Chapter 11

Metal Casting Processes

QUALITATIVE PROBLEMS

11.15 What are the reasons for the large variety of casting processes that have been developed over the years? Explain with specific examples.

By the student. There are a large number of acceptable answers depending on the interpretation of the problem by the student. Students may approach this as processes have been application driven, material driven, or economics driven. For example, while investment casting is more expensive than sand casting, closer dimensional tolerances are possible and thus for certain parts, e.g., barrels for handguns, investment casting is preferable. Consider also the differences between the hot- and cold-chamber permanent-mold casting operations. While the hot-chamber process is more automated, thus reducing cost, there are certain disadvantages.

11.16 Why are risers not as useful in die casting as they are in sand casting?

There are a number of reasons that risers are not as useful in die casting as they are in sand casting. Recall that in sand casting, a riser is sized and located so that it provides molten metal to the die cavity to compensate for metal shrinkage. In sand casting, the cooling rate is relatively low, so that the cooling rate can be effectively manipulated by placement and size of a riser. In die casting, it is essential that the cooling rate be high, or else the economic justification for tooling and equipment cannot be made. Using risers would of course slow the cooling time, and therefore they are economically undesirable. Further, the metals that are used in die casting will therefore be ones that develop internal shrinkage porosity, but do not separate from the mold wall, so that risers are not as necessary.

11.17 Describe the drawbacks to having a riser that is (a) too large and (b) too small.

The main drawbacks to having a riser too large are: the material in the riser is eventually scrapped and has to be recycled; the riser hass to be cut off, and a larger riser will cost more to machine; an excessively large riser slows solidification; the riser may interfere with solidification elsewhere in the casting; the extra metal may cause buoyancy forces sufficient to separate the mold halves, unless they are properly weighted or clamped. The drawbacks to having too small a riser are mainly associated with defects in the casting, either due to insufficient feeding of liquid to compensate for solidification shrinkage, or shrinkage pores because the solidification front is not uniform.

11.18 Why can blind risers be smaller than open-top risers?

Risers are used as reservoirs for a casting in regions where shrinkage is expected to occur, i.e, areas which are the last to solidify. Thus, risers must be made large enough to ensure that they are the last to solidify. If a riser solidifies before the cavity it is to feed, it is useless. As a result, an open riser in contact with air must be larger to ensure that it will not solidify first. A blind riser is less prone to this phenomenon, as it is in contact with the mold on all surfaces; thus a blind riser may be made smaller.

11.19 Why does die casting produce the smallest cast parts?

Note that because of the high pressures involved in die casting, wall thicknesses less than those attainable by other casting methods are possible. Also, because of the high pressures, the velocity of metal in the runners is higher than other processes; small parts can be cast before the runner solidifies. This can even be accelerated by using vacuum in the die. It should be noted that small parts can also be produced in processes such as investment casting, but the smallest parts are in die casting for these reasons.

11.20 Why is the investment-casting process capable of producing fine surface detail on castings?

The mold in investment casting is produced by coating a wax pattern. The pattern itself can have extremely good detail and surface finish, as it can be produced by die casting or even machining or rapid prototyping and finishing operations. The mold is produced by coating the pattern with ceramic slurry. The first layers can use a slurry with small particles that result in especially fine reproduction of the surface detail. This can be carefully done, even with a fine paintbrush for small detailed parts, ensuring good reproduction of the pattern. Subsequent layers can be produced with thicker slurries with larger particles, or even slurries combined with dry particles, in order to build the mold wall thickness.

11.21 What differences, if any, would you expect in the properties of castings made by permanent-mold versus sandcasting processes?

This is an open-ended problem, and a large number of answers are acceptable. Most of the different answers are associated with the students' interpretation of the word 'properties', which can be restricted to mechanical properties or can incorporate design attributes. Examples of answers are that permanent-mold castings generally possess a better surface finish, closer dimensional tolerances, more uniform mechanical properties, and more sound thin-walled sections than sand castings. However, sand castings generally will be of more intricate shapes, larger overall sizes, and (depending upon the alloy) lower in cost than permanent-mold casting.

11.22 Would you recommend preheating the molds used in permanent-mold casting? Would you remove the casting soon after it has solidified? Explain your reasons.

Preheating the molds in permanent-mold casting is advisable in order to reduce the chilling effect of the metal mold, which could lead to low metal fluidity. Also, the molds are heated to reduce thermal damage (fatigue, shock) which may result from repeated contact with the molten metal. Considering casting removal, the casting should be allowed to cool in the mold until there is no danger of distortion or developing defects during shakeout. While this may be a very short period of time for small castings, large castings may require an hour or more.

11.23 Give reasons for, and examples of, using die inserts.

Die inserts are used to reduce the production costs of castings. They allow the modularization of casting dies so that unique parts can be produced. Die inserts are commonly done to identify a part with a part number, production date, or code that identifies a lot or batch number. Special features in the die allow for insertion of a die insert for such circumstances.

11.24 Referring to Fig. 11.3, do you think it is necessary to weigh down or clamp the two halves of the mold? Explain your reasons. Do you think that the kind of metal cast, such as gray cast iron versus aluminum, should make a difference in the clamping force? Explain.

Due to the force exerted on the cope portion of the mold by the molten metal, it is necessary to weigh down or clamp the two halves of the mold. Furthermore, a metal with higher density will exert a higher pressure on the cope; thus, the clamping force depends on the metal cast.

11.25 Explain why squeeze casting produces parts with better mechanical properties, dimensional accuracy, and surface finish than do expendable-mold processes.

The squeeze-casting process involves a combination of casting and forging. The pressure applied to the molten metal by the punch or the upper die keeps the entrapped gases in solution, and thus porosity generally is not found in these products. Also, the rapid heat transfer results in a fine microstructure with good mechanical properties. Due to the applied pressure and the type of die material used, good dimensional accuracy and surface finish are typically obtained for squeeze-cast parts.

11.26 How are the individual wax patterns attached on a "tree" in investment casting?

Heat is applied to the wax pattern and/or tree at the contact surface. The surface of the pattern and/or tree melts, at which time the pattern and tree are brought into contact and firmly held in place until the wax solidifies. This is repeated for each pattern until the "tree" is completed.

11.27 Describe the measures that you would take to reduce core shifting in sand casting.

Core shifting is reduced in a sand mold by core prints, chaplets, or both. Core prints (see Fig. 11.6 on p. 265) are recesses in the pattern to support the core inside the mold. If excessive shifting occurs, chaplets may be used. Chaplets are small metal supports which act both as a spacer for the core to assure proper core location and as an added support to resist shifting.

11.28 You have seen that, even though die casting produces thin parts, there is a limit to how thin they can be. Why can't even thinner parts be made by this process?

Because of the high thermal conductivity the metal dies exhibit, there is a limiting thickness below which the molten metal will solidify prematurely before completely filling the mold cavity.

11.29 How are hollow parts with various cavities made by die casting? Are cores used? If so, how? Explain.

Hollow parts and cavities are generally made using unit dies (see Fig. 11.21d on p. 281), although cores also can be used. Core setting occurs mechanically, e.g., for an aluminum tube, as the die closes. A rod, which extends the length of the cavity, is pushed into the mold and the molten metal is then injected. This "core" must be coated with an appropriate parting agent or lubricant to ensure easy ejection of the part without damaging it.

11.30 It was stated that the strength-to-weight ratio of diecast parts increases with decreasing wall thickness. Explain why.

Because the metal die acts as a chill for the molten metal, the molten metal chills rapidly, forming a fine-grained hard skin (see, for example, Fig. 10.3 on p. 239) with higher strength. Consequently, the strength-to-weight ratio of die-cast parts increases with decreasing wall thickness.

11.31 How are risers and sprues placed in sand molds? Explain, with appropriate sketches.

Risers and sprues are usually created from plastic or metal shapes which are produced specifically for this purpose. Thus, a metal sprue is machined to duplicate the desired shape in the mold. This sprue model is then affixed to the pattern plate before the flask is filled with sand. The sand mold is prepared as discussed in the chapter (see Fig. 11.8 on p. 267). When the pattern plate is removed, the riser and sprue patterns are removed at the same time.

11.32 In shell-mold casting, the curing process is critical to the quality of the finished mold. In this stage of the process, the shell-mold assembly and cores are placed in an oven for a short period of time to complete the curing of the resin binder. List probable causes of unevenly cured cores or of uneven core thicknesses.

In the production of shell molds and cores, lack of temperature control is often the most probable cause of problems. Unevenly cured cores or uneven core thicknesses are usually caused by furnace- or temperature-control related problems, such as:

(a) Insufficient number of burners or inoperative burners in the curing furnace.

(b) One-half of the core box is higher in temperature that the other half.

(c) Mixture of low- and high-temperature melting-point sands that were improperly blended, thus causing different parts of the core to cure differently.

(d) Temperature controllers not functioning properly.

(e) The core was removed too slowly from the furnace, allowing some of it to be heated longer.

11.33 Why does the die-casting machine shown in Fig. 11.20 have such a large mechanism to close the dies? Explain.

As discussed in the text, the molten metal in die casting is introduced into the mold cavity under great pressure. This pressure has thus a tendency to separate the mold halves, resulting in large flash and unacceptable parts. The large clamp is therefore needed to hold the mold together during the entire casting cycle.

11.34 Chocolate forms are available in hollow shapes. What process should be used to make these chocolates?

Thin shells are typically and easily made through slush casting (see Fig. 10.11 on p. 247, and also slush casting in Section 11.4.3 on p. 278), using split molds. This can be verified by obtaining such a chocolate and breaking it, and observing the interior surface is rather coarse and shows no evidence of having contacted a mold.

11.35 What are the benefits to heating the mold in investment casting before pouring in the molten metal? Are there any drawbacks? Explain.

The benefits to heating the mold include: Greater fluidity for detailed parts (in that the molten metal will not solidify as quickly), a possible reduction in surface tension and in viscous friction in the mold, and slower cooling. The main drawbacks to heating the mold are that the mold may not have as high a strength at the elevated temperature, and the metal may be less viscid and becomes turbulent as discussed in Chapter 10. Also, the solidification time will be larger with increased mold preheat, and this can adversely affect production time and process economics as a result.

11.36 The "slushy" state of alloys refers to that state between the solidus and liquidus temperatures, as described in Section 10.2.2. Pure metals do not have such a slushy state. Does this mean that pure metals cannot be slush cast? Explain.

The "slushy" state in alloy solidification refers to an intermediate state between liquid and solid. Slush casting involves casting an alloy where the molten metal is poured into the mold, allowed to begin to solidify. The molten portion of the metal is then poured out of the mold, leaving a shell behind. This can be done using pure metals as well as alloys.

11.37 Can a chaplet also act as a chill? Explain.

While, in theory, a chaplet can serve as a chill, in practice chaplets rarely do so. Chaplets are intended to support a core or a section of mold. If they are placed in a position to support the core, they may not be in a location that requires a chill. Chaplets have a large footprint, and this helps to transfer heat to the core. However, heat transfer to the core is not an option for faster cooling of the casting; heat instead must be conducted outside of the mold. Therefore, the chaplet cannot usually be considered a chill.

11.38 Rank the casting processes described in this chapter in terms of their solidification rate. (That is, which processes extract heat the fastest from a given volume of metal?)

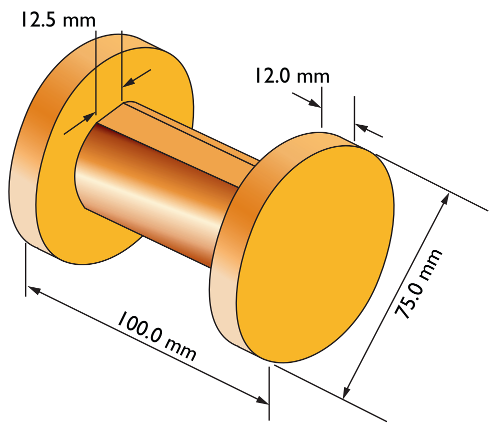
There is, as expected, some overlap between the various processes, and the rate of heat transfer can be modified when desired. However, a general ranking in terms of rate of heat extraction is as follows: Die casting (cold chamber), squeeze casting, centrifugal casting, slush casting, die casting (hot chamber), permanent mold casting, shell mold casting, investment casting, sand casting, lost foam, ceramic-mold casting, and plaster-mold casting.

QUANTITATIVE PROBLEMS

11.39 Estimate the clamping force for a die-casting machine in which the casting is rectangular with projected dimensions of 100 mm × 175 mm Would your answer depend on whether it is a hot-chamber or cold-chamber process? Explain.

The projected area is 17,500 mm^2. For the hot-chamber process and using an average pressure of 15 MPa, the force is 15 x 17,500 = 263 kN. For the cold-chamber process and using a pressure of 40 MPa, the force is 700 kN. Thus, the force depends on the process as well as shape complexity.

11.40 The blank for the spool shown in Fig. P11.40 is to be sand cast out of A-319, an aluminum casting alloy. Make a sketch of the wooden pattern for this part, and include all necessary allowances for shrinkage and machining.



The sketch for a typical green-sand casting pattern for the spool is shown below. A cross-sectional view is also provided to clearly indicate shrinkage and machining allowances, as well as the draft angles (see p. 264-265 for the required information). The important elements of this pattern are as follows (dimensions in inches):

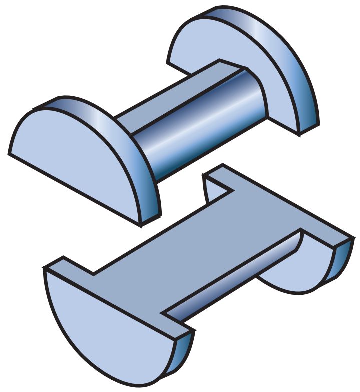
(a) Two-piece pattern.

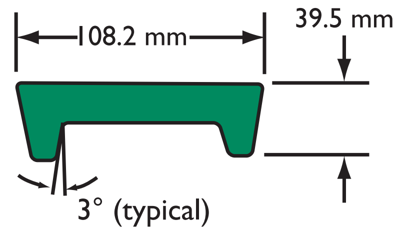
(b) Locating pins will be needed in the pattern plate to make sure these features align properly.

(c) Shrinkage allowance = 0.013 mm/mm

(d) Machining allowance = 1.5 mm

(e) Draft = 3°.





11.41 Repeat Problem 11.40, but assume that the aluminum spool is to be cast by expendable-pattern casting. Explain the important differences between the two patterns.

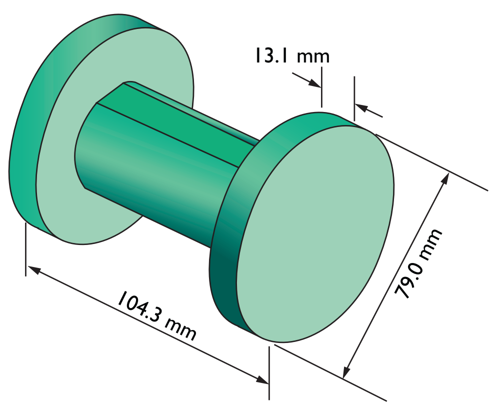
A sketch for a typical expandable-pattern casting is shown below. A cross-sectional view is also provided to clearly show the differences between green-sand (from Problem 11.40) and evaporative-casting patterns. There may be some variation in the patterns produced by students depending on which dimensions are assigned a machining allowance. The important elements of this pattern are as follows (dimensions in inches.):

(a) One-piece pattern, made of polystyrene.

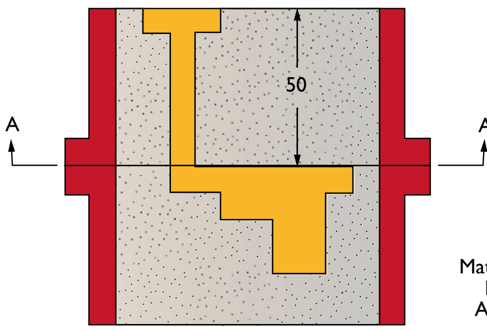
(b) Shrinkage allowance = 0.013 mm/mm

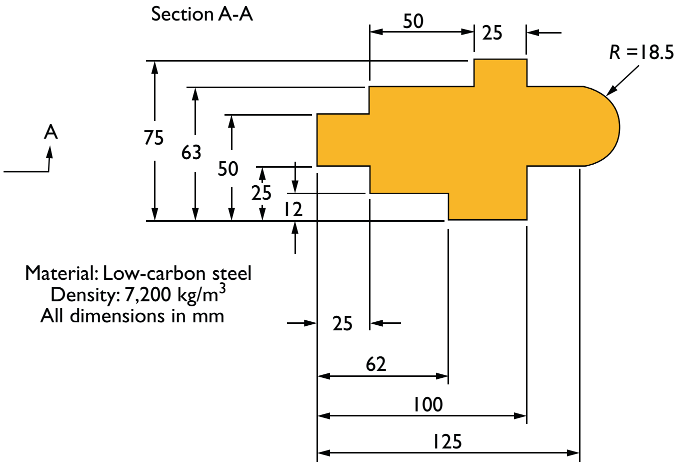
(c) Machining allowance = 1.5 mm

(d) No draft angles are necessary.



11.42 In sand casting, it is important that the cope-mold half be weighted down with sufficient force to keep it from floating when the molten metal is poured in. For the casting shown in Fig. P11.42, calculate the minimum amount of weight necessary to keep the cope from floating up as the molten metal is poured in. (*Hint*: The buoyancy force exerted by the molten metal on the cope is dependent on the effective height of the metal head above the cope.)





The cope mold half must be heavy enough or be weighted sufficiently to keep it from floating when the molten metal is poured into the mold. The buoyancy force, F, on the cope is exerted by the metallostatic pressure (caused by the metal in the cope above the parting line) and can be calculated using the formula

$$F = pA$$

where p is the pressure at the parting line and A is the projected area of the mold cavity. The pressure is

$$p = wh = (7200 \times 9.81)(0.05) = 3,530 \text{ Pa}$$

The projected mold-cavity area can be calculated from the dimensions given on the right figure in the problem, and is found to be 7,956 mm^2. Thus the force F is

$$F = \frac{(3530)(7956)}{10^6} = 28 \text{ N}$$

11.43 If an acceleration of 120 g is necessary to produce a part in true centrifugal casting and the part has an inner diameter of 200 mm, a mean outer diameter of 350 mm, and a length of 6 m, what rotational speed is needed?

The angular acceleration is given by $\alpha = \omega^2 r$. Recognizing that the largest force is experienced at the outside radius, this value for r is used in the calculation:

$$\alpha = \omega^2 r = 120 \text{ g} = 1177 \text{ m/s}^2$$

Therefore, solving for ω,

$$\omega = \sqrt{\alpha / r} = \sqrt{\left(1177 \text{ m/s}^2\right) / (0.175 \text{ m})} = 82 \text{ rad/s} = 783 \text{ rpm}$$

11.44 A jeweler wishes to produce 24 gold rings in one investment-casting operation, as illustrated in Fig. II.1b. The wax parts are attached to a wax central sprue 12 mm in diameter. The rings are located in four rows, each 12 mm from the other on the sprue. The rings require a 3-mm diameter, 12-mm-long runner to the

sprue. Estimate the weight of gold needed to completely fill the rings, runners, and sprues. The specific gravity of gold is 19.3.

The particular answer will depend on the geometry selected for a typical ring. Let's approximate a typical ring as a tube with dimensions of 25 mm outer diameter, 16 mm inner diameter, and 10 mm width. The volume of each ring is then 2898 mm^3, and a total volume for 24 rings is 69,552 mm^3. There are 24 runners to the sprue, so this volume component is

$$V = 24\left(\frac{\pi}{4}d^2\right)L = 24\left(\frac{\pi}{4}(3\text{ mm})^2\right)(12\text{ mm}) = 2,036\text{ mm}^3$$

Assume the central sprue has a length of 38 mm, so that its volume is

$$V = \frac{\pi}{4}d^2L = \frac{\pi}{4}(12\text{ mm})^2(38\text{ mm}) = 4,298\text{ mm}^3$$

The total volume is then 75,886 mm^3, not including the metal in the pouring basin, if any. The specific gravity of gold is 19.3, thus its density is 19.3(1000 kg/m^3) = 19,300 kg/m^3. Therefore, the jeweler needs 1.46 kg of gold.

11.45 Assume that you are an instructor covering the topics described in this chapter, and you are giving a quiz on the numerical aspects of casting processes to test the understanding of the students. Prepare two quantitative problems and supply the answers.

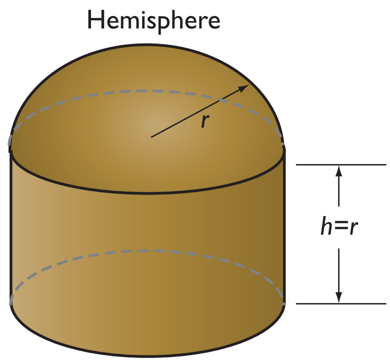
By the student. This is a challenging, open-ended question that requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

SYNTHESIS, DESIGN, AND PROJECTS

11.46 Describe the procedures that would be involved in making a large outdoor bronze statue. Which casting process(es) would be suitable? Why?

By the student. Very large statues, such as those found in parks and museums, are produced in a number of methods. One is by first manufacturing or sculpting a blank from wax and then using investment casting. Another involves producing a plaster mold from a wax or wooden blank, which is closely related to plaster mold and investment casting.

11.47 The optimum shape of a riser is spherical to ensure that it cools more slowly than the casting it feeds. However, spherically shaped risers are difficult to cast. (a) Sketch the shape of a blind riser that is easy to mold, but also has the smallest possible surface-area-to-volume ratio. (b) Compare the solidification time of the riser in part (a) with that of a riser shaped like a right circular cylinder. Assume that the volume of each riser is the same and the height of each is equal to the diameter. (See Example 10.1 on p. 248.)



A sketch of a blind riser that is easy to cast is shown above, consisting of a cylindrical and a hemispherical portion. Note that the height of the cylindrical portion is equal to its radius (so that the total height of the riser is equal to its diameter). The volume, V, of this riser is

$$V = \pi r^2 h + \left(\frac{1}{2}\right)\left(\frac{4\pi r^3}{3}\right) = \left(\frac{5\pi r^3}{3}\right)$$

Letting V be unity, we have $r = (3\pi/5)^{1/3}$. The surface area A of this riser is

$$A = 2\pi rh + \pi r^2 + (1/2)(4\pi r^2) = 5\pi r^2 = 5\pi(3\pi/5)^{2/3} = 5.21$$

Thus, from Eq. (10.7) on p. 272, the solidification time, t, for the blind riser will be

$$t = C(V/A)^2 = C(1/5.21)^2 = 0.037C$$

From Example 10.1 on p. 248, we know that the solidification time for a cylinder with a height equal to its diameter is $0.033C$. Thus, the blinder riser in (a) will cool a little slower.

11.48 Sketch and describe a casting line consisting of machinery, conveyors, robots, sensors, etc., that automatically could perform the expendable-pattern casting process.

By the student. Several designs for an automated casting line could be developed. The student should consider the proper sequence of operations and place the required machinery in a logical and efficient order, including material handling capability.

11.49 Outline the casting processes that would be most suitable for making small toys. Explain your choices.

Small toys, such as metal cars, are produced in large quantities so that the mold cost is spread over many parts. Referring to Table 11.1 on page 259, to produce the intricate shapes needed at large quantities reduces the options to investment casting and die casting. Since the parts are nonferrous, die casting is the logical choice.

11.50 Make a list of the mold and die materials used in the casting processes described in this chapter. Under each type of material, list the casting processes that are employed and explain why these processes are suitable for that particular mold or die material.

- Sand: Used because of its ability to resist very high temperatures, availability, and low cost. Used for sand, shell, expanded-pattern, investment, and ceramic-mold casting processes.
- Metal: Such as steel or iron. Result in excellent surface finish and good dimensional accuracy. Used for die, slush, pressure, centrifugal, and squeeze-casting processes.

- Graphite: Used for conditions similar to those for metal molds; however, lower pressures are tolerable for this material. Used in pressure- and centrifugal-casting processes.
- Plaster of paris: Used in the plaster-mold casting process in the production of small components, such as fittings and valves.

11.51 Write a brief report on the permeability of molds and the techniques that are used to determine permeability.

By the student. Good sources for such a literature search are machine tool design handbooks and texts on casting operations. Permeability suggests that there is a potential for material to penetrate into the porous mold material. This penetration can be measured through a number of experimental setups, such as using a standard sized slug or shape of sand, and applying a known pressure to one side and measuring the flow rate through the sand.

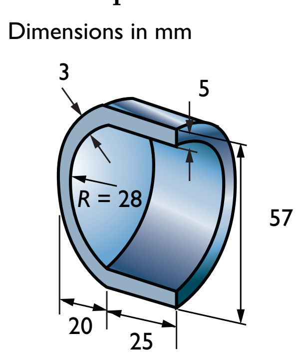
11.52 Light metals commonly are cast in vulcanized rubber molds. Conduct a literature search and describe the mechanics of this process.

By the student. The basic mechanics are that an elastomer in a container is used along with a blank of the desired part. The elastomer is compressed against the blank, the container is clamped against the part and then the elastomer is vulcanized (see Section 7.9 on p. 191) and maintains its shape. This is restricted to light metals because the rubber molds would chemically degrade at the casting temperatures for other metals. A complete description is given in Gonicberg, J.A., and Ritch, M.L., *Principles of Centrifugal Rubber Mold Casting*, Providence, A.J. Oster Co., 1980.

11.53 It sometimes is desirable to cool metals more slowly than they would be if the molds were maintained at room temperature. List and explain the methods you would use to slow down the cooling process.

The cooling process can be slowed, first by cooling the mold in a room at elevated temperature. This is similar to the single-crystal casting technique shown in Fig. 11.25 on page 285. In addition, one could place a container, such as a steel drum, around the mold to slow the convected heat transfer to the ambient air. One could also reheat the mold at some stage during the cooling cycle, perhaps even with a simple approach as with a gas torch.

11.54 The part shown in Fig. P11.54 is a hemispherical shell used as an acetabular (mushroom-shaped) cup in a total hip replacement. Select a casting process for making this part, and provide a sketch of all the patterns or tooling needed if it is to be produced from a cobalt–chrome alloy.



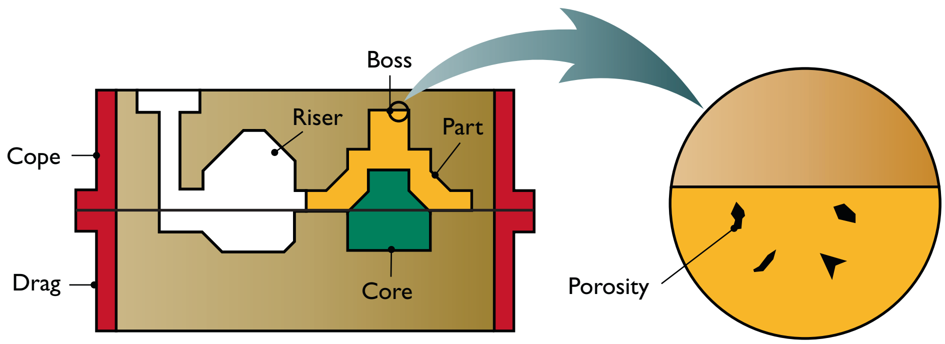
By the student. Various answers are possible, depending on the student's estimates of production rate and equipment costs. In practice, such a part would be produced through an investment-casting operation, where the individual parts with runners are injection molded and then attached to a central sprue. The tooling that would be needed include:

(a) A mold for injection molding of wax into the cup shape.

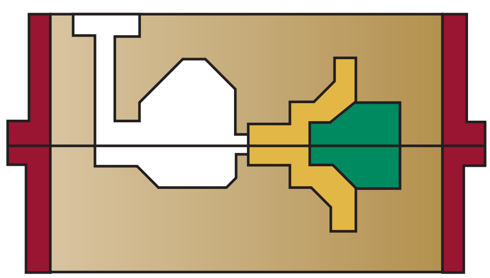
(b) Templates for placement of the cup shape onto the sprue, in order to assure proper spacing for evenly controlled cooling.

(c) Machining fixtures. It should also be noted that the wax pattern will be larger than the desired casting, because of shrinkage as well as the incorporation of shrinkage.

11.55 Porosity that has developed in the boss of a casting is illustrated in Fig. P11.55. Show that the porosity can be eliminated simply by repositioning the parting line of this casting.



Note in the figure below that the boss is at some distance from the blind riser; consequently, the boss can develop porosity as shown because of a lack of supply of molten metal from the riser. The sketch below shows a repositioned parting line that would eliminate porosity in the boss. Note that the boss can now be supplied with molten metal as it begins to solidify and shrink.



Chapter 12

Metal Casting: Design, Materials, and Economics

QUALITATIVE PROBLEMS

12.10 Describe your observation concerning the design changes shown in Fig. 12.1.

Several observations can be made regarding this figure. Figure 12.1a on p. 296 is further emphasized in Fig. 12.2 on p. 296, and shows that hot spots can develop where the section thickness changes abruptly or where corners exist. Figure 12.2b shows how deep cavities should be located on one side of the casting to greatly simplify pattern design as well as removal of the pattern from the sand mold. Due to large temperature gradients (which may form along flat surfaces during cooling) warping may occur. The design of a mold with ribs and serrations shown in Fig. 12.1d can reduce this effect and result in a more sound (not warped) casting. Ribs may be used, for example, on steel flanges at the recessed portion in order to avoid warping of both surfaces with which it is in contact.

12.11 If you need only a few castings of the same design, which three processes would be the most expensive per piece cast?

Die casting, shell-mold casting, and centrifugal casting would be the three most expensive processes per piece because these processes involve high equipment costs and a high degree of automation. Both of these factors require large production runs to justify their high cost. The high tooling cost can be mitigated somewhat by rapid tooling technologies, as discussed in Section 20.5 on p. 542. As an interesting comparison, refer to the answer to Problem 12.30 for a discussion regarding the most cost-effective means of producing only a few cast parts.

12.12 Do you generally agree with the cost ratings in Table 12.6? If so, why?

The cost ratings given in Table 12.6 on p. 308 are based on initial investment (die and equipment) and the labor required to run the processes. The labor cost depends on the extent of process automation. Thus, die casting has a low labor cost (highly automated) and investment casting has a high labor cost (little automation).

12.13 Describe the nature of the design differences shown in Fig. 12.3. What general principles do you observe in this figure?

Several observations can be made regarding Fig. 12.3 on p. 301, and students are encouraged to think creatively in analyzing these design features. Some of the observations that can be made are:

- In (a), the "poor" design would result in a very thin wall next to the counterbore (which may lead to potential failure), whereas the "good" design eliminates this thin wall.
- In (b), a large flat area may not be acceptable because of casting defects or warpage. The surface can be made much more aesthetically pleasing by incorporating featuers such as serrations and stripling.
- In (c), a radius makes the part much easier to cast; the likelihood of a large pore near the corner is reduced and the mold integrity is improved. Furthermore, a sharp inner corner may create difficulties durign assembly with components that may eb isnerted into the cavity.
- In (d), the "poor" design is difficult to machine (hence costly) into a die; the "good" design is much easier to produce.
- In (e), The "poor" design requires a sharp, knife edge in the die, which could reduce die life. The "good" design eliminates the need for a knife edge in the die.
- In (f), when casting threaded inserts in place, it is good practice to have a length of shank exposed before the threaded section so that the cast metal does not compormise the threads and interfere with their function.

12.14 Note in Fig. 12.4 that the ductility of some cast alloys is very low. Do you think that this should be a significant concern in engineering applications of castings? Explain.

The low ductility of some cast alloys shown in Fig. 12.4 on p. 303 should certainly be taken into consideration in engineering applications of the casting. Low ductility will adversely affect properties such as toughness (since the area under the stress-strain curve will be much smaller) and fatigue life. This is particularly significant in applications where the casting is subjected to impact forces.

12.15 Do you think that there will be fewer defects in a casting made by gravity pouring versus one made by pouring under pressure? Explain.

When an external pressure is applied, defects such as gas porosity, poor surface finish, and surface porosity are reduced or eliminated. Since gravity pouring does not exert as much pressure as pouring under pressure, gravity pouring generally will produce more defects.

12.16 Explain the difference in the importance of drafts in green-sand casting versus permanent-mold casting.

Draft is provided in a mold to allow the removal of the pattern from the mold without damaging the mold (see, for example, Fig. 11.5 on p. 264). If the mold material is sand and the pattern has no draft (taper), the mold cavity can be damaged upon pattern removal due to the low strength of the sand mold. However, a die made of high-strength steel, which is typical for permanent-mold casting, is not likely to be damaged during the removal of the part; thus smaller draft angles can be employed.

12.17 What type of cast iron would be suitable for heavy machine bases, such as presses and machine tools? Why?

Because of its relatively high strength and excellent castability (which generally means low cost), a pearlitic gray cast iron would probably be most suitable for this application. Note that, as no significant ductility is required for this application, the low ductility of gray irons is of little consequence. An important further advantage is the damping capacity of these cast irons, especially for machine tools (see Section 25.4 on p. 706).

12.18 Explain the advantages and limitations of sharp and rounded fillets, respectively, in casting design.

Sharp corners and fillets should be avoided in casting design because of their tendency to cause cracking and tearing of the casting during solidification. Fillet radii should be large enough to avoid stress concentrations and yet small enough to avoid a low rate of cooling and hot spots that can cause shrinkage cavities in the casting.

12.19 Explain why the elastic modulus, E, of gray cast iron varies so widely, as shown in Table 12.4.

Because the shape, size, and distribution of the second phase, i.e., the graphite flakes, vary greatly for gray cast irons, there is a large corresponding variation of properties attainable. The elastic modulus is one property which is affected by this factor.

12.20 If you were to incorporate lettering or numbers on a sand-cast part, would you make them protrude from the surface or recess them into the surface? What if the part were to be made by investment casting? Explain your answer.

The answer depends on the casting process used. In both processes, letters are commonly machined, and it is easiest to machine recessed letters. In sand casting, a pattern will be machined; the recessed pattern letters will produce sand molds of protruding letters. The parts will then have recessed letters. In investment casting (see Section 11.3.2 on p. 273), the mold will likely be machined directly; the parts will then have protruding letters.

12.21 The general design recommendations for a well in sand casting (see Fig. 11.3) are that (a) its diameter should be at least twice the exit diameter of the sprue and (b) its depth should be approximately twice the depth of the runner. Explain the consequences of deviating from these guidelines.

(a) Regarding this rule, if the well diameter is much smaller than twice the exit diameter, then the liquid will not fill the well (see Fig. 11.3 on p. 263), and aspiration of the molten metal will result. If the diameter is much larger than twice the exit diameter, the metal may solidify in the well because of longer time there.

(b) If the depth of the well is not greater than that of the runner, turbulent metal that first splashed into the well is immediately fed into the casting, leading to aspiration and defects. If the depth is much greater, then the liquid metal stays too long in the well and thus it can solidify prematurely.

12.22 The heavy regions of parts typically are placed in the drag in sand casting and not in the cope. Explain why.

Heavy parts are placed in the drag (see Fig. 11.3 on p. 297) so that the buoyancy force on the cope is reduced. If the buoyancy force becomes high enough, the cope can separate from the drag, resulting in excessive flash in the casting. This requires expensive removal operations such as machining or cropping (see Fig. 14.8 on p. 341 for a similar example).

QUANTITATIVE PROBLEMS

12.23 When designing patterns for casting, patternmakers use special rulers that automatically incorporate solid shrinkage allowances into their designs. For example, a 300-mm patternmaker's ruler is longer than 300 mm. How long should a patternmaker's ruler be for making patterns for (a) aluminum castings and (b) high-manganese steel?

Referring to Table 12.1 on p. 326, we note that the shrinkage allowance for the two metals are: (a) aluminum alloy = 1.3% and (b) high-manganese steel = 2.6%. From the formula below,

$$L_f = L_o(1 + \text{shrinkage})$$

we find that for aluminum we have

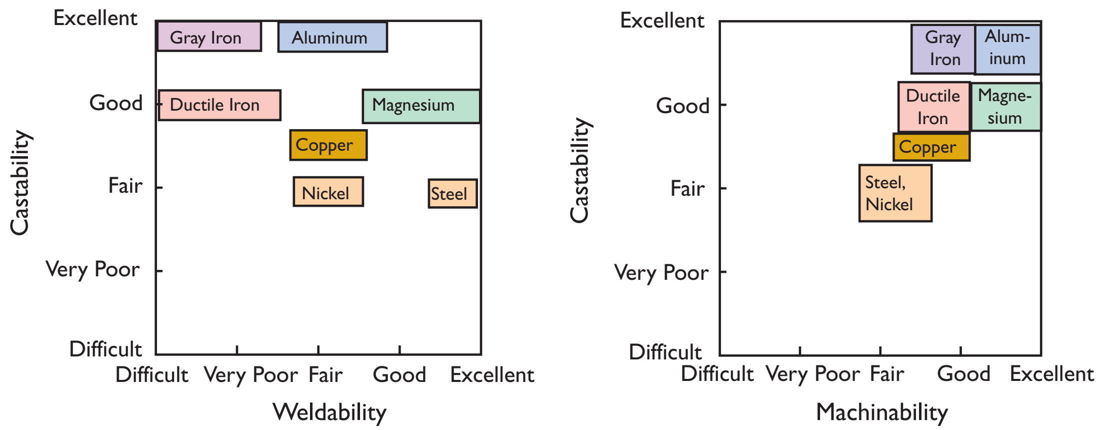
$$L_f = (300)(1.013) = 303.9 \text{ mm}$$

and for high-manganese steel

$$L_f = (300)(1.026) = 307.8 \text{ mm}$$

12.24 Using the data given in Table 12.2, develop approximate plots of (a) castability versus weldability and (b) castability versus machinability, for at least five of the materials listed in the table.

The plots are as follows:



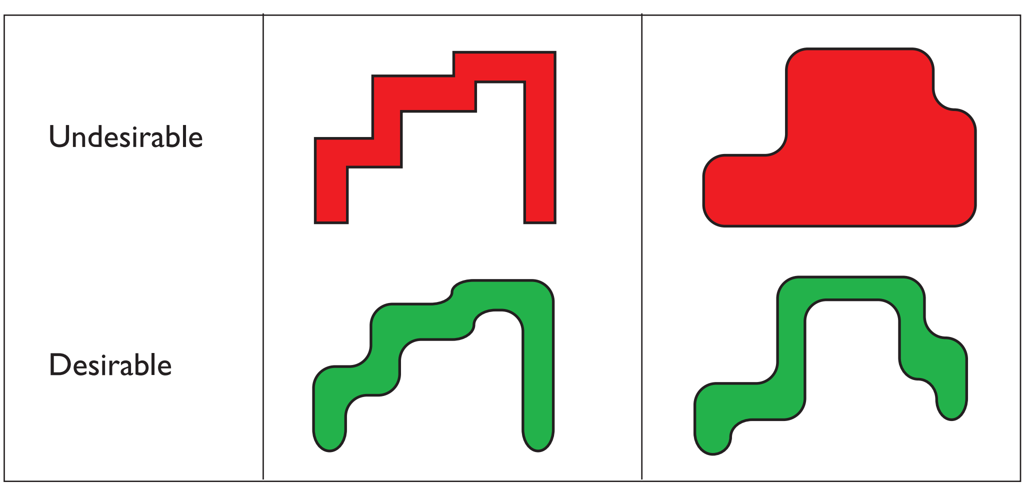
SYNTHESIS, DESIGN, AND PROJECTS

12.25 Describe the general design considerations pertaining to metal casting.

By the student. The design considerations are summarized in Section 12.2.1. This is a challenging problem to do well; it is difficult to provide a succinct summary of design considerations.

12.26 Add more examples to those shown in Fig. 12.2.

By the student. A wide variety of potential examples can be presented. The main consideration is maintaining a uniform section thickness and eliminating corners in order to avoid hot spots. Students should be encouraged to sketch designs that involve varying cross-sections, but also to place chills as an alternative to modifying the shape of the casting. Some examples of these rules are shown in Fig. 12.1c and 12.1e. Some additional designs that attempt to maintain section thickness are shown below:



12.27 Explain how ribs and serrations are helpful in casting flat surfaces that otherwise may warp. Give a specific illustration.

Due to large temperature gradients which may develop along flat surfaces during cooling, warping may be a problem. The design of a mold with ribs and serrations can reduce this effect and result in a more sound (unwarped) casting because these increase the stiffness of the casting and reduce the strain associated with a residual stress. Ribs may be used, for example, on steel flanges at the recessed portion in order to avoid warping of both surfaces with which it is in contact. An illustration of a situation where a rib is beneficial is given in Fig. 12.1d on p. 296.

12.28 List casting processes that are suitable for making hollow parts with (a) complex external features, (b) complex internal features, and (c) both complex external and complex internal features. Explain your choices.

This is an open-ended problem, and students should be encouraged to produce original answers that are based on their education and experience. This solution discusses some of the considerations that can be incorporated into an answer for this problem.

The answers depend on the size of the part under consideration and the materials used. Although complex features are always difficult to cast, sometimes they can be accomodated. For example, for complex external features:

- Within limits, a pattern plate can create intricate patterns in a sand mold, so sand casting could be suitable.
- Investment casting can utilize any pattern that allows metal to flow into and fill the cavity; these can be rapid prototyped or carved by hand, and can have very intricate external features.
- Shell molding has similar capabilities as sand casting with respect to external features.
- Die casting can produce complex features as long as they do not interfere with ejection of parts from the dies.

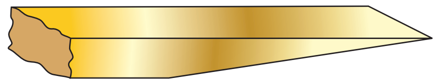
Internal features are more difficult to produce; however, the following are possible:

- In sand casting, a core with complex features can be used when necessary.
- In investment casting, internal features can be produced as long as they can be reproduced on the pattern.

When both are featuers are required, sand or investment casting may be suitable.

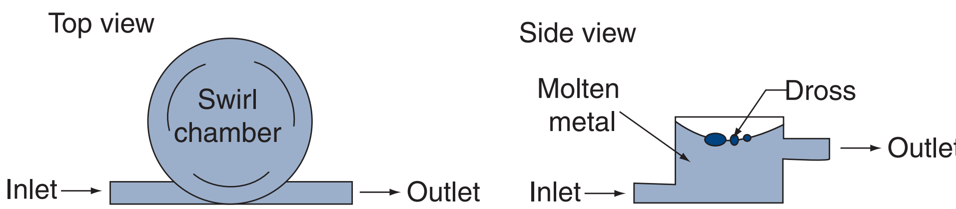
12.29 Small amounts of slag and dross often persist after skimming and are introduced into the molten metal flow in casting. Recognizing that slag and dross are less dense than the molten metal, design mold features that will remove small amounts of slag before the metal reaches the mold cavity.

There are several trap designs in use in foundries. An excellent discussion of dross trap design is given in J. Campbell, *Castings*, 1991, Reed Educational Publishers, pp. 53-55. A conventional and effective dross trap is the following design:



The design is based on the principle that a trap at the end of a runner will capture the first material through the runner and keep it away from the gates. The design shown above is a wedge-type trap. Metal entering the runner contacts the wedge, and the leading front of the metal wave is chilled and attaches itself to the runner wall, and thus it is kept out of the mold cavity. The wedge must be designed to avoid reflected waves that would recirculate the dross or slag.

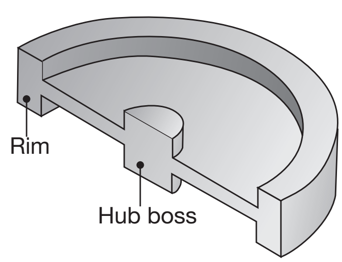
The following design is a swirl trap, which is based on the principle that the dross or slag is less dense than the metal. The metal enters the trap off of the center, inducing a swirl in the molten metal as the trap is filled with molten metal. Since it is much less dense than the metal, the dross or slag remains in the center of the swirl trap. Since the metal is tapped from the outside periphery, dross or slag is excluded from entering the casting.



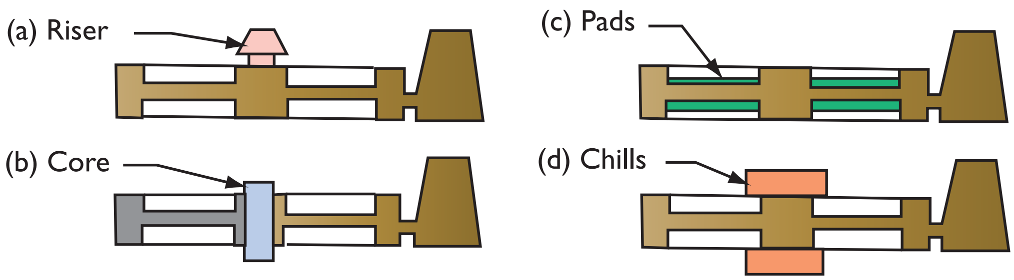
12.30 If you need only a few units of a particular casting, which process(es) would you use? Why?

Refer to Table 11.2 on p. 261. The obvious answer from this table suggests that sand casting is justifiable for production lots as small as one. However, there is a note in the table that explains that the minimum production quantity is one when rapid prototyping is used. To select a particular casting process then requires consideration of what equipment is readily available, the material that needs to be cast, and the size of the casting, among other factors. For example, a large cast iron part may be best produced by sand casting, whereas a small aluminum part with fine detail could be produced through investment casting. Clearly, the problem as stated is open-ended, and students should offer solutions that they can then justify.

12.31 For the cast metal wheel illustrated in Fig. P12.31, show how (a) riser placement, (b) core placement, (c) padding, and (d) chills may be used to help feed molten metal and eliminate porosity in the isolated hub boss.



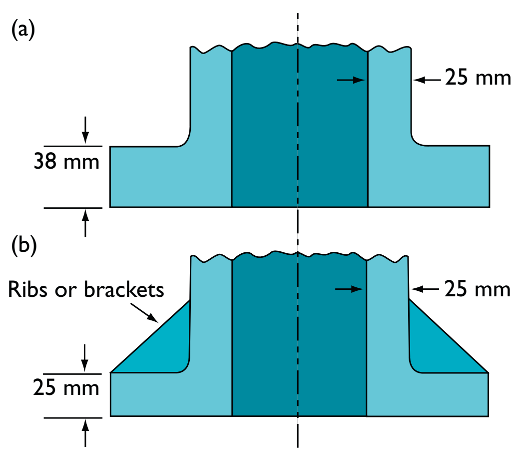
Four different methods are shown below.



12.32 Assume that the introduction to this chapter is missing. Write a brief introduction to highlight the importance of the topics covered in it.

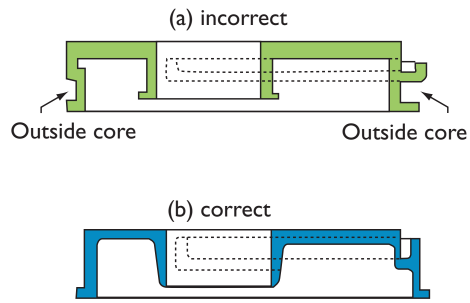
By the student. The most challenging aspect of this problem is to make the introduction sufficiently brief.

12.33 In Fig. P12.33, the original casting design shown in (a) was resized and modified to incorporate ribs in the design shown in (b). The casting is round and has a vertical axis of symmetry. What advantages do you think the new design has as a functional part over the old one?



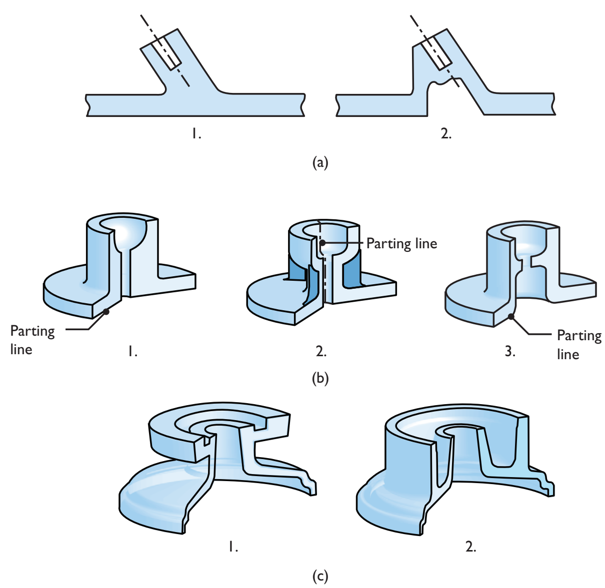
By the student. There are a number of advantages, including the fact that the part thickness is more uniform, so that large shrinkage porosity is less likely, and the ribs will control warpage due to thermal stresses as well as increase joint stiffness. This redesign illustrates the recommendations given in Figs. 12.1 and 12.2 on pp. 296.

12.34 An incorrect and a correct design for casting are shown in Fig. P12.34. Review the changes made and comment on their advantages.



By the student. The main advantage of the new part is that it can be easily cast without using an external core. The original part requires two such cores because the shape is such that it cannot be obtained in a sand mold without using cores.

12.35 Three sets of designs for die casting are shown in Fig. P12.35. Note the changes made to design 1 and comment on the reasons for then or them.



By the student. There are many observations, usually with the intent of minimizing changes in section thickness, eliminating inclined surfaces to simplify mold construction, and to orient flanges so that they can be easily cast.

Chapter 13

Rolling of Metals

QUALITATIVE PROBLEMS

13.12 Explain why the rolling process was invented and developed.

By the student. Machinery, structures, bridges, boilers, pressure vessels, etc. typically require metal plates or sheets. Consequently, there was urgent need for developing the rolling process which could economically deliver large amounts of the necessary plate. Note in Table I.2 on p. 3 that the word rolling first appears in the 1500s.

13.13 Flat rolling reduces the thickness of plates and sheets. It is possible, instead, to reduce their thickness simply by stretching the material? Would this be a feasible process? Explain.

By the student. Although stretching reduces the thickness of materials, there are several limitations associated with it as compared to rolling. Stretching process is a batch process and it cannot be continuous as it is in rolling. The reduction in thickness is limited by necking of the sheet, depending on its strain-hardening exponent, n (see Section 2.2.4 on p. 64). Furthermore, as the sheet is stretched, the surface finish becomes dull due to the orange-peel effect. Stretching the sheet requires some means of clamping the material at its ends which, in turn, will leave marks on the sheet.

13.14 Explain how the residual stress patterns shown in Fig. 13.9 become reversed when the roll radius or reduction-per- pass is changed.

As shown in Fig. 13.9a on p. 325, with small rolls and/or small reductions, the workpiece is deformed, as expected, at its surfaces more than it is in the bulk. With large rolls and/or large reductions, the reverse is true. The large roll-strip contact area develops a situation similar to that shown in Fig. 13.9b, namely, that the material flows more along the inside while the surfaces are more constrained.

13.15 Explain whether it would be practical to apply the roller-leveling technique shown in Fig. 13.7a to thick plates.

It is doubtful that the roller-leveling process, shown in Fig. 13.7 on p. 324, can be applied to plates. In this process, the strip is flattened by repeatedly flexing it in opposite directions. To do the same with a plate would require much higher forces in order to develop stresses that are of the same magnitude at the plate surface as they are in sheet. Also, unless it is sufficiently ductile, the plate may develop cracks if bent to small radii.

13.16 Describe the factors that influence the magnitude of the roll force, F, in Fig. 13.2c.

By the student. As can be deduced by observing the equations on p. 319, the roll force, F, is influenced by the roll radius, strip width, draft (hence the roll-strip contact area), coefficient of friction, and the strength of the material at the rolling temperature. If the material is strain-rate sensitive (i.e., high m value), the rolling speed would also influence the roll force; this is particularly important in hot rolling.

13.17 Explain how you would go about applying front and back tensions to sheet metals during rolling. How would you go about controlling these tensions?

Front tensions are applied and controlled by the take-up reel of a rolling mill (see Fig. 13.11 on page 326). The greater the torque to this reel, the greater the front tension. Back tension is applied by the pay-off reel of the rolling mill, whereby increasing the brake force on the pay-off reel increases the back tension.

13.18 What typically is done to make sure that the product in flat rolling is not crowned?

To make sure that the product in flat rolling is not unreasonably crowned, a number of strategies can be followed, which basically compensate for roll bending. These include:

- The use of backing rolls.
- Using crowned rollers so that roll deflections are compensated by the geometry of the roller to produce a flat workpiece.
- Superimposing a deflection on the rolls by bending them; the elastic deformation of the rollers is then compensated by the deflection from the bending moment.
- Using a front and/or back tension to reduce the rolling pressure, and hence the force on the rolls.

13.19 Make a list of some parts that can be made by (a) shape rolling and (b) thread rolling.

Parts that can be made by shape rolling include railroad rails, I-beams, and other structural channels. Note that there is a similarly-named process for sheet metals described in Section 16.6 on p. 403-404 which uses sheet metal workpieces and can be used for gutters as well as some structural channels. Thread rolling obviously produces bolts and screws, but also can produce threaded surfaces on anything that needs to be assembled through mechanical fasteners.

13.20 Describe the methods by which roll flattening can be reduced. Which property or properties of the roll material can be increased to reduce roll flattening?

Flattening is elastic deformation of the roll and results in a larger contact length in the roll gap; therefore, the elastic modulus of the roll should be increased, for example, by making it from materials with high modulus of elasticity, such as carbides (see Tables 2.1 on p. 59, 2.2 on p. 67, and 22.1 on p. 593. Roll flattening also can be reduced by (a) decreasing the reduction per pass and (b) reducing friction at the roll-sheet interface.

13.21 In the chapter, it was stated that spreading in flat rolling increases with (a) a decreasing width-to-thickness ratio of the entering material, (b) decreasing friction, and (c) a decreasing ratio of the roll radius to the strip thickness. Explain why.

See the p. 319. (a) If the width-to-thickness ratio is small, the material in the roll bite is less restrained by the frictional force in the width direction and, as a result, spreading increases. (b) The lower the friction, the lower the resistance to relative motion between the rolls and the workpiece and, hence, the greater the spreading. (c) If the roll radius is large as compared to the strip thickness, there will be lower frictional resistance in the rolling direction than across it, and thus the material will flow more in the longitudinal direction, hence spreading will decrease.

13.22 As stated in this chapter, flat rolling can be carried out by front tension only, using idling rolls (Steckel rolling). Since the torque on the rolls is now zero, where, then, is the energy coming from to supply the work of deformation in rolling?

The energy for work of deformation in Steckel rolling (p. 320) is supplied by the front tension required to pull the strip through the roll gap between the idling rolls. The product of tension and exiting strip velocity is power supplied in rolling. This power is provided by the coil winder or draw bench.

13.23 Explain the consequence of applying too high a back tension in rolling.

If the back tension is too high, the rolls will begin to slip and no reduction in thickness will take place. An analogy would be the slipping of the wheels of an automobile while pulling a heavy trailer.

13.24 Note in Fig. 13.3d that the driven rolls (powered rolls) are the third set from the work roll. Why isn't power supplied through the work roll itself? Is it even possible? Explain.

We note in Fig. 13.3d on p. 321 that the diameter of the rolls increases as we move away from the work (smallest) roll. The reason why power cannot be supplied through the work roll is that the significant power required for this rolling operation will subject the work roll to a high torque. Since its diameter is small, the torsional stresses on the roll would be too high; the roll will either fracture or undergo permanent twist. With the setup shown in the figure, the power is applied to a larger-diameter roll, which can support a large torque.

13.25 Describe the importance of controlling roll speeds, roll gaps, temperature, and other process variables in a tandem-rolling operation, as shown in Fig. 13.11. Explain how you would go about determining the distance between the stands.

Referring to the tandem rolling operation shown in Fig. 13.11 on p. 326, we note that mass continuity has to be maintained during rolling. Thus, if the roll speed is not synchronized with the strip thickness in a particular stand, excessive tensions or slack may develop between the stands; some rolls may slip. Also, if the temperature is not controlled properly, strip thickness will change, thus affecting reduction per pass and, consequently, the roll forces involved. This, in turn, will also affect the actual roll gap and roll deflections. Complex control systems have been developed for monitoring and controlling such operations at high rolling speeds.

13.26 In Fig. 13.9a, if you remove the top compressive layer by, say, grinding, will the strip remain flat? If not, which way will it curve and why?

We can model the residual stresses in the strip in Fig. 13.9a on p. 325 by three horizontal and parallel springs: compression spring (top), tension spring (middle), and compression spring (bottom). Note that the top layer is in compression, and when we remove the top spring, the balance of internal moment and internal horizontal forces will be disturbed. The strip will thus distort, in a manner that it will hold water, i.e., like cupping your hand. The remaining residual stresses in the strip will rearrange themselves to ensure balancing of the internal moment and internal horizontal forces.

13.27 Name several products that can be made by each of the operations shown in Fig. 13.1.

By the student. Examples of parts from cold rolled strip are car bodies and aluminum foil for food packaging. Examples of plate are tractor and machinery frames and warship hulls. Rolled shapes include architectural beams and railroad rails.

13.28 List the possible consequences of rolling at (a) too high of a speed and (b) too low of a speed.

There are advantages and disadvantages to each. Rolling at high speed is advantageous in that production rate is increased, but it has disadvantages as well, including:

- The lubricant film thickness entrained will be larger, which can reduce friction and lead to a slick mill condition where the rolls slip against the workpiece. This can lead to a damaged surface finish on the workpiece.
- The thicker lubricant film associated with higher speeds can result in significant oil peel, or surface roughening.
- Because of the higher speed, chatter may occur, compromising the surface quality or process viability.
- There is a limit to speed associated with the motor and power source that drive the rolls.

Rolling at low speed is advantageous because the surface roughness in the workpiece can match that of the rolls (which can be polished). However, rolling at too low a speed has consequences such as:

- Production rate will be low, and thus the cost per unit weight will be higher.
- Because a thick lubricant film cannot be developed and maintained, there is a danger of transferring material from the workpiece to the roll (pickup), thus compromising surface finish.
- The workpiece may cool excessively before contacting the rolls. This is because a long billet that is rolled slowly loses some of its heat to the environment and also through conduction through the roller conveyor.

QUANTITATIVE PROBLEMS

13.29 In Example 13.1, calculate the roll force and the power for the case in which the workpiece material is 1100-O aluminum and the roll radius, R, is 200 mm.

As discussed in Example 13.1 on p. 320, the roll-strip contact length, L, is given by

$$L = \sqrt{R\Delta h} = \sqrt{(200)(25-20)} = 31.6 \text{ mm}$$

Referring to Fig. 2.6 on p. 63 we find that for 1100-O aluminum the yield stress is about 55 MPa, and that at a true strain of 0.223, the true stress (flow stress) is about 110 MPa. Thus the average stress Y_{avg} is 82.5 MPa, and the roll force, F, is given by Eq. (13.2) on p. 319 as

$$F = LwY_{\text{avg}} = \frac{(31.6)}{1000} \times \frac{(228 \times 82.5 \text{ MPa})}{1000} = 0.59 \text{ MN}$$

and the power is given by Eq. (13.3) on page 319 as:

$$P = \frac{2\pi FLN}{60,000 \text{ hp}} = \frac{2\pi(0.59 \times 10^6)(31.6)(100)}{1000 \times 60,000} = 195 \text{ kW}$$

13.30 Calculate the individual drafts in each of the stands in the tandem-rolling operation shown in Fig. 13.11.

The answers are:

- Stand 5: 2.25 - 1.45 = 0.80 mm, or 36%.
- Stand 4: 1.45 - 0.90 = 0.55 mm, or 38%.
- Stand 3: 0.90 - 0.56 = 0.34 mm, or 38%.
- Stand 2: 0.56 - 0.34 = 0.22 mm, or 39%.
- Stand 1: 0.34 - 0.26 = 0.08 mm, or 24%.

13.31 Estimate the roll force, F, and the torque for an AISI 1020 carbon-steel strip that is 200 mm wide, 10 mm thick, and rolled to a thickness of 7 mm. The roll radius is 200 mm, and it rotates at 200 rpm.

The roll force is given by $F = LwY_{\text{avg}}$, where L is the roll-strip contact length, w is the strip width, and Y_{avg} is the average stress during the operation. As discussed in Example 13.1 on p. 320, L is given by

$$L = \sqrt{R\Delta h} = \sqrt{(0.2\text{ m})(0.01\text{ m} - 0.007\text{ m})} = 0.0245\text{ m}$$

The true strain for this operation is

$$\epsilon = \ln(10/7) = 0.36$$

and the average flow stress, Y_{avg}, is given by

$$Y_{\text{avg}} = \frac{K\epsilon^n}{n+1}$$

For AISI 1020 carbon steel (from Table 2.3 on p. 62), $K = 530$ MPa and $n = 0.26$; therefore

$$Y_{\text{avg}} = 323\text{ MPa}$$

and thus the roll force, F, is

$$F = LwY_{\text{avg}} = (0.0245)(0.2)(323) = 1.58\text{ MN}$$

and the required torque, T, is

$$T = FL/2 = (1.58)(0.0245)/2 = 0.019\text{ MN-m}$$

13.32 Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

By the student. This is a challenging open-ended question and requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

SYNTHESIS, DESIGN, AND PROJECTS

13.33 A simple sketch of a four-high mill stand is shown in Fig. 13.3a. Make a survey of the technical literature and present a more detailed sketch for such a stand, showing the major components.

By the student. The results will vary widely depending on the age of the machine, the material, and the size of the plates rolled. For example, a fully automated aluminum rolling mill will have a complex system of sensors and controls, whereas a specialty jewelry manufacturer may have a manually powered (hand crank) four-high rolling mill for producing gold foil.

13.34 **Obtain a piece of soft, round rubber eraser, such as that at the end of a pencil, and duplicate the process shown in Fig. 13.18b. Note how the central portion of the eraser will begin to erode, producing a hole.**

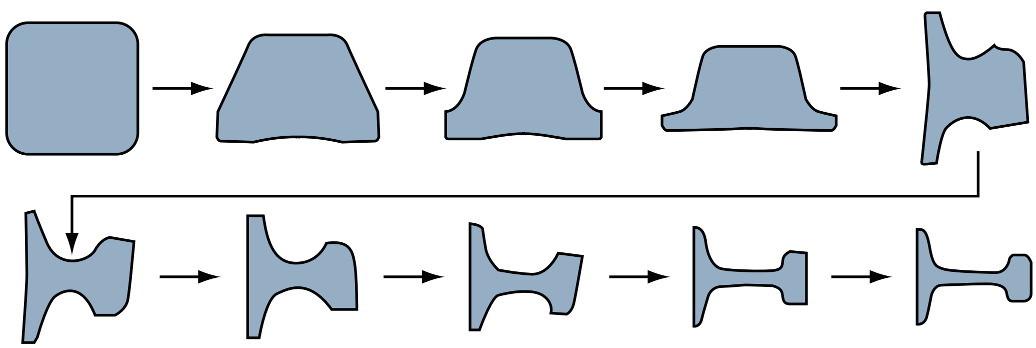
By the student. This is an interesting project, but is a little tricky to perform and may need several tries. Also, the hole needs to have the eroded material from the center removed periodically, such as by brisk blowing, to make a well-defined hole.

13.35 **If you repeat the experiment in Problem 13.34 with a harder eraser, such as that used for erasing ink, you will note that the whole eraser will begin to crack and crumble. Explain why.**

By the student. The main reason for this behavior is that with an ordinary (tougher) eraser, the deterioration of the material starts at the center of the eraser and grows outward at a slow rate. With a hard eraser (typically containing small abrasive particles such as fine sand), the crack growth is very fast, and fracture occurs before any noticeable cavity is formed.

13.36 **Design a set of rolls to produce cross sections other than those shown in Fig. 13.12.**

By the student. There are several possible designs, such as the following for producing railroad rails:



Chapter 14

Forging of Metals

QUALITATIVE PROBLEMS

14.11 How can you tell whether a certain part is forged or cast? Explain the features that you would investigate.

Numerous nondestructive and destructive tests (see Sections 36.10 on p. 1040 and 36.11 on p. 1044) are available to allow identification between cast and forged parts. Forged parts generally exhibit greater ductility when subjected to a tension test, and are generally tougher than cast parts. Depending on the processes and heat treatments used, grain size will usually be smaller in forgings, and the grains will have undergone deformation in specific directions (preferred orientation). Cast parts, on the other hand, will be more isotropic than forged parts. Surface characteristics are also likely to be non-uniform, depending on the specific casting processes used and factors such as the condition of the mold or die surfaces.

14.12 Identify casting design rules, described in Section 12.2, that also can be applied to forging.

By the student. Note that there are several rules that apply equally well to casting and forging, including the following:

- Corners, angles, and fillets should be avoided.
- Large flat areas should be avoided.
- A small draft angle (taper) is useful for removing a cast part from a mold, and for removing a forged part from a die.
- Lettering in a casting should be raised because it is easier to machine the design into a mold, and in a forging because it is easier to machine into a die.

The student is encouraged to observe other design features that are common among the various casting and forging processes.

14.13 Describe the factors involved in precision forging.

Precision forming is outlined in general terms in Table 14.1 on p. 337, which also identifies the important design considerations and manufacturing process variables. Precision forming involves high tolerances and detailed geometries; these can only be achieved with intricate dies (so that machining and finishing costs of the dies will be high) and high forging forces (which have adverse effects on die life). Precision forming is usually done cold, so that there is no thermal strain-induced warping, and this also means forging forces will be high. Also, effective lubrication is a concern, since a thick lubricant film may result in a part not achieving the die shape, and also may result in orange peel.

14.14 Why is control of the volume of the blank important in closed-die forging?

If too large a billet is placed into the dies in a closed-die forging operation, presses can jam and thus not be able to complete their stroke. In turn, this would cause high loads to the press structure. Numerous catastrophic failures in presses have been attributed to such excessive loads. If, on the other hand, the blank is too small, obviously the desired shape will not be completely imparted onto the workpiece.

14.15 Why are there so many types of forging machines available? Describe the capabilities and limitations of each.

By the student. Each type of forging machine (see Section 14.8 on p. 353) has its own advantages, each being ideally suited for different applications. The factors involved in equipment selection may be summarized as follows: (a) Force and energy requirements, (b) force-stroke characteristics, (c) length of ram travel, (d) production-rate requirements, (e) strain-rate sensitivity of the workpiece material, and (f) cooling of the workpiece in the die in hot forging and its consequences regarding die filling and forging forces.

14.16 What are the advantages and limitations of (a) a cogging operation and (b) isothermal forging?

Since the contact area in cogging is relatively small compared to the workpiece size (see Fig. 14.4a on p. 338) large cross-sections of bars can be reduced at low loads, thus requiring lower-capacity machinery, which is an economic advantage. Furthermore, various cross-sections can be produced along the length of the bar by varying the stroke during cogging steps. Note that the process is similar to what a blacksmith does in making various wrought-iron shapes and ornamental objects. A corresponding disadvantage is the time and large number of strokes required to shape long workpieces, as well as the difficulty in controlling straightness, flatness, and deformation with sufficient dimensional accuracy. The advantages to isothermal forging (see p. 346) are that (a) the workpiece has better formability because of elevated temperatures, and (b) the temperatures are maintained because the hot tooling doesn't conduct heat from the workpiece. The limitations of this process are somewhat low life of costly dies (which require high-temperature strength and wear resistance) because of the elevated temperatures involved and difficulties in properly lubricating isothermal forging operations.

14.17 Describe your observations concerning Fig. 14.16.

By the student. Figure 14.16 on p. 349 clearly shows the importance of properly planning all stages of an impression-die forging operation, and shows how laps, cracks, and shuts can develop in forging. Note that cracking is not related to the total or average strain, but can be a local problem in a particular die area.

14.18 What are the advantages and limitations of using die inserts? Give some examples.

Die inserts (see Fig. 14.6 on p. 340) are useful because they allow stronger and wear-resistant materials to be placed in locations where wear is most critical. They can be inexpensively and easily replaced when worn or broken, and thus avoid the necessity of replacing entire dies. Furthermore, inserts reduce die production costs because of the possibility of modular die construction.

14.19 Review Fig. 14.5d and explain why internal draft angles are larger than external draft angles. Is this also true for permanent-mold casting?

Draft angles (shown in Fig. 14.5d on p. 340) are necessary to assist in part removal from dies. Hot forgings will shrink radially (inward in the figure) and longitudinally upon cooling. Therefore, larger angles or tapers are required on the surfaces which will oppose the shrinkage. By definition, these are the inner surfaces. On the other hand, the workpiece shrinks away from the outer surfaces, and thus outer surfaces do not need as large a draft angle as do inner surfaces. This is also true for permanent-mold castings; see the discussion of drafts in castings on p. 264.

14.20 Comment on your observations regarding the grainflow pattern in Fig. 14.12.

The type of information obtained from Fig. 14.12 on p. 344 would be important in situations where certain regions of a forged part are to be subjected to, for example, high loads, excessive wear, and impact. In such cases, every attempt should be made so that the part is forged in such a way that those regions acquire the desired final properties. The student is encouraged to give examples of products where such considerations would be important.

14.21 Describe your observations concerning the control of the final tube thickness in Fig. 14.15.

By the student. It is difficult to control the final tube thickness in Fig. 14.15a on p. 347 without a mandrel because the compressive action of the swaging machine results in radial, circumferential (hoop), or axial strains; these strains will vary depending on the particular workpiece and die geometry, as well as lubrication. To accurately control the final tube thickness, a mandrel as shown in Fig. 14.15b is needed, but this can be problematic for long workpieces or closed-ended workpieces such as the baseball bat shown in the middle of Fig. 14.14d.

14.22 By inspecting some forged products, such as hand tools, you will note that the lettering on them is raised rather than sunk. Offer an explanation as to why they are made that way.

By the student. It is much easier and economical to produce cavities in a die (thus producing lettering on a forging that are raised from its surface) than producing protrusions (thus producing lettering that are like impressions on the forged surface). See also answer to Problem 12.20. Various conventional and unconventional methods of producing dies are described in Section 14.7 starting on p. 351 and in Part IV of the text.

14.23 Describe the difficulties involved in defining the term "forgeability" precisely.

By the student. Forgeability is a relative term (see Section 14.5 on p. 348), and various tests have been developed to define it. The fundamental problem is that, in view of the numerous parameters involved, it is difficult to develop a specific forgeability test that will simulate material's performance in an actual forging operation.

QUANTITATIVE PROBLEMS

14.24 Take two solid, cylindrical specimens of equal diameter, but different heights, and compress them (frictionless) to the same percent reduction in height. Show that the final diameters will be the same.

Let's identify the shorter cylindrical specimen with the subscript s and the taller with t, and their original diameter as D. Subscripts f and o indicate final and original, respectively. Because both specimens undergo the same percent reduction in height, we can write

$$h_{tf}/h_{to} = h_{sf}/h_{so}$$

and from volume constancy,

$$h_{tf}/h_{to} = (D_{to}/D_{tf})^2$$

and

$$h_{sf}/h_{so} = (D_{so}/D_{sf})^2$$

Because $D_{to} = D_{so}$, we find that $D_{tf} = D_{sf}$.

14.25 Calculate the forging force for a solid, cylindrical workpiece made of 1020 steel that is 90 mm high and 125 mm in diameter and is to be reduced in height by 30%. Let the coefficient of friction be 0.15.

The forging force for a cylindrical workpiece is given by Eq. (14.1) on p. 339:

$$F = Y_f \pi r^2 \left(1 + \frac{2\mu r}{3h}\right)$$

(a) Forging force to initiate yielding in the material: $Y = 294$ MPa as obtained from Table 5.2 on p. 139 (assuming that the workpiece is annealed), $r = 62.5$ mm, $h = 90$ mm, and hence

$$F = Y_f \pi r^2 \left(1 + \frac{2\mu r}{3h}\right) = (294\text{ MPa})\pi(62.5\text{ mm})^2 \left[1 + \frac{2(0.15)(62.5\text{ mm})}{3(90\text{ mm})}\right] = 3.86\text{ MN}$$

(b) Forging force at end of stroke: The true strain is

$$\epsilon = \ln(0.7) = -0.36$$

However, we need only consider the absolute value of the strain for determination of the mean stress. Therefore, let's take $\epsilon = 0.36$, whereby we find from Fig. 2.6 on p. 63 that, approximately, $Y_f = 480$ MPa. Since the reduction in height is 30%, $h = (0.70)(90 \text{ mm}) = 63$ mm The value of the radius r is determined through volume constancy. Thus,

$$\pi r_1^2 h_1 = \pi r_2^2 h_2 \quad \rightarrow \quad r_2 = \sqrt{\frac{r_1^2 h_1}{h_2}} = \sqrt{\frac{(62.5 \text{ mm})^2 (90 \text{ mm})}{(63 \text{ mm})}} = 75 \text{ mm}$$

and therefore,

$$F = Y_f \pi r^2 \left(1 + \frac{2\mu r}{3h}\right) = (480 \text{ MPa})\pi(75 \text{ mm})^2 \left[1 + \frac{2(0.15)(75 \text{ mm})}{3(63 \text{ mm})}\right] = 9.49 \text{ MN}$$

14.26 Using Eq. (14.2), estimate the forging force for the workpiece in Problem 14.25, assuming that it is a complex forging and that the projected area of the flash is 30% greater than the projected area of the forged workpiece.

The forging force is given approximately by $F = kY_f A$, where k is taken as 12 because of the complex forging. From Fig. 2.6 on p. 63 note that, approximately, $Y_f = 480$ MPa, and $A = (1.3)(\pi)(75)^2 = 22,973 \text{ mm}^2$. Therefore,

$$F = (12)(480)(22,973) = 132 \text{ MN}$$

14.27 To what thickness can a cylinder of 5052-O aluminum that is 100 mm in diameter and 50 mm high be forged in a press that can generate 450 kN?

Note from Table 6.3 on p. 153 that the yield strength of 5052-O aluminum is 90 MPa. Examine Eq. (14.1) on p. 339, which gives the forging force as

$$F = Y_f \pi r^2 \left(1 + \frac{2\mu r}{3h}\right)$$

For a frictionless condition ($\mu = 0$), this reduces to

$$F = Y_f \pi r^2$$

For the initial cylinder, the required forging force is

$$F = Y_f \pi r^2 = (90 \text{ MPa})(\pi)(50)^2 = 707 \text{ kN}$$

Therefore, such a small press cannot reduce the thickness of such a workpiece at all. The thickness will remain 50 mm.

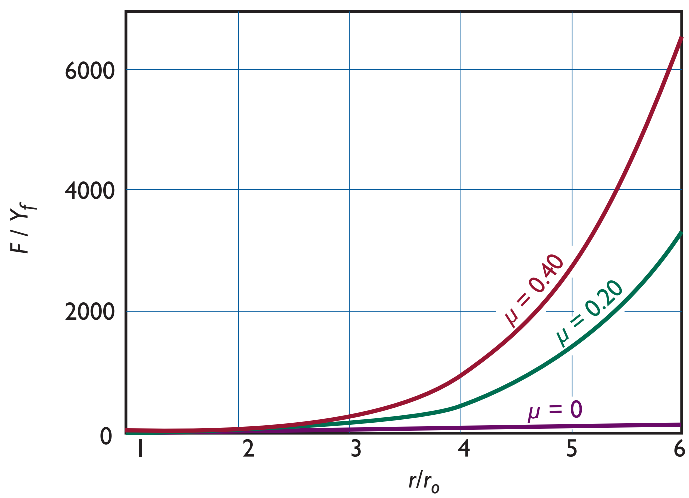
14.28 In Example 14.1, calculate the forging force, assuming that the material is 1100-O aluminum and that the coefficient of friction is 0.10.

All conditions being the same, for 1100-O aluminum we have, from Fig. 2.6 on p. 63, a flow stress $Y_f = 140$ MPa. Thus,

$$F = Y_f \pi r^2 \left(1 + \frac{2\mu r}{3h}\right) = (140 \text{ MPa})\pi(0.106 \text{ m})^2 \left[1 + \frac{2(0.1)(0.106 \text{ m})}{3(0.050 \text{ m})}\right] = 5.6 \text{ MN}$$

14.29 Using Eq. (14.1), make a plot of the forging force, F, as a function of the radius, r, of the workpiece. Assume that the flow stress, of the material is constant. Remember that the volume of the material remains constant during forging; thus, as h decreases, r increases.

The curve for an initial r/h of unity is given below.



14.30 How would you go about calculating the punch force required in a hubbing operation, assuming that the material is mild steel and the projected area of the impression is 320 mm^2? Explain clearly. (*Hint*: See Section 2.6 on hardness.)

We note on p. 344 that the piercing force involves a stress level that is the same as the hardness of the material. Also note from p. 72 in Section 2.6 that UTS is related to the hardness. From Fig. 2.15 on p. 73 we estimate the HB for mild steel to be 130. Thus, from Eq. (2.14),

$$\text{UTS} = (3.5)(130) = 455 \text{ MPa}$$

and hence the punch force, F, would be

$$F = (455)(320) = 146 \text{ kN}$$

14.31 A mechanical press is powered by a 23-kW motor and operates at 40 strokes per minute. It uses a flywheel, so that the crankshaft speed does not vary appreciably during the stroke. If the stroke is 150 mm, what is the maximum constant force that can be exerted over the entire stroke length?

Assume that the press stroke is at a constant velocity. Although this is a poor approximation, it does not affect the answer because a constant force is assumed later. In reality, both the force and velocity will vary. At forty strokes per minute, with a 6-in. stroke, we would require a velocity of

$$V = (40 \text{ rpm})(300 \text{ mm/rev})/(60 \text{ min/s}) = 200 \text{ mm/s or } 0.2 \text{ m/s}$$

The power exerted is the product of force and velocity; therefore

$$P = 23 \text{ kW} = 23,000 \text{ Nm/s} = FV = F(0.2 \text{ m/s}) \quad \rightarrow \quad F = 115 \text{ kN}$$

14.32 Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

By the student. This is a challenging open-ended question and requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

SYNTHESIS, DESIGN, AND PROJECTS

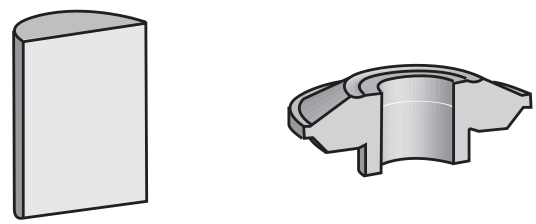
14.33 Devise an experimental method whereby you can measure only the force required for forging the flash in impression- die forging.

This is an open-ended problem, and students should be encouraged to develop their own answers. An experimental method to determine the forces required to forge only the flash (for an axisymmetric part) would involve making the die (see Fig. 14.5c on p. 340) in two concentric pieces, each with its own load cell to measure forces. The central die would only cover the projected area of the part itself, and the outer die (ring shaped) would cover the projected area of the circular flash. During forging, the load cells are monitored individually and thus the loads for the part and the flash, respectively, can be measured independently. Students are encouraged to devise other possible and practical methods.

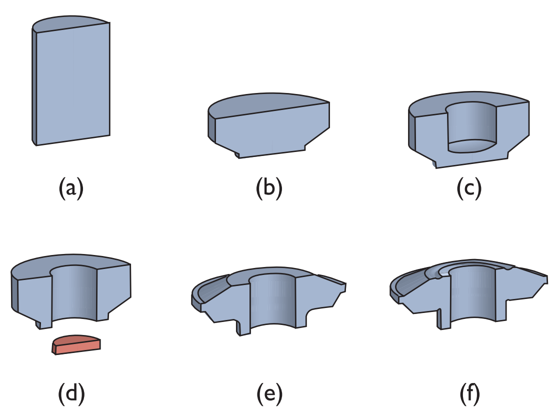
14.34 Assume that you represent the forging industry and that you are facing a representative of the casting industry. What would you tell that person about the merits of forging processes?

By the student. Some of the highlights the students may wish to emphasize are the following. Forgings have the advantages of better strength, toughness, surface finish, and dimensional accuracy. Forgings have the advantages of economic viability (depending on lot size), good mechanical properties, and the ability to produce complex parts with good surface finish. Forgings are available in a wide variety of sizes and materials, and the equipment for forging is widespread in industry.

14.35 Figure P14.35 shows a round impression-die forging made from a cylindrical blank, as illustrated on the left. As described in this chapter, such parts are made in a sequence of forging operations. Suggest a sequence of intermediate forging steps to make the part on the right, and sketch the shape of the dies needed.



By the student. A possible set of intermediate forging steps is shown in the figure below. Note how the hole is produced by first piercing the blank in stage (c) then punching out the slug, as shown in stage (d). Other similar set of forming steps are also possible.



14.36 In comparing forged parts with cast parts, we have noted that the same part may be made by either process. Comment on the pros and cons of each process, considering factors such as part size, shape complexity, design flexibility, mechanical properties developed, and performance in service.

By the student. Typical answers may address cost issues (forging will be expensive for short production runs), performance (castings may lack ductility and have lower strength-to-weight ratios), fatigure performance, grain flow, etc.

14.37 From the data given in Table 14.3, obtain the approximate value of the yield strength of the materials listed at hot-forging temperatures. Plot a bar chart showing the maximum diameter of a hot-forged part produced on a press with a 60-ton capacity as a function of the material.

By the student. The particular answers will vary widely depending on the particular strengths and temperatures considered; this is especially the case because alloys have not been designated in Table 14.3 on p. 348. Examples of calculations are included in the table below, where the diameter was calculated by using $\mu = 0$ in Eq. (14.1) on p. 339 to obtain the maximum diameter:

$$d = 2r = 2\sqrt{\frac{F}{\pi Y_f}}$$

where $F = 60$ tons $= 120$ kip $= 534$ kN.

Material	Temperature (°C)	Flow Stress (MPa)	Diameter (m)
Aluminum (pure)	400	18	0.19
	500	8	0.29
C15 Steel	1100	200	0.058
Rene 88 (a nickel superalloy)	1070	41	0.13

14.38 Review the sequence of operations in the production of the stepped pin shown in Fig. 14.13. If the conical-upsetting step is not performed, how would the final part be affected?

By the student. The sequence shown in Fig. 14.13b on p. 345 is a revised version of the sequence that previously had led to excessive defects. When the conical upsetting step was not included, the heading process that produced the flange with the largest diameter would fail, with the workpiece cracking at the outside diameter.

14.39 Using a flat piece of wood, perform simple cogging operations on pieces of clay and make observations regarding the spread of the pieces as a function of the original cross sections (for example, square or rectangular with different thickness-to-width ratios).

By the student. If the part has a low height to width ratio, the spread will be minimal. However, as the height and width approach each other (i.e., square cross-section), the spread will be extensive. Other observations also can be made, including the shape of thecross-sections developed after cogging.

14.40 Discuss the possible environmental concerns regarding the operations described in this chapter.

By the student. The environmental concerns are mostly associated with metalworking and cleaning fluids used in the forging process and the finishing operations involved, as well as other exhausts such as fumes from furnaces. For example, forged parts are routinely coated in a phosphate soap (see conversion coatings on p. 986), which may or may not be environmentally benign. Scrap from forging, such as trimmed flash, can be recovered and recycled.

Chapter 15

Extrusion and Drawing of Metals

QUALITATIVE PROBLEMS

15.14 Explain why extrusion is a batch, or semicontinuous, process. Do you think it can be made into a continuous process? Explain.

By the student. Extrusion is a batch process because the chamber size and the hydraulic ram stroke are limited. Also, the material is subjected to compression while it is in the chamber, and the high compressive forces required are difficult to develop continuously with means other than hydraulic rams. Hydrostatic extrusion can be regarded as a continuous process when reducing the small-diameter coiled stock which can be placed in the chamber of the setup.

15.15 Explain why cold extrusion is an important manufacturing process.

Cold extrusion is used to make parts that are similar to cold forgings, but have a length of reduced cross section. Such parts are very common, and are used as shafts, fasteners, and rods in a wide variety of applications. Such parts could be produced through other means such as machining, but the cold work achieved in cold extrusion results in work hardnening and superior mechanical properties.

15.16 What is the function of a stripper plate in impact extrusion?

As stated in the caption to Fig. 15.15 on p. 371, the stripper plate is needed because the parts tend to stick to the punch. This is especially important in presses that operate at high speed, and an effective means of removing the parts are essential.

15.17 Explain the different ways by which changing the die angle affects the extrusion process.

Some of the effects of die angle on the extrusion process are:

- Increasing the die angle restricts lubricant flow into the die.

- A larger die angle increases the redundant work.
- A dead metal zone may develop at large die angles.
- For a given reduction in area, friction forces may be lower with high die angles. This is because the friction force is proportional to the area of contact, and this area is reduced at higher die angles.

15.18 Glass is a good lubricant in hot extrusion. Would you use glass for impression-die forging also? Explain.

Glass, in various forms, is used as a lubricant in hot forging operations because of its superior properties at elevated temperatures (see p. 367). However, in impression-die forging thick lubricant films can prevent the workpiece from acquiring the die cavity shape and quality, and may prevent forging of desired shapes because of the glass being trapped in corners of the die. Also, one of the purposes of the lubricant is to ease part removal. This is impeded if the glass solidifies at the end of the forging cycle. Removing the lubricant from the part, and especially from the dies, is much more difficult with glass than with other liquid lubricants.

15.19 How would you go about avoiding center-cracking defects in extrusion? Explain why your methods would be effective.

Centerburst defects are attributed to a state of hydrostatic tensile stress at the centerline of the deformation zone in the die. The two major variables affecting hydrostatic tension are the die angle and extrusion ratio. Centerburst defects can be reduced or eliminated by lowering the die angles, because this increases the contact length for the same reduction, and thereby increases the deformation zone. Similarly, higher extrusion ratios also increase the size and depth of the deformation zone, and thus will reduce or eliminate these cracks.

15.20 Table 15.1 gives temperature ranges for extruding various metals. Describe the possible consequences of extruding at a temperature (a) below and (b) above these ranges.

If you extrude at below the temperatures given in Table 15.1 on p. 365, the yield stress will be higher and ductility will be reduced. If you extrude at higher temperatures, you risk greater oxide formation (resulting in poor surface finish) and less strain hardening and thus lower strength. Furthermore, temperature affects the performance of the lubricant, as viscosity and other lubricant characteristics will change. Die wear also will be affected by temperature and lubricant effectiveness.

15.21 Will the force in direct extrusion vary as the billet becomes shorter? If so, why?

Yes; the force in direct extrusion is a function of the length of the billet still in the chamber (see Fig. 15.4 on p. 363). The initial force is high because the billet is at its full length. As extrusion progresses, the billet becomes shorter and hence the frictional force is lower, thus lowering the extrusion force.

15.22 Comment on the significance of grain-flow patterns, such as those shown in Fig. 15.6.

Grain-flow pattern has a major effect on the properties of the material, and in possible initiation of cracks within the part. Note in Fig. 15.6 on p. 364 that, depending on processing parameters, there is severe internal deformation in extrusion. The extruded material undergoes much higher strains and much less homogeneous deformation with increasing dead-metal zone, which invariably leads to higher residual stresses and internal defects (see Section 15.5 on p. 413). Materials whose strength increases rapidly with decreasing temperature will have larger dead-metal zones because of cooling of billet surfaces; the material in the center of the billet remains at a higher temperature and thus deforms much more readily.

15.23 In which applications could you use the type of impact-extruded parts shown in Fig. 15.16?

By the student. As described in Section 15.4.1 on p. 370, typical parts are for collapsible tubes, automotive parts, light fixtures, and small pressure vessels. Note that the process is generally confined to nonferrous metals, hence their use for structural strength is limited.

15.24 Can spur gears be made by (a) drawing and (b) extrusion? Can helical gears? Explain.

Spur gears can be made by drawing and/or extrusion (see, for a similar example, Fig. 15.2b on p. 361). One would extrude or draw a part with the cross-section identical to a spur gear, and then slice the extruded part to the proper thickness. Helical gears, with their spiraling cross-section, can also be extruded or drawn in this manner using appropriate dies.

15.25 How would you prepare the end of a wire in order to be able to feed it through a die so that a drawing operation can commence?

A round rod may be machined to produce a point, which is then fed through the die and clamped for drawing to start. For smaller diameter rods, it is common practice to rotary swage the end of the rod or wire (see p. 346 and Fig. 14.14 on p. 347), thereby producing a pointed end that can be fed through the drawing die.

15.26 What is the purpose of a dummy block in extrusion? Explain.

A dummy block (see Fig. 15.3a on p. 362) is needed in extrusion to make sure that the entire billet is forced out the die. This is advantageous because the dummy block need not be as expensive of an alloy as the workpiece material; this ensures that the desired material is utilized fully while relegating the scrap to a less expensive alloy. The dummy block also protects the punch or ram tip against the high temperature of the billet.

15.27 Describe your observations concerning Fig. 15.9.

By the student. Note, for example, that the dies are complex, expensive to manufacture, and require proper maintenance. They are balanced, in that there is an equal number of ports on one side of the die compared to the other. The various components must be well supported.

15.28 Occasionally, steel wire drawing will take place within a sheath of a soft metal, such as copper or lead. What is the purpose of this sheath?

The soft metal will act as a solid lubricant and reduce the friction stresses at the die-wire interfaces (see p. 367), especially if other lubricants are not effective. Thus technique is also useful in drawing metals that are reactive; the coating prevents contamination with the environment or with the die material itself (see also jacketing or canning on p. 367).

15.29 Explain the advantages of bundle drawing.

As discussed on pp. 375-376, bundle drawing has the advantage of higher production rates and therefore lower production cost when drawing very small diameter wire. One can appreciate the difficulties in drawing wire with diameters as small as 4 μm if they are drawn individually. Furthermore, dies may be difficult to produce and die life may be critical.

15.30 Under what circumstances would backwards extrusion be preferable to direct extrusion?

Comparing Figs. 15.1 and 15.3 on pp. 301-302 it is obvious that the main difference is that in backwards extrusion the billet is stationary, and in direct extrusion it is moving relative to the container walls. The main advantage becomes clear if a glass pillow is used to provide lubricant between the workpiece and the die. On the other hand, if there is significant friction between the workpiece and the chamber, then energy losses associated with friction are avoided in backwards extrusion (because of lack of movement between the bodies involved).

15.31 Why is lubrication detrimental in extrusion with a porthole die?

These types of dies are shown in Fig. 15.9 on p. 366. It is important to note that any lubricant present at the interfaces within the die can interfere with the rewelding of the workpiece before it exits the die.

15.32 Describe the purpose of a container liner in direct extrusion, as shown in Fig. 15.1.

The container liner is used as a sacrificial wear part, similar to the pads used in an automotive disk brake. When worn, it is far less expensive to replace a liner than to replace the entire container. Clearly, wear of the chamber surface is important because the clearance increases and the billet could conceivably extrude backwards.

QUANTITATIVE PROBLEMS

15.33 Estimate the force required in extruding 70–30 brass at 700°C if the billet diameter is 150 mm and the extrusion ratio is 30.

From Fig. 15.5 on p. 363, k for 70–30 brass at 700 °C is approximately 200 MPa. Noting that R is 30 and $d_o = 150$ mm $= 0.150$ m, and using Eq. (15.1) on p. 363, we find that

$$F = A_o l \ln \frac{A_o}{A_f} = \left(\frac{\pi}{4}\right)(0.155)^2(200)(\ln 30) = 12 \text{ MN}$$

15.34 Assuming an ideal drawing process, what is the smallest final diameter to which an 80-mm diameter rod can be drawn?

As discussed on p. 374, the ideal maximum reduction per pass is 63%. For an original area of $A_o = \pi(80)^2/4$, or 5026 mm^2, this means that the final area is (1-0.63)(5026) = 1860 mm^2. Thus the final diameter is 48.7 mm.

15.35 If you include friction in Problem 15.34, would the final diameter be different? Explain.

If we include friction in the calculations in Problem 15.34, the stresses required to draw the material through the dies for a given reduction will increase because of the frictional work involved. As a result, the tensile stress in the wire will be higher and therefore the maximum reduction per pass will be less than 63%. Hence, the wire diameter will be larger than 60.8 mm.

15.36 Calculate the extrusion force for a round billet 300 mm in diameter, made of stainless steel, and extruded at 1000°C to a diameter of 70 mm.

From Fig. 15.5 on p. 363, k for stainless steel at 1000 °C is approximately 400 MPa. The extrusion ratio is

$$R = \frac{300^2}{70^2} = 18.4$$

Using Eq. (15.1) on p. 363 and noting that $d_o = 0.30$ m, we have

$$F = A_o k \ln\left(\frac{A_o}{A_f}\right) = \left(\frac{\pi}{4}\right)(0.30)^2(400)(\ln 18.4) = 82 \text{ MN}$$

15.37 A planned extrusion operation involves steel at 1000°C with an initial diameter of 100 mm and a final diameter of 20 mm. Two presses, one with capacity of 20 MN and the other with a capacity of 10 MN, are available for the operation. Is the smaller press sufficient for this operation? If not, what recommendations would you make to allow the use of the smaller press?

For steel at 1000°C, $k = 325$ MPa (From Fig. 15.5 on p. 363). The initial and final areas are 0.00785 m^2 and 3.14×10^{-4} m^2, respectively. From Eq. (15.1) on p. 363, the extrusion force required is

$$F = A_o k \ln\left(\frac{A_o}{A_f}\right) = (0.00785 \text{ m}^2)(325 \text{ MPa}) \ln\left(\frac{0.00785}{3.14 \times 10^{-4}}\right) = 8.2 \text{ MN}$$

Thus, the smaller and easier to use press is just barely suitable for this operation, and probably wouldn't be used because it is so close to the press capacity. However, if the extrusion temperature can be increased or if friction can be reduced (see Section 33.4 on p. 957), the smaller machine would be certainly feasible. Otherwise, since this is a marginal applicaition, the larger machine may need to be used.

15.38 A round wire made of a perfectly plastic material with a yield stress of 275 MPa is being drawn from a diameter of 2.5 to 1.5 mm in a draw die of 15°. Let the coefficient of friction be 0.15. Using both Eq. (15.3) and Eq. (15.4), estimate the drawing force required. Comment on the differences in your answer.

In this problem, $d_o = 2.5$ mm, so that the initial cross-sectional area is

$$A_o = \frac{\pi}{4} d_o^2 = \frac{\pi}{4}(2.5 \text{ mm})^2 = 4.9 \text{ mm}^2$$

Similarly, since $d_f = 1.5$ mm, $A_f = 1.8$ mm^2. From Eq. (15.3) on p. 374, the force required for drawing is

$$F = Y_{\rm avg} A_f \ln \frac{A_o}{A_f} = (275)(1.8) \ln \left(\frac{4.9}{1.8} \right) = 496 \text{ N}$$

For $\mu = 0.15$ and $\alpha = 15° = 0.262$ radians, Eq. (15.4) on p. 374 yields

$$\begin{aligned} F &= Y_{\rm avg} A_f \left[\left(1 + \frac{\mu}{\alpha} \right) \ln \left(\frac{A_o}{A_f} \right) + \frac{2}{3}\alpha \right] \\ &= (275)(1.8) \left[\left(1 + \frac{0.15}{0.262} \right) \ln \left(\frac{4.9}{1.8} \right) + \frac{2}{3}(0.262) \right] \end{aligned}$$

or $F = 866$ N. Note that Eq. (15.3) does not include friction or redundant work effects. Both of these factors will increase the forging force, and this is reflected by these results.

15.39 Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

By the student. This is a challenging open-ended question and requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

SYNTHESIS, DESIGN, AND PROJECTS

15.40 Assume that the summary to this chapter is missing. Write a one-page summary of the highlights of the wiredrawing process.

By the student. This is a valuable exercise and a challenging task. The major difficulty is in highlighting the main points in only one page.

15.41 Review the technical literature, and make a detailed list of the manufacturing steps involved in the manufacture of common metallic hypodermic needles.

By the student. There are many manufacturers of hypodermic needles, and while each one uses a slightly different process for production, the basic steps remain the same, including needle formation, plastic component molding, piece assembly, packaging, labeling, and shipping. The basic steps are as follows:

(a) Making the needle. The needle is produced from extruded and drawn tubular steel, which is passed through a die designed to meet the size requirements of the needle. The wire is appropriately cut to form the needle. Some needles are significantly more complex and are produced directly from a die casting. Other metal components on the needle are also produced in this manner.

(b) Making the barrel and plunger. There are various ways that the syringe tube can be fashioned, depending on the design needed and the raw materials used. One method of production is extrusion molding. The plastic or glass is supplied as granules or powder and is fed into a large hopper. The extrusion process involves a large spiral screw, which forces the material through a heated chamber and makes it a thick, flowing mass. It is then forced through a die, producing a continuous tube that is cooled and cut.

(c) For pieces that have more complex shapes like the ends, the plunger, or the safety caps, injection molding is used. In this process the plastic is heated, converting it into a liquid. It is then forcibly injected into a mold that is the inverse of the desired shape. After it cools, it solidifies and maintains its shape after the die is opened. Although the head of the plunger is rubber, it can also be manufactured by injection molding. Later, the head of the plunger is attached to the plunger handle.

(d) Assembly and packaging. When all of the component pieces are available, final assembly can occur. As the tubes travel down a conveyor, the plunger is inserted and held into place. The ends that cap the tube are affixed. Graduation markings may also be printed on the main tube body at this point in the manufacturing process. The machines that print these markings are specially calibrated to ensure they print measurements on accurately. Depending on the design, the needle can also be attached at this time, along with the safety cap.

(e) After all of the components are in place and printing is complete, the hypodermic syringes are put into appropriate packaging. Since sterility of the device is imperative, steps are taken to ensure they are free from disease-causing agents. They are typically packaged individually in airtight plastic. Groups of syringes are packed into boxes, stacked on pallets, and shipped to distributors.

15.42 Figure 15.2 shows examples of discrete parts that can be made by cutting extrusions into individual pieces. Name several other products that can be made in a similar fashion.

By the student. Examples include cookies, pasta, blanks for bearing races, and support brackets of all types. Case Study 14.2 on p. 356 shows a support bracket for an automobile axle that was made in this manner. Using the Internet, the students should have no difficulty in obtaining numerous other examples.

15.43 Survey the technical literature, and explain how external vibrations can be applied to a wire-drawing operation to reduce friction. Comment also on the possible directions of vibration, such as longitudinal or torsional.

By the student. It is not clear whether or not this is advantageous. Some research suggests that the energy input to drive the vibration source is roughly the same energy saved from lower friction. See J.A. Schey, *Tribology in Metalworking*, ASM International, 1984, pp. 374-376.

15.44 Assume that you are the technical director of trade associations of (a) extruders and (b) rod- and wire-drawing operations. Prepare a technical leaflet for potential customers, stating all of the advantages of these processes.

By the student, based on the subjects covered in this chapter. This is a good project for students to demonstrate their knowledge of the advantages (as well as limitations) of these processes. Students should be encouraged to obtain graphics from the Internet and to tabulate material properties and process capabilities.

Chapter 16

Sheet-Metal Forming Processes

QUALITATIVE PROBLEMS

16.18 Explain the differences that you have observed between products made of sheet metals and those made by casting and forging.

By the student. The most obvious difference between sheet-metal parts and those that are forged or cast is the difference in cross-section or thickness. Sheet-metal parts typically have large surface area-to-thickness ratios and are less stiff, hence easier to distort or flex. Sheet-metal parts are rarely for structural uses unless they are loaded in pure tension because they otherwise would buckle at relatively low compressive loads. Sheet-metal parts generally have a smoother surface than forgings or castings unless a finishing operation has been performed. Forged and cast structural parts can be subjected to various combinations of loads.

16.19 Identify the material and process variables that influence the punch force in shearing, and explain how each of them affects this force.

The punch force, P, is basically the product of the shear strength of the sheet metal and the cross-sectional area being sheared. However, friction between the punch and the workpiece can substantially increase this force. An approximate empirical formula for calculating the maximum punch force is given by

$$P = 0.7(\mathrm{UTS})(t)(L)$$

where UTS is the material's ultimate tensile strength, t is part thickness, and L is the total length of the sheared edge.

16.20 Explain why springback in bending depends on yield stress, elastic modulus, sheet thickness, and bend radius.

Plastic deformation (such as in bending processes) is unavoidably followed by elastic recovery. For a given elastic modulus, a higher yield stress results in greater springback because the elastic strain is greater. A high modulus of elasticity with a given yield stress will result in less elastic strain, hence less springback. Equation (16.6) on p. 443 gives the relation between radius and thickness; thus, increasing the radius increases the springback and increasing the sheet thickness reduces the springback.

16.21 Explain why cupping tests may not predict well the formability of sheet metals in actual forming processes.

The difficulty with cupping tests is that deformations are axisymmetric, that is, they are the same in all directions. Sheet-metal forming operations, on the other hand, rarely take place in an axisymmetric state of strain. However, cupping tests are easy to perform on the shop floor and will give some approximate indication of formability.

16.22 Identify the factors that influence the deep-drawing force, F, in Fig. 16.31b, and explain why they do so.

Referring to p. 408 and to Eq. (16.9), the blank diameter affects the force because the larger the diameter, the greater the circumference, and therefore the greater the volume of material to be deformed. The clearance, c, between the punch and die directly affects the force because at smaller clearances, ironing begins to take place, thus increasing the force. The yield strength and strain-hardening exponent, n, of the workpiece affect the force, because as these parameters increase, higher forces will be required to cause deformation. Blank thickness also increases the area of the volume deformed, and therefore increases the force. The blankholder force and friction affect the punch force because they restrict the flow of the material into the die.

16.23 Why are the beads in Fig. 16.35b placed in those particular locations?

By the student. Beads are placed to restrict metal flow in regions where it flows most easily. Note in Fig. 16.35b on p. 411 that the sheet metal will obviously flow into the die cavity more easily along the edges of the die rather than at the corners.

16.24 A general rule for dimensional relationships for successful drawing without a blankholder is given by Eq. (16.14). Explain what would happen if this limit were exceeded.

By the student. If this limit is exceeded, one can expect the walls of the drawn part to buckle or wrinkle.

16.25 Section 16.2.1 stated that the punch stripping force is difficult to estimate because of the many factors involved. Make a list of these factors with brief explanations about why they would affect the stripping force.

By the student. Punch stripping force is difficult to estimate because of factors such as:

- The sheared surfaces contact the punch, leading to friction, which is difficult to estimate.
- Temperatures generated at interfaces can lead to distortion and adhesion between workpiece and punch.
- Anisotropy in the workpiece, causing nonuniform contact stresses between the workpiece and punch.

- Lubricants on the punch can be depleted during the operation.

16.26 Is it possible to have ironing take place in an ordinary deep-drawing operation? What is the most important factor?

Recall that ironing refers to a thinning of the can wall. If the clearance in a deep-drawing operation is large, the walls of the cup will be thicker at the rim than at the base of the cup (see Fig. 16.34 on p. 410); this is because more and more material has to be reduced in diameter as the cup is being drawn. If the clearance is controlled, such as by reducing it, the wall thickness of the cup, after a certain stroke, will become equal to the clearance. In practice, ironing during deep drawing is relatively minor, and deep drawing is often approximated as a process with a constant sheet thickness.

16.27 Note the roughness of the periphery of the flanged hole in Fig. 16.25c, and comment on its possible effects when the part is used in a product.

The quality of the sheared edge (see Fig. 16.5a on p. 387) is important in subsequent forming operations, especially in subsequent operations such as stretch flanging (see, for example, Fig. 16.25a on p. 403). Depending on the notch sensitivity of the sheet material, a rough periphery can cause cracks to initiate. In service, this can cause additional problems such as decreased fatigue life of the part, as well as crevice corrosion.

16.28 What recommendations would you make in order to eliminate the cracking of the bent piece shown in Fig. 16.17c? Explain your reasons.

By the student. We have seen that formability of materials depends not only on the inherent ductility of the material (which is a function of temperature and material quality) but also on factors such as surface finish of the sheet metal and direction of its roughness (if any), planar anisotropy, and strain rate. One or more of these factors should be considered in bending if cracking is a problem. Although not practical to perform, such cracks also can be eliminated by bending under high hydrostatic pressure (see also Section 2.2.8 on p. 66).

16.29 Give several specific examples from this chapter in which friction is desirable and several in which it is not desirable.

By the student. For example, high friction in sheet-metal forming can result in high localized strain and thus lowers formability. In ironing, high friction increases press forces. Friction is desirable, for example, with draw beads to improve their effectiveness and in clamps to secure blanks.

16.30 As you can see, some of the operations described in this chapter produce considerable scrap. Describe your thoughts regarding the reuse, recycling, or disposal of this scrap. Consider its size, its shape, and its contamination by metalworking fluids during processing.

By the student. The scrap is usually relatively easy to recycle because it is from the same known raw material used for the product, thus it can be easily sorted and recycled. Although not desirable, contaminants such as residual lubricants are not a major concern since most of these contaminants are removed during melting of the scrap metal.

16.31 Through changes in clamping or die design, it is possible for a sheet metal to undergo a negative minor strain. Explain how this effect can be advantageous.

From the forming-limit diagram shown in Fig. 16.14b on p. 395, note that much larger major strains can be achieved with a negative minor strain. If through a change, such as in clamping or die design, a minor strain is allowed, then the safe zone in the diagram is larger and thus a reduction in part cracking can be achieved.

16.32 How would you produce the part shown in Fig. 16.40b other than by tube hydroforming?

Hydroforming has become very popular for producing these parts. Prior to the development of hydroforming, these parts had to be simpler in design and were typically made by bending tube segments and welding them together. Hydroforming eliminates this requirement, combines all of the bending operations into one step, and thus allows more elaborate designs with much less welding. Consequently, it provides improved flexibility of operation while simultaneously reducing costs.

QUANTITATIVE PROBLEMS

16.33 Calculate for a metal where the R values for the 0°, 45°, and 90° directions are 0.8, 1.7, and 1.8, respectively. What is the limiting drawing ratio (LDR) for this material?

From Eq. (16.12) on p. 409 we have

$$R = \frac{R_o + 2R_{45} + R_{90}}{4} = \frac{0.8 + 3.4 + 1.8}{4} = 1.50$$

The limiting drawing ratio (LDR) is defined as the maximum ratio of blank diameter to punch diameter that can be drawn without failure, i.e., D_o/D_p. From Fig. 16.33 on p. 410, we estimate the LDR for this steel to be approximately 2.5.

16.34 Calculate the value of ΔR in Problem 16.33. Will any ears form when this material is deep drawn? Explain.

From Eq. (16.13) on p. 410 we have

$$\Delta R = \frac{R_o - 2R_{45} + R_{90}}{2} = \frac{0.8 - 3.4 + 1.8}{2} = -0.40$$

Ears will not form if $\Delta R = 0$. Since this is not the case here, ears will form.

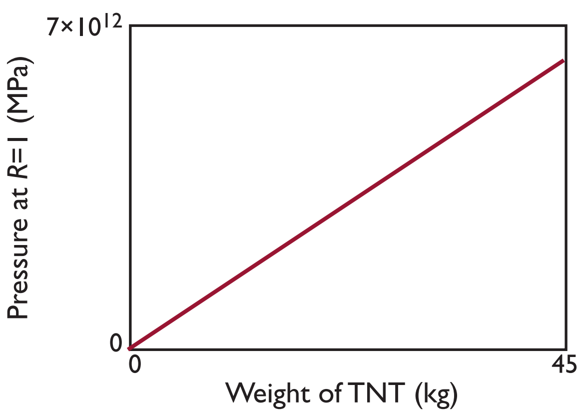
16.35 Estimate the limiting drawing ratio for the materials listed in Table 16.4.

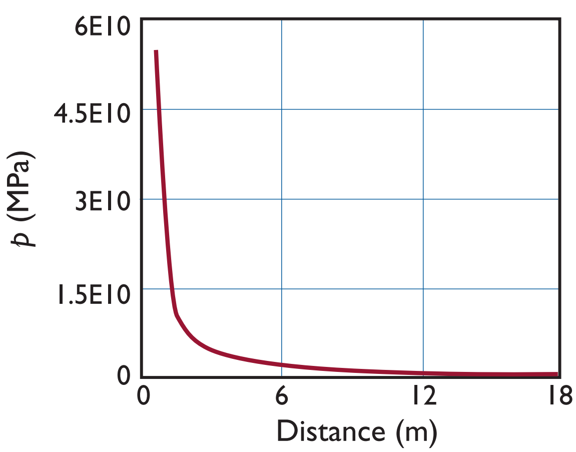
Using the data in Table 16.4 on p. 409, and referring to Fig. 16.33 on p. 410, we estimate the following values for LDR:

Material	LDR
Zinc	1.8
Hot-rolled steel	2.3-2.4
Cold-rolled rimmed steel	2.3-2.5
Cold-rolled aluminum-killed steel	2.5-2.6
Aluminum	2.2-2.3
Copper and brass	2.3-2.4
Titanium	2.9-3.0

16.36 Using Eq. (16.15) and the K value for TNT, plot the pressure as a function of weight (W) and R, respectively. Describe your observations.

Note that, as expected, the pressure increases with increasing weight of the explosive, W, but decays rapidly with increasing standoff distance, R. A plot for TNT in water is shown below.





16.37 Section 16.5 states that the k values in bend allowance depend on the relative magnitudes of R and T. Explain why this relationship exists.

The bend allowance is based on the length of the neutral axis. As described in texts on mechanics of solids, the neutral axis can shift in bending depending on the dimensions of the cross-section and the bend radius. Consequently, the k values will vary.

16.38 For explosive forming, calculate the peak pressure in water for 1.2 N of TNT at a standoff distance of 1.2 m. Comment on whether or not the magnitude of this pressure is sufficiently high to form sheet metals.

Using Eq. (16.15) on p. 422, we find that

$$p = k\left(\frac{\sqrt[3]{W}}{R}\right) = 21.43 \times 10^6 \left(\frac{\sqrt[3]{1.2}}{1.2}\right)^{1.15} = 18.6 \text{ MPa}$$

This level of pressure would be sufficiently high for forming sheet metal, particularly thin sheet of relatively low strength. This can be proven by using examples such as expansion of thin-walled spherical or cylindrical shells by internal pressure, p, using yield criteria.

16.39 Measure the respective areas of the solid outlines in Fig. 16.14a, and compare them with the areas of the original circles. Calculate the final thicknesses of the sheets, assuming that the original sheet is 1 mm thick.

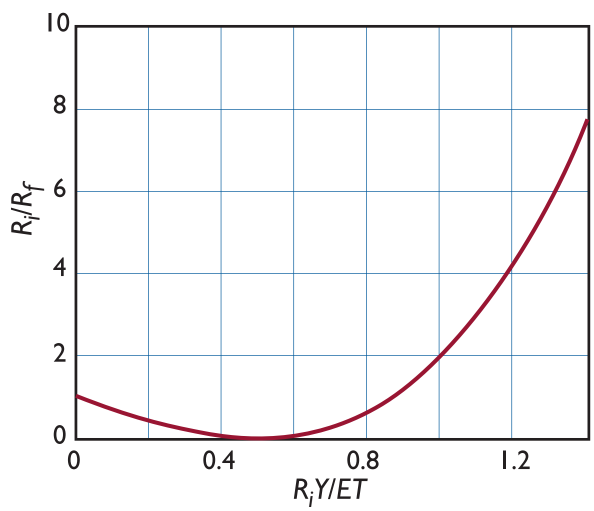
For the example on the left of Fig. 16.14a on p. 395, the original diameter is about 7 mm, and the ellipse has major and minor axes of 13 and 4.5 mm, respectively. Therefore, the strains in this plane are $\epsilon_{\text{maj}} = \ln(13/7) = 0.619$ and $\epsilon_{\text{min}} = \ln(4.5/7) = -0.44$. The strain in the thickness direction is then:

$$\epsilon_1 + \epsilon_2 + \epsilon_3 = 0 \quad \rightarrow \quad \epsilon_{\text{thickness}} = -0.619 + 0.44 = -0.179$$

Since $\epsilon_t = \ln(t/1 \text{ mm})$, the new thickness is 0.84 mm. For the ellipse on the right of the figure, the new dimensions are 13 mm and 9 mm, giving strains of 0.619 and 0.25, so that the thickness strain is -0.87, giving a new thickness of 0.42 mm.

16.40 Plot Eq. (16.6) in terms of the elastic modulus, E, and the yield stress, Y, of the material, and describe your observations.

By the student. The plot of Eq. (16.6) on p. 399 is shown below:



16.41 What is the minimum bend radius for a 1.5-mm thick sheet metal with a tensile reduction of area of 30%? Does the bend angle affect your answer? Explain.

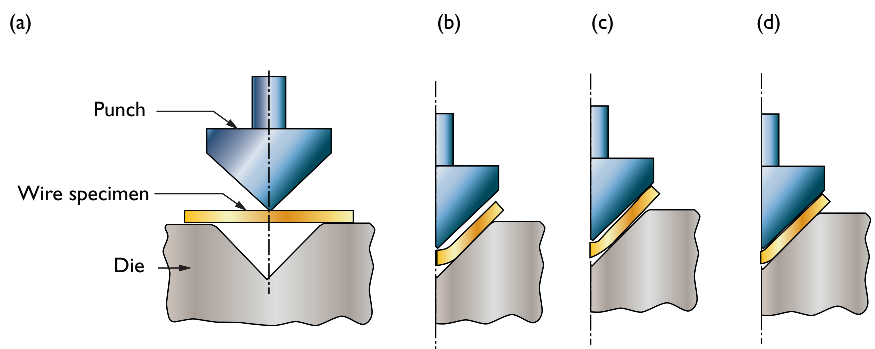
In Eq. (16.5) on p. 398, the value of r is now 30 and $T = 1.5$ mm. Thus, we have

$$R = 1.5\left[\left(\frac{50}{30}\right) - 1\right] = 1.0 \text{ mm}$$

The bend angle has no effect on the answer because it is not a factor in the strains involved in bending, as can be seen in Eq. (16.4) on p. 398.

16.42 Survey the technical literature and explain the mechanism by which negative springback can occur in V-die bending. Show that negative springback does not occur in air bending.

By the student. The development of negative springback can be explained by observing the sequence of deformation in the sketch below (see also Fig. 16.20c on p. 400). If we remove the bent piece at stage (b), it will undergo regular (positive) springback. At stage (c) the ends of the piece are touching the male punch; note that between stages (c) and (d), the part is actually being bent in the direction opposite to that between stages (a) and (b). Note also the lack of conformity of the punch radius and the inner radius of the part in both (b) and (c); in stage (d), however, the two radii are the same. Upon unloading (retracting the punch), the part in stage (d) will springback inward because it is being unbent from stage (c), both at the tip of the punch and in the two arms of the part. The amount of this inward (negative) springback can be greater than the positive springback because of the large strains that the material has undergone in the small bend area in stage (b). The net result is negative springback.



16.43 Using the data in Table 16.3 and referring to Eq. (16.5), calculate the tensile reduction of area for the materials and the conditions listed in the table.

By the student. The reduction of area for these materials at room temperature are calculated and are presented below (the numbers are rounded):

Material	Soft	Hard
Aluminum alloys	50	7
Beryllium copper	50	10
Brass, low-leaded	50	17
Magnesium	8	4
Steels		
austenitic stainless	33	7
low-C, low-alloy and HSLA	33	10
Titanium	29	13
Titanium alloys	14	10

16.44 What is the force required to punch a square hole 60 mm on each side in a 1-mm-thick 5052-O aluminum sheet by using flat dies? What would be your answer if beveled dies are used?

The maximum punch force, F, is given by Eq. (16.1) on p. 385 as

$$F = 0.7TL(\text{UTS})$$

For this case $L = 240$ mm $= 0.24$ m, $T = 1$ mm $= 0.001$ m, and UTS is 190 MPa for 5052-O aluminum (see Table 6.3 on p. 153). Therefore,

$$F = 0.7(0.001)(0.24)(190 \times 10^6) = 31.9 \text{ kN}$$

If the dies were beveled, the force would be much lower and would approach zero using very sharp bevel angles.

16.45 In Example 16.1, it was stated that the reason for reducing the tops of cans (necking) is to save material for making the lid. How much material will be saved if the lid diameter is reduced by 10%? By 15%?

By the student. In Example 16.1 on p. 412, the final diameter is 2.6 in., so that the projected area is 5.3 in^2. If the diameter is reduced by 10%, so that the diameter is now 2.34 in., the lid area would be 4.30 in^2, indicating a reduction of 19%. If the diameter is reduced by 15%, to 2.21 in., the lid area would be 3.84 in^2, for a reduction of 27.6%. These are very significant numbers considering the fact that about 100 billion cans are produced each year in the United States alone.

16.46 Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

By the student. This is a challenging open-ended question and requires considerable focus and understanding on the part of the students, and has been found to be a very valuable homework problem.

SYNTHESIS, DESIGN, AND PROJECTS

16.47 Examine some of the products in your home or in an automobile that are made of sheet metal, and discuss the process or combination of processes by which you think they were made.

By the student. Some examples are:

(a) Aluminum foil: Produced by rolling two sheets at once, as evidenced by the difference in the appearance of the two surface finishes: one surface is shiny (roll side) and the other is dull (facing the other sheet). The foil can be cut to desired widths and lengths in slitting lines (see Fig. 16.6 on p. 387).

(b) Housings for appliances such as refrigerators, washers, and dryers: Produced by cold-rolled steel stock, then leveled (see Fig. 13.7 on p. 324) and slit to desired dimensions.

(c) Baking pans and saucepans: Rolled stock drawn or stamped to final dimensions, edges trimmed, and turned in.

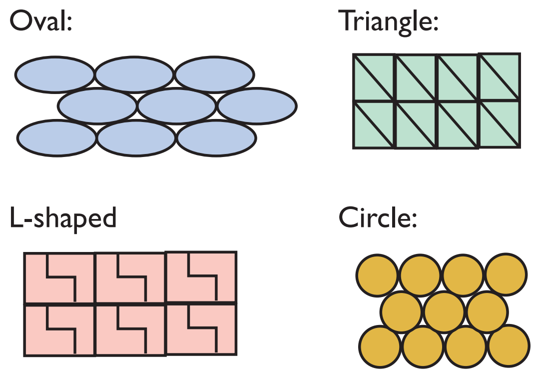
(d) Automobile body panels are obtained from sheet-metal forming and shearing.

(e) Automibile frame members (only visible when looked at from underneath) are made by roll forming.

(f) Ash trays are made from stamping, combined with shearing.

16.48 Consider several shapes to be blanked from a large sheet (such as oval, triangular, L-shaped, and so forth) by laser-beam cutting, and sketch a nesting layout to minimize scrap generation.

By the student. There are many possible answers depending on the particular shapes analyzed. Because laser cutting allows flexibility (see Section 27.6 on p. 774), some possible nesting layouts are shown below.



16.49 Give several specific product applications for (a) hemming and (b) seaming.

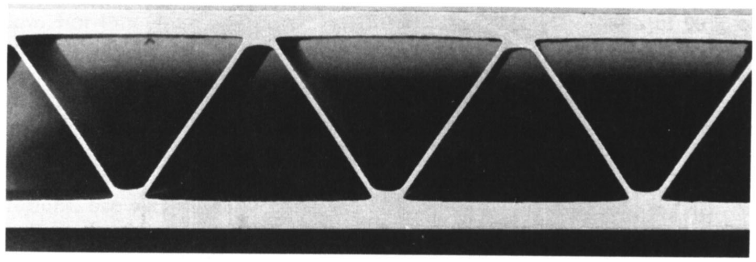
By the student. Some examples of hemming include oil pans and edges of metal tables and automobile hoods. Seaming is commonly done on cans such as for shaving cream and on beverage containers to attach the top to the can body (see, for example, Fig. 16.30 on p. 409).

16.50 Many axisymmetric missile bodies are made by spinning. What other methods could you use if spinning processes were not available?

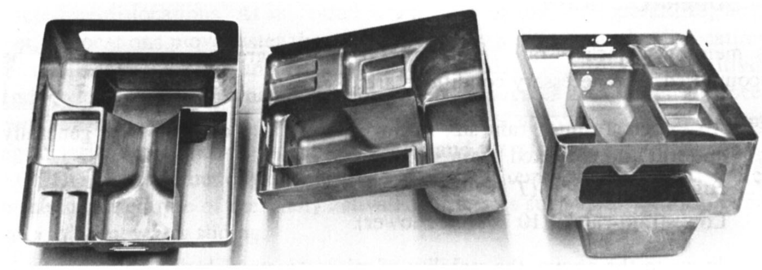
By the student. Missile components which are spun usually have large cross-sections. Some of these parts could be made by explosive forming or welding of a number of smaller rolled and stamped pieces. Smaller components could possibly be forged or formed by stretch forming.

16.51 Give several structural designs and applications in which diffusion bonding and superplastic forming can be used jointly. Comment on whether this combination is capable of producing parts at high volume.

By the student. Applications of superplastic forming are mostly in the aerospace industry. Some structural frame members, which normally are placed behind aluminum sheet and thus are not visible, are made by superplastic forming techniques. Two examples shown below (from W.F. Hosford and R.M. Cadell, *Metal Forming, Mechanics and Metallurgy*, 2nd ed., Prentice Hall, 1993).



Aircraft wing panel, produced through internal pressurization.



Sheet-metal parts.

16.52 Metal cans are either two-piece (in which the bottom and sides are integral) or three-piece (in which the sides, the bottom, and the top are each separate pieces). For a three-piece can, should the vertical seam in the can body be (a) in the rolling direction, (b) normal to the rolling direction, or (c) oblique to the rolling direction? Prove your answer.

By the student. Among the major concerns for a beverage can is that the wall not fail under internal pressurization. Because the can be assumed to be a thin-walled, closed-end, internally pressurize container, the hoop stress, σ_h, and the axial stress, σ_a, are given by

$$\sigma_h = \frac{pr}{t} \qquad \sigma_a = \frac{1}{2}\sigma_h = \frac{pr}{2t}$$

where p is the internal pressure, r is the can radius, and t is the sheet thickness. These are two principal stresses; the third principal stress is in the radial direction, but it is so small that it can be neglected. The body of a three-piece can is made by bending the cold-rolled sheet into a cylindrical shape (see, for example, Fig. 16.22 on p. 401). Since the sheet is strong in its rolling direction and noting that the hoop stress is the major stress, the seam should be normal to the rolling direction of sheet, as also shown in Fig. 16.17b on p. 397.

16.53 The design shown in Fig. P16.53 is proposed for a metal tray, the main body of which is made from cold-rolled sheet steel. Noting its features and that the sheet is bent in two different directions, comment on various manufacturing considerations. Include factors such as anisotropy of the rolled sheet, its surface texture, the bend directions, the nature of the sheared edges, and the way the handle is snapped in for assembly.

By the student. Several observations can be made. Note that a relief notch design, as shown in Fig. 16.56 on p. 428, has been used. It is a valuable experiment to have the students cut the blank from paper and verify that the tray is produced by bending only because of this notch. As such, the important factors are bendability, and scoring such as shown in Fig. 16.59 on p. 429, and avoiding wrinkling such as discussed in Fig. 16.57 on p. 429.

16.54 Suggest consumer-product designs that could utilize honeycomb structures. For example, an elevator can use a honeycomb laminate as a stiff and lightweight floor material.

This is an open-ended problem, and students should be encouraged to develop their own solutions. Solutions should use the high stiffness-to-weight ratio of these structures, or utilize the novel hexagonal cells in their application. Examples include:

- The example given in the problem, of the floor of an elevator, can be extended to support surfaces for floors, catwalks, aircraft aisles, etc.
- There are many applications in professional theater where a set needs to be quickly assembled and disassembled. A honeycomb structure with paper backing can be decorated as needed and quickly moved off stage because of its light weight.
- A section of honeycomb structure can serve as a unique packaging design.
- A honeycomb structure can serve as a retainer for springs for mattresses or chair seats.

16.55 Using a ball-peen hammer, strike the surface of aluminum sheets of various thicknesses until they develop a curvature. Describe your observations about the shapes produced.

By the student. This is an interesting experiment; it is the principle of forming sheet metals into various shapes using simple hammers (or even round rocks) and dates back many millennia (see Table I.2 on pp. 3-5). It involves basically the shot peening mechanism, described in Section 34.2 on p. 974. See also Fig. 2.14c on p. 71 and consider the effects of a round indenter in hardness testing, noting the depth of the surface layer of material that would be deformed with a ball-peen hammer with respect to the sheet thickness. For thinner sheets, this layer would complete penetrate the sheet, expanding the bottom surface laterally, and thus making it curve upward (i.e., holds water). Conversely, for thicker sheets and plates, only the top layer is expanded laterally, and thus the sheet bends downward (i.e., sheds water).

16.56 Inspect a common paper punch and observe the shape of the punch tip. Compare it with those shown in Fig. 16.10 and comment on your observations.

By the student. Hand punches will rarely be beveled because the forces are so low that the functioning of the punch is not compromised by the lack of beveling. However, many paper punches have a bevel (or a similar shape) to make the punching operation smoother. The students may make simple punches with various shapes and make observations regarding this topic and validate the statements made on p. 390.

16.57 Obtain an aluminum beverage can and slit it in half lengthwise with a pair of tin snips. Using a micrometer, measure the thickness of the can bottom and the wall. Estimate the thickness reductions in ironing and the diameter of the original blank.

By the student. Note that results can vary somewhat based on the specific practices at the canmaking facility. The results of one such measurement are: sidewall thickness=0.075 mm, the can bottom=0.3 mm, can diameter=65 mm, and can height=127 mm. From this data, the thickness reduction in ironing can be found to be

$$\%\text{red} = \frac{t_o - t_f}{t_o} \times 100\% = \frac{0.3 - 0.075}{0.3} \times 100\% = 75\%$$

The initial blank diameter is obtained by volume constancy. The volume of the can after deep drawing and ironing is

$$V_f = \frac{\pi d_c^2}{4} t_o + \pi d t_w h = \frac{\pi (65\text{ mm})^2}{4}(0.3\text{ mm}) + \pi(65\text{ mm})(0.075\text{ mm})(127\text{ mm}) = 2,940\text{ mm}^3$$

Since the initial blank thickness, t_o, is the same as the can bottom thickness (that is, 0.3 mm), the diameter of the original blank is found as

$$2,940\text{ mm}^3 = \frac{\pi d^2}{4} t_o = \frac{\pi d^2}{4}(0.3\text{ mm}) \quad \rightarrow \quad d = 112\text{ mm}$$

Chapter 17

Processing of Metal Powders

QUALITATIVE PROBLEMS

17.11 Why is there density variation in the compacting of powders? How is it reduced?

The main reason for density variation in compacting of powders (Section 17.3 on p. 444) is associated with mechanical locking and friction among the particles; this leads to variations in pressure depending on distance from the punch and from the container walls (see Fig. 17.11 on p. 493). The variation can be reduced by having double-acting presses, lowering the frictional resistance of the punch and die surfaces, or by adding lubricants that reduce inter-particle friction among the powders.

17.12 What is the magnitude of the stresses and forces involved in powder compaction?

Compaction pressures depend, among others, on the powder metal and are given in Table 17.1 on p. 446. The students should compare this values with the strength of sold metals, such as those given in Table 2.2 on p. 59 and various other tables in the text (see also Table 40.1 on p. 1137). Although the forces required in most PM parts production are usually less than 100 tons, press capacities generally range from 200 to 300 tons, and can be higher. Comparing the pressures with the yield strengths, one can note that the pressures are roughly on the same order.

17.13 Give some reasons that powder-injection molding is an important process.

Powder-injection molding (p. 449) has become an important process because of its versatility and economics. Complex shapes can be obtained at high production rates using powder metals that are blended with a polymer or wax (see PIM in Fig. 17.14 on p. 448). Also, the parts can be produced with high density to net or near-net shape.

17.14 How does the equipment used for powder compaction vary from those used in other metalworking operations in the preceding chapters?

As described in Section 17.3.1 starting on p. 446, several types of presses are used for PM compaction, depending on various factors. For ease of operation, these presses are vertical and highly automated. Metalworking operations also utilize similar equipment, including horizontal presses, as described in sections of chapters on processes such as forging and cold extrusion (see, for example, Sections 14.8 on p. 353 and 15.6 on p. 373). Abrasive resistance is a major factor in PM die and punch material selection; consequently, the dies in all these operations are made of similar and sometimes identical materials. Processes such as isostatic pressing utilize flexible molds, which is not the case in forging and extrusion. An important difference is that in PM, it can be advantageous to have a multi-action press so that compaction densities are more uniform (see Fig. 17.11d on p. 446). The students are encouraged to make further comments.

17.15 Explain why the mechanical and physical properties depend on their density.

The mechanical properties, especially strength, ductility, and elastic modulus, depend on density (see also bottom of p. 445). Not only is there less material in a given volume for less dense PM parts, but voids are stress concentrations, and the less dense material will have more and larger voids. Physical properties, such as electrical and thermal conductivity, are also adversely affected because (since air is a poor conductor) the less dense the PM part is, the less material is available to conduct electricity or heat, as shown in Fig. 17.10 on p. 492. (See also answer to Problem 10.21.)

17.16 What are the effects of the different shapes and sizes of metal particles in PM processing?

The shape, size, size distribution, porosity, chemical purity, and bulk and surface characteristics of metal particles (see Fig. 17.3 on p. 439) are all important because, as expected, they have significant effects on permeability and flow characteristics during compaction and in subsequent sintering operations. It is beneficial to have angular shapes with approximately equally sized particles to aid in bonding.

17.17 Describe the relative advantages and limitations of cold and hot isostatic pressing.

Cold isostatic pressing (CIP) and hot isostatic pressing (HIP) both have the advantages of producing compacts with effectively uniform grain structure and density, thereby making shapes with uniform strength and toughness (see Section 17.3.2 on p. 447). The main advantage of HIP is its ability to produce compacts with essentially 100% density, good metallurgical bonding of powders, and very good mechanical properties; however, the process is relatively expensive and is therefore used mainly for aerospace applications.

17.18 How different, if any, are the requirements for punch and die materials in powder metallurgy from those for forging and extrusion operations? Explain.

In processes such as forging and extrusion and PM compaction, abrasive wear resistance (see Section 33.5 on p. 961) is a major factor in die and punch material selection. For that reason, the dies on these operations utilize similar and sometimes identical materials. Processes such as isostatic pressing utilize flexible molds, which is not used in forging and extrusion. (See also answer to Problem 17.14.)

17.19 The powder metallurgy process can be competitive with processes such as casting and forging. Explain why this is so.

By the student. Powder metallurgy has become economically competitive with other operations for several reasons. One is the major advantage of producing net or near-net shapes, thus eliminating costly and time-consuming finishing operations. Also, scrap is reduced or eliminated. Functionally, PM parts are advantageous because of their lubricant-entrapment characteristics, thus reducing the need for external lubricantion in some applications. The high initial cost associated with tooling applies equally to forging, so this can be considered a common drawback to both operations.

17.20 What are the reasons for the shapes of the curves shown in Fig. 17.10 and for their relative positions on the charts?

The end points of the curves in Fig. 17.10a on p. 446 are not surprising because at low compaction pressures, the density of the PM parts is low, and at high compacting pressures it approaches the theoretical density (i.e., that of the bulk material). Note that the concavity of the curves is downward, because to increase the density further, smaller and smaller voids must be filled which require much higher pressures. Thus, it is easier to shrink larger cavities in the material than smaller ones. The reasons for the beneficial aspects of density increases (Fig. 17.10b) have been discussed in the answer to Problem 17.17.

17.21 Should green compacts be brought up to the sintering temperature slowly or rapidly? Explain your reasoning.

Rapid heating can cause excessive thermal stresses in the part being sintered and can lead to distortion or cracking; on the other hand, it reduces cycle times. Slow heating has the advantage of allowing heating and diffusion to occur more uniformly.

17.22 Because they undergo special processing, metal powders are more expensive than the same metals in bulk form, especially powders used in powder-injection molding. How is the additional cost justified in processing powder-metallurgy parts?

By the student. The additional cost can easily be justified because of the numerous advantages inherent in PM production (see also Section 17.8 starting on p. 460). For example, PM parts can be produced at net or near-net shapes, thus reducing or eliminating finishing operations. Powder metallurgy allows the production of relatively complex shapes from exotic alloys which would otherwise be difficult to manufacture by other means. Also, the self-lubricating capability of sintered metal powders makes PM parts attractive for bushings, gears, races, and cams; the ability to make alloys with compositions that cannot be cast is attractive for particular applications, especially in the electronics industry. Compaction of powders has certain advantages over other forming operations, such as forging, because by controlling porosity (hence their density) makes them advantageous in applications where weight is critical. (See Chapter 40 for various cost considerations.)

17.23 In Fig. 17.11e, it can be seen that the pressure is not uniform across the diameter of the compact at a particular distance from the punch. What is the reason for this variation?

The nonuniformity of the pressure in the figure (on p. 446) is due to the frictional resistance at the die walls and within the powder particles throughout the compact. The pressure will drop away from the punch because these effects are cumulative, and are similar to the pressure drop in a water-pumping system.

17.24 Why do the compacting pressure and the sintering temperature depend on the type of powder metal?

The compacting pressure depends on the type of metal because interparticular adhesion must take place to develop (minimal) strength in the greenware stage. The compacting pressure is dependant on the powder metal because the softer the material, the larger the contact areas for a given pressure. In sintering, diffusion and vapor and liquid phase transport are dependent on the melting temperature of th material.

QUANTITATIVE PROBLEMS

17.25 Estimate the maximum tonnage required to compact a brass slug 75 mm in diameter. Would the height of the slug make any difference in your answer? Explain your reasoning.

As we can see in Table 17.2 on p. 453, the compacting pressure for brass can be as high as 700 MPa. Thus the force required can be as high as

$$F = (700 \text{ MPa})(A) = (700 \text{ MPa})(\pi/4)(75 \text{ mm})^2 = 3.09 \text{ MN} = 315 \text{ metric ton}$$

As can be seen in Fig. 17.11e on p. 446, the higher the slug the greater is the pressure drop. This situation can be alleviated by using double punches. Also, note that we have used the highest pressure listed in the table.

17.26 Refer to Fig. 17.10a. What should be the volume of loose, fine iron powder in order to make a solid cylindrical compact 25 mm in diameter and 20 mm high?

The volume of the cylindrical compact is $V = \pi[(25)^2/4]20 = 9817 \text{ mm}^3$. Loose, fine iron powder has a density of 1.40 g/cm^3 (see Fig. 17.10a on p. 446). Density of iron is 7.86 g/cm^3 (see Table 3.1 on p. 189). Therefore, the weight of iron used is

$$W = \rho V = (7.86 \text{ g/cm}^3)(9817 \text{ mm}^3)(10^{-3} \text{ cm}^3/\text{mm}^3) = 77.2 \text{ g}$$

Therefore, the initial volume is

$$V = W/\rho = 77.2/1.40 = 55.1 \text{ cm}^3$$

17.27 Determine the shape factors for (a) a cylinder with a dimensional ratio of 1:1:1 and (b) a flake with a ratio of 1:10:10.

(a) The volume of this cylinder is

$$V = (\pi/4)(1)^2(1) = \pi/4$$

The equivalent diameter for a sphere of the same volume is

$$D = (6V/\pi)^{1/3} = 1.14$$

The surface area is

$$A = (\pi)(1)(1) + (2)(\pi/4)(1)^2 = 3\pi/2$$

Therefore, $A/V = (3\pi/2)/(\pi/4) = 6$. Hence the shape factor SF is $(1.14)(6) = 6.84$.

(b) The volume of the flakelike particle is $V = (10)(10)(1) = 100$. Note that this is in arbitrary units. The equivalent diameter for a sphere is

$$D = (6V/\pi)^{1/3} = 5.75$$

The surface area A of the particle is

$$A = (2)(10)(10) + (4)(10)(1) = 240$$

Therefore, $A/V = 240/100 = 2.4$. Thus the shape factor SF is $(5.75)(2.4) = 13.8$.

17.28 Estimate the number of particles in a 500-g sample of iron powder if the particle size is 75 μm. The density of iron is 7.86 g/cm^3. The particle diameter D is 75 μm = 0.0075 cm. The volume of each spherical particle is

$$V = (4/3)(\pi)(D/2)^3 = (\pi/6)(5.27 \times 10^{-8}) \text{ cm}^3$$

Thus its mass is $(5.27)(\pi/6)(10^{-8}) = 2.75 \times 10^{-8}$ g. Therefore, the number of particles N in the 500-g sample is

$$N = 500/2.75 \times 10^{-8} = 1.82 \times 10^{10}$$

17.29 Assume that the surface of a copper particle is covered by an oxide layer 0.1 μm in thickness. What is the volume (and the percentage of volume) occupied by this layer if the copper particle itself is 60 μm in diameter?

Because $60 \gg 0.1$, the volume of the oxide layer can be estimated as

$$V = 4\pi r^2 t = (4\pi)(30)^2(0.1) = 1130\mu\text{m}^3$$

17.30 A coarse copper powder is compacted in a mechanical press at a pressure of 275 MPa. During sintering, the green part shrinks an additional 7%. What is the final density?

From Figure 17.10 on p. 492, the copper density after compaction is around 7 g/cm^3. If the material shrinks an additional 7%, then the volume is $1/(0.93)^3$ times the original volume, so the density will be around 8.7g/cm^3.

17.31 A gear is to be manufactured from iron powders. It is desired that it have a final density 90% that of cast iron, and it is known that the shrinkage in sintering will be approximately 5%. For a gear that is 90 mm in diameter and has a 15-mm hub, what is the required press force?

From Table 3.1 on p. 89, the density of iron is 7.86 g/cm^3. For the final part to have a final density of 90% of this value, the density after sintering must be 7.07 g/cm^3. Since the part contracts 5% during sintering, the density before sintering must be 6.06 g/cm^3. Referring to Fig. 17.10 on p. 446, the required pressure for this density is around 275 MPa. The projected area is $A = (\pi/4)(90^2 - 15^2) = 6,185$ mm^2. The required force is then 1.7 MN, or 173 metric tons.

17.32 Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

By the student. This is an outstanding, open-ended question that requires considerable focus and understanding from the students, and has been found to be a very valuable homework problem.

SYNTHESIS, DESIGN, AND PROJECTS

17.33 Make sketches of PM products in which density variations (see Fig. 17.11) would be desirable. Explain why in terms of the functions of these parts.

Any kind of minimum-weight design application, such as aerospace and automotive, where lightly loaded areas can be reduced in weight by making the areas more porous. With bearing surfaces, a greater density at the surface is desirable, while a substrate need not be as dense.

17.34 Compare the design considerations for PM products with those for (a) casting and (b) forging. Describe your observations.

The design considerations for PM parts are similar to those for casting and forging. The similarities are due to the necessity of removing the parts from the dies or molds. Hence, tapers should be used whenever possible and internal cavities are difficult to manufacture. Large flat surfaces should be avoided, the section thickness should be uniform. Some of the design considerations are shown in Figs. 17.21-17.23 on pp. 457-459. There are many simularities with casting and forging part design, mainly because PM parts need to be ejected just as forgings and the pattern for casting need to be ejected. However, there are some differences. For example, engraved or embossed lettering is difficult in PM but can be done easily in casting. PM parts should be easily ejectable; castings are more flexible in this regards.

17.35 Are there applications in which you, as a manufacturing engineer, would not recommend a PM product? Explain.

PM products have many advantages, but they do not completely attain the strength of forgings in a given part volume. Any application where a volume is restricted but strength needs to be maximized are poor applications for PM parts. For example, bolts, rivets, architectural channels, and biomedical implants are poor PM applications. Also, fatigue applications are not good applications for PM parts, because cracks can propagate easier through the (porous) structure.

17.36 Describe in detail other methods of manufacturing the parts shown in Fig. 17.1.

By the student. These parts could be produced through forging, casting or machining processes.

17.37 Using the Internet, locate suppliers of metal powders and compare the cost of the powder with the cost of ingots for five different materials.

By the student. Ingot costs can vary depending on the size and the popularity of the material. This can be very challenging since the particular alloys may not be found in both powder and ingot forms.

17.38 Explain why powder-metal parts are commonly used for machine elements requiring good frictional and wear characteristics and for mass-produced parts.

There are many acceptable answers to this question. Powder-metal parts are very commonly used for tribological machine elements like gears, bearings, races, and cams, because they can be impregnated with liquid lubricant. The main advantage to impregnating the PM part with lubricant is that the component becomes self-lubricating. That is, when the temperature increases, the impregnated lubricant expands and percolates from the surface, thereby providing lubrication and wear ressistance. Mass produced parts are common because the high tooling costs of PM and the additional processing steps of sintering makes PM unattractive for low production runs.

17.39 It was stated that powder-injection molding competes well with investment casting and small forgings for various materials, but not with zinc and aluminum die castings. Explain why.

MIM is commonly performed for metals with high melting temperatures. These metals are also very stiff in general, and would need very high compaction forces. MIM needs a fine enough powder that can be mixed with a polymer and injection molded, thus the material costs are high. On the other hand, the applications for magnesium and aluminum die castings are large-volume applications where cost is a concern. Examples are camera frames, fittings, toys, etc., and these applications are not well-suited for MIM as a result.

17.40 Describe how the information given in Fig. 17.14 would be helpful to you in designing PM parts.

There are many possible answers to this question, and the answer depends on the experiences of the student. In general, the value is to consider a part and then judge its complexity. This allows one to quickly determine which powder metallurgy processes are suitable for that part. For example, if a part is a tube with a length of 0.5 m, then one would consider this to be simple; perhaps the complexity is 1.5 (it would be lower if the part were a cylinder instead of a tube). Clearly, one would not use compaction and sintering (P/F) because of the large size, and this would be a valuable conclusion. One would instead investigate CIP and HIP for this large part. Thus, Fig. 17.14 on p. 448 can quickly aid in identifying the best process for a part.

17.41 It was stated that, in the process shown in Fig. 17.19, shapes produced are limited to axisymmetric parts. Do you think it would be possible to produce other shapes as well? Describe how you would modify the design of the setup to produce other shapes, and explain the difficulties that may be encountered.

The spray deposition or Osprey process can be used to make parts that are assymetric, but it is in general not used to do so. First of all, it should be noted that sometimes a cylindrical billet is produced, and the billet is withdrawn in the same direction as the metal spray. If a die is used to define the shape, then an assymetric shape can be produced. Another option would be to perform shape rolling forms of powder rolling on the workpiece.

Chapter 18

Processing of Ceramics, Glass, and Superconductors

QUALITATIVE PROBLEMS

18.13 Inspect various products; noting their shape, color, and transparency, identify those that are made of (a) ceramic, (b) glass, and (c) glass ceramics.

By the student. The following are typical examples (see also p. 465):

- Ceramic: Opaque or translucent materials, such as coffee cups, ovenware, floor tiles, and plates.
- Glass: Transparent materials, such as drinking glasses, windows, lenses, and TV and desktop computer screens.
- Glass ceramic: A typically white material, such as cookware (Corningware); other applications of ceramic glasses are rarer but include high-temperature heat exchangers.

18.14 Describe the differences and similarities in processing metal powders vs. ceramics.

By the student. Some of the similarities are:

- Both involve an initial powder form.
- Both involve sintering or firing.
- Both can produce porous parts.
- Both can be injection molded.

Some of the differences include:

- Ceramics are commonly glazed in a second firing operation, whereas this is rare for metals except when enameling.
- Ceramic processing involves water-based slurries, while this does not occur with metals.

18.15 Which property of glasses allows them to be expanded to large dimensions by blowing? Can metals undergo such behavior? Explain.

The property of glass which allows bottle production (see Fig. 18.10 on p. 475) is the fact that glass behaves in a superplastic manner (high strain-rate sensitivity; Section 2.2.7 on p. 64) and can undergo very large uniform elongations at elevated temperatures. Glass is a supercooled liquid, without a clearly defined melting point. Thus, glasses will deform readily at temperatures above their glass-transition temperature and will solidify into shapes imparted by the molds.

18.16 Explain why ceramic parts may distort or warp during drying. What precautions should be taken to avoid this situation?

Ceramic parts may warp during drying because of uneven shrinkage across the part, due to uneven diffusion and evaporation of moisture. The moisture loss can be made more uniform by drying the ceramic in a more humid or less hot environment; these of course also result in longer drying times.

18.17 What properties should plastic sheets have to be used in laminated glass? Why?

The plastic sheets should have high ductility and toughness (to dissipate energy) and be able to form a strong bond with the glass on both side of the plastic (to hold the broken glass pieces together).

18.18 It is stated that the higher the coefficient of thermal expansion of a glass and the lower its thermal conductivity, the higher the level of the residual stresses developed. Explain why.

The coefficient of thermal expansion is important in the development of residual stresses because a given temperature gradient will result in a greater residual strain upon complete cooling. Thermal conductivity is important because the higher the thermal conductivity, the more uniform the temperature throughout the molten glass and the more uniform the strains upon cooling. The more uniform the strains, the less the magnitude of residual stresses.

18.19 Are any of the processes used for making discrete glass products similar to ones described in preceding chapters? Describe them.

By the student. For example:

- Pressing of glass is similar to closed-die forging.
- Blowing of glass is similar to bulging or hydroforming.
- Production of glass fibers is similar to extrusion and drawing.
- Flat glass sheet or plate production is similar to drawing or rolling, depending on the particular method used.

18.20 Injection molding is a process that is used for powder metals, polymers, and ceramics. Explain why is this so.

Powder metals and ceramics are initially in powder form, and when mixed with a thermoplastic, create a material that can flow and be formed in molds using injection molding. Ultimately, the thermoplastic is still used for the molding process, but powder metals and ceramics can use this process because they are particles suspended in the polymer. Thermoplastics have the attractive ability to flow readily as a fluid and solidify in a cooled mold, and injection molding of plastics is a straightforward and well-established process (see Section 19.3 on p. 493).

18.21 Explain the phenomenon of static fatigue and how it affects the service life of a ceramic or glass component.

Static fatigue occurs under a constant load and in environments where water vapor is present. Typical examples of applications that are susceptible to static fatigue include load-bearing members (such as a glass rod under tension) and glass shelving (supporting various objects, including books).

18.22 Describe and explain the differences in the manner in which each of the following would fracture when struck with a heavy piece of rock: (a) ordinary window glass, (b) tempered glass, and (c) laminated glass.

By the student. The students are encouraged to conduct simple experiments with these types of glasses. (a) Will typically develop radial cracks as well as various secondary cracks, e.g., window glass, when a rock or baseball is thrown at it. (b) Will shatter into a large number of small pieces, e.g., fireplace glass. (c) Will shatter into numerous pieces but the pieces will be held together due to the toughness of the plastic layer in between the two glass layers, e.g., windshields.

18.23 Is there any flash that develops in slip casting? How would you propose to remove such flash?

There is typically a flash at the parting line of the mold halves (see Fig. 18.3 on p. 468) or parts where the mold has more than two sections. The flash can be gently removed through trimming with a knife or wire brush while the ceramic is in the green state, or they can be ground after the ceramic is fired.

QUANTITATIVE PROBLEMS

18.24 Using Example 18.1, calculate (a) the porosity of the dried part if the porosity of the fired part is to be 5% and (b) the initial length, of the part if the linear shrinkages during drying and firing are 8 and 7%, respectively.

(a) For this case we have

$$V_a = (1 - 0.09)V_f = 0.91V_f$$

Because the linear shrinkage during firing is 7%, we write

$$V_d = V_f/(1 - 0.07)^3 = 1.24V_f$$

Therefore,

$$\frac{V_a}{V_d} = \frac{0.91}{1.24} = 0.73, \text{ or } 73\%$$

Consequently, the porosity of the dried part is (1 - 0.73) = 0.27, or 27%.

(b) We can now write

$$\frac{(L_d - L)}{L_d} = 0.07$$

or

$$L = (1 - 0.07)L_d$$

Since $L = 20$ mm, we have

$$L_d = 20/0.93 = 21.51 \text{ mm}$$

And thus

$$L_o = (1 + 0.08)L_d = (1.08)(21.51) = 23.23 \text{ mm}$$

18.25 What would be the answers to Problem 18.24 if the quantities given were halved?

(a) For this case we have

$$V_a = (1 - 0.045)V_f = 0.955V_f$$

Because the linear shrinkage during firing is 3.5%, we write

$$V_d = V_f/(1 - 0.035)^3 = 1.112V_f$$

Therefore,

$$V_a/V_d = 0.955/1.112 = 0.86, or 86\%$$

Consequently, the porosity of the dried part is (1 - 0.86) = 0.14, or 14%.

(b) We can now write

$$\frac{(L_d - L)}{L_d} = 0.035$$

or

$$L = (1 - 0.035)L_d$$

Since $L = 20$ mm, we have

$$L_d = \frac{20}{0.965} = 20.73 \text{ mm}$$

And thus

$$L_o = (1 + 0.04)L_d = (1.04)(20.73) = 21.56 \text{ mm}$$

18.26 Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

By the student. This is an outstanding, open-ended question that requires considerable focus and understanding from the students, and has been found to be a very valuable homework problem.

SYNTHESIS, DESIGN, AND PROJECTS

18.27 List same similarities and differences between the processes described in this chapter and those in (a) Part II on metal casting and (b) Part III on forming and shaping.

By the student. For example, between PM and ceramics parts and castings, there are similarities in that parts are porous, the part complexity is similar, and PM and casting both use metals. For PM and forgings, we note that similar equipment and tooling materials are used, and finishing operations are similar. The student is encouraged to elaborate further.

18.28 Consider some ceramic products with which you are familiar, and outline a sequence of processes that you think were used to manufacture them.

By the student. Some of the most common ceramic parts include coffee cups, dishes, electronic components and automotive spark plugs. The sequence of processes used will vary widely depending on the particular part to be made. A coffee cup is an interesting example: It is generally slip cast or injection molded, depending on the number needed; the handle is attached in a separate process if the cup was slip cast and the flash is removed if the cup was injection molded. The greenware is then fired, resulting in the ceramic part. In some cases, tints or stains will then be applied, and glazing (glass particles in a slurry) is applied for improved appearance; the ceramic is then re-fired to obtain the glazed surface (see p. 520) suitable for food contact.

18.29 Make a survey of the technical literature, and describe the differences, if any, between the quality of glass fibers made for use in reinforced plastics and those made for use in fiber-optic communications. Comment on your observations.

By the student. The glass fibers in reinforced plastics has a much smaller diameter and has to be high quality for high strength (see Sections 9.2.1 on p. 219 and 18.3.4 on p. 476). The glass fibers for communications applications are formulated for optical properties and the strength is not a major concern, although some strength is needed for installation.

18.30 How different, if any, are the design considerations for ceramics from those for other materials? Explain.

By the student. Ceramics are brittle, very notch sensitive and hence not suitable for impact loadings. On the other hand, ceramics have exceptional properties at high temperatures, are very strong in compression, have corrosion resistance, and are resistant to wear because of their high hardness. (See also Section 18.5 on p. 478 and various sections on materials processing.)

18.31 Visit a ceramics/pottery shop, and investigate the different techniques used for coloring and decorating a ceramic part. What are the methods of applying a metallic finish to the part?

By the student. Decorations can be done in a number of ways. For example, while still in the green state, a dye can be applied (such as by spraying or with a brush) to the ceramic part which permeates into the part. When fired, the dye remains in the lattice to provide color, and may also change color. Another option is to use conventional paints and coatings after firing.

18.32 Give examples of designs and applications in which static fatigue should be taken into account.

By the student. Static fatigue occurs under a constant load and in environments where water vapor is present. See also Problem 18.21.

18.33 Perform a literature search, and make a list of automotive parts or components that are made of ceramics. Explain why they are made of ceramics.

By the student. Typical parts are: Spark plugs, decorative knobs, fuel filters, valve lifters, and heating coils. These parts utilize different aspects of ceramics; for example, the spark plugs use the high-temperature electrically insulative properties of ceramics, the knobs use the aesthetic advantages, and valve lifter use the high wear resistance that can be attained with ceramics.

18.34 Describe your thoughts on the processes that can be used to make (a) a small ceramic ball, (b) a small statue, (b) whiteware for bathrooms, (c) common brick, and (d) floor tile.

By the student. The answers will vary because of the different manufacturing methods used for these products. Some examples are:

(a) Ceramic balls can be made by pressing and firing.

(b) Small ceramic statues are usually made by slip casting, followed by firing to fuse the particles and develop strength, followed by decorating and glazing.

(c) Whiteware for bathrooms are either slip cast or pressed, then fired, and sometimes glazed and re-fired.

(d) Common brick is wet pressed or slip cast, then fired.

(e) Floor tile is hot pressed or dry pressed, fired, and sometimes glazed and re-fired.

18.35 One method of producing superconducting wire and strip is by compacting powders of these materials, placing them into a tube, and drawing them through dies or rolling them. Describe your thoughts concerning the steps and possible difficulties encountered at each stage of this process.

By the student. Concerns include fracture of the green part before or during drawing, and its implications; inhomogeneous deformation that can occur during drawing and rolling and its possible effects as a fracture-causing process; the inability of the particles to develop sufficient strength during this operation; and possible distortion of the part from its drawn or rolled shape during sintering.

Chapter 19

Forming and Shaping Plastics and Composite Materials

QUALITATIVE PROBLEMS

19.17 Describe the features of a screw extruder and its functions.

By the student. A typical extruder is shown in Fig. 19.2 on p. 487. The three principal features of the screw shown are:

- Feed section: In this region, the screw is intended to entrain powder or pellets from the hopper; as a result, the flight spacing and depth is larger than elsewhere on the screw.
- Melt section: In the melt section, the flight depth is very low and the plastic is melted against the hot barrel; also, gases that are entrained in the feed section are vented.
- Metering section: This region produced the pressure and flow rate needed for the extrusion operation.

Note that screws are designed for particular polymers, so the feed, melt, and metering sections are polymer-specific. Also, some extruders use two screws to increase the internal shearing and mixing of the polymer.

19.18 Explain why injection molding is capable of producing parts with complex shapes and fine detail.

The reason is mainly due to the attractive features of thermoplastics. When melted, they are a viscous liquid that can flow into intricate cavities under pressure, and then cool and solidify in the desired shape (see also Section 19.3 on p. 493).

19.19 Describe the advantages of applying the traditional metal-forming techniques, described in Chapters 13 through 16, to making (a) thermoplastic and (b) thermoset products.

By the student. Applying traditional metalworking techniques to shaping of plastics is advantageous for a number of reasons. Since the desired stock shapes are similar (e.g., sheet), efficient and reliable processes can be used. Being able to utilize similar machines allows the application of many years of research, development, and experience associated with machine design and process optimization to materials which have only existed for the last few decades.

19.20 Explain the reasons that some plastic-forming processes are more suitable for certain polymers than for others. Give examples.

By the student. For example, it is difficult to extrude thermosets because curing is impossible during the extrusion process. Plastics which are produced through reaction molding are difficult to produce through other means, and other processes are not readily adaptable to allowing sufficient mixing of the two ingredients. Injection molding of composites is difficult because fluidity of the material is essential to ensure proper filling of the die, but characteristics and presence of the fibers interferes with this process.

19.21 Describe the problems involved in recycling products made from reinforced plastics.

By the student. The main problems are that recycling usually requires the use of a single type of material, and that some plastics (mainly hard and brittle polymers) are more difficult to chop into small pieces for further processing than others. With reinforced plastics, this requires that the reinforcement be separated from the matrix, a very difficult task and uneconomical task. Note that matrices are often thermosets, so it is not practical to melt the matrix and separate the fibers from a molten phase.

19.22 Can thermosetting plastics be used in injection molding? Explain.

Thermosetting plastics are suitable for injection molding. The basic modification which must be made to the process is that the molds must be heated to allow polymerization and cross-linking to occur in the mold cavity (see pp. 498-499). The major drawback associated with this change is that, because of the longer cycle times, the process will not have as high a production rate as injection molding of thermoplastics.

19.23 Inspect some plastic containers, such as those containing talcum powder, and note that the integral lettering on them is raised rather than depressed. Explain.

By the student. The containers are produced through blow molding. The parison is pressed against the container walls by the internal pressure and then cooled upon contact with the die. The reason why the lettering is usually raised is due to the fact that it is much easier to produce the lettering on the mold walls by machining or shaping into it, using processes such as end milling (see Fig. 24.2d on p. 661). Raised letters on mold walls would be very difficult and expensive to produce, and in fact unnecessary. (See also Problem 14.22.)

19.24 An injection-molded nylon gear is found to contain small pores. It is recommended that the material be dried before molding it. Explain why drying will solve this problem.

The probable reason is that the porosity is due to entrapped moisture in the material. Note also that nylon absorbs water (hygroscopic; see p. 183) thus drying will alleviate this situation.

19.25 Explain why operations such as blow molding and film-bag making are performed vertically.

By the student. Film-bag making is done vertically (see Fig. 19.5 on p. 491) to keep the symmetry of the part and prevent sagging (due to gravitational force) of one side, which would the case if done horizontally. Blow molding can be done either vertically or horizontally.

19.26 Comment on the principle of operation of the tapelaying machine shown in Fig. 19.23b.

By the student. As the caption to Fig. 19.23 on p. 510 states, these machines are numerically controlled, as discussed in Chapter 38. These are, in effect, very large gantry robots that are programmed to dispense tape in programmed patterns. The cost for such a machine is justified, as is usually the case, by analyzing the desired production quantities and costs associated with alternate production methods. The example in Fig. 19.23 shows a rather large part; hand lay-up of tape would be labor intensive, which cannot be justified for larger production runs.

19.27 Typical production rates are given in Table 19.2. Comment on your observations and explain why there is such a wide range.

By the student. Consider the characteristics and cycle times involved in each of these processes listed in Table 19.2 on p. 521, as described in various sections of the chapter. Note that production quantities depend on factors such as the type of process, the type of plastics used and the time required for cooling in mold cavities, type of machinery and its level of automation. For comparison, casting topics are covered in Chapters 10 through 12 and forging in Chapter 14. The wide variety of machining processes and machinery are covered in Part IV.

19.28 What determines the cycle time for (a) injection molding, (b) thermoforming, and (c) compression molding? Explain.

The cycle time for injection molding is determined by several factors, including:

- Material: Thermoplastics need much less time than thermosets, and certain thermoplastics will need less time to cool and solidify than others (different thermal properties).
- Part shape: If the part has a low volume and large surface area, it will cool rapidly.
- Initial temperature: If a plastic is injected at a temperature much above its solidification temperature, it will require more time to cool.

The considerations for thermoforming and compression molding are similar. The students are encouraged to analyze and elaborate further.

19.29 Does the pull-in defect (sink marks) shown in Fig. 19.31c also occur in metal-forming and casting processes? Explain.

The type of defect shown in Fig. 19.31c on p. 519 also occurs in metal forming (because of the flow of the material into the die cavity) and casting processes (because of excessive, localized surface shrinkage during solidification and cooling in the mold). This is described in different handbooks, but it should be noted that 'sink marks' is a terminology restricted to polymer parts. For example, in Bralla, J.G., *Design for Manufacturability Handbook*, 2nd. ed., pp. 5.51, the sink marks are referred to as 'dishing' for investment casting, and on p. 5.64 the same features are referred to as 'shrink marks'.

19.30 What determines the intervals at which the indexing head in Fig. 19.14c rotates from station to station?

By the student. The question is basically asking what factors determine the cycle time in blow molding. The answer depends on several factors, including: The particular polymer used (which affects melting and processing temperature, thermal conductivity, and specific heat), tooling material and tooling temperature, bottle and parison shape, injection pressure, and the use (if any) of release agents.

19.31 Identify processes that would be suitable for small production runs on plastic parts, of, say, 100.

By the student. Refer to the last column (economical production quantity) in Table 19.2 on p. 521 and note that low quantities involve processes in which tooling costs must be kept low. Thus, the most suitable processes would be casting and machining (because of the readily available and versatile machine tools). Rapid prototyping operations, described in Chapter 20, may also be suitable if the quantities are sufficiently small and part characteristics are acceptable.

19.32 Identify processes that are capable of producing parts with the following fiber orientations in each: (a) uniaxial, (b) cross-ply, (c) in-plane random, and (d) three-dimensional random.

By the student. Some suggestions are:

(a) Uniaxial fiber orientations can be produced though pultrusion, tape lay-up, and filament winding.

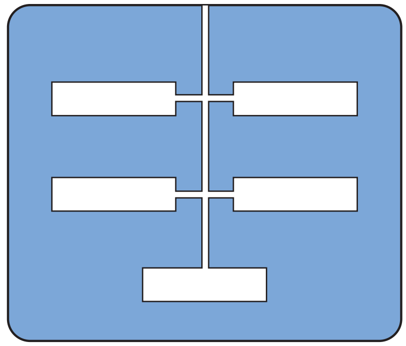
(b) Cross-ply can be produced by tape lay-up and filament winding.

(c) Random orientations can be produced with prepregs and vacuum forming, open-mold processing, and injection molding.

QUANTITATIVE PROBLEMS

19.33 Estimate the die-clamping force required for injection molding five identical 200-mm-diameter disks in one die. Include the runners of appropriate length and diameter.

Assuming a pressure of 69 MPa, which is rather low pressure, and that the die is set up as follows, with 6.5-mm diameter runners and 50-mm thick disks:



The surface area is approximately $A = (5)(200 \text{ mm})(50 \text{ mm}) + (6.5 \text{ mm})(500 \text{ mm}) = 53,250 \text{ mm}^2$. The clamping force required to balance the injection pressure is then

$$F = pA = (69 \text{ MPa})(53,250 \text{ mm}^2) = 3.7 \text{ MN} = 377 \text{ metric tons}$$

19.34 A 2-L plastic beverage bottle is made by blow molding a parison 125 mm long and with a diameter that is the same as that of the threaded neck of the bottle. Assuming uniform deformation during molding, estimate the wall thickness of the tubular portion of the parison.

A typical two-liter plastic beverage bottle is approximately $L = 230$ mm long and $D = 110$ mm in diameter; its wall thickness t is 0.38 mm. Thus, the volume of material is

$$V = \pi DLt = \pi(110)(230)(0.38) = 30,200 \text{ mm}^3$$

The parison is 125 mm long and its diameter is about 28 mm. Thus, its thickness, t_p, should be

$$t_p = (30,200)/(\pi)(28)(125) = 2.7 \text{ mm}$$

19.35 Consider a Styrofoam drinking cup. Measure the volume of the cup and its weight. From this information, estimate the percent increase in volume that the polystyrene beads have undergone.

By the student. The answer will vary somewhat, depending the cup manufacturer and method and accuracy of measurement. It is not unusual to find that the polystyrene has expanded by 80% or more during its processing.

SYNTHESIS, DESIGN, AND PROJECTS

19.36 Make a survey of a variety of sports equipment, such as bicycles, tennis racquets, golf clubs, and baseball bats, and identify the components made of composite materials. Explain the reasons for and advantages of using composites for these specific applications.

By the student. There is a wide variety of sporting goods that utilize composites, including all of the items mentioned as well as gun stocks, skis, hiking and ski poles, and bicycle frames. Enterprising students will also recognize that baseballs, footballs and rugby balls are composite materials. The reasons for using composite materials for these specific applications are invariably the advantages in strength-to-weight ratio, stiffness-to-weight ratio and increased damping capability.

19.37 Explain the design considerations involved in replacing a metal beverage can with one made completely of plastic.

There are a number of design considerations, including:

- Cost is a primary consideration.
- Metal beverage cans are extremely reliable; plastic containers need to preserve this reliability or be unaccepted in the marketplace.
- The recycling strategies for metals, and the infrastructure associated with metals, is more straightforward than for plastics.
- The plastic should not adulterate the contents.
- The plastic should have the ability to be decorated.
- The weight should be comperable.

19.38 Give examples of several parts suitable for insert molding. How would you manufacture these parts if insert molding were not available?

By the student. Most examples are from the electronics industry, but there are others (see, for example, the parts shown in Fig. 19.9a on p. 495). Propeller shafts for toy boats can be insert molded with plastic propellers on shafts that are knurled (see Fig. 23.11 on p. 616) to keep the propeller from slipping. If insert molding were not available, suitable operations would be press fitting the inserts into molded holes or cavities, and mechanical assembly using various fasteners.

19.39 Give other examples of design modifications in addition to those shown in Fig. 19.31.

By the student. Other examples would include referring to die swell, as shown in Fig. 19.3 on p. 488, and noting that the die opening must be smaller than the desired shape. In addition, strengthening ribs also can be used to eliminate or control part distortion. There are a large number of design modifications that can be found in the technical literature. For example, Bralla, J.G., *Design for Manufacturability Handbook*, 2nd. ed., contains many recommendations in Chapter 6, pp. 6.1-6.207.

19.40 With specific examples, discuss the design issues involved in making products out of plastics vs. reinforced plastics.

By the student. Design considerations are covered in Section 19.15 starting on p. 518. Reinforced plastics are superior to conventional plastics in terms of strength and strength-to-weight ratios (see, for example, Table 7.1 on p. 172), but not in cost. As an example, consider the design of pressure vessels for delivering oxygen for emergency passenger use on aircraft. Certainly a container can be produced from plastic, but the weight of an optimized pressure vessel will be lower for a reinforced filament-wound container, even though the cost is higher.

19.41 Inspect various plastic components in a typical automobile, and identify the processes that could have been used in making them.

By the student. As examples: (a) Small components such as coffee-cup holders and the like are injection molded. (b) Dashboards are thermoformed or vacuum-bag formed from fiber-reinforced prepregs. (c) Radio knobs can be insert molded or injection molded. (d) Body panels can be thermoformed.

19.42 Inspect several similar products that are made either from metals or from plastics, such as a metal bucket and a plastic bucket of similar shape and size. Comment on their respective shapes and thicknesses and explain the reasons for their differences.

By the student. The basic difference between metals and plastics have been discussed on various occasions; see also Section 7.1 on p. 171. Some examples:

(a) Metal buckets are thinner than plastic ones, and are more rigid; plastic buckets have to be thicker because of their much lower elastic modulus.

(b) Metal pens (mechanical pencils) and plastic pens; the polymer pens are much thicker, because they must feel rigid for its intended use.

(c) Plastic vs. metal forks and spoons; although no major difference in overall size, the plastic ones are more flexible but they are made more rigid by increasing the section modulus (as can be observed by inspecting the handle designs).

19.43 Write a brief paper on how plastic coatings are applied to (a) electrical wiring, (b) sheet-metal panels, (c) wire baskets, racks, and similar structures, and (d) handles for electrician's tools, such as wire cutters and pliers requiring electrical insulation.

By the student. The paper should elaborate on the differences between various processes, such as coextrusion, hot dipping, and insert molding.

19.44 It is well known that plastic forks, spoons, and knives are not particularly rigid. What suggestions would you have to make them better? Describe processes that could be used for producing them.

By the student. Plastic spoons, forks, and knives are not particularly strong or rigid, but they are inexpensive because they are mass produced typically by injection molding. Stiffening ribs can, for example, be designed into them to increase their stiffness, or they can be made larger and thicker. If strength is a key issue, then stronger plastics can be used (see Table 7.1 on p. 172).

19.45 Make a survey of the technical literature, and describe how different types of (a) pneumatic tires, (b) automotive hoses, and (c) garden hoses are manufactured.

By the student. Tires are produced by molding, followed by vulcanization to develop the highly cross-linked polymer structure. Some reinforced automotive hoses are coextruded with a metal reinforcement. Garden hoses are similary manufactured using reinforcing polymeric webs during extrusion.

19.46 Obtain a boxed kit for assembling a model car or airplane. Examine the injection-molded parts provided, and describe your thoughts on the layout of the molds to produce these parts.

By the student. This is an interesting project and allows a simple study of a complex mold layout. The layout of the mold shows part balance - note that the material is fairly evenly distributed across the mold cross section. The gate is well made allowing parts to be broken off with ease. The molds are well crafted, with great details.

19.47 In injection-molding operations, it is common practice to remove the part from its runner, place the runner in a shredder, and recycle the runner by producing pellets. List the concerns you may have in using such recycled pellets for products, as against "virgin" pellets.

By the student. Some concerns are:

- The polymer may become chemically contaminated by tramp oils or parting agents used in the die.
- Wear particles from the shredder may contaminate the polymer.
- The polymer may be chemically degraded from the heating and cooling cycle encountered in injection molding.
- The molecular weight of the shredded polymer may be much smaller than the original polymer so that the mechanical properties of the recycled stock may be inferior.

19.48 An increasing environmental concern is the very long period required for the degradation of polymers in landfills. Noting the information given in Section 7.8 on biodegradable plastics, conduct a literature search on the trends and developments in the production of these plastics.

By the student. A recent trend is to use polymers that, if they do not degrade in sufficiently short time, can be incinerated without producing volatile organic compounds as combustion products. Also, the problem has been mitigated somewhat in recent years through introduction of new materials. For example, perhaps the problem receiving the most meadia attention in the 1980s was the degredation time associated with diapers for babies and small children. Modern diapers use hydrogel powders that degrade rapidly when exposed to rain or groundwater, and they also use innovative paper liners to eliminate the environmentally suspect polymers. In summary, most polymers in use today are (a) able to be recycled; (b) able to be safely incinerated or (c) quickly degradable.

19.49 Examine some common and colorful plastic poker chips and give an opinion on how they were manufactured.

By the student. Inexpensive poker chips are injection molded, as can be seen by careful examination of the chip surfaces, where a parting line and gate are still visible. Higher-end poker chips, such as those in casinos, are insert molded with a metal core to add weight, and are then coated and decorated.

19.50 Obtain different styles of toothpaste tubes, carefully cut them across, and comment on your observations regarding (a) the type of materials used and (b) how the tubes were produced.

By the student. It will be noted that some collapsible tubes are blow molded, others are injection molded at one end and the other end is joined by hot-tool welding (see Section 32.6 on p. 943). Another design is injection-molded rigid tubing where the toothpaste is pumped out. Also, some collapsible tubes have walls that are mutlilayers of different materials and welded on the closed end.

Chapter 20

Rapid-Prototyping Operations

QUALITATIVE PROBLEMS

20.10 Examine a ceramic coffee cup and determine in which orientation you would choose to produce the part if you were using (a) fused-deposition manufacturing or (b) laminated-object manufacturing.

By the student. In fused-deposition modeling the coffee cup would be prototyped in the same orientation as when it holds coffee; this orientation is selected to minimize the volume of support material and structures needed (see Fig. 20.5 on p. 532). In laminated-object manufacturing the coffee cup would be placed on its side to minimize the numbers of layers since a "support" material is always produced. Note, however, that parts are often fit into a workspace containing many parts, so these options may not always be followed.

20.11 How would you rapidly manufacture tooling for injection molding? Explain any difficulties that may be encountered.

By the student. There are a number of options. Depending on the polymer to be injection molded, the tooling could be made by

(a) producing a polymer tool in a rapid-prototyping operation, suitable for injection molding. (Note that injection molding can take place in polymer molds, but the cool time is longer and the mold life is lower than if aluminum or copper alloys are used for the mold.)

(b) A pattern is produced from a soft polymer or wax. The pattern is placed on a tree and investment casting from a castable alloy (such as high-silicon aluminum or cast brasses).

(c) A polymer model of a pattern plate is produced, from which one can make a sand mold for sand casting

(d) machining a block of copper or aluminum in a CNC milling machine (see, for example, Fig. 24.17 on p. 673).

20.12 Explain the significance of rapid tooling in manufacturing.

Rapid tooling has the potential to fundamentally change manufacturing processes such as forging, die casting and PM operations. Traditionally, these processes have had limits to their applications because of the high tooling costs and long lead times. The high tooling costs are attributable to material costs, but mostly to machining and finishing; the high lead times were due to incorporating long times for rework when required. With rapid tooling, the costs and lead times for tooling are drastically reduced. The economic benefits are most significant for moderate to low production runs, where forging, die casting, PM, etc, could not even be considered using traditional die manufacturing methods because of economic considerations. However, with rapid tooling, such processes can be used for a wider range of parts and production runs.

20.13 List the processes described in this chapter that are best suited for the production of ceramic parts. Explain.

For direct production of ceramic parts, three-dimensional printing is likely the best option. With the proper binder, this can also be accomplished by fused-deposition modeling, and is also possible by selective laser sintering. However, the ceramic particles will abrade the tooling in FDM and require much heat to fuse in SLS. The 3D printing approach, where a binder is sprayed onto the ceramic particles, is the best approach for making green parts, which are then fired in a furnace to fuse the powder.

20.14 Few parts in commercial products today are directly manufactured through rapid-prototyping operations. Explain.

The two main reasons why so few parts are produced by rapid-prototyping operations are production cost and production time. Note that the materials used in rapid prototyping are very expensive; also, although they can be produced quickly as compared to conventional forming operations (and machining unless very expensive CNC equipment is used) mass production is not realistic. There is a quip that the production of a first forging takes six months and a million dollars, but the second forging is then almost free and takes only seconds for manufacture. With rapid prototyping, the first part takes a few hours. The second part takes a few hours, and so on, with no economies of scale. These processes are ideally suited for making single examples of products, but are not intended for mass production.

20.15 Can rapid-prototyped parts be made of paper? Explain.

Yes, rapid-prototyped parts can be made of paper. The laminated-object manufacturing process produced parts from paper or plastic.

20.16 Careful analysis of a rapid-prototyped part indicates that it is made up of layers with a distinct filament outline visible on each layer. Is the material a thermoset or a thermoplastic? Explain.

The filament outline suggests that the material was produced in fused-deposition modeling. This process requires adjacent layers to fuse after being extruded. Extrusion and bonding is obviously possible with thermoplastics but very difficult for a thermoset.

20.17 Why are the metal parts in three-dimensional printing often infiltrated by another metal?

There are a number of reasons for this infiltration. Note that infiltration is also a common approach for PM parts, and the reasons for infiltrating parts produced in three-dimensional printing are the same. There are obvious benefits to the mechanical properties that can be achieved in such materials by infiltrating the structure with another metal. Also, such materials cannot be contaminated, so that finishing operations such as electroplating can take place if the material is infiltrated.

20.18 Make a list of the advantages and limitations of each of the rapid-prototyping operations described in this chapter.

By the student. As examples, the students could investigate cost (FDM, STL have advantages over solid-ground curing, for example), material properties (see Table 20.2 on p. 529) where selective laser sintering with bronze-infiltrated steel powder would be superior, or dimensional tolerances or surface finish.

20.19 In making a prototype of a toy automobile, list the post-rapid-prototyping finishing operations that you think would be necessary. Explain.

By the student. The answer, as expected, depends on the particular rapid-prototyping process used to create the toy. Consider, for example, fused-deposition modeling: It may be desirable to sand or finish the surface because of the surface texture that exists from the extruded filament. A base coat and paint then can be applied, followed by detailed decorative paint, if desired. Stereolithography may require (and generally it does so) post-curing, followed by roughening (such as by sanding) to allow paint to bond well, followed by painting, as above.

QUANTITATIVE PROBLEMS

20.20 Using an approximate cost of \$160 per liter for the liquid polymer, estimate the material cost of a rapid-prototyped rendering of a typical computer mouse.

Recognizing that a mouse is mostly hollow, with a wall thickness of approximately 3 mm, and from the overall dimensions of the mouse, the volume of plastic in it can be calculated as around 20,480 mm^3. (The dimensions will of course vary by mouse manufacturer). Since one liter is equal to 10^6 mm^3, the cost of the plastic in the mouse would be \$3.28 (which is a very small fraction of the cost of the mouse).

20.21 The extruder head in a fused-deposition modeling setup has a diameter of 1.25 mm and produces layers that are 0.25 mm thick. If the extruder head and polymer extrudate velocities are both 50 mm/s, estimate the production time for the generation of a 38-mm solid cube. Assume that there is a 10-second delay between layers as the extruder head is moved over a wire brush for cleaning.

Note that although the calculations are shown below, in practice the rapid-prototyping software can easily make this calculation. First, if the thickness of the cube is 38 mm, and the layers are 0.25 mm thick, there are 152 layers, for a total 'inactive' time of (152)(15 s)=2280

s. Note also that the cross-section of the extruded filament in this case is highly elliptical, and thus its shape is not easily determined from the information given in the problem. However, we know that the polymer extrudate speed is 50 mm/s and the orifice diameter is 1.25 mm, hence the volume flow rate is

$$Q = vA = (50 \text{ mm/s}) \left[\frac{\pi}{4}(1.25 \text{ mm})^2\right] = 61.36 \text{ mm}^3/\text{sec}$$

The cube has a volume of (38)(38)(38)=54,900 mm^3 and the time required to extrude this volume is 54,900/61.36=895 s. Hence the total production time is 895 s + 2280 s = 3175 s = 52 mins.

20.22 Using the data for Problem 20.21 and assuming that the porosity for the support material is 50%, calculate the production rate for making a 100-mm (4-in.) high cup with an outside diameter of 90 mm (3.5 in.) and a wall thickness of 4 mm (0.16 in.). Consider the cases (a) with the closed end up and (b) with the closed end down.

(a) Closed-end down. For this case, there is no support material needed. There are 400 layers, so the 'inactive' time is 6000s. The cup wall volume is

$$V = \frac{\pi}{4}d^2t + \pi dht = \frac{\pi}{4}(90 \text{ mm})^2(4 \text{ mm}) + \pi(90 \text{ mm})(100 \text{ mm})(4 \text{ mm})$$

or $V = 138,000$ mm^3. This takes $138,000/61.36 = 2260$ s to extrude; the total time is $6000 + 2260 = 8260$ s $= 2.3$ hours.

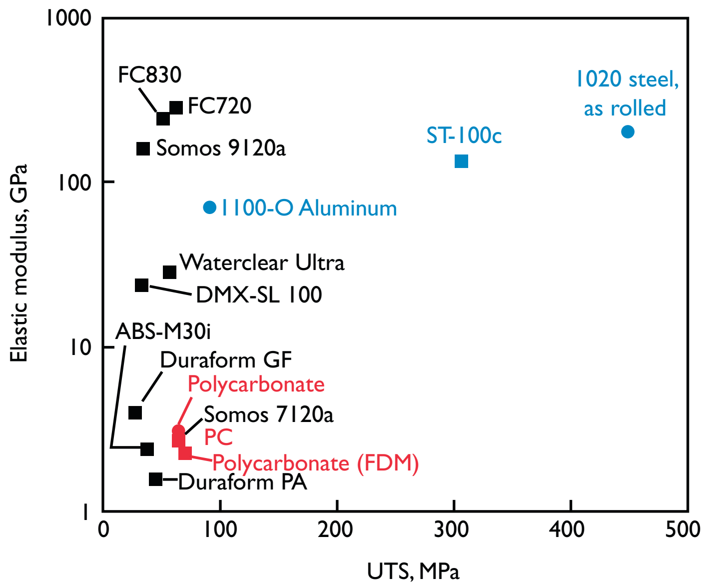
(b) Closed-end up. Now, in addition to the wall, the interior must be filled with support for the closed-end on top. The volume of the cup is

$$V = \frac{\pi}{4}d^2h = \frac{\pi}{4}(87.5 \text{ mm})^2(100 \text{ mm}) = 601,000 \text{ mm}^3$$

Since the support material has a porosity of 50% (so $V_{\text{eff}} = 300,500$), the time required to extrude the support material is $t = 300,500/61.36 = 4900$ s $= 1.36$ hrs. Therefore, the total time for producing the part and the support is $2.6 + 1.36 = 3.96$, or about four hours.

20.23 Inspect Table 20.2 and compare the numerical values given with those for metals and other materials, as can be found in Part I of this text. Comment on your observations.

This is an open-ended problem, and students should be encouraged to develop their own answers. As an example of a good comparison, the figure below shows a two-parameter chart of tensile strength and elastic modulus for the materials in Table 20.2 as well as for selected other materials. When a range of values is given, the mean value is used in this graph. Note that Table 17.5 on p. 456 provides a good comparison for Ti-6Al-4V, which is a workpiece material for electron beam melting.



In this figure, note that squares correspond to rapid prototyped materials, circles to materials from other processes. Blue materials are metals, the red materials are three forms of polycarbonate. Note that the mechanical properties of materials from rapid prototyping operations are comparable, but slightly lower than, equivalents from other processes.

SYNTHESIS, DESIGN, AND PROJECTS

20.24 Rapid-prototyping machines represent a large capital investment; consequently, few companies can justify the purchase of their own system. Thus, service companies that produce parts based on their customers' drawings have become common. Conduct an informal survey of such service companies, identify the classes of rapid-prototyping machines that they use, and determine the percentage use of each class.

By the student. There are numerous such services that can be quickly found on Internet search engines. However, as the cost of rapid-prototyping machines continues to decrease and their use becomes more widespread, more and more companies are acquiring in-house rapid-prototyping capabilities. An interesting modification to this problem is to investigate the annual volume of rapid-prototyping projects outsourced by companies.

20.25 One of the major advantages of stereolithography is that it can use semitransparent polymers, so that internal details of parts can readily be discerned. List and describe several parts in which this feature is valuable.

By the student. The transparent feature is especially useful for (a) flow visualization, such as with a new heat-exchanger design; (b) investigating mating parts to make sure the interface is as intended; and (c) implantable medical devices, where the body part is made from stereolithography for visualization of how the devices function.

20.26 A manufacturing technique is being proposed that uses a variation of fused-deposition modeling in which there are two polymer filaments that are melted and mixed prior to being extruded to make the part. What advantages does this method have?

By the student. There are several advantages to this approach, including:

- If the polymers have different colors (for example, black and white or blue and white) blending the polymers can produce a part with a built-in color scheme.
- If the polymers have different mechanical properties, then functionally graded materials can be produced, that is, materials with a designed blend of mechanical properties.
- Higher production rates and workpiece properties may be achieved.
- If the second polymer can be leached, it can be developed into a technique for producing porous polymers or ship-in-the-bottle type parts.

20.27 Identify the rapid-prototyping processes described in this chapter that can be performed with materials available in your home or that you can purchase easily at low cost. Explain how you would go about it. Consider materials such as thin plywood, thick paper, glue, and butter, as well as the use of various tools and energy sources.

Numerous answers can be given to this problem and the students are encouraged to apply their creativity in formulating a solution. Some suggestions are:

- Paper, plywood, or cardboard can be cut and glued together to form three-dimensional objects, similar to those made by laminated-object manufacturing.
- Glue, butter, or chocolate can be drizzled or placed onto wax paper, and chilled. The chilled layer can then be attached to other layers, thus simulating fused-deposition modeling or three-dimensional printing.
- Sand can be placed on sheets of paper, and drizzled on top with glue to make layers, similar to three-dimensional printing.

20.28 Design a machine that uses rapid-prototyping technologies to produce ice sculptures. Describe its basic features, commenting on the effect of size and shape complexity on your design.

By the student. A number of machines can be designed, including:

- A machine can use the principles of ballistic particle manufacturing to spray small droplets of water onto a frozen base and produce the sculpture layer-by-layer.
- Sheets of ice can be produced and then cut with a laser. To do so, it is likely that small particles suspended in the ice will be needed to cause localized heating, or else water-jet cutting (see Section 27.8 on p. 778) can produce the layers .
- Layers of shaved ice can be sprayed using a water jet, similar to three-dimensional printing.

20.29 Because of relief of residual stresses during curing, long unsupported overhangs in parts made by stereolithography tend to curl. Suggest methods of controlling or eliminating this problem.