Homework solutions for test 2

HW for Lecture 7

22.2 What is meant by the term faying surface?
   Answer. The faying surfaces are the contacting surfaces in a welded joint.

22.3 Define the term fusion weld.
   Answer. A fusion weld is a weld in which the metal surfaces have been melted in order to cause coalescence.

22.4 What is the fundamental difference between a fusion weld and a solid state weld?
   Answer. In a fusion weld, the metal is melted. In a solid state weld, the metal is not melted.

22.8 Name and sketch the five joint types.
   Answer. Five joint types are (1) butt, (2) corner, (3) lap, (4) tee, (5) edge. For sketches see Figure 22.2 in the text.

22.9 Define and sketch a fillet weld.
   Answer. A fillet weld is a weld joint of approximately triangular cross section used to fill in the edges of corner, lap, and tee joints. See Figure 22.4 in text for sketch.

22.10 Define and sketch a groove weld.
   Answer. A groove weld is a weld joint used to fill in the space between the adjoining edges of butt and other weld types except lap. See Figure 22.5 in text for sketch.

22.15 What is the heat-affected zone (HAZ) in a fusion weld?
   Answer. The HAZ is a region of base metal surrounding the fusion zone in which melting has not occurred, but temperatures from welding were high enough to cause solid state microstructural changes.

23.2 What is the fundamental feature that distinguishes fusion welding from solid-state welding?
   Answer. In fusion welding, melting occurs at the faying surfaces; in solid state welding, no melting occurs.

23.5 Electrodes in arc welding are divided into two categories. Name and define the two types.
   Answer. The two categories are consumable and nonconsumable. The consumable type, in addition to being the electrode for the process, also provides filler metal for the welding joint. The nonconsumable type is made of materials that resist melting, such as tungsten or carbon.

23.6 What are the two basic methods of arc shielding?
   Answer. (1) Shielding gas, such as argon and helium; and (2) flux, which covers the welding operation and protects the molten pool from the atmosphere.
23.8 Describe the shielded metal arc-welding (SMAW) process.

**Answer.** SMAW is an arc-welding process that uses a consumable electrode consisting of a filler metal rod coated with chemicals that provide flux and shielding.

23.20 What is friction stir welding (FSW), and how is it different from friction welding?

**Answer.** Friction stir welding (FSW) is a solid state welding process in which a rotating tool is fed along the joint line between two workpieces, generating friction heat and mechanically stirring the metal to form the weld seam. FSW is distinguished from conventional friction welding (FRW) by the fact that friction heat is generated by a separate wear-resistant tool rather than by the parts themselves.

23.22 Distortion (warping) is a serious problem in fusion welding, particularly arc welding. What are some of the techniques that can be taken to reduce the incidence and extent of distortion?

**Answer.** The following techniques can be used to reduce warping in arc welding: (1) Welding fixtures can be used to physically restrain movement of the parts during welding. (2) Heat sinks can be used to rapidly remove heat from sections of the welded parts to reduce distortion. (3) Tack welding at multiple points along the joint can create a rigid structure prior to continuous seam welding. (4) The base parts can be preheated to reduce the level of thermal stresses experienced by the parts. (5) Stress relief heat treatment can be performed on the welded assembly, either in a furnace for small weldments, or using methods that can be used in the field for large structures.

23.23 What are some of the important welding defects?

**Answer.** Some of the important welding defects are (1) cracks, (2) cavities, (3) solid inclusions, (4) incomplete fusion, and (5) imperfect shape or contour of weld cross section.

24.1 How do brazing and soldering differ from the fusion-welding processes?

**Answer.** In brazing and soldering, no melting of the base metal(s) occurs.

24.2 How do brazing and soldering differ from the solid-state welding processes?

**Answer.** In brazing and soldering, a filler metal is added, whereas in solid state welding no filler metal is added.

24.3 What is the technical difference between brazing and soldering?

**Answer.** In brazing the filler metal melts at a temperature above 450°C (840°F). In soldering the filler metal melts at a temperature of 450°C or below.

24.7 The molten filler metal in brazing is distributed throughout the joint by capillary action. What is capillary action?

**Answer.** Capillary action is the physical tendency of a liquid to be drawn into a small diameter tube or other narrow openings in spite of the force of gravity. It is caused by the adhesive attraction between the liquid molecules and the solid surfaces that define the narrow openings.

24.10 Define braze welding.
Answer. Braze welding is used for adding braze metal to a more conventional geometry weld joint, such as a V-joint. It differs from the typical brazing operation in that no capillary action occurs. It differs from a conventional welding operation in that no melting of the base metals occurs.

24.11 What are some of the disadvantages and limitations of brazing?

Answer. Disadvantages and limitations of brazing include (1) the strength of the brazed joint is generally less than that of a welded joint, (2) high service temperatures may weaken a brazed joint, (3) part sizes are limited, and (4) the color of the filler metal is often different than the color of the base metals.

24.15 What are the disadvantages and drawbacks of soldering?

Answer. Disadvantages and drawbacks of soldering include (1) low mechanical strength unless reinforced and (2) elevated service temperatures can weaken the joint.

HW for Lecture 8

Review Questions

12.2 Extrusion is a fundamental shaping process. Describe it.

Answer. Extrusion is a compression process in which the work material is forced to flow through a die orifice, thereby forcing its cross section to assume the profile of the orifice.

12.4 What is the difference between deep drawing and bar drawing?

Answer. Deep drawing is a sheet metal forming process used to fabricate cup-shaped parts; bar drawing is a bulk deformation process used to reduce the diameter of a cylindrical workpart.

12.5 Indicate the mathematical equation for the flow curve.

Answer. The flow curve is defined in Eq. (12.1) as $Y_f = K \varepsilon^n$.

12.6 How does increasing temperature affect the parameters in the flow curve equation?

Answer. Increasing temperature decreases both $K$ and $n$ in the flow curve equation.

12.7 Indicate some of the advantages of cold working relative to warm and hot working.

Answer. Advantages of cold working are (1) better accuracy, (2) better surface finish, (3) increased strength due to work hardening, (4) possible directional properties due to grain flow, and (5) no heating of work required.

12.9 Why is friction generally undesirable in metal forming operations?

Answer. Reasons why friction is undesirable in metal forming include the following: (1) it inhibits metal flow during deformation, causing residual stresses and product defects; (2) it increases forces and power required; and (3) it increases wearing of the tools.

Problems
12.1 The strength coefficient = 550 MPa and strain-hardening exponent = 0.22 for a certain metal. During a forming operation, the final true strain that the metal experiences = 0.85. Determine the flow stress at this strain and the average flow stress that the metal experienced during the operation.

**Solution:** Flow stress \( Y_f = 550(0.85)^{0.22} = 531 \text{ MPa} \).
Average flow stress \( \bar{Y}_f = 550(0.85)^{0.22}/1.22 = 435 \text{ MPa} \).

12.2 A metal has a flow curve with strength coefficient = 850 MPa and strain-hardening exponent = 0.30. A tensile specimen of the metal with gage length = 100 mm is stretched to a length = 157 mm. Determine the flow stress at the new length and the average flow stress that the metal has been subjected to during the deformation.

**Solution:** \( \varepsilon = \ln (157/100) = \ln 1.57 = 0.451 \)
Flow stress \( Y_f = 850(0.451)^{0.30} = 669.4 \text{ MPa} \).
Average flow stress \( \bar{Y}_f = 850(0.451)^{0.30}/1.30 = 514.9 \text{ MPa} \).

12.3 A particular metal has a flow curve with strength coefficient = 35,000 lb/in\(^2\) and strain-hardening exponent = 0.26. A tensile specimen of the metal with gage length = 2.0 in is stretched to a length = 3.3 in. Determine the flow stress at this new length and the average flow stress that the metal has been subjected to during deformation.

**Solution:** \( \varepsilon = \ln (3.3/2.0) = \ln 1.65 = 0.501 \)
Flow stress \( Y_f = 35,000(0.501)^{0.26} = 29,240 \text{ lb/in}^2 \).
Average flow stress \( \bar{Y}_f = 35,000(0.501)^{0.26}/1.26 = 23,206 \text{ lb/in}^2 \).

12.5 For a certain metal, the strength coefficient = 700 MPa and strain-hardening exponent = 0.27. Determine the average flow stress that the metal experiences if it is subjected to a stress that is equal to its strength coefficient \( K \).

**Solution:** \( Y_f = K = 700 = Ke^\varepsilon = 700e^{0.27} \)
\( \varepsilon \) must be equal to 1.0.
\( \bar{Y}_f = 700(1.0)^{0.27}/1.27 = 700/1.27 = 551.2 \text{ MPa} \)

12.6 Determine the value of the strain-hardening exponent for a metal that will cause the average flow stress to be 3/4 of the final flow stress after deformation.

**Solution:** \( \bar{Y}_f = 0.75 \ Y_f \)
\( Ke^\varepsilon/(1+n) = 0.75 \ Ke^\varepsilon \)
\( 1/(1+n) = 0.75 \)
\( 1 = 0.75(1+n) = 0.75 + 0.75n \)
\( 0.25 = 0.75n \quad n = 0.333 \)

12.8 In a tensile test, two pairs of values of stress and strain were measured for the specimen metal after it had yielded: (1) true stress = 217 MPa and true strain = 0.35, and (2) true stress = 259 MPa and true strain = 0.68. Based on these data points, determine the strength coefficient and strain-hardening exponent.

**Solution:** Solve two equations, two unknowns: \( \ln K = \ln \sigma - n \ln \varepsilon \)
(1) \( \ln K = \ln 217 \ - \ n \ln 0.35 \)
(2) \( \ln K = \ln 259 \ - \ n \ln 0.68 \)
\begin{align*}
(3) \quad \ln K &= 5.3799 - (-1.0498)n = 5.3799 + 1.0498n \\
(4) \quad \ln K &= 5.5568 - (-0.3857)n = 5.5568 + 0.3857n \\
5.3799 + 1.0498n &= 5.5568 + 0.3857n \\
1.0498n - 0.3857n &= 5.5568 - 5.3799 \\
0.6641n &= 0.1769 \quad n = 0.2664 \\
\ln K &= 5.3799 + 1.0498(0.2664) = 5.6596 \quad K = 287 \text{ MPa}
\end{align*}

**HW for Lecture 9**

**Review Questions:**

13.10 What is forging?

**Answer.** Forging is a deformation process in which the workpiece is compressed between two dies, using impact or gradual pressure to form the part.

13.11 One way to classify forging operations is by the degree to which the work is constrained in the die. By this classification, name the three basic types.

**Answer.** The three basic types are (1) open die forging, (2) impression die forging, and (3) flashless forging.

13.12 Why is flash desirable in impression die forging?

**Answer.** Because its presence constrains the metal in the die so that it fills the details of the die cavity.

13.14 What are the two basic types of forging equipment?

**Answer.** The two types of forging machines are hammers, which impact the workpart, and presses, which apply a gradual pressure to the work.

**Problems:**

13.10 A cylindrical part is warm upset forged in an open die. The initial diameter is 45 mm and the initial height is 40 mm. The height after forging is 25 mm. The coefficient of friction at the die-work interface is 0.20. The yield strength of the work material is 285 MPa, and its flow curve is defined by a strength coefficient of 600 MPa and a strain-hardening exponent of 0.12. Determine the force in the operation (a) just as the yield point is reached (yield at strain = 0.002), (b) at a height of 35 mm, (c) at a height of 30 mm, and (d) at a height of 25 mm. Use of a spreadsheet calculator is recommended.

**Solution:** (a) \( V = \pi D^2 L/4 = \pi(45)^2(40)/4 = 63,617 \text{ mm}^3 \)
\[ \text{Given } \varepsilon = 0.002, \quad Y_f = 600(0.002)^{0.12} = 284.6 \text{ MPa, and } h = 40 - 40(0.002) = 39.92 \]
\[ A = V/h = 63,617/39.92 = 1594 \text{ mm}^2 \]
\[ K_f = 1 + 0.4(0.2)(45)/39.92 = 1.09 \]
\[ F = 1.09(284.6)(1594) = 494,400 \text{ N} \]

(b) Given \( h = 35, \quad \varepsilon = \ln(40/35) = \ln 1.143 = 0.1335 \)
\[ Y_f = 600(0.1335)^{0.12} = 471.2 \text{ MPa} \]
\[ V = 63,617 \text{ mm}^3 \text{ from part (a) above.} \]
At \( h = 35, \quad A = V/h = 63617/35 = 1818 \text{ mm}^2 \]
Corresponding \( D = 48.1 \text{ mm} \text{ (from } A = \pi D^2/4) \)
\[ K_f = 1 + 0.4(0.2)(48.1)/35 = 1.110 \]
\[ F = 1.110(471.2)(1818) = 950,700 \text{ N} \]
(c) Given $h = 30$, $\varepsilon = \ln(40/30) = \ln 1.333 = 0.2877$

$Y_T = 600(0.2877)^{0.12} = 516.7$ MPa

$V = 63,617$ mm$^3$ from part (a) above.

At $h = 30$, $A = V/h = 63,617/30 = 2120.6$ mm$^2$

Corresponding $D = 51.96$ mm (from $A = \pi D^2/4$)

$K_T = 1 + 0.4(0.2)(51.96)/30 = 1.138$

$F = 1.138(516.7)(2120.6) = 1,247,536$ N

(d) Given $h = 25$, $\varepsilon = \ln(40/25) = \ln 1.6 = 0.4700$

$Y_T = 600(0.470)^{0.12} = 548.0$ MPa

$V = 63,617$ mm$^3$ from part (a) above.

At $h = 25$, $A = V/h = 63,617/25 = 2545$ mm$^2$

Corresponding $D = 56.9$ mm (from $A = \pi D^2/4$)

$K_T = 1 + 0.4(0.2)(56.9)/25 = 1.182$

$F = 1.182(548.0)(2545) = 1,649,000$ N

13.12 A cold heading operation is performed to produce the head on a steel nail. The strength coefficient for this steel is 600 MPa, and the strain hardening exponent is 0.22. Coefficient of friction at the die-work interface is 0.14.

The wire stock out of which the nail is made is 5.00 mm in diameter. The head is to have a diameter of 9.5 mm and a thickness of 1.6 mm. The final length of the nail is 120 mm. (a) What length of stock must project out of the die in order to provide sufficient volume of material for this upsetting operation? (b) Compute the maximum force that the punch must apply to form the head in this open-die operation.

**Solution:** (a) Volume of nail head $V = \pi D^2 h_f/4 = \pi (9.5)^2 (1.6)/4 = 113.4$ mm$^3$.

$A_o = \pi D_o^2/4 = \pi (5)^2/4 = 19.6$ mm$^2$

$h_o = V/A_o = 113.4/19.6 = 5.78$ mm

(b) $\varepsilon = \ln(5.78/1.6) = \ln 3.61 = 1.3837$

$Y_T = 600(1.3837)^{0.22} = 634$ MPa

$A_f = \pi (9.5)^2/4 = 70.9$ mm$^2$

$K_T = 1 + 0.4(0.14)(9.5/1.6) = 1.33$

$F = 1.33(634)(70.9) = 59,886$ N

13.14 A hot upset forging operation is performed in an open die. The starting workpart has a diameter = 25 mm and height = 50 mm. The part is upset to an average diameter = 50 mm. The work metal at this elevated temperature yields at 85 MPa ($n = 0$). Coefficient of friction at the die-work interface = 0.40. Determine (a) final height of the part, and (b) maximum force in the operation.

**Solution:** (a) $V = \pi D_o^2 h_o/4 = \pi (25)^2 (50)/4 = 24,544$ mm$^3$.

$A_f = \pi D_f^2/4 = \pi (50)^2/4 = 1963.5$ mm$^2$.

$h_f = V/A_f = 24,544/1963.5 = 12.5$ mm.

(b) $\varepsilon = \ln(50/12.5) = \ln 4 = 1.3863$

$Y_T = 85(1.3863)^0 = 85$ MPa

Force is maximum at largest area value, $A_f = 1963.5$ mm$^2$

$D = (4 \times 1963.5/\pi)^{0.5} = 50$ mm

$K_T = 1 + 0.4(0.4)(50/12.5) = 1.64$

$F = 1.64(85)(1963.5) = 273,712$ N
HW for Lecture 10

Review Questions

13.2 Name the four basic bulk deformation processes.

Answer. The four basic bulk deformation processes are (a) rolling, (2) forging, (3) extrusion, and (4) wire and bar drawing.

13.5 What is draft in a rolling operation?

Answer. Draft is the difference between the starting thickness and the final thickness as the workpiece passes between the two opposing rolls.

13.8 What is a two-high rolling mill?

Answer. A two-high rolling mill consists of two opposing rolls between which the work is compressed.

13.16 What is extrusion?

Answer. Extrusion is a compression forming operation in which a workpiece is forced to flow through a die opening, thus taking the cross-sectional shape of the die opening.

13.17 Distinguish between direct and indirect extrusion.

Answer. In direct extrusion, also known as forward extrusion, a metal billet is loaded into a container, and a ram compresses the material, forcing it to flow through a die opening at the opposite end of the container. In indirect extrusion, also known as backward extrusion, the die is incorporated into the ram, and as the ram compresses into the metal billet, the metal is forced to flow through the die opening in a direction that is opposite (backwards) of the ram motion.

Problems:

13.3 A series of cold rolling operations are used to reduce the thickness of a plate from 50 mm down to 25 mm in a reversing two-high mill. Roll diameter = 700 mm and coefficient of friction between rolls and work = 0.15. The specification is that the draft is to be equal on each pass. Determine (a) minimum number of passes required, and (b) draft for each pass?

Solution: (a) Maximum draft \( d_{\text{max}} = \mu^2 R = (0.15)^2 (350) = 7.875 \text{ mm} \)

Minimum number of passes = \( (t_o - t_f) / d_{\text{max}} = (50 - 25) / 7.875 = 3.17 \rightarrow 4 \) passes

(b) Draft per pass \( d = (50 - 25) / 4 = 6.25 \text{ mm} \)

13.5 A plate that is 250 mm wide and 25 mm thick is to be reduced in a single pass in a two-high rolling mill to a thickness of 20 mm. The roll has a radius = 500 mm, and its speed = 30 m/min. The work material has a strength coefficient = 240 MPa and a strain hardening exponent = 0.2. Determine (a) roll force, (b) roll torque, and (c) power required to accomplish this operation.

Solution: (a) Draft \( d = 25 - 20 = 5 \text{ mm} \),

Contact length \( L = (500 \times 5)^{0.5} = 50 \text{ mm} \)

True strain \( \varepsilon = \ln(25/20) = \ln 1.25 = 0.223 \)

\( \bar{Y}_f = 240(0.223)^{0.20}/1.20 = 148.1 \text{ MPa} \)

Rolling force \( F = 148.1(250)(50) = 1,851,829 \text{ N} \)
(b) Torque \( T = 0.5(1,851,829)(50 \times 10^{-3}) = 46,296 \text{ N-m} \)

(c) \( N = (30 \text{ m/min})/(2\pi \times 0.500) = 9.55 \text{ rev/min} = 0.159 \text{ rev/s} \)

Power \( P = 2\pi(0.159)(1,851,829)(50 \times 10^{-3}) = 92,591 \text{ N-m/s} = 92,591 \text{ W} \)

13.8 A single-pass rolling operation reduces a 20 mm thick plate to 18 mm. The starting plate is 200 mm wide. Roll radius = 250 mm and rotational speed = 12 rev/min. The work material has a strength coefficient = 600 MPa and a strain-hardening exponent = 0.22. Determine (a) roll force, (b) roll torque, and (c) power required for this operation.

Solution: (a) Draft \( d = 20 - 18 = 2.0 \text{ mm} \),
Contact length \( L = (250 \times 2)^{0.5} = 22.36 \text{ mm} = 0.02236 \text{ m} \)
True strain \( \varepsilon = \ln(20/18) = \ln 1.111 = 0.1054 \)
\( \bar{Y}_f = 600(0.1054)^{0.22}/1.22 = 300 \text{ MPa} \)
Rolling force \( F = 300(0.02236)(0.2) = 1.34 \text{ MN} = 1.34 \times 10^6 \text{ N} \)

(b) Torque \( T = 0.5(1340000)(0.02236) = 14,981 \text{ N-m} \)

(c) Given that \( N = 12 \text{ rev/min} \)
Power \( P = 2\pi(12/60)(1340000)(0.02236) = 34,824 \text{ W} \)

13.18 A cylindrical billet that is 100 mm long and 50 mm in diameter is reduced by indirect (backward) extrusion to a 20 mm diameter. The die angle is 90°. In the Johnson equation, \( a = 0.8 \) and \( b = 1.4 \). In the flow curve for the work metal, the strength coefficient = 800 MPa and strain hardening exponent = 0.13. Determine (a) extrusion ratio, (b) true strain (homogeneous deformation), (c) extrusion strain, (d) ram pressure, and (e) ram force.

Solution: (a) \( r_x = A_o/A_f = D_o^2/D_f^2 = (50)^2/(20)^2 = 6.25 \)
(b) \( \varepsilon = \ln r_x = \ln 6.25 = 1.833 \)
(c) \( \varepsilon_x = a + b \ln r_x = 0.8 + 1.4(1.833) = 3.366 \)
(d) \( \bar{Y}_f = 800(1.833)^{0.13}/1.13 = 766.0 \text{ MPa} \)
\( p = 766.0(3.366) = 2578 \text{ MPa} \)
(e) \( A_o = \pi D_o^2/4 = \pi(50)^2/4 = 1963.5 \text{ mm}^2 \)
\( F = 2578(1963.5) = 5,062,000 \text{ N} \)

13.20 A billet that is 75 mm long with diameter = 35 mm is direct extruded to a diameter of 20 mm. The extrusion die has a die angle = 75°. For the work metal, \( K = 600 \text{ MPa} \) and \( n = 0.25 \). In the Johnson extrusion strain equation, \( a = 0.8 \) and \( b = 1.4 \). Determine (a) extrusion ratio, (b) true strain (homogeneous deformation), (c) extrusion strain, and (d) ram pressure and force at \( L = 70, 60, 50, 40, 30, 20, \) and \( 10 \text{ mm} \). Use of a spreadsheet calculator is recommended for part (d).

Solution: (a) \( r_x = A_o/A_f = D_o^2/D_f^2 = (35)^2/(20)^2 = 3.0625 \)
(b) \( \varepsilon = \ln r_x = \ln 3.0625 = 1.119 \)
(c) \( \varepsilon_x = a + b \ln r_x = 0.8 + 1.4(1.119) = 2.367 \)
(d) \( \bar{Y}_f = 600(1.119)^{0.25}/1.25 = 493.7 \text{ MPa} \)
\( A_o = \pi(35)^2/4 = 962.1 \text{ mm}^2 \)
It is appropriate to determine the volume of metal contained in the cone of the die at the start of the extrusion operation, to assess whether metal has been forced through the die opening by the time the billet has been reduced from \( L = 75 \text{ mm} \) to \( L = 70 \text{ mm} \). For a cone-shaped die with angle = 75°, the height \( h \) of the frustum is formed by metal
being compressed into the die opening: The two radii are: \( R_1 = 0.5D_o = 17.5 \text{ mm} \) and \( R_2 = 0.5D_f = 10 \text{ mm} \), and \( h = (R_1 - R_2)/\tan 75 = 7.5/\tan 75 = 2.01 \text{ mm} \).

Frustum volume \( V = 0.333\pi h(R_1^2 + R_1R_2 + R_2^2) = 0.333\pi(2.01)(17.5^2 + 10 \times 17.5 + 10^2) = 1223.4 \text{ mm}^3 \). Compare this with the volume of the portion of the cylindrical billet between \( L = 75 \text{ mm} \) and \( L = 70 \text{ mm} \).

\[ V = \frac{\pi D_o^2}{4} (L - 70) = 0.25\pi(35)^2(75 - 70) = 4810.6 \text{ mm}^3 \]

Since this volume is greater than the volume of the frustum, this means that the metal has extruded through the die opening by the time the ram has moved forward by 5 mm.

\[ L = 70 \text{ mm}: \text{ pressure } p = 493.7(2.367 + 2 \times 70/35) = 3143.4 \text{ MPa} \]
\[ \text{Force } F = 3143.4(962.1) = 3,024,321 \text{ N} \]

\[ L = 60 \text{ mm}: \text{ pressure } p = 493.7(2.367 + 2 \times 60/35) = 2861.3 \text{ MPa} \]
\[ \text{Force } F = 2861.3(962.1) = 2,752,890 \text{ N} \]

\[ L = 50 \text{ mm}: \text{ pressure } p = 493.7(2.367 + 2 \times 50/35) = 2579.2 \text{ MPa} \]
\[ \text{Force } F = 2579.2(962.1) = 2,481,458 \text{ N} \]

\[ L = 40 \text{ mm}: \text{ pressure } p = 493.7(2.367 + 2 \times 40/35) = 2297.1 \text{ MPa} \]
\[ \text{Force } F = 2297.1(962.1) = 2,210,027 \text{ N} \]

\[ L = 30 \text{ mm}: \text{ pressure } p = 493.7(2.367 + 2 \times 30/35) = 2014.9 \text{ MPa} \]
\[ \text{Force } F = 2014.9(962.1) = 1,938,595 \text{ N} \]

\[ L = 20 \text{ mm}: \text{ pressure } p = 493.7(2.367 + 2 \times 20/35) = 1732.8 \text{ MPa} \]
\[ \text{Force } F = 1732.8(962.1) = 1,667,164 \text{ N} \]

\[ L = 10 \text{ mm}: \text{ pressure } p = 493.7(2.367 + 2 \times 10/35) = 1450.7 \text{ MPa} \]
\[ \text{Force } F = 1450.7(962.1) = 1,395,732 \text{ N} \]

**HW for Lecture 11**

**Review Questions**

13.20 What are wire drawing and bar drawing?

**Answer.** Wire and bar drawing are bulk deformation processes in which the cross section of a wire or bar is reduced by pulling (drawing) it through a die opening.

13.21 Although the workpiece in a wire drawing operation is obviously subjected to tensile stresses, how do compressive stresses also play a role in the process?

**Answer.** Compressive stresses are present in wire drawing because the starting metal is compressed as it is forced through the approach of the die opening.

13.22 In a wire drawing operation, why must the drawing stress never exceed the yield strength of the work metal?

**Answer.** Because if the drawing stress exceeded the yield strength, the metal on the exit side of the draw die would stretch rather than force metal to be pulled through the die opening.

14.9 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, hollow 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.
14.10 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 \( DR = D/D_p \); (2) reduction \( r = (D - D_p)/D \); and (3) thickness-to-diameter ratio, \( t/D \); where \( t \) = stock thickness, \( D \) = blank diameter, and \( D_p \) = punch diameter.

14.12 What are some of the possible defects in drawn sheet-metal parts?

**Answer.** Drawing defects include (1) wrinkling, (2) tearing, (3) earing, and (4) surface scratches, as described in Section 14.3.4.

**Problems**

13.29 A spool of wire has a starting diameter of 2.5 mm. It is drawn through a die with an opening that is 2.1 mm. The entrance angle of the die is 18° degrees. Coefficient of friction at the work-die interface is 0.08. The work metal has a strength coefficient of 450 MPa and a strain hardening coefficient of 0.26. The drawing is performed at room temperature. Determine (a) area reduction, (b) draw stress, and (c) draw force required for the operation.

**Solution:** (a) \( r = (A_o - A_f)/A_o \)
\[
A_o = 0.25\pi(2.50)^2 = 4.91 \text{ mm}^2
\]
\[
A_f = 0.25\pi(2.1)^2 = 3.46 \text{ mm}^2
\]
\[r = (4.91 - 3.46)/4.91 = 0.294\]

(b) Draw stress \( \sigma_d \):
\[
\varepsilon = \ln(4.91/3.46) = \ln 1.417 = 0.349
\]
\[
\bar{Y} = 450(0.349)^{0.26}/1.26 = 271.6 \text{ MPa}
\]
\[
\phi = 0.88 + 0.12(D/L_c)
\]
\[
D = 0.5(2.5 + 2.1) = 2.30
\]
\[
L_c = 0.5(2.5 - 2.1)/\sin 18 = 0.647
\]
\[
\phi = 0.88 + 0.12(2.30/0.647) = 1.31
\]
\[
\sigma_d = \bar{Y}((1 + \mu/\tan \alpha)\phi(ln A_o/A_f) = 271.6(1 + 0.08/\tan 18)(1.31)(0.349) = 154.2 \text{ MPa}
\]

(c) Draw force \( F \):
\[
F = A_f \sigma_d = 3.46(154.2) = 534.0 \text{ N}
\]

13.31 Bar stock of initial diameter = 90 mm is drawn with a draft = 15 mm. The draw die has an entrance angle = 18°, and the coefficient of friction at the work-die interface = 0.08. The metal behaves as a perfectly plastic material with yield stress = 105 MPa. Determine (a) area reduction, (b) draw stress, (c) draw force required for the operation, and (d) power to perform the operation if exit velocity = 1.0 m/min.

**Solution:** (a) \( r = (A_o - A_f)/A_o \)
\[
A_o = 0.25\pi(90)^2 = 6361.7 \text{ mm}^2
\]
\[
D_r = D_o - d = 90 - 15 = 75 \text{ mm}
\]
\[
A_f = 0.25\pi(75)^2 = 4417.9 \text{ mm}^2
\]
\[r = (6361.7 - 4417.9)/6361.7 = 0.3056\]

(b) Draw stress \( \sigma_d \):
\[
\varepsilon = \ln(6361.7 /4417.9) = \ln 1.440 = 0.3646
\]
\[
\bar{Y} = k = 105 \text{ MPa}
\]
\[
\phi = 0.88 + 0.12(D/L_c)
\]
\[
D = 0.5(90 + 75) = 82.5 \text{ mm}
\]
\[
L_c = 0.5(90 - 75)/\sin 18 = 24.3 \text{ mm}
\]
\[
\phi = 0.88 + 0.12(82.5/24.3) = 1.288
\]
\[
\sigma_d = \frac{Y_f}{(1 + \mu/\tan \alpha)} \phi (\ln A_o/A_f) = 105(1 + 0.08/\tan 18)(1.288)(0.3646) = 61.45 \text{ MPa}
\]
\[
(c) \ F = A_f \sigma_d = 4417.9 \times 61.45 = 271,475 \text{ N}
\]
\[
(d) \ P = 271,475(1 \text{ m/min}) = 271,475 \text{ N-m/min} = 4524.6 \text{ N-m/s} = 4524.6 \text{ W}
\]

14.14 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 \( DR = D_b/D_p \)

\[
r = \frac{D_b}{D_b} - \frac{D_p}{D_b} = 1 - \frac{D_p}{D_b} = 1 - 1/DR
\]

14.15 A cup is to be drawn in a deep drawing operation. The height of the cup is 75 mm and its inside diameter = 100 mm. Sheet-metal thickness = 2 mm. If the blank diameter = 225 mm, determine (a) drawing ratio, (b) reduction, and (c) thickness-to-diameter ratio. (d) Does the operation seem 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%).

14.19 A cup-drawing operation is performed in which the inside diameter = 80 mm and the height = 50 mm. Stock thickness = 3.0 mm, and starting 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. \( t \) is constant.

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

(b) \( r = (D_b - D_p)/D_b = (150 - 80)/150 = 0.46 \)

14.22 A drawing operation is performed on 3.0 mm stock. The part is a cylindrical cup with height = 50 mm and inside diameter = 70 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:** Use surface area computation, assuming thickness \( t \) remains constant.

Cup area = wall area + base area = \( \pi D_p h + \pi D_p^2/4 = \pi(70)(50) + 0.25\pi(70)^2 = 14,846 \text{ mm}^2. \)

Blank area = \( \pi D_b^2/4 = 0.7855D_b^2 \)

Setting blank area = cup area: \( 0.7855D_b^2 = 14,846 \)

\( D_b^2 = 14,846/0.7855 = 18,900 \)

\( D_b = 137.48 \text{ mm} \)

Test for feasibility: \( DR = D_b/D_p = 137.48/70 = 1.964; \ t/D_b = 3/137.48 = 0.0218 = 2.18\%. \) 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.

14.25 The foreman in the drawing section of the shop brings to you several samples of parts that have been drawn in the shop. The samples have various defects. One has ears, another has wrinkles, and still a third has torn sections at its base. What are the causes of each of these defects 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 ratio by using a thicker gage sheet metal. This may not be possible since a design change is required. (b) Increase the blankholder 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 large punch radius. Tearing can also occur due to a die corner radius that is too small.

**HW for Lecture 12**

**Review Questions**

14.3 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.

14.6 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 14.10.

14.7 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.

14.8 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.

**Problems**

14.1 A power shears is used to cut soft cold-rolled steel that is 4.75 mm thick. At what clearance should the shears be set to yield an optimum cut?

**Solution:** From Table 14.1, $A_c = 0.060$. Thus, $c = A_c t = 0.060(4.75) = 0.285$ mm

14.2 A blanking operation is to be performed on 2.0 mm thick cold-rolled steel (half hard). The part is circular with diameter = 75.0 mm. Determine the appropriate punch and die sizes for this operation.

**Solution:** From Table 14.1, $A_c = 0.075$. Thus, $c = 0.075(2.0) = 0.15$ mm. 

- Punch diameter = $D_p - 2c = 75.0 - 2(0.15) = 74.70$ mm.
- Die diameter = $D_b = 75.0$ mm.

14.3 A compound die will be used to blank and punch a large washer out of 6061ST aluminum alloy sheet stock 3.50 mm thick. The outside diameter of the washer is 50.0 mm and the inside diameter is 15.0 mm. Determine (a) the punch and die sizes for the blanking operation, and (b) the punch and die sizes for the punching operation.
Solution: From Table 14.1, $A_c = 0.060$. Thus, $c = 0.060(3.50) = 0.210$ mm
(a) Blanking punch diameter $= D_b - 2c = 50 - 2(0.21) = 49.58$ mm
Blanking die diameter $= D_b = 50.00$ mm
(b) Punching punch diameter $= D_h = 15.00$ mm
Punching die diameter $= D_h + 2c = 30 + 2(0.210) = 15.42$ mm

14.10 A bending operation is to be 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 is 25 mm long. The resulting sheet metal part has an acute angle of 30° and a bend radius of 6 mm. Determine (a) the bend allowance and (b) the length of the neutral axis of the part after the bend. (Hint: the length of the neutral axis before the bend = 100.0 mm).

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, $K_{ba} = 0.333$
$A_b = 2\pi(150/360)(6.0 + 0.333 \times 4.0) = 19.195$ 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 $= 20.944 - 19.195 = 1.75$ mm
Thus, the final length of the neutral axis will be $L = 100 + 1.75 = 101.75$ 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) = $(19.195/20.944)(4.0) = 3.67$ mm. Now let us 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 $= 2\pi(150/360)(6.0 + 0.5 \times 3.74) = 20.512$ mm. Now the difference between the length of the bent section and the bend allowance $= 20.512 - 19.195 = 1.317$ mm. The new final length of the neutral axis is $L = 100 + 1.32 = 101.32$ 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
$(19.195/20.512)(4.0) = 3.74$ mm, and recalculating the length of the bent section based on this value, we have the following:
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 $= 20.608 - 19.195 = 1.413$ mm, and the new final length of the neutral axis is $L = 100 + 1.41 = 101.41$ mm

One more iteration: The thickness of the stretched sheet is $(19.195/20.608)(4.0) = 3.73$ mm, and recalculating the length of the bent section based on this value, we have $2\pi(150/360)(6.0 + 0.5 \times 3.73) = 20.585$ mm. The new before and after difference $= 20.585 - 19.195 = 1.39$ mm, and the new final length of the neutral axis is $L = 100 + 1.39 = 101.39$ mm