## 19 SHEET METALWORKING

### Review Questions

19.1 Identify the three basic types of sheet metalworking operations.

**Answer**. The three basic types are (1) cutting, (2) bending, and (3) drawing.

19.2 In conventional sheet metalworking operations, (a) what is the name of the tooling and (b) what is the name of the machine tool used in the operations?

**Answer**. (a) The tooling is called a punch and die. (b) The machine tool is called a stamping press.

19.3 In blanking of a circular sheet metal part, is the clearance applied to the punch diameter or the die diameter?

**Answer**. The die diameter equals the blank diameter, and the punch diameter is smaller by twice the clearance.

19.4 What is the difference between a cutoff operation and a parting operation?

**Answer**. A cutoff operation separates parts from a strip by shearing one edge of each part in sequence. A parting operation cuts a slug between adjacent parts in the strip. See Figure 19.8.

19.5 What is the difference between a notching operation and a seminotching operation?

**Answer**. A notching operation cuts out a portion of the sheet metal from the side of the sheet or strip, while a seminotching operation removes a portion of the sheet metal from the interior of the sheet or strip.

19.6 Describe each of the two types of sheet metal-bending operations: V-bending and edge bending.

**Answer**. In V-bending, a simple punch and die that each have the included angle are used to bend the part. In edge bending, the punch forces a cantilevered sheet metal section over a die edge to obtain the desired bend angle. See Figure 19.12.

19.7 For what is the bend allowance intended to compensate?

**Answer**. The bend allowance is intended to compensate for stretching of the sheet metal that occurs in a bending operation when the bend radius is small relative to the stock thickness. In principle the bend allowance equals the length of the bent metal along its neutral axis.

19.8 What is springback in sheet metal bending?

**Answer**. Springback is the elastic recovery of the sheet metal after bending; it is usually measured as the difference between the final included angle of the bent part and the angle of the tooling used to make the bend, divided by the angle of the tooling.

19.9 Define drawing in the context of sheet metalworking.

**Answer**. Drawing is a sheet metalworking operation used to produce cup-shaped or box-shaped, or other complex-curved and concave parts. Drawing is accomplished by placing a piece of sheet metal over a die cavity and then using a punch to push the metal into the cavity.

19.10 What are some of the simple measures used to assess the feasibility of a proposed cup-drawing operation?

**Answer**. Measures of drawing feasibility include (1) drawing ratio $DR = D_b/D_p$; (2) reduction $r = (D_b - D_p)/D_b$ ; and (3) thickness-to-diameter ratio, $t/D_b$; where $t$ = stock thickness, $D_b$ = blank diameter, and $D_p$ = punch diameter.

19.11 What are some possible defects in drawn sheet metal parts?

**Answer**. Drawing defects include (1) wrinkling, (2) tearing, (3) earing, and (4) surface scratches.

19.12 What is the difference between redrawing and reverse drawing?

**Answer**. In redrawing, the shape change is significant enough (e.g., drawing ratio greater than 2.0) that it must be carried out in two drawing steps, probably with an annealing operation between the steps. In reverse drawing, two draws are accomplished on the part, one in one direction, the second in the opposite direction.

19.13 What are the two basic categories of structural frames used in stamping presses?

**Answer**. Two basic categories of press frame are (1) gap frame, also called C-frame because its profile is the shape of the letter “C”, and (2) straight-sided frame, which has full sides for greater strength and stiffness of the frame.

19.14 What are the relative advantages and disadvantages of mechanical presses versus hydraulic presses in sheet metalworking?

**Answer**. The main advantage of mechanical presses is faster cycle rates. Advantages of hydraulic presses are longer ram strokes and uniform force throughout stroke.

19.15 What is an embossing operation?

**Answer**. Embossing is a sheet metalworking operation used to create indentations in the sheet, such as raised lettering or strengthening ribs.

19.16 What is the Guerin process?

**Answer**. The Guerin process is a sheet metal forming process that uses a rubber die that flexes to force the sheet metal to take the shape of a form block (punch).

19.17 What is stretch forming?

**Answer**. Stretch forming of sheet metal consists of simultaneously stretching and bending the sheet metal work part to achieve shape change.

19.18 What is the difference between roll bending and roll forming?

**Answer**. Roll bending involves the forming of large sheet and plate metal sections into curved forms. Roll forming involves feeding a lone strip or coil through rotating rolls so that the shape of the rolls is imparted to the strip.

19.19 What is a major technical problem in tube bending?

**Answer**. A major technical problem in tube bending is collapse of the tube walls during the bending process.

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**Problems**

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

**Cutting Operations**

19.1 (SI units) Power shears are used to cut a sheet of soft cold-rolled steel that is 2.4 mm thick and 1.25 m wide. The steel has a yield strength = 175 MPa and tensile strength = 300 MPa. Determine the (a) clearance that should be used to produce an optimum cut and (b) cutting force in the operation.

**Solution**: (a) From Table 19.1, $A_c = 0.060$. Thus, $c = A_c t = 0.060(2.4) =$ **0.144 mm**

(b) Cutting force $F = 0.7(300)(2.4)(1250) =$ **630,000 N**

19.2 **(A)** (USCS units) A blanking operation is performed on 1/8-in-thick cold-rolled steel (half hard). The part is circular with diameter = 2.500 in. The shear strength of the steel = 40,000 lb/in$^2$ and tensile strength = 55,000 lb/in$^2$. Determine the (a) appropriate punch and die sizes for the operation and (b) blanking force required.

**Solution**: (a) From Table 19.1, $A_c = 0.075$. Thus, $c = 0.075(1/8) = 0.0094$ in
Punch diameter = $D_b - 2c = 2.500 - 2(0.0094) =$ **2.481 in**
Die diameter = $D_b =$ **2.500 in**

(b) $F = StL$, $L = \pi D = 2.5\pi = 7.854$ in
$F = StD = 40{,}000(0.125)(7.854) =$ **39,270 lb**
If tensile strength is used, then $F = 0.7(55{,}000)(0.125)(7.854) =$ **37,797 lb**
The two values are within ~4% of each other. Close enough for this kind of calculation

19.3 (SI units) A compound die is used to blank and punch a large washer out of 6061ST aluminum alloy sheet stock 3.2 mm thick. The outside diameter of the washer is 25.0 mm, and the inside diameter is 12.0 mm. Determine the punch and die sizes for the (a) blanking operation and (b) punching operation.

**Solution**: From Table 19.1, $A_c = 0.060$. Thus, $c = 0.060(3.2) = 0.192$ mm

(a) Blanking punch diameter = $D_b - 2c = 25.0 - 2(0.192) =$ **24.62 mm**
Blanking die diameter = $D_b =$ **25.00 mm**

(b) Punching punch diameter = $D_h =$ **12.00 mm**
Punching die diameter = $D_h + 2c = 12.0 + 2(0.192) =$ **12.38 mm**

19.4 (SI units) In the previous problem, determine the force required to perform the blanking and punching operation under the following conditions: (a) blanking and punching occur simultaneously and (b) the punches are staggered so that punching occurs first, then blanking. The aluminum has a tensile strength = 350 MPa.

**Solution**: (a) $F = 0.7(TS)tL$
$L = 25\pi + 12\pi = 37\pi = 116.2$ mm
$F = 0.7(350)(3.2)(116.2) =$ **91,101 N**

(b) Longest length will determine the minimum tonnage press required, if punching and blanking are performed separately. For the punching length of cut, $L = 12\pi$, and for the

blanking length of cut, $L=25\pi = 78.5$ mm. Use the blanking operation to determine press capacity.
$F = 0.7(350)(3.2)(78.5) =$ **61,575 N**

19.5 (SI units) A blanking die must be designed to blank the part outline shown in Figure P19.5. The material is 4-mm-thick stainless steel (half hard). Determine the (a) dimensions of the blanking punch and the die opening and (b) cutting force required, given that the stainless steel has a yield strength = 275 MPa, shear strength = 450 MPa, and tensile strength = 650 MPa.

**Solution**: (a) From Table 19.1, $A_c = 0.075$. Thus, $c = 0.075(4.0) = 0.30$ mm
Blanking die: dimensions are the same as for the part in Figure P19.5.
Blanking punch: 85 mm length dimension = 85 – 2(0.3) = **84.4 mm**
50 mm width dimension = 50 – 2(0.3) = **49.4 mm**
Top and bottom 25 mm extension widths = 25 – 2(0.3) = **24.4 mm**
The 25 mm inset dimension remains the same.

(b) $F = StL$
$L = 85 + 50 + 25 + 25 + 35 + 25 + 25 + 50 = 320$ mm
$F = 450(4.0)(320) =$ **576,000 N**
If tensile strength is used, then $F = 0.7(650)(4)(320) =$ **582,400 N**
The two values are within ~1% of each other. Close enough for this kind of calculation

19.6 The foreman in the pressworking section comes to you with the problem of a blanking operation that is producing parts with excessive burrs. (a) What are the possible reasons for the burrs, and (b) what can be done to correct the condition?

**Solution**: (a) Reasons for excessive burrs: (1) clearance between punch and die is too large for the material and stock thickness; and (2) punch and die cutting edges are worn (rounded) which has the same effect as excessive clearance.

(b) To correct the problem: (1) Check the punch and die cutting edges to see if they are worn. If they are, regrind the faces to sharpen the cutting edges. (2) If the die is not worn, measure the punch and die clearance to see if it equals the recommended value. If not, the die maker must refabricate the punch and/or die.

## Bending

19.7 **(A)** (SI units) A bending operation is to be performed on 5.00 mm thick cold-rolled steel. The part drawing is shown in Figure P19.7. Determine the (a) blank size required and (b) bending force if the bend is performed in a V-die with a die opening dimension = 40 mm. The steel has a tensile strength = 350 MPa and shear strength = 250 MPa.

**Solution**: (a) From part drawing in Figure P19.7, $\alpha' = 40°$, $R = 8.50$ mm
$\alpha = 180 - \alpha' = 140°$
$A_b = 2\pi(\alpha/360)(R + K_{ba}t)$
$R/t = (8.5)/(5.00) = 1.7$, which is less than 2.0; therefore, $K_{ba} = 0.333$
$A_b = 2\pi(140/360)(8.5 + 0.33 \times 5.0) = 24.80$ mm
Dimensions of starting blank: $w =$ **35 mm**, $L = 58 + 24.80 + 46.5 =$ **129.30 mm**

(b) For V-bending, $K_{bf} = 1.33$.

$F = K_{bf}(TS)wt^2/D = 1.33(350)(35)(5.0)^2/40 =$ **10,183 N**

19.8 (SI units) Solve part (a) of the previous problem except that the bend radius $R = 10.5$ mm.

**Solution**: From drawing, $\alpha' = 40°$, $R = 11.35$ mm
$\alpha = 180 - \alpha' = 140°$
$A_b = 2\pi(\alpha/360)(R + K_{ba}t)$
$R/t = (10.5)/(5.00) = 2.1$; therefore, $K_{ba} = 0.5$
$A_b = 2\pi(140/360)(10.5 + 0.5 \times 5.00) = 31.76$ mm
Dimensions of starting blank: $w =$ **35 mm**, $L = 58 + 31.76 + 46.5 =$ **136.26 mm**

19.9 (SI units) A bending operation is performed on 4.0-mm-thick cold-rolled steel sheet that is 25 mm wide and 100 mm long. The sheet is bent along the 25 mm direction, so that the bend axis is 25 mm long. The resulting sheet metal part has an acute angle of 30° and a bend radius of 6 mm. Determine the (a) bend allowance, and (b) length of the neutral axis of the part after the bend.

**Solution**: (a) Given that $\alpha' = 30°$, $R = 6.0$ mm, and $t = 4.0$ mm
$\alpha = 180 - \alpha' = 150°$.
$A_b = 2\pi(\alpha/360)(R + K_{ba}t)$
$R/t = 6/4 = 1.5$, which is less than 2.0; therefore, $K_{ba} = 0.33$
$A_b = 2\pi(150/360)(6.0 + 0.33 \times 4.0) = 19.164$ mm

(b) Due to stretching, the neutral axis of the final part will be greater than 100.0 mm. The amount of stretching will be the difference between the bend allowance and the length of the bent section, which is computed as $2\pi(150/360)(6.0 + 0.5 \times 4.0) = 20.944$.
The difference = 20.944 – 19.164 = 1.780 mm. Thus, the final length of the neutral axis will be $L = 100 + 1.78 =$ **101.780 mm**

However, if stretching occurs along the neutral axis of the bend, then thinning of the stretched metal will also occur, and this will affect the preceding calculated value of the length of the bent section. The amount of thinning will be inversely proportional to the amount of stretching because volume must remain constant, before and after bending. The sheet thickness after bending (assuming uniform stretching and thinning) = (19.164/20.944)(4.0) = 3.66 mm. Now recalculate the length of the bent section with this new value of $t$.

The bend radius will remain the same ($R = 6.0$ mm) because it is located at the inside of the bend. Length of neutral axis along the bend = $2\pi(150/360)(6.0 + 0.5 \times 3.66) = 20.499$ mm. Now the difference between the length of the bent section and the bend allowance = 20.499 – 19.164 = 1.335 mm. The new final length of the neutral axis is $L = 100 + 1.335 = 101.335$ mm. The amount of stretching is less than previously determined, and so is the amount of thinning. An iterative procedure must be used to arrive at the final values of stretching and thinning.
Recalculate the thickness of the stretched sheet as (19.164/20.499)(4.0) = 3.74 mm, and recalculating the length of the bent section based on this value: Length of neutral axis along the bend = $2\pi(150/360)(6.0 + 0.5 \times 3.74) = 20.608$ mm. The new difference between the length of the bent section and the bend allowance = 20.608 – 19.164 = 1.444 mm, and the new final length of the neutral axis is $L = 100 + 1.444 = 101.444$ mm.

One more iteration: The thickness of the stretched sheet is (19.164/20.608)(4.0) = 3.72 mm, and recalculating the length of the bent section based on this value, $2\pi(150/360)(6.0 + 0.5 \times 3.72) = 20.577$ mm. The new before and after difference = 20.577 – 19.164 = 1.413 mm, and the new final length of the neutral axis is $L = 100 + 1.413 =$ **101.413 mm**. This is a difference of 0.367 mm from the previous value of 101.780 that ignored thinning of the metal.

19.10 (USCS units) An angle bracket is bent in a V-bending operation on a press brake from a flat blank that is 4.0 in long by 1.5 in wide by 5/32 in thick. The 90° bend is made in the middle of the 4-in length, so that the bend axis is 1.5 in long. (a) Determine the dimensions of the two equal sides that will result after the bend, if the bend radius = 3/16 in. The sides should be measured to the beginning of the bend radius. (b) Also determine the length of the part's neutral axis after the bend. (c) Where should the machine operator set the stop on the press brake relative to the starting length of the part?

**Solution**: (a) $R/t = (3/16)/(5/32) = 1.2$. Therefore, $K_{ba} = 0.33$
$A_b = 2\pi(90/360)(0.1875 + 0.33 \times 0.15625) = 0.3756$ in
Dimensions (lengths) of each end = 0.5(4.0 – 0.3756) = **1.8122 in**

(b) Since the metal stretches during bending, its length will be greater after the bend than before. Its length before bending = 4.000 in. The stretched length of the bend along the neutral axis will be: Bent length = $2\pi(90/360)(0.1875 + 0.5 \times 0.15625) = 0.4173$ in. Therefore, the length of the neutral axis of the part will be 2(1.8122) + 0.4173 = **4.0417 in**

However, if stretching occurs along the neutral axis of the bend, then thinning of the stretched metal will also occur, and this will affect the preceding calculated value of the length of the bent section. The amount of thinning will be inversely proportional to the amount of stretching because volume must remain constant, before and after bending. The sheet thickness after bending (assuming uniform stretching and thinning) = (0.3756/0.4173)(0.15625) = 0.1406 in. Now recalculate the length of the bent section with this new value of $t$.

The bend radius will remain the same ($R$ = 3/16 = 0.1875 in) because it is located at the inside of the bend. Length of neutral axis along the bend = $2\pi(90/360)(0.1875 + 0.5 \times 0.1406) = 0.4049$ in. The new final length of the neutral axis is $L = 2(1.8122) + 0.4049 =$ 4.0293 in. The amount of stretching is less than previously determined, and so is the amount of thinning. An iterative procedure must be used to arrive at the final values of stretching and thinning.

Recalculate the thickness of the stretched sheet as (0.3756/0.4049)(0.15625) = 0.1449 in, and recalculating the length of the bent section based on this value: Length of neutral axis along the bend = $2\pi(90/360)(0.1875 + 0.5 \times 0.1449) = 0.4084$ in. The new final length of the neutral axis is $L = 2(1.8122) + 0.4084 = 4.0328$ in.

One more iteration: The thickness of the stretched sheet is (0.3756/0.4084)(0.15625) = 0.1437 in, and recalculating the length of the bent section based on this value, $2\pi(90/360)(0.1875 + 0.5 \times 0.1437) = 0.4074$ in. The new final length of the neutral axis is $L = 2(1.8122) + 0.4074 =$ **4.0318 in**. This is a difference of only 0.0099 in from the previous value of 4.0417 in that ignored thinning of the metal.

(c) The operator should set the stop so that the tip of the V-punch contacts the starting blank at a distance = 2.000 in from the end.

19.11 (USCS units) Determine the bending force required in the previous problem if the bend is performed in a V-die with a die opening dimension = 1.0 in. The material has a tensile strength = 50,000 lb/in$^2$.

**Solution**: For V-bending, $K_{bf}$ = 1.33.
$F = K_{bf}(TS)wt^2/D$ = 1.33(50,000)(1.5)(5/32)$^2$/1.0 = **2435 lb**

19.12 (SI units) A sheet metal part that is 5.0 mm thick, 85 mm long, and 20 mm wide is bent in a wiping die to an included angle = 90° and a bend radius = 7.5 mm. The bend is made in the middle of the 85-mm length, so that the bend axis = 20 mm long. The metal has a yield strength = 220 MPa and tensile strength = 340 MPa. Compute the force required to bend the part, given that the die opening dimension = 8 mm.

**Solution**: For edge-bending using a wiping die, $K_{bf}$ = 0.33.
$F = K_{bf}(TS)wt^2/D$ = 0.33(340)(20)(5)$^2$/8 = **7,013 N**

## Drawing Operations

19.13 Derive an expression for the reduction $r$ in drawing as a function of drawing ratio $DR$.

**Solution**: Reduction $r = (D_b - D_p)/D_b$
Drawing ratio $DR = D_b/D_p$
$r = D_b/D_b - D_p/D_b = 1 - D_p/D_b = 1 - 1/DR$

19.14 **(A)** (SI units) A cylindrical cup is produced in a deep drawing operation. Cup height = 75 mm, and inside diameter = 100 mm. Sheet metal thickness = 2 mm. If the blank diameter = 225 mm, determine the (a) drawing ratio, (b) reduction, and (c) thickness-to-diameter ratio. (d) Is the operation feasible?

**Solution**: (a) $DR = D_b/D_p$ = 225/100 = **2.25**

(b) $r = (D_b - D_p)/D_b$ = (225 – 100)/225 = 0.555 = **55.5%**

(c) $t/D_b$ = 2/225 = 0.0089 = **0.89%**

(d) Feasibility? **No**! $DR$ is too large (greater than 2.0), $r$ is too large (greater than 50%), and $t/D$ is too small (less than 1%).

19.15 (SI units) Solve the previous problem, except that the starting blank size diameter = 175 mm.

**Solution**: (a) $DR = D_b/D_p$ = 175/100 = **1.75**

(b) $r = (D_b - D_p)/D_b$ = (175 – 100)/175 = 0.429 = **42.9%**

(c) $t/D_b$ = 2/175 = 0.0114 = **1.14%**

(d) Feasibility? $DR$ < 2.0, $r$ < 50%, and $t/D$ > 1%. However, the operation is not feasible because the 175 mm diameter blank size does not provide sufficient metal to draw a 75 mm cup height. The actual cup height possible with a 175 mm diameter blank can be determined by comparing surface areas (one side only for convenience) between the cup and the starting blank. Blank area = $\pi D^2/4 = \pi(175)^2/4$ = 24,053 mm$^2$. To compute the cup

surface area, divide the cup into two sections: (1) walls, and (2) base, assuming the corner radius on the punch has a negligible effect in the calculations and there is no earing of the cup. Thus, Cup area = $\pi D_p h + \pi D_p^2/4 = 100\pi h + \pi(100)^2/4 = 100\pi h + 2500\pi = 314.16h + 7854$. Set surface area of cup = surface are of starting blank:
$314.16h + 7854= 24{,}053$
$314.16h = 16{,}199$
$h = 51.56$ mm. This is less than the specified 75 mm height.

19.16 (USCS units) A deep drawing operation is performed to produce a cylindrical cup in which the inside diameter = 4.25 in and height = 2.65 in. Stock thickness = 3/16 in, and blank diameter = 7.7 in. Punch and die radii = 5/32 in. The metal has a tensile strength = 65,000 lb/in$^2$, yield strength = 32,000 lb/in$^2$, and shear strength of 40,000 lb/in$^2$. Determine the (a) drawing ratio, (b) reduction, (c) drawing force, and (d) blank-holder force.

**Solution**: (a) $DR = 7.7/4.25 =$ **1.81**

(b) $r = (D_b - D_p)/D_b = (7.7 - 4.25)/7.7 = 3.45/7.70 = 0.448 =$ **44.8%**

(c) $F = \pi D_p t(TS)(D_b/D_p - 0.7) = \pi(4.25)(0.1875)(65{,}000)(7.7/4.25 - 0.7) =$ **180,900 lb**

(d) $F_h = 0.015Y\pi(D_b^2 - (D_p + 2.2t + 2R_d)^2)$
$F_h = 0.015(32{,}000)\pi(7.7^2 - (4.25 + 2.2 \times 0.1875 + 2 \times 0.15625)^2)$
$= 0.015(32{,}000)\pi(7.7^2 - 4.975^2)$ **= 52,100 lb**

19.17 **(A)** (SI units) A cup-drawing operation is performed in which the cup's inside diameter = 80 mm and its height = 50 mm. Stock thickness = 3.0 mm, and blank diameter = 150 mm. Punch and die radii = 4 mm. Tensile strength = 400 MPa and yield strength = 180 MPa for this sheet metal. Determine (a) drawing ratio, (b) reduction, (c) drawing force, and (d) blank-holder force.

**Solution**: (a) $DR = 150/80 =$ **1.875**

(b) $r = (D_b - D_p)/D_b = (150 - 80)/150 = 70/150 =$ **0.46**

(c) $F = \pi D_p t(TS)(D_b/D_p - 0.7) = \pi(80)(3)(400)(150/80 - 0.7) =$ **354,418 N**

(d) $F_h = 0.015Y\pi(D_b^2 - (D_p + 2.2t + 2R_d)^2)$
$F_h = 0.015(180)\pi(150^2 - (80 + 2.2 \times 3 + 2 \times 4)^2) = 0.015(180)\pi(150^2 - 94.6^2)$ **= 114,942 N**

19.18 (USCS units) A deep drawing operation is performed on a sheet metal blank that is 1/8 in thick. The height of the cup = 3.8 in and its diameter = 5.0 in (both inside dimensions). (a) Assuming the punch radius = 0, compute the starting diameter of the blank to complete the operation with no material left in the flange. (b) Is the operation feasible (ignoring the fact that the punch radius is too small)?

**Solution**: (a) Use surface area to compute blank diameter, assuming thickness $t$ remains constant.
Cup area = wall area + base area = $\pi D_p h + \pi D_p^2/4 = 5\pi(3.8) + 0.25\pi(5)^2 = 25.25\pi$ in$^2$
Blank area = $\pi D_b^2/4 = 0.25\pi D_b^2$
Setting blank area = cup area: $0.25\pi D_b^2 = 25.25\pi$
$D_b^2 = 25.25/0.25 = 101.0$ $\boldsymbol{D_b}$ **= 10.050 in**

(b) Test for feasibility: $DR = D_b/D_p$ = 10.050/5.0 = **2.01.** Because $DR$ > 2.0, this operation may not be feasible. Of course, the zero punch radius makes this operation infeasible anyway. With a rounded punch radius, the blank size would be slightly smaller, which would reduce $DR$.

19.19 **(A)** (USCS units) Solve the previous problem, except that the punch radius = 0.375 in.

**Solution**: Use surface area computation, assuming thickness remains constant. The surface area of the cup will be divided into three sections: (1) straight walls, whose height = 3.80 – 0.375 = 3.425 in, (2) quarter toroid formed by the 0.375 radius at the base of the cup, and (3) base, which has a diameter = 5.0 – 2 × 0.375 = 4.25 in
$A_1 = \pi D_p h = \pi(5.0)(3.425) = 53.807$ in$^2$
$A_2$ = length of the quarter circle at the base multiplied by the circumference of the circle described by the centroid (Pappus-Guldin Theorem): length of quarter circle = $\pi D/4$ = $0.25\pi(2 \times 0.375)$ = 0.589 in. The centroid is located at the center of the arc, which is 0.375 sin 45 = 0.265 beyond the center of the 0.375 in radius. Thus, the diameter of the circle described by the centroid is 4.25 + 2 × 0.265 = 4.780 in
$A_2 = 4.78\pi(0.589) = 8.847$ in$^2$
$A_3 = \pi(4.25)^2/4 = 14.188$ in$^2$
Total area of cup = 53.807 + 8.847 + 14.188 = 76.842 in$^2$
Blank area = $\pi D_b^2/4 = 0.7855D_b^2$
Setting blank area = cup area: $0.7855D_b^2 = 76.842$
$D_b^2 = 76.842/0.7855 = 97.825$ $\qquad$ $\boldsymbol{D_b}$ **= 9.890 in**

Test for feasibility: $DR = D_b/D_p$ = 9.89/5.0 = **1.978**, which is less than the limiting ratio of 2.0. The thickness to diameter ratio $t/D_b$ = 0.125/9.89 = 0.0126 = 1.26%, which is above the value of 1% used as a criterion of feasibility in cup drawing. Whereas the operation in the previous problem was not feasible, the operation in the present problem seems feasible.

19.20 (SI units) A drawing operation is performed on 3.2-mm stock. The part is a cylindrical cup with inside height = 40 mm and inside diameter = 60 mm. Assume the corner radius on the punch is zero. (a) Find the required starting blank size $D_b$. (b) Is the drawing operation feasible?

**Solution**: (a) Use surface area computation, assuming thickness t remains constant.
Cup area = wall area + base area = $\pi D_p h + \pi D_p^2/4 = \pi(60)(40) + 0.25\pi(60)^2$ = 10,367 mm$^2$
Blank area = $\pi D_b^2/4 = 0.7855D_b^2$
Setting blank area = cup area: $0.7855D_b^2$ = 10,367
$D_b^2$ = 10,367/0.7855 = 13,198 $\qquad$ $\boldsymbol{D_b}$ **= 114.9 mm**

(b) Test for feasibility: $DR = D_b/D_p$ = 114.9/60 = **1.915**; $t/D_b$ = 3.2/114.9 = 0.0279 = **2.79%**. These criteria values indicate that the operation is feasible; however, with a punch radius $R_p = 0$, this shape would be difficult to draw because the drawing punch would act on the metal like a blanking punch.

19.21 (USCS units) A cup-shaped part is drawn without a blank holder from sheet metal whose thickness = 0.25 in. The inside diameter of the cup = 2.5 in, its height = 1.5 in, and the corner radius at the base = 0.375 in. (a) What is the minimum starting blank diameter that can be used? (b) Does this blank diameter provide sufficient material to complete the cup?

**Solution**: (a) According to Equation (19.14), $D_b - D_p < 5t$
$D_b < 5t + D_p = 5(0.25) + 2.5 =$ **3.75 in**

(b) Because the sheet metal is rather thick, use volume rather than area to determine whether there is sufficient metal in a 3.75 in blank diameter. The drawn cup consists of three sections: (1) cup walls, (2) toroid at base, and (3) base.
$V_1 = (1.5 - 0.375)\pi[(2.5 + 2 \times 0.25)^2] - (2.5)^2)/4 = 1.125\pi(2.75)/4 = 2.430$ in$^3$
$V_2$ = (cross-section of quarter toroid) x (circle made by sweep of centroid)
Cross-section of quarter toroid = $0.25\pi[(0.375 + 0.25)^2 - (0.375)^2] = 0.1964$ in$^2$
Circle made by centroid sweep has diameter = $(2.5 - 2 \times 0.25) + 2(0.375 + 0.25/2)\sin 45 =$ 2.457 in
$V_2 = 2.457\pi(0.1964) = 1.516$ in$^3$
$V_3 = (2.5 - 2 \times 0.375)^2\pi(0.25)/4 = 0.601$ in$^3$
Total $V = V_1 + V_2 + V_3 = 2.430 + 1.516 + 0.601 = 4.547$ in$^3$
Volume of blank = $\pi D_b^2 t/4 = \pi(0.25)D_b^2/4 = 0.1963D_b^2$
Setting blank volume = cup volume: $0.1963D_b^2 = 4.547$
$D_b^2 = 4.547/0.1963 = 23.16$ $\qquad$ $D_b =$ **4.81 in**
The diameter of 3.75 in from (a) does not provide sufficient metal to complete the drawing. This operation is not feasible.

19.22 The foreman in the drawing section of the shop shows you several samples of parts that have been deep drawn in the shop. The samples have various defects. One has ears, another has wrinkles, and a third has torn sections at its base. What are the causes of each defect and what remedies would you propose?

**Solution**: (1) Ears are caused by sheet metal that has directional properties. The material is anisotropic. One remedy is to anneal the metal to reduce the directionality of the properties.

(2) Wrinkles are caused by compressive buckling of the flange as it is drawn inward to form the cup. There are several possible remedies: (a) increase the $t/D_b$ ratio by using a thicker gage sheet metal. This may not be possible since a design change is required. (b) Increase the blank-holder pressure against the work during drawing.

(3) Tearing occurs due to high tensile stresses in the walls of the cup near the base. A remedy would be to provide a larger punch radius. Tearing can also occur due to a die corner radius that is too small.

## Other Operations

19.23 (USCS units) A 20-in-long sheet metal workpiece is stretched in a stretch forming operation to the dimensions shown in Figure P19.23. Thickness of the beginning stock = 3/16 in and width = 8.5 in. The metal has a flow curve defined by a strength coefficient = 75,000 lb/in$^2$ and a strain-hardening exponent = 0.20. The yield strength of the material = 30,000 lb/in$^2$. (a) Find the stretching force $F$ required near the beginning of the operation when yielding first occurs. Determine the (b) true strain experienced by the metal and (c) stretching force $F$ and die force $F_{die}$ at the very end when the part is formed as indicated in Figure P19.23(b).

**Solution**: (a) Use $\varepsilon = 0.002$ as start of yielding.
$F = LtY_f$

$Y_f$ = 75,000(0.002)$^{0.20}$ = 21,600 lb/in$^2$
$F$ = (8.5)(0.1875)(21,600) = **34,500 lb**

(b) After stretching, the length of the piece is increased from 20.0 in to 2(10$^2$ + 5$^2$)$^{0.5}$ = 22.361 in
$\varepsilon$ = ln(22.361/20) = ln 1.118 = **0.1116**

(c) At the final length of 22.361 in, the thickness of the sheet metal has been reduced to maintain constant volume, assuming width $L$ = 8.5 in remains the same during stretching.
$t_f$ = 0.1875(20/22.361) = 0.168 in
$Y_f$ = 75,000(0.1116)$^{0.20}$ = 48,400 lb/in$^2$
$F$ = 8.5(0.168)(48,400) = **69,000 lb**

(d) $F_{die}$ = 2$F$ sin A
$A$ = tan$^{-1}$(5/10) = 26.57°
$F_{die}$ = 2(69,000) sin 26.57 = **61,700 lb**

19.24 **(A)** (SI units) Determine the starting disk diameter required to spin the part in Figure P19.24 using a conventional spinning operation. The starting thickness = 2.4 mm.

**Solution**: From part drawing, radius = 25 + (100 – 25)/sin 30 = 25 + 75/0.5 = 175 mm
Starting diameter $D$ = 2(175) = **350 mm**

19.25 (SI units) If the part illustrated in Figure P19.24 were made by shear spinning, determine the (a) wall thickness along the cone-shaped portion and (b) spinning reduction $r$. (c) What is the shear strain experienced by the metal?

**Solution**: (a) $t_f = t \sin \alpha$ = (2.4)sin 30 = 2.4(0.5) = **1.2 mm**

(b) $r = (t - t_f)/t$ = (2.4 – 1.2)/2.4 = **0.50 = 50%**

(c) Based on sidewise displacement of metal through a shear angle of 30°,
Shear strain $\gamma$ = cot 30 = **1.732.**

19.26 (SI units) A 75-mm-diameter tube is bent into a rather complex shape with a series of simple tube bending operations. The wall thickness on the tube = 4.75 mm. The tubes are used to deliver fluids in a chemical plant. In one of the bends where the bend radius is 125 mm, the walls of the tube are flattening badly. What can be done to correct the condition?

**Solution**: Possible solutions: (1) Use a mandrel to prevent collapsing of tube wall. (2) Request the designer to increase the bend radius to 3$D$ = 225 mm. (3) Pack sand into the tube. The sand will act as an internal flexible mandrel to support the tube wall.