IMPORTANT TERMS AND CONCEPTS

Anelasticity
Design stress
Ductility
Elastic deformation
Elastic recovery
Engineering strain
Engineering stress
Hardness
Modulus of elasticity
Plastic deformation
Poisson's ratio
Proportional limit
Resilience
Safe stress
Shear
Tensile strength
Toughness
True strain
True stress
Yielding
Yield strength

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QUESTIONS AND PROBLEMS

Concepts of Stress and Strain

6.1 Using mechanics of materials principles (i.e., equations of mechanical equilibrium applied to a free-body diagram), derive Equations 6.4a and 6.4b.

6.2 **(a)** Equations 6.4a and 6.4b are expressions for normal (σ') and shear (τ') stresses, respectively, as a function of the applied tensile stress (σ) and the inclination angle of the plane on which these stresses are taken (θ of Figure 6.4). Make a plot on which is presented the orientation parameters of these expressions (i.e., $\cos^2\theta$ and $\sin\theta\cos\theta$) versus θ.

(b) From this plot, at what angle of inclination is the normal stress a maximum?

(c) Also, at what inclination angle is the shear stress a maximum?

Stress–Strain Behavior

6.3 A specimen of copper having a rectangular cross section 15.2 mm × 19.1 mm (0.60 in. × 0.75 in.) is pulled in tension with 44,500 N (10,000 lb_f) force, producing only elastic deformation. Calculate the resulting strain.

6.4 A cylindrical specimen of a nickel alloy having an elastic modulus of 207 GPa (30×10^6 psi) and an original diameter of 10.2 mm (0.40 in.) will experience only elastic deformation when a tensile load of 8900 N (2000 lb_f) is applied. Compute the maximum length of the specimen before deformation if the maximum allowable elongation is 0.25 mm (0.010 in.).

6.5 An aluminum bar 125 mm (5.0 in.) long and having a square cross section 16.5 mm (0.65 in.) on an edge is pulled in tension with a load of 66,700 N (15,000 lb_f), and experiences an elongation of 0.43 mm (1.7×10^{-2} in.). Assuming that the deformation is entirely elastic, calculate the modulus of elasticity of the aluminum.

6.6 Consider a cylindrical nickel wire 2.0 mm (0.08 in.) in diameter and 3×10^4 mm (1200 in.) long. Calculate its elongation when a load of 300 N (67 lb_f) is applied. Assume that the deformation is totally elastic.

6.7 For a brass alloy, the stress at which plastic deformation begins is 345 MPa (50,000 psi), and the modulus of elasticity is 103 GPa (15.0×10^6 psi).

(a) What is the maximum load that may be applied to a specimen with a cross-sectional area of 130 mm^2 (0.2 $in.^2$) without plastic deformation?

(b) If the original specimen length is 76 mm (3.0 in.), what is the maximum length to which it may be stretched without causing plastic deformation?

6.8 A cylindrical rod of steel (E = 207 GPa, 30×10^6 psi) having a yield strength of 310 MPa (45,000 psi) is to be subjected to a load of 11,100 N (2500 lb_f). If the length of the rod is 500 mm (20.0 in.), what must be the diameter to allow an elongation of 0.38 mm (0.015 in.)?

6.9 Consider a cylindrical specimen of a steel alloy (Figure 6.21) 8.5 mm (0.33 in.) in diameter and 80 mm (3.15 in.) long that is pulled in tension. Determine its elongation when a load of 65,250 N (14,500 lb_f) is applied.

6.10 Figure 6.22 shows, for a gray cast iron, the tensile engineering stress–strain curve in the elastic region. Determine **(a)** the tangent modulus at 25 MPa (3625 psi), and **(b)** the secant modulus taken to 35 MPa (5000 psi).

6.11 As noted in Section 3.15, for single crystals of some substances, the physical properties are anisotropic; that is, they are dependent on crystallographic direction. One such property is the modulus of elasticity. For cubic single crystals, the modulus of elasticity in a general [uvw] direction, E_{uvw}, is described by the relationship

$$\frac{1}{E_{uvw}} = \frac{1}{E_{\langle 100\rangle}} - 3\left(\frac{1}{E_{\langle 100\rangle}} - \frac{1}{E_{\langle 111\rangle}}\right)(\alpha^2\beta^2 + \beta^2\gamma^2 + \gamma^2\alpha^2)$$

where $E_{\langle 100\rangle}$ and $E_{\langle 111\rangle}$ are the moduli of elasticity in [100] and [111] directions, respectively; α, β, and γ are the cosines of the angles between [uvw] and the respective [100], [010], and [001] directions. Verify that the $E_{\langle 110\rangle}$ values for aluminum, copper, and iron in Table 3.3 are correct.

6.12 In Section 2.6 it was noted that the net bonding energy E_N between two isolated positive and negative ions is a function of interionic distance r as follows:

$$E_N = -\frac{A}{r} + \frac{B}{r^n} \qquad (6.25)$$

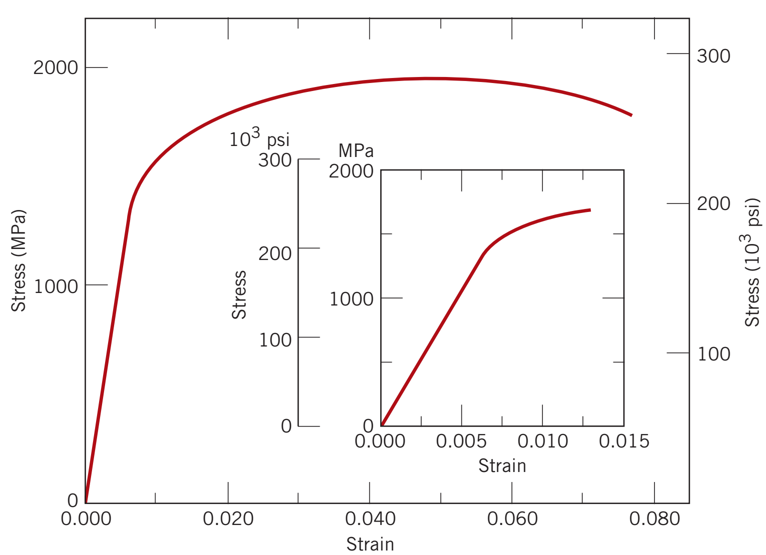

Figure 6.21 Tensile stress–strain behavior for an alloy steel.

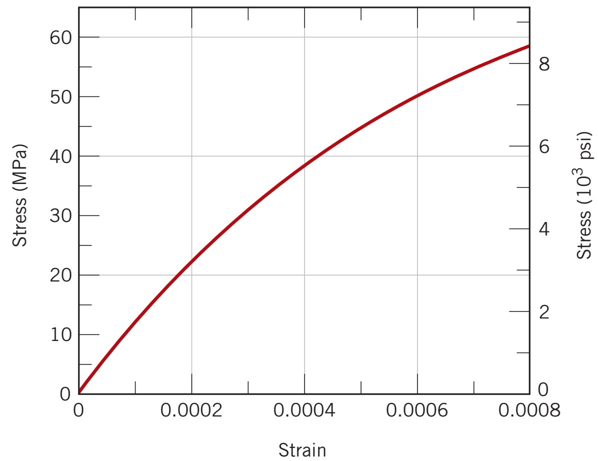

Figure 6.22 Tensile stress–strain behavior for a gray cast iron.

where A, B, and n are constants for the particular ion pair. Equation 6.25 is also valid for the bonding energy between adjacent ions in solid materials. The modulus of elasticity E is proportional to the slope of the interionic force–separation curve at the equilibrium interionic separation; that is,

$$E \propto \left(\frac{dF}{dr}\right)_{r_0}$$

Derive an expression for the dependence of the modulus of elasticity on these A, B, and n parameters (for the two-ion system) using the following procedure:

1. Establish a relationship for the force F as a function of r, realizing that

$$F = \frac{dE_N}{dr}$$

2. Now take the derivative dF/dr.

3. Develop an expression for r_0, the equilibrium separation. Since r_0 corresponds to the value of r at the minimum of the E_N-versus-r curve (Figure 2.8*b*), take the derivative dE_N/dr, set it equal to zero, and solve for r, which corresponds to r_0.

4. Finally, substitute this expression for r_0 into the relationship obtained by taking dF/dr.

6.13 Using the solution to Problem 6.12, rank the magnitudes of the moduli of elasticity for the following hypothetical X, Y, and Z materials from the greatest to the least. The appropriate A, B, and n parameters (Equation 6.25) for these three materials are tabulated below; they yield E_N in units of electron volts and r in nanometers:

Material	*A*	*B*	*n*
X	1.5	7.0×10^{-6}	8
Y	2.0	1.0×10^{-5}	9
Z	3.5	4.0×10^{-6}	7

Elastic Properties of Materials

6.14 A cylindrical specimen of steel having a diameter of 15.2 mm (0.60 in.) and length of 250 mm (10.0 in.) is deformed elastically in tension with a force of 48,900 N (11,000 lb_f). Using the data contained in Table 6.1, determine the following:

(a) The amount by which this specimen will elongate in the direction of the applied stress.

(b) The change in diameter of the specimen. Will the diameter increase or decrease?

6.15 A cylindrical bar of aluminum 19 mm (0.75 in.) in diameter is to be deformed elastically by application of a force along the bar axis. Using the data in Table 6.1, determine the force that will produce an elastic reduction of 2.5×10^{-3} mm (1.0×10^{-4} in.) in the diameter.

6.16 A cylindrical specimen of some metal alloy 10 mm (0.4 in.) in diameter is stressed elastically in tension. A force of 15,000 N (3370 lb_f) produces a reduction in specimen diameter of 7×10^{-3} mm (2.8×10^{-4} in.). Compute Poisson's ratio for this material if its elastic modulus is 100 GPa (14.5×10^6 psi).

6.17 A cylindrical specimen of a hypothetical metal alloy is stressed in compression. If its original and final diameters are 30.00 and 30.04 mm, respectively, and its final length is 105.20 mm, compute its original length if the deformation is totally elastic. The elastic and shear moduli for this alloy are 65.5 and 25.4 GPa, respectively.

6.18 Consider a cylindrical specimen of some hypothetical metal alloy that has a diameter of 10.0 mm (0.39 in.). A tensile force of 1500 N (340 lb_f) produces an elastic reduction in diameter of 6.7×10^{-4} mm (2.64×10^{-5} in.). Compute the elastic modulus of this alloy, given that Poisson's ratio is 0.35.

6.19 A brass alloy is known to have a yield strength of 240 MPa (35,000 psi), a tensile strength of 310 MPa (45,000 psi), and an elastic modulus of 110 GPa (16.0×10^6 psi). A cylindrical specimen of this alloy 15.2 mm (0.60 in.) in diameter and 380 mm (15.0 in.) long is stressed in tension and found to elongate 1.9 mm (0.075 in.). On the basis of the information given, is it possible to compute the magnitude of the load that is necessary to produce this change in length? If so, calculate the load. If not, explain why.

6.20 A cylindrical metal specimen 15.0 mm (0.59 in.) in diameter and 150 mm (5.9 in.) long is to be subjected to a tensile stress of 50 MPa (7250 psi); at this stress level the resulting deformation will be totally elastic.

(a) If the elongation must be less than 0.072 mm (2.83×10^{-3} in.), which of the metals in Table 6.1 are suitable candidates? Why?

(b) If, in addition, the maximum permissible diameter decrease is 2.3×10^{-3} mm (9.1×10^{-5} in.) when the tensile stress of 50 MPa is applied, which of the metals that satisfy the criterion in part (a) are suitable candidates? Why?

6.21 Consider the brass alloy for which the stress–strain behavior is shown in Figure 6.12. A cylindrical specimen of this material 10.0 mm (0.39 in.) in diameter and 101.6 mm (4.0 in.) long is pulled in tension with a force of 10,000 N (2250 lb_f). If it is known that this alloy has a value for Poisson's ratio of 0.35, compute **(a)** the specimen elongation, and **(b)** the reduction in specimen diameter.

6.22 A cylindrical rod 120 mm long and having a diameter of 15.0 mm is to be deformed using a tensile load of 35,000 N. It must not experience either plastic deformation or a diameter reduction of more than 1.2×10^{-2} mm. Of the materials listed below, which are possible candidates? Justify your choice(s).

Material	*Modulus of Elasticity (GPa)*	*Yield Strength (MPa)*	*Poisson's Ratio*
Aluminum alloy	70	250	0.33
Titanium alloy	105	850	0.36
Steel alloy	205	550	0.27
Magnesium alloy	45	170	0.35

6.23 A cylindrical rod 500 mm (20.0 in.) long, having a diameter of 12.7 mm (0.50 in.), is to be subjected to a tensile load. If the rod is to experience neither plastic deformation nor an elongation of more than 1.3 mm (0.05 in.) when the applied load is 29,000 N (6500 lb_f), which of the four metals or alloys listed below are possible candidates? Justify your choice(s).

Material	*Modulus of Elasticity (GPa)*	*Yield Strength (MPa)*	*Tensile Strength (MPa)*
Aluminum alloy	70	255	420
Brass alloy	100	345	420
Copper	110	210	275
Steel alloy	207	450	550

Tensile Properties

6.24 Figure 6.21 shows the tensile engineering stress–strain behavior for a steel alloy.

(a) What is the modulus of elasticity?

(b) What is the proportional limit?

(c) What is the yield strength at a strain offset of 0.002?

(d) What is the tensile strength?

6.25 A cylindrical specimen of a brass alloy having a length of 100 mm (4 in.) must elongate only 5 mm (0.2 in.) when a tensile load of 100,000 N (22,500 lb_f) is applied. Under these circumstances what must be the radius of the specimen? Consider this brass alloy to have the stress–strain behavior shown in Figure 6.12.

6.26 A load of 140,000 N (31,500 lb_f) is applied to a cylindrical specimen of a steel alloy (displaying the stress–strain behavior shown in Figure 6.21) that has a cross-sectional diameter of 10 mm (0.40 in.).

(a) Will the specimen experience elastic and/or plastic deformation? Why?

(b) If the original specimen length is 500 mm (20 in.), how much will it increase in length when this load is applied?

6.27 A bar of a steel alloy that exhibits the stress–strain behavior shown in Figure 6.21 is subjected to a tensile load; the specimen is 375 mm (14.8 in.) long and of square cross section 5.5 mm (0.22 in.) on a side.

(a) Compute the magnitude of the load necessary to produce an elongation of 2.25 mm (0.088 in.).

(b) What will be the deformation after the load has been released?

6.28 A cylindrical specimen of stainless steel having a diameter of 12.8 mm (0.505 in.) and a gauge length of 50.800 mm (2.000 in.) is pulled in tension. Use the load–elongation characteristics tabulated below to complete parts (a) through (f).

Load		*Length*	
N	***lb_f***	***mm***	***in.***
0	0	50.800	2.000
12,700	2,850	50.825	2.001
25,400	5,710	50.851	2.002
38,100	8,560	50.876	2.003
50,800	11,400	50.902	2.004
76,200	17,100	50.952	2.006
89,100	20,000	51.003	2.008
92,700	20,800	51.054	2.010
102,500	23,000	51.181	2.015
107,800	24,200	51.308	2.020
119,400	26,800	51.562	2.030
128,300	28,800	51.816	2.040
149,700	33,650	52.832	2.080
159,000	35,750	53.848	2.120
160,400	36,000	54.356	2.140
159,500	35,850	54.864	2.160
151,500	34,050	55.880	2.200
124,700	28,000	56.642	2.230
Fracture			

(a) Plot the data as engineering stress versus engineering strain.

(b) Compute the modulus of elasticity.

(c) Determine the yield strength at a strain offset of 0.002.

(d) Determine the tensile strength of this alloy.

(e) What is the approximate ductility, in percent elongation?

(f) Compute the modulus of resilience.

6.29 A specimen of magnesium having a rectangular cross section of dimensions 3.2 mm × 19.1 mm ($\frac{1}{8}$ in. × $\frac{3}{4}$ in.) is deformed in tension. Using the load–elongation data tabulated as follows, complete parts (a) through (f).

Load		*Length*	
lb_f	***N***	***in.***	***mm***
0	0	2.500	63.50
310	1380	2.501	63.53
625	2780	2.502	63.56
1265	5630	2.505	63.62
1670	7430	2.508	63.70
1830	8140	2.510	63.75
2220	9870	2.525	64.14
2890	12,850	2.575	65.41
3170	14,100	2.625	66.68
3225	14,340	2.675	67.95
3110	13,830	2.725	69.22
2810	12,500	2.775	70.49
Fracture			

(a) Plot the data as engineering stress versus engineering strain.

(b) Compute the modulus of elasticity.

(c) Determine the yield strength at a strain offset of 0.002.

(d) Determine the tensile strength of this alloy.

(e) Compute the modulus of resilience.

(f) What is the ductility, in percent elongation?

6.30 A cylindrical metal specimen having an original diameter of 12.8 mm (0.505 in.) and gauge length of 50.80 mm (2.000 in.) is pulled in tension until fracture occurs. The diameter at the point of fracture is 8.13 mm (0.320 in.), and the fractured gauge length is 74.17 mm (2.920 in.). Calculate the ductility in terms of percent reduction in area and percent elongation.

6.31 Calculate the moduli of resilience for the materials having the stress–strain behaviors shown in Figures 6.12 and 6.21.

6.32 Determine the modulus of resilience for each of the following alloys:

Material	*Yield Strength* *MPa*	*psi*
Steel alloy	830	120,000
Brass alloy	380	55,000
Aluminum alloy	275	40,000
Titanium alloy	690	100,000

Use modulus of elasticity values in Table 6.1.

6.33 A steel alloy to be used for a spring application must have a modulus of resilience of at least 2.07 MPa (300 psi). What must be its minimum yield strength?

True Stress and Strain

6.34 Show that Equations 6.18a and 6.18b are valid when there is no volume change during deformation.

6.35 Demonstrate that Equation 6.16, the expression defining true strain, may also be represented by

$$\epsilon_T = \ln\left(\frac{A_0}{A_i}\right)$$

when specimen volume remains constant during deformation. Which of these two expressions is more valid during necking? Why?

6.36 Using the data in Problem 6.28 and Equations 6.15, 6.16, and 6.18a, generate a true stress–true strain plot for stainless steel. Equation 6.18a becomes invalid past the point at which necking begins; therefore, measured diameters are given below for the last three data points, which should be used in true stress computations.

Load *N*	*Load* *lb_f*	*Length* *mm*	*Length* *in.*	*Diameter* *mm*	*Diameter* *in.*
159,500	35,850	54.864	2.160	12.22	0.481
151,500	34,050	55.880	2.200	11.80	0.464
124,700	28,000	56.642	2.230	10.65	0.419

6.37 A tensile test is performed on a metal specimen, and it is found that a true plastic strain of 0.16 is produced when a true stress of 500 MPa (72,500 psi) is applied; for the same metal, the value of K in Equation 6.19 is 825 MPa (120,000 psi). Calculate the true strain that results from the application of a true stress of 600 MPa (87,000 psi).

6.38 For some metal alloy, a true stress of 345 MPa (50,000 psi) produces a plastic true strain of 0.02. How much will a specimen of this material elongate when a true stress of 415 MPa (60,000 psi) is applied if the original length is 500 mm (20 in.)? Assume a value of 0.22 for the strain-hardening exponent, n.

6.39 The following true stresses produce the corresponding true plastic strains for a brass alloy:

True Stress (psi)	*True Strain*
60,000	0.15
70,000	0.25

What true stress is necessary to produce a true plastic strain of 0.21?

6.40 For a brass alloy, the following engineering stresses produce the corresponding plastic engineering strains, prior to necking:

Engineering Stress (MPa)	*Engineering Strain*
315	0.105
340	0.220

On the basis of this information, compute the *engineering* stress necessary to produce an *engineering* strain of 0.28.

6.41 Find the toughness (or energy to cause fracture) for a metal that experiences both elastic and plastic deformation. Assume Equation 6.5 for elastic deformation, that the modulus of elasticity is 103 GPa (15×10^6 psi), and that elastic deformation terminates at a strain of 0.007. For plastic deformation, assume that the relationship between stress and strain is described by Equation 6.19, in which the values for K and n are 1520 MPa (221,000 psi) and 0.15, respectively. Furthermore, plastic deformation occurs between strain values of 0.007 and 0.60, at which point fracture occurs.

6.42 For a tensile test, it can be demonstrated that necking begins when

$$\frac{d\sigma_T}{d\epsilon_T} = \sigma_T \tag{6.26}$$

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EQA

Using Equation 6.19, determine the value of the true strain at this onset of necking.

6.43 Taking the logarithm of both sides of Equation 6.19 yields

$$\log \sigma_T = \log K + n \log \epsilon_T \qquad (6.27)$$

Thus, a plot of $\log \sigma_T$ versus $\log \epsilon_T$ in the plastic region to the point of necking should yield a straight line having a slope of n and an intercept (at $\log \sigma_T = 0$) of $\log K$.

Using the appropriate data tabulated in Problem 6.28, make a plot of $\log \sigma_T$ versus $\log \epsilon_T$ and determine the values of n and K. It will be necessary to convert engineering stresses and strains to true stresses and strains using Equations 6.18a and 6.18b.

Elastic Recovery After Plastic Deformation

6.44 A cylindrical specimen of a brass alloy 10.0 mm (0.39 in.) in diameter and 120.0 mm (4.72 in.) long is pulled in tension with a force of 11,750 N (2640 lb_f); the force is subsequently released.

(a) Compute the final length of the specimen at this time. The tensile stress–strain behavior for this alloy is shown in Figure 6.12.

(b) Compute the final specimen length when the load is increased to 23,500 N (5280 lb_f) and then released.

6.45 A steel alloy specimen having a rectangular cross section of dimensions 19 mm × 3.2 mm ($\frac{3}{4}$ in. × $\frac{1}{8}$ in.) has the stress–strain behavior shown in Figure 6.21. If this specimen is subjected to a tensile force of 110,000 N (25,000 lb_f) then

(a) Determine the elastic and plastic strain values.

(b) If its original length is 610 mm (24.0 in.), what will be its final length after the load in part (a) is applied and then released?

Hardness

6.46 **(a)** A 10-mm-diameter Brinell hardness indenter produced an indentation 2.50 mm in diameter in a steel alloy when a load of 1000 kg was used. Compute the HB of this material.

(b) What will be the diameter of an indentation to yield a hardness of 300 HB when a 500-kg load is used?

6.47 Estimate the Brinell and Rockwell hardnesses for the following:

(a) The naval brass for which the stress–strain behavior is shown in Figure 6.12.

(b) The steel alloy for which the stress–strain behavior is shown in Figure 6.21.

6.48 Using the data represented in Figure 6.19, specify equations relating tensile strength and Brinell hardness for brass and nodular cast iron, similar to Equations 6.20a and 6.20b for steels.

Variability of Material Properties

6.49 Cite five factors that lead to scatter in measured material properties.

6.50 Below are tabulated a number of Rockwell G hardness values that were measured on a single steel specimen. Compute average and standard deviation hardness values.

47.3	48.7	47.1
52.1	50.0	50.4
45.6	46.2	45.9
49.9	48.3	46.4
47.6	51.1	48.5
50.4	46.7	49.7

Design/Safety Factors

6.51 Upon what three criteria are factors of safety based?

6.52 Determine working stresses for the two alloys that have the stress–strain behaviors shown in Figures 6.12 and 6.21.

DESIGN PROBLEMS

6.D1 A large tower is to be supported by a series of steel wires; it is estimated that the load on each wire will be 13,300 N (3000 lb_f). Determine the minimum required wire diameter, assuming a factor of safety of 2 and a yield strength of 860 MPa (125,000 psi) for the steel.

6.D2 **(a)** Gaseous hydrogen at a constant pressure of 0.658 MPa (5 atm) is to flow within the inside of a thin-walled cylindrical tube of nickel that has a radius of 0.125 m. The temperature of the tube is to be 350°C and the pressure of hydrogen outside of the tube will be maintained at 0.0127 MPa (0.125 atm). Calculate the minimum wall thickness if the diffusion flux is to be no greater than 1.25×10^{-7} mol/m^2-s. The concentration of hydrogen in the nickel, C_H (in moles hydrogen per m^3 of Ni) is a function of hydrogen pressure, P_{H_2} (in MPa) and absolute temperature (T) according to

$$C_H = 30.8\sqrt{p_{H_2}}\exp\left(-\frac{12.3 \text{ kJ/mol}}{RT}\right) \quad (6.28)$$

Furthermore, the diffusion coefficient for the diffusion of H in Ni depends on temperature as

$$D_H(\text{m}^2/\text{s}) = 4.76 \times 10^{-7}\exp\left(-\frac{39.56 \text{ kJ/mol}}{RT}\right) \quad (6.29)$$

(b) For thin-walled cylindrical tubes that are pressurized, the circumferential stress is a function of the pressure difference across the wall (Δp), cylinder radius (r), and tube thickness (Δx) as

$$\sigma = \frac{r\Delta p}{4\Delta x} \quad (6.30)$$

Compute the circumferential stress to which the walls of this pressurized cylinder are exposed.

(c) The room-temperature yield strength of Ni is 100 MPa (15,000 psi) and, furthermore, σ_y diminishes about 5 MPa for every 50°C rise in temperature. Would you expect the wall thickness computed in part (b) to be suitable for this Ni cylinder at 350°C? Why or why not?

(d) If this thickness is found to be suitable, compute the minimum thickness that could be used without any deformation of the tube walls. How much would the diffusion flux increase with this reduction in thickness? On the other hand, if the thickness determined in part (c) is found to be unsuitable, then specify a minimum thickness that you would use. In this case, how much of a diminishment in diffusion flux would result?

6.D3 Consider the steady-state diffusion of hydrogen through the walls of a cylindrical nickel tube as described in Problem 6.D2. One design calls for a diffusion flux of 2.5×10^{-8} mol/m^2-s, a tube radius of 0.100 m, and inside and outside pressures of 1.015 MPa (10 atm) and 0.01015 MPa (0.1 atm), respectively; the maximum allowable temperature is 300°C. Specify a suitable temperature and wall thickness to give this diffusion flux and yet ensure that the tube walls will not experience any permanent deformation.