orientation—see *Orientation*
Sheet quality,
  discussion 632
  effect of moisture on 640
  start-up 755
Sheet squareness, specification of 638E, 639
Sheet strength, hot 271-273
Sheet texture,
  by roll stack 607
  processing effects on 642
Sheet thickness,
  control by roll stack 607
  die gap control of 602, 604F
  monitoring 601
  ultrasonic measurement of 643
Sheet transfer 29
Sheet trimming,
  deckles 610, 611, 612F
  discussion 610, 611
  dust 611
  guillotine 611
  razor blade 611, 613F
Sheet utilization,
  discussion 461, 462, 462F, 462E, 463E, 464, 464F, 465E-467E
  heavy-gage 461-463
  optimization 461
  thin-gage 463-467
Shift factor 181, 182
Shift factor—see also *W-L-F equation*
Shower stalls 3
Shrinkage,
  amorphous polymer 563
  constrained, defined 322
  constrained, discussion 324-329
  constrained, effect on draft angle 329, 329E
  constrained, rate of cooling effect 326-327, 328F
  constrained, stress relaxation effect 326-327, 327E
  crystalline polymer 563
  discussion 320
  mold temperature effect on 557
  thermoformable polymers 325T
  unconstrained, defined 322
  unconstrained, effects on 323-324
Shuttle press 33F, 42, 43F
Signs 3
Silicone rubber, mold surface 434
SLA—see *Rapid prototyping*, *Stereolithography*
Slotting 367
Smoke—see also *Off-gassing*
Smoke 198, 199
Soaking time—see *Equilibration*
Solid,
  elastic, rubber 201
  elastoplastic 202f
Solution casting, film 585
Specific heat—see also *Heat capacity*, *Enthalpy*
Specific heat 107F
Specific volume,
  temperature-dependent 320, 320f
Specific volume 199F
Spring-back, reinforced sheet 568
Stanton number, defined 294, 295
Start-up,
  costs 752T
  discussion 768
  machine, protocol, 759-760T,

  mold, protocol 758, 759-760T, 760-764
  on virgin sheet only 768
  polymer 753
  protocol, polymer 753-758
  temperature monitoring 764, 765, 766
Static charge, discussion 642, 643, 643f
Static mixer 594, 595, 595F, 596, 596F
Steel rule die 331, 331F, 332F
  cutting edge 361, 361F
  discussion 359-361
  hardening 360-361
  mounting 363, 363F
  resharpening 362
Stereolithography 395, 478
STP—see *Scrapless thermoforming*
STP 28
Strain,
  defined 202
  engineering 204
  Hencky 204
  true 204
  ultimate 213
Strain energy function,
  coefficients, 239T
  defined 235
Strain hardening 214, 226
Strain invariants, Wagner form 241
Strain rate, 209, 229F, 234, 265
Strain recovery, discussion
Stress,
  defined 202
  engineering 204
  true 204
Stress-strain 209, 210, 212, 228, 228F, 230F, 240
  curve 214
  curve, ductile 209F
  data 242, 242F
  engineering 204, 205
  isochronous 242, 243, 243F, 244F, 245F, 246F
  true 205
  uniaxial 244
Stress-strain-rate of strain 198, 226, 233
Stress concentration factor 350T, 350F
Stress intensity factor 351T, 352
  defined 349
Stretch factor—see *Draw ratio, areal*
Stretching, biaxial, equal 236, 237
Stretching, biaxial—see also *Deformation, biaxial, Extension, biaxial*
Stretching, biaxial 207F, 208, 215, 216, 216F, 226, 228F, 278A
Stretch, uniaxial—see also *Deformation, biaxial, Extension, biaxial*
Stretching, uniaxial 208, 208F, 226, 228, 236, 237
Stretching—see also *Deformation, Elongational*
Stretching 202
Stripper plate 455
  discussion 51
Surge tank 33, 34
  discussion 32
Swimming, sheet 198, 199
Syntactic foam, plug material 439, 441
  properties 442T

Take-up roll, discussion 611, 613F, 613-614E
Tan δ 224, 225F, 226F, 227F, 228F
  defined 223
Tan δ—see also *Loss tangent*
Temperature, thermal imaging 764
Temperature measurement,
  infrared 30
  thermistor 30
  thermocouple 30
Temperature monitoring,
  during start-up 764, 765, 766
  infrared 764, 766
Tensile strength, hot 209, 210, 210F, 211F, 212, 213F, 214F, 215
Testing,
  ASTM 475, 476
  criteria 474, 475, 476
  dynamic mechanical 222, 224
  part performance effect 473
  product 473
Textured sheet forming 562
Thermal conductivity, discussion 84
Thermal diffusivity 85-86T
  definition 84, 87

Thermal expansion coefficient 87
Thermal expansion coefficient—see also *Coefficient of thermal expansion*
Thermoforming,
  applications 7, 7-8T
  competition 835, 836, 838-839T, 840T, 841T, 842F, 841, 842T
  competition to, heavy-gage 834
  competition to, thin-gage 833, 834
  continuous sheet, definition 13
  cut-sheet, definition 13
  definition 2
  description 106
  history 2, 3, 4T
  machinery, direct contact 51
  machinery, heater discussion 51
  machinery, heavy-gage check-list 38, 39-42T
  machinery, heavy-gage dual-oven shuttle press 42, 43F
  machinery, heavy-gage shuttle press 42, 43F
  machinery, heavy-gage rotary press 42, 43F, 44F
  machinery, overview, discussion 29, 30T
  machinery, pin-chain rails 50, 51
  machinery, thin-gage check-list 46, 46-49T
  machinery, vertical, discussion 51
  market growth 5, 6F
  markets 4, 9-10T
  polymers converted in 5T, 6T
  roll-fed, definition 13
  thin-gage, drink cup 50F
  thin-gage, form-fill-seal 50F
  window, discussion 81
Thermomechanical degradation,
  extrusion effect 545
  regrind 545
  thermoforming effect 545
Thin-gage, definition 12
Thread, formed
  single-sheet 563, 564F
  twin-sheet 562, 564F
TMA—see *Analysis, thermomechanical*
TPE 456
TPO 349
Transmissivity, discussion 92
Transmittance 183
Trapped sheet forming 25T, 25
Treloar, L.R.G. 257
Trim 508, 545
  definition 478, 478f
  determination of extent of 479-486, 479F, 480E, 481E, 482E
  source of 478, 479
Trim-in-place-see *Trimming, in-mold*
Trim dies, heated 359
Trim dust 285, 339, 359, 362F, 364
  elimination of 643
Trim hairs—see also *Angel hair*
Trim hairs 285
Trim press, discussion 29
Trim region, accuracy factors 336
Trimming,
  abrasion cutting 335, 336F
  abrasive wheel 344-347, 345F, 346T
  automatic, heavy-gage 15
  compression 334, 336F, 337F
  defined 329
  devices 329-331, 330F
  dinking 38
  discussion 15, 38, 285
  forged die 367
  heavy-gage 331
  in-line 38, 51
  in-mold 38, 51, 333, 334F, 335F, 383
  in-situ 38
  machined die 367
  manual, heavy-gage 15
  manual 38
  microfibers 340
  multi-axis router 38
  multiple-edged tool 342, 342F, 344, 344E
  notching 363, 364F
  polymer response to 338, 338F
  post-molding operations 333
  punch-and-die 334, 335F, 364-367, 365-367F
  registry 337, 337F
  router, multi-axis 332, 332F
  routering 335, 336F

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

 shear 334, 336F, 337F
 single-edged tool 340, 341, 341F
 steel-rule die 38
 summary 376, 377T, 378T, 379
 tabbing 363, 364, 364F
 thermal 335, 336F
 thin-gage 333
 water-jet, heavy-gage 15
Trimming press, in-line 285
Troubleshooting, forming process 769, 772, 773T, 783T
 heavy-gage 774-783T
 thin-gage 784-789T
Troubleshooting, sheet extrusion 769, 769-772T
Trouton viscosity 205, 233
Tub surrounds 3
Turbulent flow, coolant 405
Twin-sheet formers 43, 44
Twin-sheet forming,
 air temperature during 557
 blow pin location 559
Twin-sheet thermoforming—see also *Forming, twin-sheet*

UHMWPE, molecular weight 62, 62F
UHMWPE 56, 89, 354, 369
Undercut design 562, 563F

Vacuum, during start-up 761, 762, 762F, 763, 763F
Vacuum box 21, 560
Vacuum forming 17F, 17
 definition 14
 during start-up 766
 schematic 16F
Vacuum hole—see also *Vent hole*
 dimension 558
 location 558, 559F
Vacuum pressure norm 556
Vacuum pump,
 discussion 32
 specifications 36T
Vacuum system 411F, 412F
 design 411, 412, 413, 413E, 414, 414E, 415, 416, 416F-417F, 417
 design criteria 33, 34E, 35E
 discussion 32
 evacuation rate 33-35
 pressure drop 33
 recovery time 34E, 34
Vent, poppet valve 429, 430F, 430E
Vent, porous plug 429, 429F
Vent, slot 427, 427F, 428, 428F
Vent—see *Vent hole, Vent, slot, Poppet valve*
Vent hole 383
 design 417-418, 418E-419E, 420, 420E, 421, 422, 422E, 423E, 423, 425F, 425, 425E, 426, 426E, 427
 discussion 411
 fiberboard 386, 388F
 location 430, 431, 431F, 432, 432F, 433F
 plaster 388
 vacuum system 33
 wood 386
View factor 138
 definition 152, 154, 154E
Viscoelastic,
 linear 222
 liquid 205
 model 240
 model, fading memory 241
 solid model 260
Viscoelasticity 242f
 linear, defined 206, 206T
 nonlinear, defined 206, 206T
Viscosity,
 elongational 217, 217f
 elongational, defined 205
 extensional, biaxial 232T, 264
 extensional 231F, 231, 232F
 Newtonian 205
 non-Newtonian 205
 shear 217f, 218F, 218T
 shear, defined 205
Visible wavelength range 88, 88F
Voigt-Kelvin viscoelastic model 222, 234F

W-L-F equation 181, 181T, 217, 219
Wall thickness 211, 253, 508, 509, 510

A = Appendix, E = Example, f = Footnote, F = Figure, T = Table

effect on mold feature 561, 561F
local 198
part, discussion 471
prediction, discussion 510-513
structural aspects of 511

Web—see also *Trim*

Web,
  definition 478, 478f
  formation, discussion 457, 458, 458F

Web breaker,
  discussion 457
  material for 458

Web catcher, discussion 457, 458, 458F

Yield 230

Yielding, stress-strain 208

Young's modulus 208, 209
  defined 202
  in trimming 347, 348

Ziabicki equation 658

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