13 SHAPING PROCESSES FOR PLASTICS

Review Questions

13.1 What are some of the reasons why plastic shaping processes are important?

Answer. The reasons include (1) many of the processes are net shape processes; (2) in general, less energy is employed than in metalworking processes; (3) lower temperatures are required to process plastics than metals or ceramics; (4) there is great flexibility in geometry; and (5) painting and other finishing processes are generally not required.

13.2 Identify the main categories of plastics-shaping processes, as classified by the resulting product geometry.

Answer. The categories are (1) continuous extruded products with constant cross section other than sheets, films, and filaments; (2) continuous sheets and films; (3) continuous filaments (fibers); (4) molded parts that are mostly solid; (5) hollow molded parts with relatively thin walls; (6) discrete parts made of formed sheets and films; (7) castings; and (8) foamed products.

13.3 Viscosity is an important property of a polymer melt in plastics-shaping processes. Upon what parameters does viscosity depend?

Answer. Viscosity of a polymer melt depends on (1) temperature and (2) shear rate. Also, (3) the molecular weight of the polymer affects viscosity.

13.4 How does the viscosity of a polymer melt differ from most fluids that are Newtonian?

Answer. A polymer melt exhibits pseudoplasticity, which means that its viscosity decreases with increasing shear rate. The viscosity of a Newtonian fluid remains constant with increasing shear rate

13.5 What does viscoelasticity mean, when applied to a polymer melt?

Answer. Viscoelasticity is a combination of viscous and elastic properties which cause the melt to exhibit memory - the tendency to return to its previous shape, as exhibited by die swell in extrusion.

13.6 Define die swell in extrusion.

Answer. Die swell is the tendency of the extrudate to expand in cross-sectional dimensions immediately on exiting the die orifice. It results from the viscoelastic properties of the polymer melt.

13.7 Briefly describe the plastic extrusion process.

Answer. In plastic extrusion, a polymer melt is compressed to flow through a die orifice and thus the continuous length of the plastic assumes a cross-sectional shape that is approximately the same as that of the orifice.

13.8 The barrel and screw of an extruder are generally divided into three sections; identify the sections.

Answer. The sections are (1) the feed section, in which the feed stock is fed from the hopper and heated; (2) the compression section, in which the polymer changes to a viscous fluid; and (3) the metering section, in which pressure is developed to pump the plastic through the die orifice.

13.9 What are the functions of the screen pack and breaker plate at the die end of the extruder barrel?

Answer. The functions are to (1) filter dirt and lumps, (2) build pressure, (3) straighten the flow and remove memory of the polymer melt.

13.10 What are the various forms of extruded shapes and corresponding dies?

Answer. The shapes are (1) solid profiles, such as rounds and L-shapes; (2) hollow profiles, such as tubes; (3) wire and cable coating; (4) sheet and film; and (5) filaments (continuous fibers).

13.11 What is the distinction between plastic sheet and plastic film?

Answer. The distinction is based on thickness. Sheet stock has a thickness greater than 0.5 mm (0.020 in), while film stock is less than 0.5 mm (0.020 in) thick.

13.12 What is the *blown-film process* for producing film stock?

Answer. The blown-film process is a widely used process for making thin polyethylene film for packaging. It combines extrusion and blowing to produce a tube of thin film. The process begins with the extrusion of a tube that is immediately drawn upward while still molten and simultaneously expanded in size by air inflated into it through the die mandrel.

13.13 Describe the calendering process.

Answer. Calendering is a process for producing sheet and film stock out of rubber or rubbery thermoplastics such as plasticized PVC. In the process, the initial feedstock is passed through a series of rolls to work the material and reduce its thickness to the desired gage.

13.14 Polymer fibers and filaments are used in several applications. What is the most important commercial application?

Answer. Textiles.

13.15 What is the technical difference between a *fiber* and a *filament*?

Answer. A fiber is a long, thin strand of material whose length is at least 100 times its diameter; a filament is a fiber of continuous length.

13.16 Among the synthetic fiber materials, which are the most important?

Answer. Polyester is the most important commercially, followed by nylon, acrylics, and rayon.

13.17 Briefly describe the injection-molding process.

Answer. Injection molding is a process in which a polymer is heated to a highly plastic state and forced to flow under high pressure into a mold cavity, where it solidifies. The molding is then removed from the cavity.

13.18 What are the three basic types of clamping units?

Answer. The clamping units are: (1) mechanical toggle clamp, (2) hydraulic, and (3) hydromechanical units which combine hydraulic and mechanical actuations.

13.19 What is the function of gates in injection molds?

Answer. The function of gates in an injection mold is to constrict the flow of molten plastic into the cavity, which increases the shear rate and reduces the viscosity of the polymer melt.

13.20 What are the advantages of a three-plate mold over a two-plate mold in injection molding?

Answer. As the mold opens, the three-plate mold automatically separates the molded part(s) from the runner system.

13.21 Discuss some of the defects that can occur in plastic injection molding.

Answer. The defects include (1) short shots, in which the polymer melt solidifies before filling the cavity; (2) flashing, in which the polymer melt is squeezed into the parting surfaces between the mold halves and around ejection pins; (3) sink marks, in which the surface is drawn into the molding by contraction of internal material; and (4) weld lines where the melt has flowed around a core or other convex detail in the mold cavity and met from opposite directions, thus resulting in mechanical properties that are inferior to those in the rest of the part.

13.22 Describe structural foam molding.

Answer. Structural foam molding is an injection-molding process in which a gas or gas-producing ingredient is mixed with the polymer melt prior to injection into the mold cavity; this results in the part having a tough outer skin surrounded by a foam core.

13.23 What are the significant differences in the equipment and operating procedures between injection molding of thermoplastics and injection molding of thermosets?

Answer. The differences in injection molding of thermosets are (1) shorter barrel length, (2) lower temperatures in the barrel, these first two reasons to prevent premature curing; and (3) use of a heated mold to cause cross-linking of the TS polymer.

13.24 What is reaction injection molding?

Answer. Reaction injection molding involves the mixing of two highly reactive liquid ingredients and immediately injecting the mixture into a mold cavity where chemical reactions leading to solidification occur. The two ingredients form the components used in catalyst-activated or mixing-activated thermoset systems.

13.25 What kinds of products are produced by blow molding?

Answer. Blow molding is used to produce hollow, seamless containers, such as bottles.

13.26 In rotational molding, the starting polymer charge is distributed on the surfaces of the mold cavity by centrifugal force, true or false?

Answer. False. It is gravity, not centrifugal force, that causes uniform coating of the mold surfaces.

13.27 What is the form of the starting material in thermoforming?

Answer. Thermoforming starts with a thermoplastic sheet or film.

13.28 Why cannot thermosetting polymers be used in thermoforming processes?

Answer. Because sheets or films of thermosetting plastic are already cross-linked by the primary process that formed them. Heating in preparation for thermoforming would simply degrade the material.

13.29 What is the difference between a positive mold and a negative mold in thermoforming?

Answer. A positive mold has a convex shape; a negative mold has a concave cavity.

13.30 Why are the molds generally more costly in mechanical thermoforming than in pressure or vacuum thermoforming?

Answer. In mechanical thermoforming, matching mold halves are required; while in other thermoforming processes, only one mold form is required.

13.31 What are the processes by which polymer foams are produced?

Answer. There are several foaming processes: (1) mechanical agitation - mixing a liquid resin with air, then hardening the polymer by means of heat or chemical reaction; (2) mixing a physical blowing agent with the polymer - a gas such as nitrogen (N_2) or pentane (C_5H_{12}) which can be dissolved in the polymer melt under pressure, so that the gas comes out of solution and expands when the pressure is subsequently reduced; and (3) mixing the polymer with chemical compounds, called chemical blowing agents, that decompose at elevated temperatures to liberate gases such as CO_2 or N_2 within the melt.

13.32 What are some of the general considerations that product designers must keep in mind when designing components out of plastics?

Answer. Some of the general considerations are the following: (1) Plastics are not as strong or stiff as metals and should not be used in applications where high stresses will be encountered. (2) Impact resistance of plastics is general good, better than many ceramics. (3) Service temperatures of plastics are limited relative to engineering metals and ceramics. (4) Thermal expansion is greater for plastics than metals; so dimensional changes due to temperature variations are much more significant than for metals. (5) Many types of plastics degrade from sunlight and certain other forms of radiation. Also, some plastics degrade in oxygen and ozone atmospheres. Finally, plastics are soluble in many common solvents.

Problems

Answers to problems labeled **(A)** are listed in an Appendix at the back of the book.

Extrusion

13.1 **(A)** (SI units) The diameter of an extruder barrel = 85 mm and its length = 2.00 m. The screw rotates at 55 rev/min, its channel depth = 8.0 mm, and its flight angle = 18°. Head pressure at the die end of the barrel = 10.0(10^6) Pa. Viscosity of the polymer melt = 100 Pa-s. Find the volume flow rate of plastic at the die end of the barrel.

Solution: $Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5\pi^2(85\times10^{-3})^2(55/60)(8\times10^{-3})\sin 18 \cos 18$
$= 261{,}462 \times 10^{-9}(0.3090)(0.9510) = 76.83 \times 10^{-6}$ m^3/s
$p = 10.0 \times 10^6$ Pa $= 10 \times 10^6$ N/m^2
$Q_b = p\pi D d_c^3 \sin^2 A/(12\eta L) = \pi(10 \times 10^6)(85\times10^{-3})(8\times10^{-3})^3(\sin 18)^2/12(100)(2.00) =$
$54.40(10^{-6})$ m^3/s
$Q_x = 76.83 \times 10^{-6}$ m^3/s $- 54.40 \times 10^{-6}$ m^3/s $=$ $\mathbf{22.43 \times 10^{-6}}$ **m^3/s**

13.2 (USCS units) An extruder barrel has a diameter of 5.0 in and a length-to-diameter ratio of 22. The viscosity of the polymer melt = 0.0020 lb-s/in^2. The pitch of the screw = 4.5 in and channel depth = 0.25 in. The screw rotates at 50 rev/min, generating a head pressure = 500 lb/in^2. What is the volume flow rate of plastic at the die end of the barrel?

Solution:
$A = \tan^{-1}(p/(\pi D)) = \tan^{-1}(4.5/(5\pi)) = 16°$
$Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5\pi^2 (5.0^2)(50/60)\ 0.25 \sin 16 \cos 16 = 6.81$ in^3/sec
$Q_b = p\pi D d_c{}^3 \sin^2 A/(12\eta L) = 500\pi(5.0)(0.25^3)\sin^2 16/(12(0.002)(5.0)(22)) = 3.53$ in^3/sec
$Q_x = Q_d - Q_b = 6.81$ in^3/sec – 3.53 in^3/sec = **3.28 in^3/sec**

13.3 **(A)** (USCS units) An extruder barrel has a diameter of 3.0 in and length of 70 in. The screw rotates at 60 rev/min; its channel depth = 0.25 in, and its flight angle = 17.5°. Head pressure at the die end of the barrel is 800 lb/in^2. Viscosity of the polymer melt is 130(10^{-4}) lb-sec/in^2. Determine the volume flow rate of plastic in the barrel.

Solution: $Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5\pi^2(3.0)^2(1)(0.25)\sin 17.5 \cos 17.5$
$= 11.103(0.3007)(0.9537) = 3.184$ in^3/sec
$Q_b = \pi(800)(3.0)(0.25)^3(\sin 17.5)^2/12(130 \times 10^{-4})(70) = 0.975$ in^3/sec
$Q_x = 3.184 - 0.975 =$ **2.209 in^3/sec**

13.4 (SI units) The diameter of an extruder barrel = 100 mm and its length = 2.6 m. Screw channel depth = 7.0 mm, and its pitch = 95 mm. Viscosity of the polymer melt = 105 Pa-s, and head pressure in the barrel = 4.0 MPa. What rotational speed of the screw is required to achieve a volumetric flow rate of 90 cm^3/s?

Solution: $A = \tan^{-1}(p/(\pi D)) = \tan^{-1}(95/100\pi) = 16.8°$
$Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5\pi^2(0.100)^2(N)(7.0 \times 10^{-3})\sin 16.8 \cos 16.8$
$= 95.7\ N \times 10^{-6}$ m^3/s
$Q_b = p\pi D d_c{}^3 \sin^2 A/(12\eta L) = \pi(4\times10^6)(0.100)(7\times10^{-3})^3(\sin 16.8)^2/12(105)(2.6)$
$= 11.02 \times 10^{-6}$ m^3/s
$Q_x = Q_d - Q_b = 95.7\ N \times 10^{-6} - 11.02 \times 10^{-6} = 90 \times 10^{-6}$ m^3/s
$95.7\ N = 90.0 + 11.02 = 101.02$
$N = 101.02/95.7 =$ **1.056 rev/s = 63.3 rev/min**

13.5 (USCS units) An extruder has a barrel diameter of 3.5 in and a length of 7.0 ft. The screw has a channel depth of 0.25 in and a flight angle of 20°, and it rotates at 55 rev/min. The material being extruded is low density polyethylene. At the present settings, the volumetric flow rate of the polymer melt is 2.50 in^3/sec and head pressure is 500 lb/in^2. At these operating characteristics, find the viscosity of the polyethylene.

Solution: $Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5\pi^2(3.5^2)(55/60)(0.25)\sin 20 \cos 20$
$= 4.45$ in^3/sec
$Q_b = Q_d - Q_x = 4.45 - 2.50 = 1.95$ in^3/sec
$\eta = p\pi D d_c{}^3 \text{ in}^2 A/(12\ Q_b L) = 500\pi(3.5)(0.25^3)\sin^2(20)/(12(1.95)(7)(12)) =$ **0.005 lb-s/in^2**

13.6 Determine the helix angle A at which the screw pitch p is equal to the screw diameter D. This is called the “square” angle in plastics extrusion; it is the angle that provides a flight advance equal to one diameter for each rotation of the screw.

Solution: Assume flight land = zero.

From Equation (15.4), $\tan A = p/\pi D$, where p = pitch
If $p = D$, then $A = \tan^{-1}(1/\pi)$ **= 17.66°**

13.7 (SI units) An extruder barrel has diameter = 80 mm and length = 2.0 m. Its screw has a channel depth = 6 mm and flight angle = 18°, and it rotates at 1 rev/s. The plastic melt has a viscosity = 150 Pa-s. Determine the extruder characteristic by computing $Q_{\max}$ and $p_{\max}$ and then find the linear equation defining the straight line between them.

Solution: $Q_{max} = Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5\pi^2(0.08)^2(1)(6 \times 10^{-3})\sin 18 \cos 18$
$= 0.1895 \times 10^{-3}(0.3090)(0.9510) = 55.7 \times 10^{-6}$ m^3/s
$p_{max} = 6\pi DNL\eta \cot A/d_c^2 = 6\pi(0.08)(1)(2)(150)(\cot 18)/(6\times10^{-3})^2$
$= 452.4(3.077)/36 \times 10^{-6} = 38.67 \times 10^6$ Pa = 38.67 MPa
$Q_x = 55.7 \times 10^{-6} - (55.7 \times 10^{-6}/38.67)p$
$\mathbf{Q_x = 55.7 \times 10^{-6} - 1.44 \times 10^{-6}\, p}$, where p has units of MPa and Q_x has units of m^3/s

13.8 **(A)** (USCS units) An extruder barrel has a diameter = 4.5 in and its L/D ratio = 22. The screw channel depth = 0.25 in, and its pitch = 4.8 in. It rotates at 60 rev/min. Viscosity of the polymer melt is $50(10^{-4})$ lb-sec/in^2. What head pressure is required to obtain a volume flow rate = 175 in^3/min?

Solution: $A = \tan^{-1}(\text{pitch}/\pi D) = \tan^{-1}(4.8/4.5\pi) = 18.75°$
$Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5\pi^2(4.5)^2(1)(0.25)\sin 18.75 \cos 18.75$
$= 24.98(0.3214)(0.9469) = 7.602$ in^3/sec = 456.1 in^3/min
$Q_x = Q_d - Q_b = 456.1 - Q_d = 175$
$Q_b = 456.1 - 175 = 281.1$ in^3/min = 4.686 in^3/sec
$L = 4.5(22) = 99$ in
$Q_b = p\pi D d_c^3 \sin^2 A/(12\eta L) = \pi p(4.5)(0.25)^3(\sin 18.75)^2/(12(50\times10^{-4})(99)) = 4.686$
$0.003842\, p = 4.686$
$\mathbf{p = 1220}$ **lb/in^2**

13.9 (USCS units) Continuous tubing is produced in a plastic extrusion operation through a die orifice whose outside diameter = 2.5 in and inside diameter = 2.0 in. The extruder barrel diameter = 5.0 in and length = 10 ft. The screw rotates at 60 rev/min; it has a channel depth = 0.30 in and flight angle = 16°. The head pressure has a value of 700 lb/in^2 and the viscosity of the polymer melt is $90(10^{-4})$ lb-sec/in^2. A die swell ratio of 1.20 is observed in the extrudate. Under these conditions, determine (a) the outside and inside diameters of the final tubing and (b) the production rate in length of tube/min.

Solution: (a) Die swell ratio = 1.2, $OD = 2.5(1.2) = 3.0$ in and $ID = 2.0(1.2) = 2.4$ in

(b) $Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5\pi^2(5)^2(60/60)(0.3)\sin 16 \cos 16$
$= 37.0(0.2756)(0.9613) = 9.805$ in^3/sec
$Q_b = p\pi D d_c^3 \sin^2 A/(12\eta L) = \pi(700)(5)(0.3)^3(\sin 16)^2/(12(90 \times 10^{-4})(120)) = 1.740$ in^3/sec
$Q_x = 9.805 - 1.740 = 8.065$ in^3/sec
$A_x = 0.25\pi(3.0^2 - 2.4^2) = 2.545$ in^2
$v_x = 8.065/2.545 =$ **3.169 in/sec = 15.84 ft/min**

13.10 **(A)** (SI units) An extruder has a barrel diameter and length of 100 mm and 2.8 m, respectively. The screw rotates at 50 rev/min, its channel depth = 7.5 mm, and its flight angle = 17°. The plastic melt has a shear viscosity = 175 Pa-s. Determine (a) the extruder characteristic, (b) the shape factor K_s for a circular die opening with diameter = 3.0 mm and length = 12.0 mm, and (c) the operating point (Q and p).

Solution: (a) $Q_{max} = Q_d = 0.5\pi^2(.1)^2(50/60)(7.5\times10^{-3}) \sin 17 \cos 17$
$= 308.4 \times 10^{-6}(0.2924)(0.9563) = 86.2 \times 10^{-6}$ m^3/s
$p_{max} = 6\pi(0.1)(50/60)(2.8)(175)(\cot 17)/(7.5\times10^{-3})^2 = 44.75 \times 10^6$ Pa = 44.75 MPa
$\mathbf{Q_x = 86.2 \times 10^{-6} - 1.926 \times 10^{-12}}$ $\boldsymbol{p}$, where p has units of Pa

(b) Given: D_d = 3 mm, L_d = 12 mm.
$K_s = \pi D_d^4/128\eta L_d = \pi(3 \times 10^{-3})^4/(128(175)(12 \times 10^{-3})) =$ $\mathbf{0.9467 \times 10^{-12}}$ **m^5/Ns**

(c) $0.9467 \times 10^{-12}\, p = 86.2 \times 10^{-6} - 1.926 \times 10^{-12}\, p$
$2.8727 \times 10^{-12}\, p = 86.2 \times 10^{-6}$ $\qquad$ p = $\mathbf{30.0 \times 10^6}$ **Pa = 30 MPa**
$Q_x = 0.9467 \times 10^{-12}\,(30 \times 10^6) =$ $\mathbf{28.4 \times 10^{-6}}$ **m^3/s**

Check extruder characteristic: $Q_x = 86.2 \times 10^{-6} - 1.926 \times 10^{-12}\,(30 \times 10^6) = 28.4 \times 10^{-6}$ m^3/s

13.11 (USCS units) Consider an extruder in which the barrel diameter = 4.5 in and length = 11 ft. The extruder screw rotates at 60 rev/min; its channel depth = 0.35 in and flight angle = 20°. The plastic melt has a shear viscosity = 125(10^{-4}) lb-sec/in^2. Determine (a) $Q_{\max}$ and $p_{\max}$, (b) the shape factor for a circular die opening with diameter = 0.312 in and length = 0.75 in, and (c) the values of Q and p at the operating point.

Solution: (a) $Q_{max} = 0.5\pi^2(4.5)^2(1)(0.35)\sin 20 \cos 20 = 34.975(0.342)(0.9397)$
$= 11.24$ in^3/sec
$p_{max} = 6\pi(4.5)(1)(132)(0.0125)(\cot 20)/(0.35)^2 =$ **3139 lb/in^2**

(b) Given: D_d = 0.312 in, L_d = 0.75 in
$K_s = \pi D_d^4/128\eta L_d = \pi(0.312)^4/128(0.0125)(0.75) =$ **0.024808 in^5/lb-sec**

(c) From (a), $Q_x = Q_{max} - (Q_{max}/p_{max})p = 11.24 - 0.003581p$
From (b), $Q_x = 0.024808p$
Combining, $0.024808p = 11.24 - 0.003581p$
$0.02839p = 11.24$ $\qquad$ $p = 395.9$ lb/in^2
$Q_x = 11.24 - 0.003581(395.9) =$ **9.82 in^3/sec**

13.12 (USCS units) An extruder has a barrel diameter = 5.0 in and length = 12 ft. The extruder screw rotates at 50 rev/min; it has channel depth = 0.30 in and flight angle = 17.7°. The plastic melt has a shear viscosity = 100(10^{-4}) lb-sec/in^2. Find (a) the extruder characteristic, (b) the values of Q and p at the operating point if the die characteristic is $Q_x = 0.00150\, p$.

Solution: (a) $Q_{max} = 0.5\pi^2(5)^2(50/60)(0.3)\sin 17.7 \cos 17.7 = 30.84(0.3040)(0.9527)$
$= 8.93$ in^3/sec
$p_{max} = 6\pi(5)(50/60)(144)(0.01)(\cot 17.7)/(0.3)^2 = 3937.6$ lb/in^2
$Q_x = Q_{max} - (Q_{max}/p_{max})p =$ $\mathbf{8.93 - 0.002268}\boldsymbol{p}$

(b) Given die characteristic defined by $Q_x = 0.0015p$
$Q_x = 8.93 - 0.002268p = 0.0015p$
$0.00377p = 8.93$ $\qquad$ $p =$ **2370 lb/in^2**
$Q_x = 8.93 - 0.002268(2370) =$ **3.55 in^3/sec**

13.13 (USCS units) Consider the data in the previous problem, except that the flight angle of the extruder screw is a variable instead of a constant 17.7°. Use a spreadsheet calculator to determine the value of the flight angle that maximizes the volumetric flow rate Q_x. Explore values of flight angle between 10° and 20°. Determine the optimum value to the nearest tenth of a degree.

Solution: The author's spreadsheet computations returned an optimum value of 13.5°.

Injection Molding

13.14 **(A)** (SI units) One of the dimensions specified for an injection-molded part made of Nylon-6,6 = 120.00 mm. Compute the corresponding dimension to which the mold cavity should be machined.

Solution: S = 1.5% = 0.015 for Nylon-6,6 from Table 13.1.
$D_c = 120.00 + 120.00(0.015) + 120.00(0.015)^2 = 120.00 + 1.80 + 0.027 =$ **121.827 mm**

13.15 (USCS units) The part dimension for an injection-molded part made of polycarbonate is specified as 4.00 in. Compute the corresponding dimension to which the mold cavity should be machined.

Solution: S = 0.6% = 0.006 for polycarbonate from Table 13.1.
$D_c = 4.00 + 4.00(0.006) + 4.00(0.006)^2 = 4.00 + 0.024 + 0.00014 =$ **4.02414 in**

13.16 (SI units) The foreman in the injection-molding department says that a high-density polyethylene part produced in one of the operations has greater shrinkage than the calculations indicate it should have. The important dimension of the part is specified as 120.5 ±0.25 mm. However, the actual molded part measures 120.02 mm. (a) As a first step, the corresponding mold cavity dimension should be checked. Compute the correct value of the mold dimension, given that the shrinkage value for HDPE in Table 13.1. (b) What adjustments in process parameters could be made to reduce the amount of shrinkage?

Solution: (a) Given: S = 4.0% = 0.04 for HDPE from Table 13.1.
$D_c = 120.5 + 120.5(.04) + 120.5(.04)^2 =$ **125.513 mm**

(b) Adjustments to reduce shrinkage include: (1) increase injection pressure, (2) increase compaction time, and (3) increase molding temperature.

13.17 (USCS units) An injection-molded low-density polyethylene part has a dimension of 3.000 in. High-density polyethylene is now used in the same mold. What is the corresponding dimension of the HDPE molding?

Solution: For LDPE shrinkage S = 2.0% = 0.02 from Table 13.1
Die Cavity = $D_c = D_p + D_pS + D_pS^2 = 3.000 + 3.000\ (0.02) + 3.000\ (0.02)^2 = 3.0612$ in
For HDPE, shrinkage S = 4.0% = 0.04
Part dimension = $D_c/(1 + S + S^2) = 3.0612/(1 + 0.04 + 0.04^2) =$ **2.939 in**

13.18 (USCS units) A batch of 80,000 moldings is produced in an automated injection-molding operation. Assume scrap rate = 0. The plastic is low-density polyethylene (LDPE), which costs \$0.65/lb at current market prices. The density of LDPE is given in Table 4.1. The cost of the mold = \$100,000, which will be spread over 5 batches of 80,000 parts each. The mold has four cavities and the volume of each cavity = 0.58 in^3. The sprue and runner system takes up an additional 0.40 in^2 of mold volume. Virgin plastic is required for this operation, so the sprue and runner produced in each cycle are wasted material. Changeover (setup) time before the production run = 4.0 hr at a labor rate = \$32.00/hr including overhead. The cost rate of the molding machine = \$48.00/hr including overhead. Cycle time per shot = 45 sec. Periodic attention by labor to collect parts and load molding compound = \$3.50/hr. What is the cost per part produced in this operation?

Solution: For polyethylene the density = 0.033 lb/in^3 from Table 4.1
Volume of each part plus apportioned sprue and runner = 0.58 + 0.40/4 = 0.68 in^3
Weight of each part plus apportioned sprue and runner = 0.68(0.033) = 0.02244 lb
Cost of each part plus apportioned sprue and runner = 0.65(0.02244) = \$0.01459/pc
Cost of mold per part = 100,000/(5 × 80,000) = \$0.25/pc
With a cycle time of 45 sec and 4 parts per cycle, the time to produce 80,000 parts (including setup) = 4.0(60) + (80,000/4)(45/60) = 15,240 min = 254 hr
At a rate of \$48/hr, the machine cost = 48(254) = \$12,192 for the batch
Cost of machine time per part = \$12,192/80,000 = \$0.1524/pc
Cost of labor = 4.0(\$32) + 250(\$3.50) = 128.00 + 875.00 = \$1003 for the batch
Cost of labor per part = \$1003/80,000 = 0.0125/pc
Cost per part = 0.0146 + 0.25 + 0.1524 + 0.0125 = \$0.4295/pc

13.19 An injection-molding operation is producing parts with flash. In addition, some of the part dimensions are oversized, indicating that either the corresponding mold dimensions are too large or part shrinkage is less than anticipated. Batches of this part have been produced several times before without these quality problems, so the mold size must be correct. Make some recommendations that might alleviate the problems.

Solution: Flash on plastic moldings can be caused by vents and clearances in the mold that are too large. However, because the parts have been produced before without these problems, this possible cause can be ruled out. Other possible reasons for flash include (1) high injection pressure compared to clamping force, (2) melt temperatures that are too high, and (3) excessive amount of polymer melt injected into the mold cavity. Thus, recommendations include (1) reduce injection pressure or increase clamping force, or both, (2) reduce melt temperatures in barrel, and (3) reduce shot size per cycle. These changes should also bring the shrinkage of the part closer to the anticipated value.

Other Molding Operations and Thermoforming

13.20 **(A)** (SI units) The extrusion die for a polyethylene parison used in blow molding has a mean diameter of 20.0 mm. The size of the ring opening in the die = 2.0 mm. The mean diameter of the parison is observed to swell to a size of 23.0 mm after exiting the die orifice. If the diameter of the blow-molded container = 125 mm, determine (a) the corresponding wall thickness of the final container and (b) the inside diameter of the parison.

Solution: (a) $r_s = D_p/D_d$ = 23/20 = 1.15
$t_m = t_p D_p/D_m = r_s t_d D_p/D_m$ = (1.15)(2.0)(23)/125 = **0.423 mm**

(b) $t_p = r_s t_d$ = (1.15)(2.0) = 2.3 mm
Mean diameter of the parison = 23.0 mm, so mean radius *IR* = 23.0/2 = 11.5 mm
Inside radius = mean radius minus one-half wall thickness = 11.5 – 2.3/2 = 10.35 mm
Parison *ID* = 2(*IR*) = 2(10.35) = **20.7 mm**

13.21 (SI units) A parison is extruded from a die with outside diameter = 11.5 mm and inside diameter = 7.5 mm. The observed die swell = 1.25. The parison is used to blow mold a beverage container whose outside diameter = 112 mm (a standard 2-L soda bottle). (a) What is the corresponding wall thickness of the container? (b) Obtain an empty 2-L plastic soda bottle and (carefully) cut it across its diameter. Using a micrometer, measure the wall thickness to compare with your answer in (a).

Solution: (a) D_d = (11.5 + 7.5)/2 = 9.5 mm, and t_d = (11.5 – 7.5)/2 = 2.0 mm
$t_m = (1.25)^2(2.0)(9.5)/112 =$ **0.265 mm (= 0.010 in)**

(b) Measured value should be close to calculated value. Some wall thicknesses are less.

13.22 (USCS units) An extrusion blow-molding operation is used to produce a bottle with diameter = 4.000 in and wall thickness = 0.040 in. The parison wall has a thickness = 0.180 in. The observed die swell ratio = 1.22. (a) What is the mean diameter of the parison? (b) What is the mean diameter of the die?

Solution: (a) $D_p = t_mD_m/t_p = (0.040)(4.000)/0.180 =$ **0.889 in**

(b) $D_d = D_p/r_s = 0.889/1.22 =$ **0.729 in**

13.23 (SI units) An extrusion operation produces a parison whose mean diameter = 25 mm. The inside and outside diameters of the extrusion die are 18 mm and 22 mm, respectively. If the minimum wall thickness of the blow-molded container is 0.40 mm, what is the maximum possible diameter of the blow mold?

Solution: D_d = (22 + 18)/2 = 20 mm, and t_d = (22 – 18)/2 = 2 mm
r_s = 25/20 = 1.25
Rearranging Equation (13.23) in text, $D_m = r_{sd}^2t_dD_d/t_m = (1.25)^2(2)(20)/(0.40) =$ **156.25 mm**

13.24 (SI units) An injection-molding operation produces a cylindrical parison whose outside diameter = 20 mm and wall thickness = 4.0 mm. If the diameter of the blow-mold cavity = 150 mm, what is the wall thickness of the blow-molded container?

Solution: Using Equation (13.22), $t_m = D_pt_p/D_m = 20(4.0)/150 =$ **0.533 mm**

13.25 (USCS units) A rotational molding operation is used to mold a hollow playing ball out of polypropylene (PP). The diameter of the ball = 1.00 ft and its wall thickness = 1/8 in. What weight of PP molding compound should be loaded into the mold in order to meet these specifications? The specific gravity of the PP grade = 0.90 (the density of water = 62.4 lb/ft^3).

Solution: Density ρ = specific gravity of polymer × ρ_{water} = 0.90(62.4 lb/ft^3) = 56.2 lb/ft^3
Convert to lb/in^3: ρ = 56.2 lb/ft^3/(1728 in^3/ft^3) = 0.0325 lb/in^3
Volume = $\pi(D_o^3 - D_i^3)/6 = \pi[(12)^3 - (12 - 2/8)^3]/6$ = 55.38 in^3
Weight W = (55.38)(0.0325) = **1.80 lb**

13.26 The problem in a thermoforming operation is too much thinning in the walls of the large cup-shaped part. The operation is conventional pressure thermoforming using a positive mold, and the plastic is an ABS sheet with an initial thickness of 3.2 mm. (a) Why is thinning occurring in the walls of the cup? (b) What changes could be made in the operation to correct the problem?

Solution: (a) As the starting flat sheet is draped over the convex cup-shaped mold, the portion contacting the base of the cup experiences little stretching. However, the remaining portions of the sheet must be stretched significantly to conform to the sides of the cup. Hence, thinning in these sides results.

(b) The problem could be solved by either (1) fabricating a negative mold to replace the current positive mold, since a negative mold will distribute the material more uniformly and result in approximately equal thinning throughout the sheet; or (2) prestretch the sheet as in Figure 13.40 in the text.