QUIZ MS204
Bulk Deformation Processes
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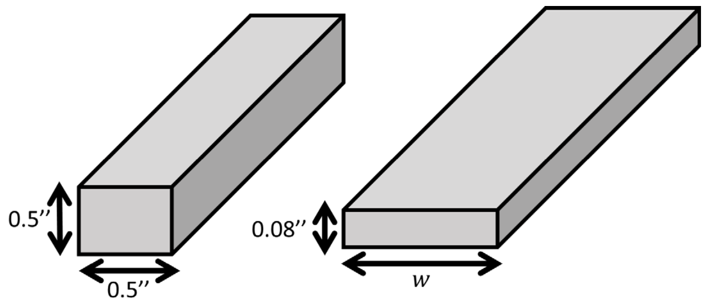
PROBLEM - PLAIN STRAIN COMPRESSION

Problem 1 (Creese, 1999)

A square bar, 0.5 × 0.5 in. in cross-section and 5 in. long is to be flattened into a section that is only 0.08 in. thick and will remain 5 in. in length. The press velocity is 60 in./min and the coefficient of friction is 0.12. The strength coefficient and strain-hardening exponent for cold working are 63,300 psi and 0.33, respectively. For hot working at the pertinent temperature, the values are 12,700 psi and 0.06. True or false?



1.( ) The final width of the bar is greater than 3 in.
2.( ) The absolute value of the engineering strain is greater than 0.8.
3.( ) The absolute value of the true strain is greater than 2.0.
4.( ) The engineering strain rate is greater than 3 sec^{-1}.
5.( ) The true strain rate is greater than 14 sec^{-1}.
6.( ) The pressure multiplying factor is greater than 15.
7.( ) The flow stress for cold working is greater than 75,000 psi.
8.( ) The mean flow stress for cold working is greater than 60,000 psi.
9.( ) The flow stress for hot working is greater than 12,000 psi.
10.( ) The force needed for the hot working operation is greater than 1500 tons.

PROBLEMS - EXTRUSION

Problem 2 (Kalpakjian & Schmid, 2010)

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 100 mm. The extrusion constant is 180 MPa.

A) F = 9.51 MN
B) F = 15.0 MN
C) F = 21.5 MN
D) F = 28.0 MN

Problem 3 (Kalpakjian & Schmid, 2010)

A planned extrusion operation involves stainless steel at 1000°C with an initial diameter of 100 mm and a final diameter of 50 mm. Two presses are available for the operation: press 1 has a capacity of 20 MN and press 2 has a capacity of 10 MN. Are the presses sufficient for this operation? The extrusion constant is 320 MPa.

A) Both presses are suitable for the operation.
B) Press 1 is suitable for the operation, but press 2 is not.
C) Press 2 is suitable for the operation, but press 1 is not.
D) Neither press is suitable for the operation.

Problem 4 (Groover, 2013, w/ permission)

A cylindrical billet 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°. The Johnson equation has a = 0.8 and b = 1.4. The ram speed is 50 cm/min. In the flow curve for the work metal, the strength coefficient is 800 MPa and the strain hardening exponent is 0.13. True or false?

1.( ) The extrusion ratio is greater than 6.0.
2.( ) The true strain is greater than 2.0.
3.( ) The extrusion strain is greater than 3.6.
4.( ) The ram pressure is greater than 2400 MPa.
5.( ) The ram force is greater than 6 MN.
6.( ) The power required to carry out the extrusion is greater than 38 kW.

Problem 5 (Groover, 2013, w/ permission)

A 3.0-in.-long cylindrical billet whose diameter = 1.5 in. is reduced by indirect extrusion to a diameter = 0.375 in. The die angle is 90°. In the Johnson equation, a = 0.8 and b = 1.5. The ram speed is 20 in./min. In the flow curve for the work metal, K = 75,000 lb/in.² and n = 0.25. True or false?

1.( ) The extrusion ratio is greater than 18.
2.( ) The true strain is greater than 2.4.
3.( ) The extrusion strain is greater than 5.5.
4.( ) The ram pressure is greater than 400 ksi.
5.( ) The ram force is greater than 650 kip.
6.( ) The power required to carry out the extrusion is greater than 30 hp.

PROBLEMS - WIRE DRAWING AND SHEET METAL DRAWING

Problem 6 (Groover, 2013, w/ permission)

A spool of wire has a starting diameter of 2.5 mm. It is drawn through a die with an opening that is to 2.1 mm. The entrance angle of the die is 18 degrees. The 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 exponent of 0.26. The exit velocity of the stock is 0.6 m/s. The drawing is performed at room temperature. True or false?

1.( ) The area reduction is greater than 0.25.
2.( ) The draw stress is greater than 175 MPa.
3.( ) The draw force is greater than 500 N.
4.( ) The power required to carry out the operation is greater than 360 W.

Problem 7 (Groover, 2013, w/ permission)

Red stock that has an initial diameter of 0.50 in. is drawn through a draw die with an entrance angle of 13 degrees. The final diameter of the rod is 0.375 in. The metal has a strength coefficient of 40,000 lb/in.² and a strain hardening exponent of 0.20. The coefficient of friction at the work-die interface is 0.1. The exit velocity of the stock is 2 ft/sec. True or false?

1.( ) The area reduction is greater than 0.5.
2.( ) The draw stress is greater than 27,200 psi.
3.( ) The draw force is greater than 3200 lb.
4.( ) The power required to carry out the operation is greater than 10 hp.

Problem 8 (Groover, 2013, w/ permission)

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. The sheet-metal thickness = 2 mm. If the blank diameter = 225 mm, determine drawing ratio, reduction, and thickness-to-diameter ratio. True or false?

1.( ) The drawing ratio is greater than 2.0.
2.( ) The reduction is greater than 50%.
3.( ) The thickness-to-diameter ratio is greater than 1%.
Repeat the calculations if the starting blank diameter = 175 mm.
4.( ) The drawing ratio is greater than 1.6.
5.( ) The reduction is greater than 45%..
6.( ) The thickness-to-diameter ratio is greater than 1.1%.

Problem 9 (Groover, 2013, w/ permission)

A cup-drawing operation is performed in which the inside diameter = 80 mm and the height = 50 mm. The stock thickness = 3.0 mm and the starting blank diameter = 150 mm. Punch and die radii = 4 mm. Tensile strength = 400 MPa and yield strength = 180 MPa for this sheet metal. True or false?

1.( ) The drawing ratio is greater than 1.8.

2.( ) The reduction is greater than 50%.

3.( ) The drawing force is greater than 320 kN.

4.( ) The blankholder force is greater than 120 kN.

Problem 10 (Kalpakjian & Schmid, 2010, w/ permission)

For a metal, the normal anisotropy in the 0°, 45°, and 90° directions are 0.8, 1.7, and 1.8, respectively. True or false?

1.( ) The average normal anisotropy equals 1.4.

2.( ) The limiting drawing ratio is greater than 2.5.

3.( ) The metal will not develop ears when deep drawn.

PROBLEMS - ROLLING

Problem 11.1 (Groover, 2013, w/ permission)

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

A) Minimum number of passes = 3

B) Minimum number of passes = 4

C) Minimum number of passes = 5

D) Minimum number of passes = 6

Problem 11.2

Determine the draft for each pass.

A) d = 4.10 mm

B) d = 4.95 mm

C) d = 6.25 mm

D) d = 7.70 mm

Problem 12 (Groover, 2013, w/ permission)

A 42-mm-thick plate made of low carbon steel is to be reduced to 34.0 mm in one pass in a rolling operation. As the thickness is reduced, the plate widens by 4%. The yield strength of the steel plate is 174 MPa and the tensile strength is 290 MPa. The entrance speed of the plate is 15.0 m/min. The roll radius is 325 mm and the rotational speed is 49.0 rev/min. True or false?

1.( ) The coefficient of friction that makes the operation possible is greater than 0.14.

2.( ) The exit velocity of the plate is greater than 19 m/min.

3.( ) The forward slip is greater than 0.097.

Problem 13 (Groover, 2013, w/ permission)

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. True or false?

1.( ) The roll force is greater than 2.0 MN.

2.( ) The roll torque is greater than 40 kN·m.

3.( ) The power required to carry out the operation is greater than 100 kW.

Repeat the calculations if the roll radius = 250 mm.

4.( ) The roll force is greater than 1.2 MN.

5.( ) The roll torque is greater than 25 kN·m.

6.( ) The power required to carry out the operation is greater than 86 kW.

Problem 14 (Groover, 2013, w/ permission)

A hot rolling mill has rolls of diameter = 24 in. It can exert a maximum force = 400,000 lb. The mill has maximum horsepower = 100 hp. It is desired to reduce a 1.5-in. thick plate by the maximum possible draft in one pass. The starting plate is 10 in. wide. In the heated condition, the work material has a strength coefficient = 20,000 lb/ft^2 and a strain hardening exponent = zero. True or false?

1.( ) The maximum possible draft is greater than 0.28 in.
2.( ) The true strain is greater than 0.29.
3.( ) The maximum speed of the rolls is greater than 45 ft/min.

PROBLEMS - FORGING

Problem 15 (Groover, 2013, w/ permission)

A hot upset forging operation is performed in an open die. The workpart has initial diameter = 25 mm and initial height = 50 mm. The work metal at this elevated temperature yields at 85 MPa (strain-hardening exponent = 0). The coefficient of friction at the die-work interface = 0.40. Determine the final height of the part and the forging force.

A) h = 12.5 mm and F = 144 kN
B) h = 12.5 mm and F = 273 kN
C) h = 23.5 mm and F = 144 kN
D) h = 23.5 mm and F = 273 kN

Problem 16 (Groover, 2013, w/ permission)

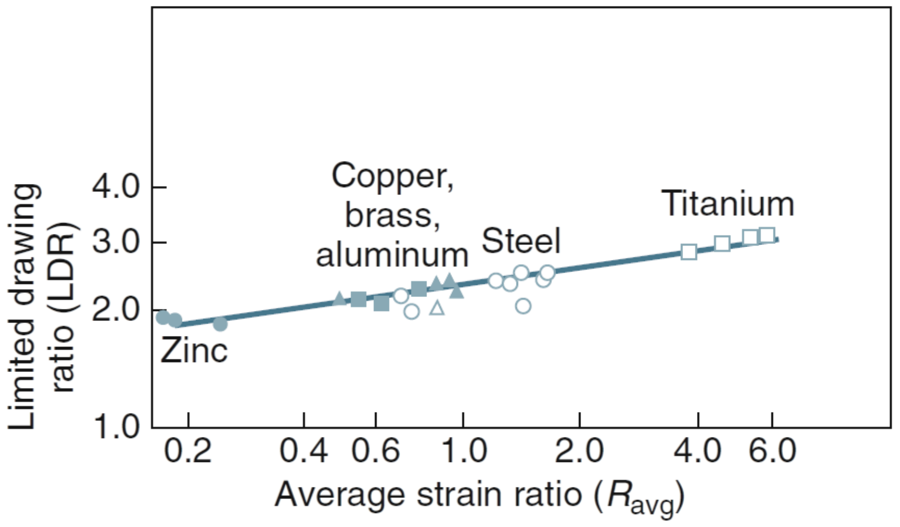
A cylindrical part is warm upset forged in an open die. The initial diameter is 45 mm and the initial height is 40 mm. The height after forging is 25 mm. The coefficient of friction at the die-work interface is 0.20. The yield strength of the work material is 285 MPa, and its flow curve is defined by a strength coefficient of 600 MPa and a strain-hardening exponent of 0.12. Determine the force in the operation just as the yield point is reached (strain at yield = 0.002), at a height of 35 mm, a height of 30 mm, a height of 25 mm, and a height of 20 mm.

Problem 17 (Groover, 2013, w/ permission)

A cylindrical workpart has a diameter = 2.5 in. and a height = 4.0 in. It is upset forged to a height = 2.75 in. The coefficient of friction of the die-work interface = 0.10. The work material has a flow curve with strength coefficient = 25,000 lb/in.^{2} and strain hardening exponent = 0.22. Prepare a plot of force vs. work height.

ADDITIONAL INFORMATION

Figure 1 Relationship between average normal anisotropy and limiting drawing ratio for various sheet metals.



Equations

1 → *Pressure-multiplying factor for plain strain compression ($\mu L/h \leq 1$)*

$$Q = 1 + \frac{\mu L}{2h}$$

where μ is the coefficient of friction, L is length (or width), and h is height.

2 → *Pressure-multiplying factor for plain strain compression ($\mu L/h > 1$)*

$$Q = 1 + \frac{L}{4h}$$

where μ is the coefficient of friction, L is length (or width), and h is height.

3 → *Extrusion force*

$$F = A_o k \ln\left(\frac{A_o}{A_f}\right)$$

where A_o is initial area, A_f is final area, and k is the extrusion constant.

4 → *Johnson equation for extrusion strain*

$$\varepsilon_x = a + b \ln r_x$$

where r_x is extrusion ratio and a and b are coefficients.

5 → *Schey equation for wire and bar drawing*

$$\sigma_d = \bar{\sigma}_f \left(1 + \frac{\mu}{\tan\alpha}\right) \phi \ln\left(\frac{A_o}{A_f}\right)$$

where $\bar{\sigma}_f$ is average flow stress, μ is coefficient of friction, α is die angle (half-angle), A_o is initial area, and A_f is final area; ϕ is a factor that accounts for inhomogeneous deformation, which, in the case of a round cross-section, is given by

$$\phi = 0.88 + 0.12 \frac{D}{L_c}$$

where D is average diameter of work during drawing and L_c is the contact length of the work with the draw die, which can be estimated as

$$L_c = \frac{D_o - D_f}{2 \sin\alpha}$$

6 → *Drawing force (sheet metal working)*

$$F = \pi D_p t \sigma_T \left(\frac{D_b}{D_p} - 0.7\right)$$

where D_b is starting blank diameter, D_p is starting punch diameter, t is thickness, and σ_T is tensile strength.

7→ *Blankholder force (sheet metal working)*

$$F_b = 0.015 \sigma_Y \pi \left[D_b^2 - \left(D_p + 2.2t + 2R_d\right)^2\right]$$

where σ_Y is yield strength, D_b is starting blank diameter, D_p is starting punch diameter, t is thickness, and R_d is die corner radius.

8 → *Average normal anisotropy*

$$R_{\text{avg}} = \frac{R_0 + 2R_{45} + R_{90}}{4}$$

where R_{n} is the normal anisotropy when n is the angle with respect to the rolling direction of the sheet.

9 → *Average normal anisotropy*

$$\Delta R = \frac{R_0 - 2R_{45} + R_{90}}{2}$$

where R_n is the normal anisotropy when n is the angle with respect to the rolling direction of the sheet.

10 → *Forging shape factor*

$$K_f = 1 + \frac{0.4\mu D}{h}$$

where μ is friction factor, D is diameter, and h is height.

SOLUTIONS

P.1 ■ Solution

1. True. The volume of the material is conserved, so the final width can be determined as

$$0.5 \times 0.5 \times 5 = w \times 0.08 \times 5 \rightarrow \boxed{w = 3.13\text{ in.}}$$

2. True. The engineering strain is given by

$$\varepsilon = \frac{0.08 - 0.5}{0.5} = \boxed{-0.84}$$

3. False. The true strain is given by

$$\varepsilon = \ln\left(\frac{0.08}{0.5}\right) = \boxed{-1.83}$$

4. False. The engineering strain rate is

$$\dot{\varepsilon} = \frac{60\text{ in./min} \times 1\text{ min}/60\text{ sec}}{0.5} = \boxed{2\text{ s}^{-1}}$$

5. False. The true strain rate is

$$\dot{\varepsilon} = \frac{60\text{ in./min} \times 1\text{min/}60\text{ sec}}{0.08} = \boxed{12.5\text{ s}^{-1}}$$

6. True. If $\mu L/h \leq 1$, the pressure multiplying factor is computed with equation 1, namely

$$Q = 1 + \frac{\mu L}{2h}$$

If, on the other hand, $\mu L/h > 1$, the expression to use is equation 2,

$$Q = 1 + \frac{L}{4h}$$

In the case at hand,

$$\frac{\mu L}{h} = \frac{0.12 \times 5}{0.05} = 12$$

which implies that the relation to use is equation 2. Accordingly,

$$Q = 1 + \frac{L}{4h} = 1 + \frac{3.13}{4 \times 0.05} = \boxed{16.7}$$

7. True. If cold working is performed, the values of K and n in the flow curve are 63,300 psi and 0.33, respectively. Therefore,

$$\sigma_f = K\varepsilon^n = 63,300 \times 1.83^{0.33} = \boxed{77,300\text{ psi}}$$

Although the strain was in fact −1.83, the absolute value is entered in the equation. The minus sign implies compression instead of tension, but the formula is for either.

8. False. The mean flow stress for cold working is

$$\bar{\sigma}_f = \frac{63,300 \times 1.83^{0.33}}{1 + 0.33} = \boxed{58,100\text{ psi}}$$

9. True. If hot working is done instead, the values of K and n in the flow curve are 12,700 psi and 0.06, respectively. Thus,

$$\sigma_f = K\varepsilon^n = 12,700 \times 1.83^{0.06} = \boxed{13,200 \text{ psi}}$$

10. True. If hot working is used, and the flow stress and pressure-multiplying factor have been computed, the surface area is the only additional information needed. The surface area is A_f = 5 × 3.13 = 15.7 in.². Accordingly,

$$F = Q\sigma_f A_f = 16.7 \times 13,200 \times 15.7 = 3.46 \times 10^6 \text{ lb}$$

$$\therefore F = 3.46 \times 10^6 \text{ lb} \times \frac{1 \text{ ton}}{2000 \text{ lb}} = \boxed{1730 \text{ tons}}$$

P.2 ■ Solution

The extrusion force required is given by equation 3,

$$F = A_o k \ln\left(\frac{A_o}{A_f}\right)$$

where A_o = π × 0.3²/4 = 0.0707 m² is the initial cross-sectional area, A_f = π × 0.1²/4 = 0.00785 m² is the final cross-sectional area, and k = 180 MPa is the extrusion constant. Thus,

$$F = A_o k \ln\left(\frac{A_o}{A_f}\right) = 0.0707 \times 180 \ln\left(\frac{0.0707}{0.00785}\right) = \boxed{28.0 \text{ MN}}$$

♦ The correct answer is **D**.

P.3 ■ Solution

The initial cross-sectional area is A_o = π × 0.1²/4 = 0.00785 m² and the final cross-sectional area is A_f = π × 0.05²/4 = 4.91×10⁻⁴ m². The extrusion force is then

$$F = A_o k \ln\left(\frac{A_o}{A_f}\right) = 0.00785 \times 320 \ln\left(\frac{0.00785}{0.00196}\right) = 6.96 \text{ MN}$$

Accordingly, both the smaller press and the larger press can accommodate this extrusion operation. The smaller press would probably not be used because it is so close to the required force. Reducing friction or increasing the extrusion temperature may reduce the required extrusion force.

♦ The correct answer is **A**.

P.4 ■ Solution

1. True. The extrusion ratio is the ratio of initial cross-sectional area to final cross-sectional area; that is,

$$r_x = \frac{A_o}{A_f} = \frac{D_o^2}{D_f^2} = \frac{50^2}{20^2} = \boxed{6.25}$$

2. False. The true strain follows as

$$\varepsilon = \ln r_x = \ln 6.25 = \boxed{1.83}$$

3. False. The extrusion strain follows from the Johnson equation (equation 4)

$$\varepsilon_x = a + b\ln r_x = 0.8 + 1.4\ln 6.25 = \boxed{3.37}$$

4. True. Before computing the ram pressure, we require the flow stress $\bar{\sigma}_f$; that is,

$$\bar{\sigma}_f = \frac{800 \times 1.83^{0.13}}{1 + 0.13} = 766 \text{ MPa}$$

Therefore,

$$p = \varepsilon_x \bar{\sigma}_f = 3.37 \times 766 = \boxed{2580 \text{ MPa}}$$

5. False. The initial cross-sectional area is A_o = π × 50²/4 = 1960 mm². The corresponding ram force is

$$F = pA_o = 2580 \times 1960 = \boxed{5.06 \text{ MN}}$$

6. True. The ram speed is converted as

$$V = 0.5 \frac{\text{m}}{\text{min}} \times \frac{1}{60} \frac{\text{min}}{\text{sec}} = 0.00833 \text{ m/s}$$

so that

$$P = FV = \left(5.06 \times 10^6\right) \times 0.00833 = \boxed{42.1 \text{ kW}}$$

P.5 ■ Solution

1. False. The extrusion ratio is the ratio of initial cross-sectional area to final cross-sectional area; that is,

$$r_x = \frac{A_o}{A_f} = \frac{D_o^2}{D_f^2} = \frac{1.5^2}{0.375^2} = \boxed{16}$$

2. True. The true strain is given by

$$\varepsilon = \ln r_x = \ln 16 = \boxed{2.77}$$

3. False. The extrusion strain follows from the Johnson equation,

$$\varepsilon_x = a + b \ln r_x = 0.8 + 1.5 \ln 16 = \boxed{4.96}$$

4. False. Before computing the ram pressure, we require the flow stress $\bar{\sigma}_f$; that is,

$$\bar{\sigma}_f = \frac{75,000 \times 2.77^{0.25}}{1 + 0.25} = 77,400 \text{ psi}$$

Accordingly,

$$p = \varepsilon_x \bar{\sigma}_f = 4.96 \times 77,400 = \boxed{384 \text{ ksi}}$$

5. True. The initial cross-sectional area is $A_o = \pi \times 1.5^2/4 = 1.77$ in.^{2} The corresponding ram force is

$$F = pA_o = 384 \times 1.77 = \boxed{680 \text{ kip}}$$

6. True. The power associated with the extrusion process is

$$P = FV = 680,000 \times 20 = 1.36 \times 10^7 \text{ in.-lb/min}$$

$$\therefore P = 1.36 \times 10^7 \text{ in.-lb/min} \times \frac{1}{396,000} \frac{\text{hp}}{\text{in.-lb/min}} = \boxed{34.3 \text{ hp}}$$

P.6 ■ Solution

1.True. The initial area is $A_o = \pi \times 2.5^2/4 = 4.91$ mm^2 and the final area is $A_f = \pi \times 2.1^2/4 = 3.46$ mm^2. The area reduction is then

$$r = \frac{A_o - A_f}{A_o} = \frac{4.91 - 3.46}{4.91} = \boxed{0.295}$$

2.False. The true strain is

$$\varepsilon = \ln\left(\frac{A_o}{A_f}\right) = \ln \frac{4.91}{3.46} = 0.350$$

and the corresponding flow stress is

$$\bar{\sigma}_f = \frac{450 \times 0.350^{0.26}}{1 + 0.26} = 272 \text{ MPa}$$

The homogeneous deformation factor ϕ is given by

$$\phi = 0.88 + 0.12 \frac{D}{L_c}$$

Here, D is the average diameter of work during drawing,

$$D = \frac{D_o + D_f}{2} = \frac{2.1 + 2.5}{2} = 2.3 \text{ mm}$$

and L_c is the contact length of the work with the draw die, calculated as

$$L_c = \frac{D_o - D_f}{2\sin\alpha} = \frac{2.5 - 2.1}{2\sin 18^\circ} = 0.647 \text{ mm}$$

where we have used the die angle α = 18°. Substituting in the formula for ϕ brings to

$$\phi = 0.88 + 0.12 \times \frac{2.3}{0.647} = 1.31$$

We can now compute the drawing stress using equation 5,

$$\sigma_d = \bar{\sigma}_f \left(1 + \frac{\mu}{\tan\alpha}\right) \phi \ln\left(\frac{A_o}{A_f}\right) = 272 \times \left(1 + \frac{0.08}{\tan 18^\circ}\right) \times 1.31 \times \ln\left(\frac{4.91}{3.46}\right) = \boxed{155 \text{ MPa}}$$

3.True. The draw force is the product of the final cross-sectional area and draw stress; that is,

$$F_d = \sigma_d A_f = 155 \times 3.46 = \boxed{536 \text{ N}}$$

4.False. The power required to carry out the operation is

$$P = F_d V = 536 \times 0.6 = \boxed{322 \text{ W}}$$

P.7 ■ Solution

1.False. The initial area is $A_o = \pi \times 0.5^2/4 = 0.196$ in.² and the final area is $A_f = \pi \times 0.375^2/4 = 0.110$ in.². The area reduction is, accordingly,

$$r = \frac{A_o - A_f}{A_o} = \frac{0.196 - 0.110}{0.196} = \boxed{0.439}$$

2.False. The true strain is

$$\varepsilon = \ln\left(\frac{A_o}{A_f}\right) = \ln\frac{0.196}{0.110} = 0.578$$

and the corresponding flow stress is

$$\bar{\sigma}_f = \frac{40{,}000 \times 0.578^{0.20}}{1 + 0.20} = 29{,}900 \text{ psi}$$

The homogeneous deformation factor ϕ is given by

$$\phi = 0.88 + 0.12\frac{D}{L_c}$$

Here, D is the average diameter of work during drawing,

$$D = \frac{D_o + D_f}{2} = \frac{0.5 + 0.375}{2} = 0.438 \text{ in.}$$

and L_c is the contact length of the work with the draw die, namely

$$L_c = \frac{D_o - D_f}{2\sin\alpha} = \frac{0.5 - 0.375}{2\sin 13^\circ} = 0.278 \text{ in.}$$

where we have used the die angle α = 13°. Substituting in the formula for ϕ gives

$$\phi = 0.88 + 0.12 \times \frac{0.438}{0.278} = 1.07$$

The draw stress is determined to be

$$\sigma_d = \bar{\sigma}_f \left(1 + \frac{\mu}{\tan\alpha}\right) \phi \ln\left(\frac{A_o}{A_f}\right) = 29{,}900 \times \left(1 + \frac{0.1}{\tan 13^\circ}\right) \times 1.07 \times \ln\left(\frac{0.196}{0.110}\right) = \boxed{26{,}500 \text{ psi}}$$

3.False. The draw force is the product of the final cross-sectional area and draw stress,

$$F_d = \sigma_d A_f = 26,500 \times 0.110 = \boxed{2920 \text{ lb}}$$

4.True. The exit velocity is converted as

$$V = 2\,\frac{\text{ft}}{\text{sec}} \times 12\,\frac{\text{in.}}{\text{ft}} \times 60\,\frac{\text{sec}}{\text{min}} = 1440 \text{ in./min}$$

The power required to carry out the operation is

$$P = F_d V = 2920 \times 1440 = 4.20 \times 10^6 \text{ in.-lb/min}$$

$$\therefore P = 4.20 \times 10^6 \text{ in.-lb/min} \times \frac{1}{396,000 \text{ in.-lb/min}} \frac{\text{hp}}{} = \boxed{10.6 \text{ hp}}$$

P.8 ■ Solution

1.True. The drawing ratio is the ratio of blank diameter to inside diameter, namely

$$DR = \frac{D_b}{D_p} = \frac{225}{100} = \boxed{2.25}$$

2.True. The reduction is given by

$$r = \frac{D_b - D_p}{D_b} = \frac{225 - 100}{225} = \boxed{55.6\%}$$

3.False. The thickness-to-diameter ratio is

$$\frac{t}{D_b} = \frac{2}{225} = 0.00889 = \boxed{0.89\%}$$

Note

It is important to appreciate that these data may not indicate a feasible drawing operation. Approximate upper limits are 2.0 for the drawing ratio and 0.5 for the reduction; the thickness-to-diameter ratio should be greater than 1%. Since the values at hand satisfy none of these requirements, we surmise that this system does not represent a viable drawing operation.

4.True. The drawing ratio is now

$$DR = \frac{D_b}{D_p} = \frac{175}{100} = \boxed{1.75}$$

5.False. The reduction, in turn, now becomes

$$r = \frac{D_b - D_p}{D_b} = \frac{175 - 100}{175} = \boxed{42.9\%}$$

6.True. The thickness-to-diameter ratio is

$$\frac{t}{D_b} = \frac{2}{175} = \boxed{1.14\%}$$

In this case, $DR < 2.0$, $r < 50\%$, and $t/D_b > 1\%$. However, Groover observes that 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. The blank area = $\pi \times 175^2/4 = 24{,}100$ mm². To compute the cup surface area, let us divide the cup into two sections: (1) walls and (2) base, assuming the corner radius on the punch has a negligible effect in our calculations and there is no earing of the cup. The cup area = $\pi D_p h + \pi D_p^2/4 = \pi \times 100h + \pi \times 100^2/4 = 314h + 7850$. Setting the surface area of cup = surface area of the blank, it follows that

$$A_{\text{cup}} = A_{\text{blank}} \rightarrow 314h + 7850 = 24,100$$

$$\therefore 314h = 16,300$$

$$\therefore h = 51.9 \text{ mm}$$

This is less than the specified 75 mm height.

P.9 ■ Solution

1.True. The drawing ratio is

$$DR = \frac{D_b}{D_p} = \frac{150}{80} = \boxed{1.88}$$

2.False. The reduction is

$$r = \frac{D_b - D_p}{D_b} = \frac{150-80}{150} = \boxed{46.7\%}$$

3.True. The drawing force is given by equation 6,

$$F = \pi D_p t \sigma_T \left(\frac{D_b}{D_p} - 0.7\right) = \pi \times 0.08 \times 0.003 \times \left(400\times10^6\right)\times\left(1.88-0.7\right) = \boxed{356 \text{ kN}}$$

4.False. The blankholder force is given by equation 7,

$$F_b = 0.015\pi\sigma_Y\left[D_b^2 - \left(D_p + 2.2t + 2R_d\right)^2\right]$$

$$\therefore F_b = 0.015\pi\times180\times\left[150^2 - \left(80+2.2\times3+2\times4\right)^2\right] = \boxed{115 \text{ kN}}$$

P.10 ■ Solution

1. False. The average normal anisotropy is given by equation 8,

$$R_{\text{avg}} = \frac{R_0 + 2R_{45} + R_{90}}{4} = \frac{0.8+2\times1.7+1.8}{4} = \boxed{1.5}$$

2. True. The limiting drawing ratio (LDR) is plotted as a function of average normal anisotropy/strain ratio in Figure 1. Entering R_{avg} = 1.5 in this chart, we read a LDR of about 2.8.

3. False. The planar anisotropy is given by equation 9,

$$\Delta R = \frac{R_0 - 2R_{45} + R_{90}}{2} = \frac{0.8-2\times1.7+1.8}{2} = -0.4$$

If ΔR = 0, no ears would form. In the case at hand, $\Delta R \neq 0$, hence we cannot conclude that ears will not form in the metal.

P.11 ■ Solution

Part 1: The maximum draft is

$$d_{\max} = \mu^2 R = 0.15^2 \times 350 = 7.88 \text{ mm}$$

The minimum number of passes follows as

$$\text{Min. number of passes} = \frac{t_o - t_f}{d_{\max}} = \frac{50-25}{7.88} = \lceil 3.17 \rceil = \boxed{4}$$

♦ The correct answer is **B.**

Part 2: The draft per pass is given by the ratio

$$d = \frac{50-25}{4} = \boxed{6.25 \text{ mm}}$$

♦ The correct answer is **C.**

P.12 ■ Solution

1.True. The maximum draft is given by $d_{\max} = \mu^2 R$. We know that d = 42 − 34 = 8 mm and R = 325 mm. Accordingly,

$$d_{\max} = \mu^2 R \rightarrow \mu = \left(\frac{d_{\max}}{R}\right)^{1/2}$$

$$\therefore \mu = \left(\frac{8}{325}\right)^{1/2} = \boxed{0.157}$$

2.False. From conservation of volume, we can write

$$t_o w_o v_o = t_f w_f v_f$$

Since the plate widens by 4%, we have w_f = 1.04w_o. Substituting this and other data brings to

$$t_o w_o v_o = t_f w_f v_f \rightarrow v_f = \frac{t_o w_o v_o}{t_f w_f}$$

$$\therefore v_f = \frac{42 \times w_o \times 15.0}{34 \times 1.04 w_o}$$

$$\therefore \boxed{v_f = 17.8 \text{ m/min}}$$

3.False. The roll speed is given by

$$v_r = \pi r^2 N = \pi \times 0.325^2 \times 49 = 16.3 \text{ m/min}$$

The forward slip follows as

$$s = \frac{v_f - v_r}{v_r} = \frac{17.8 - 16.3}{16.3} = \boxed{0.0920}$$

P.13 ■ Solution

1.False. The contact length is

$$L = \sqrt{R(t_o - t_f)} = \sqrt{500 \times (25 - 20)} = 50 \text{ mm}$$

The true strain is

$$\varepsilon = \ln\left(\frac{25}{20}\right) = 0.223$$

and the average flow stress follows as

$$\bar{\sigma}_f = \frac{240 \times 0.223^{0.2}}{1 + 0.2} = 148 \text{ MPa}$$

The roll force is determined next,

$$F = \bar{\sigma}_f wL = 148 \times 0.25 \times 0.05 = \boxed{1.85 \text{ MN}}$$

2.True. The roll torque is

$$T = 0.5FL = 0.5 \times 1850 \times 0.05 = \boxed{46.3 \text{ kN} \cdot \text{m}}$$

3.False. The rotational speed is converted as N = 30 ÷ (2π × 0.5) ÷ 60 = 0.159 rev/s. It remains to compute the required power,

$$P = 2\pi NFL = 2\pi \times 0.159 \times (1.85 \times 10^6) \times 0.05 = \boxed{92.4 \text{ kW}}$$

4.True. The draft continues to be 5 mm, but the contact length is now shifted to

$$L = \sqrt{R(t_o - t_f)} = \sqrt{250 \times (25 - 20)} = 35.4 \text{ mm}$$

The true strain continues to be 0.223, which implies that the flow stress still equals 148 MPa. The roll force is

$$F = \bar{\sigma}_f wL = 148 \times 0.25 \times 0.0354 = \boxed{1.31 \text{ MN}}$$

5.False. The roll torque is

$$T = 0.5FL = 0.5 \times 1310 \times 0.0354 = \boxed{23.2 \text{ kN} \cdot \text{m}}$$

6.True. The rotational speed is converted as N = 30 ÷ (2π × 0.25) ÷ 60 = 0.318 rev/s. Lastly, the required power is determined to be

$$F = 2\pi NFL = 2\pi \times 0.318 \times (1.31 \times 10^6) \times 0.0354 = \boxed{92.7 \text{ kW}}$$

P.14 ■ Solution

1.True. The contact length is approximated as

$$L = \sqrt{R\underbrace{\left(t_o - t_f\right)}_{=d}} = \sqrt{12d}$$

The flow stress is calculated as

$$\bar{\sigma}_f = \frac{20,000\times\varepsilon^0}{0+1.0} = 20,000 \text{ psi}$$

The limiting force of the rolling mill is 400,000 lb. Accordingly,

$$F = \bar{\sigma}_f wL \rightarrow 400,000 = 20,000\times 10\times\left(12d\right)^{0.5}$$

$$\therefore 400,000 = 200,000\left(12d\right)^{0.5}$$

$$\therefore 2 = \left(12d\right)^{0.5}$$

$$\therefore \boxed{d = 0.333 \text{ in.}}$$

2.False. Before computing the true strain, we require the final thickness t_f. Given the draft d = 0.333 in., we write

$$d = t_o - t_f \rightarrow t_f = t_o - d$$

$$\therefore t_f = 1.5 - 0.333$$

$$\therefore t_f = 1.17 \text{ in.}$$

Thus, the true strain is

$$\varepsilon = \ln\left(\frac{t_o}{t_f}\right) = \ln\left(\frac{1.5}{1.17}\right) = \boxed{0.248}$$

3.True. The maximum possible power is P = 100 hp × 396,000 (in-lb/min)/hp = 3.96×10^7 (in-lb/min). The contact length is L = (12×0.333)$^{0.5}$ = 2.0 in. The rotational speed that corresponds to maximum power is

$$P = 2\pi NFL \rightarrow N = \frac{P}{2\pi FL}$$

$$\therefore N = \frac{3.96\times 10^7}{2\pi\times 400,000\times 2.0} = 7.88 \text{ rev/min}$$

Lastly, the maximum speed of the rolls is

$$v_r = 2\pi RN = 2\pi\times\left(12/12\right)\times 7.88 = \boxed{49.5 \text{ ft/min}}$$

P.15 ■ Solution

The volume of the workpart is $V = \pi \times 25^2 \times 50/4$ = 24,500 mm^3 and the final area is $A_f = \pi \times 50^2/4$ = 1960 mm^2. The final height of the part is then

$$V = A_f h \rightarrow h = \frac{V}{A_f}$$

$$\therefore h = \frac{24,500}{1960} = \boxed{12.5 \text{ mm}}$$

The strain associated with the operation is

$$\varepsilon = \ln\left(\frac{50}{12.5}\right) = 1.39$$

The force is maximum at the largest area value A_f = 1960 mm^2, which corresponds to a diameter D = 50 mm. Appealing to equation 10, the forging shape factor is calculated as

$$K_f = 1 + \frac{0.4\mu D}{h} = 1 + \frac{0.4\times 0.4\times 50}{12.5} = 1.64$$

Lastly, the forging force is

$$F = K_f \sigma_f A = 1.64 \times 85 \times 1960 = \boxed{273 \text{ kN}}$$

♦ The correct answer is **B.**

P.16 ■ Solution

The initial volume of the part is

$$V = \pi D^2 L/4 = \pi \times 45^2 \times 40/4 = 63,600 \text{ mm}^3$$

The flow stress at yield is

$$\sigma_f = 600 \times 0.002^{0.12} = 285 \text{ MPa}$$

The height of the part at yield is

$$h = 40 - 40 \times 0.002 = 39.92 \text{ mm}$$

and the corresponding area is

$$V = Ah \rightarrow A = \frac{V}{h}$$

$$\therefore A = \frac{63,600}{39.92} = 1590 \text{ mm}^2$$

The forging shape factor is determined next,

$$K_f = 1 + \frac{0.4\mu D}{h} = 1 + \frac{0.4 \times 0.20 \times 45}{39.92} = 1.09$$

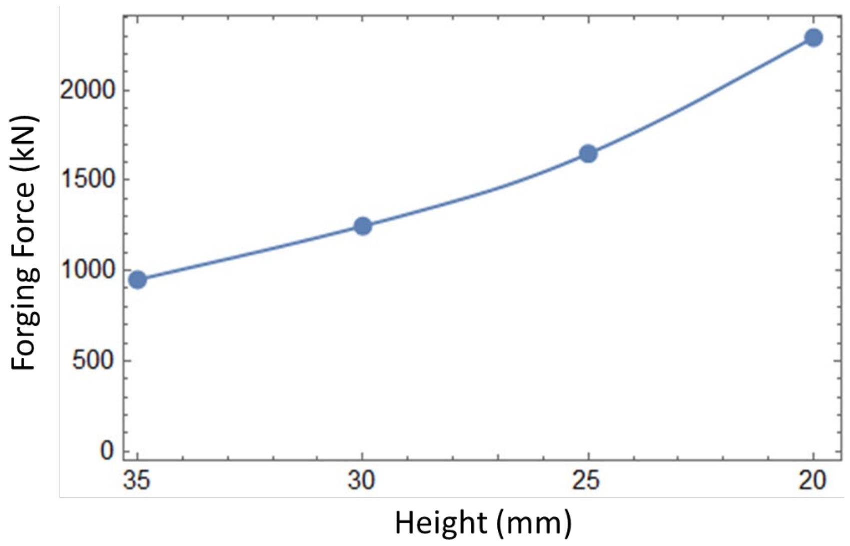
It remains to compute the forging force,

$$F = K_f \sigma_f A = 1.09 \times 285 \times 1560 = \boxed{485 \text{ kN}}$$

The forces for other deformation values are tabulated below.

h (mm)	Strain	σ_f (MPa)	A (mm²)	D (mm)	K_f	F (kN)
35	0.134	471	1817	48.1	1.11	950
30	0.288	517	2120	52.0	1.14	1247
25	0.470	548	2544	56.9	1.18	1648
20	0.693	574	3180	63.6	1.25	2291

A plot of force (red column) vs. work height (blue column) is shown in continuation.



P.17 ■ Solution

The volume of the cylinder is $V = \pi \times 2.5^2 \times 4.0/4 = 19.6$ in.³ At $h = 4.0$ in., we assume yielding has just occurred and the height has not changed significantly. As usual, we take the yield strain to be $\varepsilon = 0.002$. The flow stress is

$$\sigma_f = 25,000 \times 0.002^{0.22} = 6370 \text{ psi}$$

The height for this strain is

$$h = 4.0 - 0.002 \times 4.0 = 3.992 \text{ in.}$$

and the corresponding area is

$$V = Ah \rightarrow A = \frac{V}{h}$$

$$\therefore A = \frac{19.6}{3.992} = 4.91 \text{ in.}^2$$

The forging shape factor is

$$K_f = 1 + \frac{0.4\mu D}{h} = 1 + \frac{0.4 \times 0.10 \times 2.5}{4.0} = 1.03$$

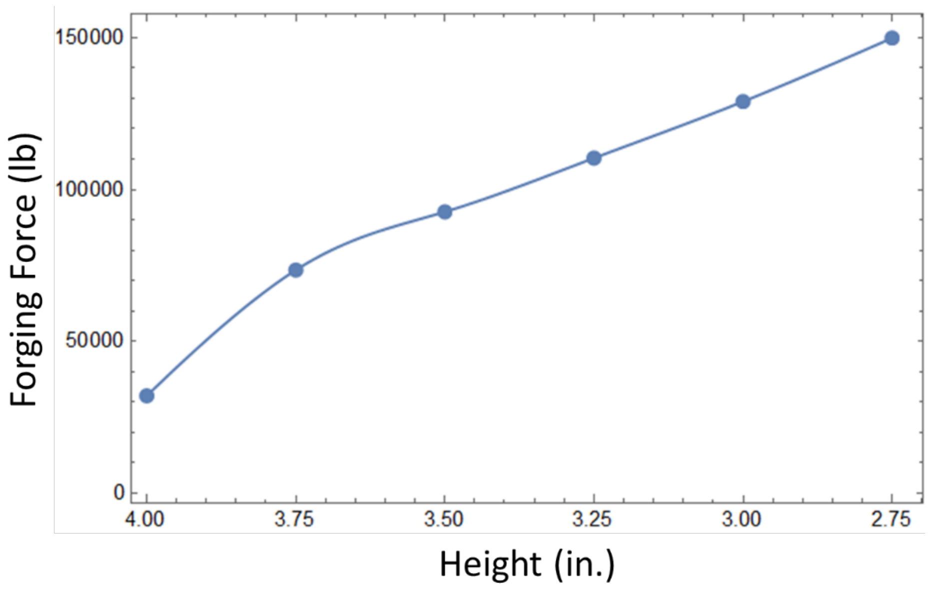
Lastly, the forging force is

$$F = K_f \sigma_f A = 1.03 \times 6370 \times 4.91 = 32,200 \text{ lb}$$

Forging forces for other values of final height are tabulated below.

h (in)	Strain	σ_f (psi)	*A* (in.²)	D (in.)	K_f	*F* (lb)
4	0.002	6370	4.91	2.50	1.03	32060
3.75	0.065	13680	5.23	2.58	1.03	73471
3.5	0.134	16053	5.60	2.7	1.03	92643
3.25	0.208	17691	6.03	2.8	1.03	110329
3	0.288	19006	6.53	2.9	1.04	128952
2.75	0.375	20144	7.13	3.0	1.04	149865

The load stroke curve is a plot of force (red column) versus height (blue column), as shown in continuation.



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