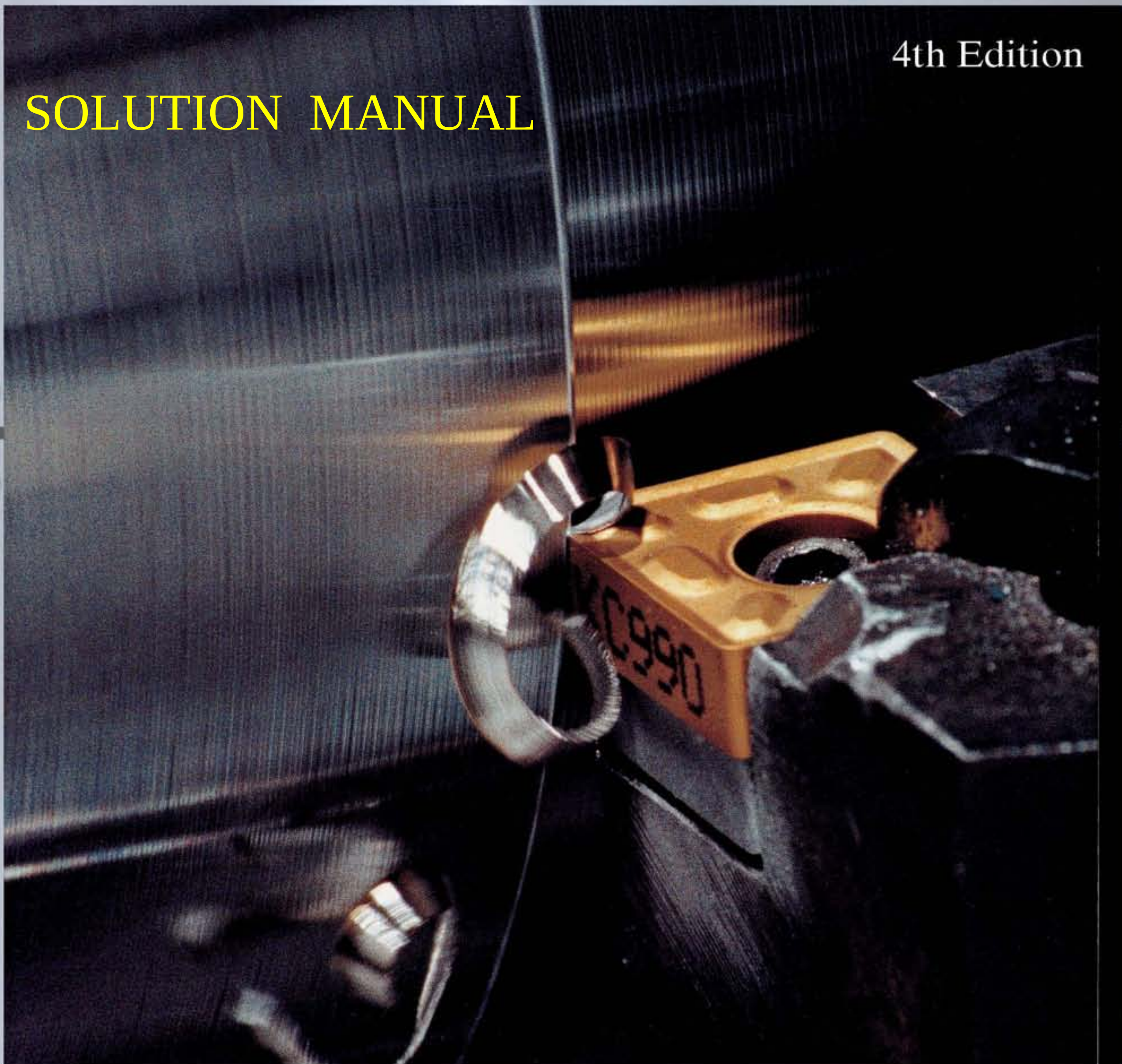
Fundamentals of Modern Manufacturing

Materials, Processes, and Systems



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1 INTRODUCTION

Review Questions

1.1 What are the differences between primary, secondary, and tertiary industries? Give an example of each category.

Answer. A primary industry is one that cultivates and exploits natural resources, such as agriculture or mining. A secondary industry takes the outputs of primary industries and converts them to consumer and capital goods. Examples of secondary industries are textiles and electronics. A tertiary industry is in the service sector of the economy. Examples of tertiary industries are banking and education.

1.2 What is a capital good? Provide an example.

Answer. Capital goods are those purchased by companies to produce goods or provide services. Examples of capital goods are aircraft and construction equipment.

1.3 How are product variety and production quantity related when comparing typical factories?

Answer. Generally production quantity is inversely related to product variety. A factory that produces a large variety of products will produce a smaller quantity of each. A company that produces a single product will produce a large quantity.

1.4 Define manufacturing capability.

Answer. Manufacturing capability refers to the technical and physical limitations of a manufacturing firm and each of its plants. Three categories of capability mentioned in the text are (1) technological processing capability, (2) physical size and weight, and (3) production capacity.

1.5 Name the three basic categories of materials.

Answer. The three basic categories of engineering materials are (1) metals, (2) ceramics, and (3) polymers. A fourth category, composites, is a non-homogeneous mixture of the other types and therefore is not a basic category.

1.6 How does a shaping process differ from a surface processing operation?

Answer. A shaping process changes the geometry of the work material (machining or forging). A surface processing operation does not alter the geometry, but instead alters surface of the work (painting or plating).

1.7 What are two subclasses of assembly processes? Provide an example process for each subclass.

Answer. The two subclasses of assembly processes are (1) permanent joining and (2) mechanical fastening. Examples of permanent joining include welding or adhesive bonding. Examples of mechanical fastening include threaded fasteners, such as nuts and bolts, and rivets.

1.8 Define batch production and describe why it is often used for medium-quantity production products.

Answer. Batch production is where groups, lots, or batches or materials or parts are processed together through the manufacturing operations. All units in the batch are processed at a given station before the group proceeds to the next station. In a medium or low quantity production situation, the same machines are used to produce many types of products. Whenever a machine switches from one product to another, a changeover occurs. The changeover requires the machine setup to be torn down and set up for the new product. Batch production allows the changeover time to be distributed across a larger number of parts and hence reduce the average operation time per part.

1.9 What is the difference between a process layout and a product layout in a production facility?

Answer. A process layout is one where the machinery in a plant is arranged based on the type of process it performs. To produce a product it must visit the departments in the order of the operations that must be performed. This often includes large travel distances within the plant. A process layout is often used when the product variety is large the operation sequences of products are dissimilar. A product layout is one where the machinery is arranged based on the general flow of the products that will be produced. Travel distance is reduced because products will generally flow to the next machine in the sequence. A product layout works well when all products tend to follow the same sequence of production.

1.10 Name two departments that are typically classified as manufacturing support departments.

Answer. A common organizational structure includes the following three manufacturing support departments: (1) manufacturing engineering, (2) production planning and control, and (3) quality control.

Multiple Choice Quiz

There are 18 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

1.1 Which of the following industries are classified as secondary industries (three correct answers): (a) beverages (b) financial services, (c) fishing, (d) mining, (e) power utilities, (f) publishing, and (g) transportation?

Answer. (a), (e), and (f).

1.2 Mining is classified in which one of the following industry categories: (a) agricultural industry, (b) manufacturing industry, (c) primary industry, (d) secondary industry, (e) service industry, or (f) tertiary industry?

Answer. (c).

1.3 Inventions of the Industrial Revolution include which one of the following: (a) automobile, (b) cannon, (c) printing press, (d) steam engine, or (e) sword?

Answer. (d).

1.4 Ferrous metals include which of the following (two correct answers): (a) aluminum, (b) cast iron, (c) copper, (d) gold, and (e) steel?

Answer. (c) and (e).

1.5 Which one of the following engineering materials is defined as a compound containing metallic and nonmetallic elements: (a) ceramic, (b) composite, (c) metal, or (d) polymer?

Answer. (a).

1.6 Which of the following processes start with a material that is in a fluid or semifluid state and solidifies the material in a cavity (two best answers): (a) casting, (b) forging, (c) machining, (d) molding, (e) pressing, and (f) turning?

Answer. (a) and (d).

1.7 Particulate processing of metals and ceramics involves which of the following steps (two best answers): (a) adhesive bonding, (b) deformation, (c) forging, (d) material removal, (e) melting, (f) pressing, and (g) sintering?

Answer. (f) and (g).

1.8 Deformation processes include which of the following (two correct answers): (a) casting, (b) drilling, (c) extrusion, (d) forging, (e) milling, (f) painting, and (g) sintering?

Answer. (c) and (d).

1.9 Which one of the following is a machine used to perform extrusion: (a) forge hammer, (b) milling machine, (c) rolling mill, (d) press, (e) torch?

Answer. (d).

1.10 High-volume production of assembled products is most closely associated with which one of the following layout types: (a) cellular layout, (b) fixed position layout, (c) process layout, or (d) product layout?

Answer. (d).

1.11 A production planning and control department accomplishes which of the following functions in its role of providing manufacturing support (two best answers): (a) designs and orders machine tools, (b) develops corporate strategic plans, (c) orders materials and purchased parts, (d) performs quality inspections, and (e) schedules the order of products on a machine?

Answer. (c) and (e).

2 THE NATURE OF MATERIALS

Review Questions

2.1 The elements listed in the Periodic Table can be divided into three categories. What are these categories and give an example of each?

Answer. The three types of elements are metals (e.g., aluminum), nonmetals (e.g., oxygen), and semimetals (e.g., silicon).

2.2 Which elements are the noble metals?

Answer. The noble metals are copper, silver, and gold.

2.3 What is the difference between primary and secondary bonding in the structure of materials?

Answer. Primary bonding is strong bonding between atoms in a material, for example to form a molecule; while secondary bonding is not as strong and is associated with attraction between molecules in the material.

2.4 Describe how ionic bonding works?

Answer. In ionic bonding, atoms of one element give up their outer electron(s) to the atoms of another element to form complete outer shells.

2.5 What is the difference between crystalline and noncrystalline structures in materials?

Answer. The atoms in a crystalline structure are located at regular and repeating lattice positions in three dimensions; thus, the crystal structure possesses a long-range order which allows a high packing density. The atoms in a noncrystalline structure are randomly positioned in the material, not possessing any repeating, regular pattern.

2.6 What are some common point defects in a crystal lattice structure?

Answer. The common point defects are (1) vacancy - a missing atom in the lattice structure; (2) ion-pair vacancy (Schottky defect) - a missing pair of ions of opposite charge in a compound; (3) interstitialcy - a distortion in the lattice caused by an extra atom present; and (4) Frenkel defect - an ion is removed from a regular position in the lattice and inserted into an interstitial position not normally occupied by such an ion.

2.7 Define the difference between elastic and plastic deformation in terms of the effect on the crystal lattice structure.

Answer. Elastic deformation involves a temporary distortion of the lattice structure that is proportional to the applied stress. Plastic deformation involves a stress of sufficient magnitude to cause a permanent shift in the relative positions of adjacent atoms in the lattice. Plastic deformation generally involves the mechanism of slip - relative movement of atoms on opposite sides of a plane in the lattice.

2.8 How do grain boundaries contribute to the strain hardening phenomenon in metals?

Answer. Grain boundaries block the continued movement of dislocations in the metal during straining. As more dislocations become blocked, the metal becomes more difficult to deform; in effect it becomes stronger.

2.9 Identify some materials that have a crystalline structure.

Answer. Materials typically possessing a crystalline structure are metals and ceramics other than glass. Some plastics have a partially crystalline structure.

2.10 Identify some materials that possess a noncrystalline structure.

Answer. Materials typically having a noncrystalline structure include glass (fused silica), rubber, and certain plastics (specifically, thermosetting plastics).

2.11 What is the basic difference in the solidification (or melting) process between crystalline and noncrystalline structures?

Answer. Crystalline structures undergo an abrupt volumetric change as they transform from liquid to solid state and vice versa. This is accompanied by an amount of energy called the heat of fusion that must be added to the material during melting or released during solidification. Noncrystalline materials melt and solidify without the abrupt volumetric change and heat of fusion.

Multiple Choice Questions

There are 20 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

2.1 The basic structural unit of matter is which one of the following: (a) atom, (b) electron, (c) element, (d) molecule, or (e) nucleus?

Answer. (a).

2.2 Approximately how many different elements have been identified (one best answer): (a) 10, (b) 50, (c) 100, (d) 200, or (e) 500?

Answer. (c).

2.3 In the Periodic Table, the elements can be divided into which of the following categories (three best answers): (a) ceramics, (b) gases, (c) liquids, (d) metals, (e) nonmetals, (f) polymers, (g) semi-metals, and (h) solids?

Answer. (d), (e), and (g).

2.4 The element with the lowest density and smallest atomic weight is which one of the following: (a) aluminum, (b) argon, (c) helium, (d) hydrogen, or (e) magnesium?

Answer. (d).

2.5 Which of the following bond types are classified as primary bonds (three correct answers): (a) covalent bonding, (b) hydrogen bonding, (c) ionic bonding, (d) metallic bonding, and (e) van der Waals forces?

Answer. (a), (c), and (d).

2.6 How many atoms are there in the face-centered cubic (FCC) unit cell (one correct answer): (a) 8, (b) 9, (c) 10, (d) 12, or (e) 14?

Answer. (e).

2.7 Which of the following are not point defects in a crystal lattice structure (three correct answers): (a) edge dislocation, (b) grain boundaries, (c) interstitialcy, (d) Schottky defect, (e) screw dislocation, or (f) vacancy?

Answer. (c), (d), and (f).

2.8 Which one of the following crystal structures has the fewest slip directions and therefore the metals with this structure are generally more difficult to deform at room temperature: (a) BCC, (b) FCC, or (c) HCP?

Answer. (c).

2.9 Grain boundaries are an example of which one of the following types of crystal structure defects: (a) dislocation, (b) Frenkel defect, (c) line defects, (d) point defects, or (e) surface defects?

Answer. (e).

2.10 Twinning is which of the following (three best answers): (a) elastic deformation, (b) mechanism of plastic deformation, (c) more likely at high deformation rates, (d) more likely in metals with HCP structure, (e) slip mechanism, and (f) type of dislocation?

Answer. (b), (c), and (d).

2.11 Polymers are characterized by which of the following bonding types (two correct answers): (a) adhesive, (b) covalent, (c) hydrogen, (d) ionic, (e) metallic, and (f) van der Waals?

Answer. (b) and (f).

3 MECHANICAL PROPERTIES OF MATERIALS

Review Questions

3.1 What is the dilemma between design and manufacturing in terms of mechanical properties?

Answer. To achieve design function and quality, the material must be strong; for ease of manufacturing, the material should not be strong, in general.

3.2 What are the three types of static stresses to which materials are subjected?

Answer. tensile, compressive, and shear.

3.3 State Hooke's law.

Answer. Hooke's Law defines the stress-strain relationship for an elastic material: $\sigma = E\varepsilon$, where E = a constant of proportionality called the modulus of elasticity.

3.4 What is the difference between engineering stress and true stress in a tensile test?

Answer. Engineering stress divides the load (force) on the test specimen by the original area; while true stress divides the load by the instantaneous area which decreases as the specimen stretches.

3.5 Define tensile strength of a material.

Answer. The tensile strength is the maximum load experienced during the tensile test divided by the original area.

3.6 Define yield strength of a material.

Answer. The yield strength is the stress at which the material begins to plastically deform. It is usually measured as the 0.2% offset value, which is the point where the stress-strain curve for the material intersects a line that is parallel to the straight-line portion of the curve but offset from it by 0.2%.

3.7 Why cannot a direct conversion be made between the ductility measures of elongation and reduction in area using the assumption of constant volume?

Answer. Because of necking that occurs in the test specimen.

3.8 What is work hardening?

Answer. Work hardening, also called strain hardening, is the increase in strength that occurs in metals when they are strained.

3.9 In what case does the strength coefficient have the same value as the yield strength?

Answer. When the material is perfectly plastic and does not strain harden.

3.10 How does the change in cross-sectional area of a test specimen in a compression test differ from its counterpart in a tensile test specimen?

Answer. In a compression test, the specimen cross-sectional area increases as the test progresses; while in a tensile test, the cross-sectional area decreases.

3.11 What is the complicating factor that occurs in a compression test?

Answer. Barreling of the test specimen due to friction at the interfaces with the testing machine platens.

3.12 Tensile testing is not appropriate for hard brittle materials such as ceramics. What is the test commonly used to determine the strength properties of such materials?

Answer. A three-point bending test is commonly used to test the strength of brittle materials. The test provides a measure called the transverse rupture strength for these materials.

3.13 How is the shear modulus of elasticity G related to the tensile modulus of elasticity E, on average?

Answer. $G = 0.4\ E$, on average.

3.14 How is shear strength S related to tensile strength TS, on average?

Answer. $S = 0.7\ TS$, on average.

3.15 What is hardness, and how is it generally tested?

Answer. Hardness is defined as the resistance to indentation of a material. It is tested by pressing a hard object (sphere, diamond point) into the test material and measuring the size (depth, area) of the indentation.

3.16 Why are different hardness tests and scales required?

Answer. Different hardness tests and scales are required because different materials possess widely differing hardnesses. A test whose measuring range is suited to very hard materials is not sensitive for testing very soft materials.

3.17 Define the recrystallization temperature for a metal.

Answer. The recrystallization temperature is the temperature at which a metal recrystallizes (forms new grains) rather than work hardens when deformed.

3.18 Define viscosity of a fluid.

Answer. Viscosity is the resistance to flow of a fluid material; the thicker the fluid, the greater the viscosity.

3.19 What is the defining characteristic of a Newtonian fluid?

Answer. A Newtonian fluid is one for which viscosity is a constant property at a given temperature. Most liquids (water, oils) are Newtonian fluids.

3.20 What is viscoelasticity, as a material property?

Answer. Viscoelasticity refers to the property most commonly exhibited by polymers that defines the strain of the material as a function of stress and temperature over time. It is a combination of viscosity and elasticity.

Multiple Choice Quiz

There are 15 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

3.1 Which of the following are the three basic types of static stresses to which a material can be subjected (three correct answers): (a) compression, (b) hardness, (c) reduction in area, (d) shear, (e) tensile, (f) true stress, and (f) yield?

Answer. (a), (d), and (e).

3.2 Which one of the following is the correct definition of ultimate tensile strength, as derived from the results of a tensile test on a metal specimen: (a) the stress encountered when the stress-strain curve transforms from elastic to plastic behavior, (b) the maximum load divided by the final area of the specimen, (c) the maximum load divided by the original area of the specimen, or (d) the stress observed when the specimen finally fails?

Answer. (c).

3.3 If stress values were measured during a tensile test, which of the following would have the higher value: (a) engineering stress or (b) true stress?

Answer. (b).

3.4 If strain measurements were made during a tensile test, which of the following would have the higher value: (a) engineering strain, or (b) true strain?

Answer. (a).

3.5 The plastic region of the stress-strain curve for a metal is characterized by a proportional relationship between stress and strain: (a) true or (b) false?

Answer. (b). It is the elastic region that is characterized by a proportional relationship between stress and strain. The plastic region is characterized by a power function - the flow curve.

3.6 Which one of the following types of stress strain relationship best describes the behavior of brittle materials such as ceramics and thermosetting plastics: (a) elastic and perfectly plastic, (b) elastic and strain hardening, (c) perfectly elastic, or (d) none of the above?

Answer. (c).

3.7 Which one of the following types of stress strain relationship best describes the behavior of most metals at room temperature: (a) elastic and perfectly plastic, (b) elastic and strain hardening, (c) perfectly elastic, or (d) none of the above?

Answer. (b).

3.8 Which one of the following types of stress strain relationship best describes the behavior of metals at temperatures above their respective recrystallization points: (a) elastic and perfectly plastic, (b) elastic and strain hardening, (c) perfectly elastic, or (d) none of the above?

Answer. (a).

3.9 Which one of the following materials has the highest modulus of elasticity: (a) aluminum, (b) diamond, (c) steel, (d) titanium, or (e) tungsten?

Answer. (b).

3.10 The shear strength of a metal is usually (a) greater than or (b) less than its tensile strength?

Answer. (b).

3.11 Most hardness tests involve pressing a hard object into the surface of a test specimen and measuring the indentation (or its effect) that results: (a) true or (b) false?

Answer. (a).

3.12 Which one of the following materials has the highest hardness: (a) alumina ceramic, (b) gray cast iron, (c) hardened tool steel, (d) high carbon steel, or (e) polystyrene?

Answer. (a).

3.13 Viscosity can be defined as the ease with which a fluid flows: (a) true or (b) false?

Answer. (b). Viscosity is the resistance to flow.

Problems

Strength and Ductility in Tension

3.1 A tensile test uses a test specimen that has a gage length of 50 mm and an area = 200 mm^2. During the test the specimen yields under a load of 98,000 N. The corresponding gage length = 50.23 mm. This is the 0.2 percent yield point. The maximum load of 168,000 N is reached at a gage length = 64.2 mm. Determine (a) yield strength, (b) modulus of elasticity, and (c) tensile strength. (d) If fracture occurs at a gage length of 67.3 mm, determine the percent elongation. (e) If the specimen necked to an area = 92 mm^2, determine the percent reduction in area.

Solution: (a) Y = 98,000/200 = **490 MPa.**

(b) $s = E e$
Subtracting the 0.2% offset, e = (50.23 - 50.0)/50.0 - 0.002 = 0.0026
$E = s/e$ = 490/0.0026 = **188.5 x 10^3 MPa.**

(c) TS = 168,000/200 = **840 MPa.**

(d) EL = (67.3 - 50)/50 = 17.3/50 = 0.346 = **34.6%**

(e) AR = (200 - 92)/200 = 0.54 = **54%**

3.2 A test specimen in a tensile test has a gage length of 2.0 in and an area = 0.5 in^2. During the test the specimen yields under a load of 32,000 lb. The corresponding gage length = 2.0083 in. This is the 0.2 percent yield point. The maximum load of 60,000 lb is reached at a gage length = 2.60 in. Determine (a) yield strength, (b) modulus of elasticity, and (c) tensile strength. (d) If fracture occurs at a gage length of 2.92 in, determine the percent elongation. (e) If the specimen necked to an area = 0.25 in^2, determine the percent reduction in area.

Solution: (a) Y = 32,000/0.5 = **64,000 lb/in^2**

(b) $s = E e$
Subtracting the 0.2% offset, e = (2.0083 - 2.0)/2.0 - 0.002 = 0.00215
$E = s/e$ = 64,000/0.00215 = **29.77 x 10^6 lb/in^2**

(c) TS = 60,000/0.5 = **120,000 lb/in^2**

(d) EL = (2.92 - 2.0)/2.0 = 0.92/2.0 = 0.46 = **46%**

(e) AR = (0.5 - 0.25)/0.5 = 0.50 = **50%**

3.3 During a tensile test in which the starting gage length = 125.0 mm and the cross-sectional area = 62.5 mm^2, the following force and gage length data are collected (1) 17,793 N at 125.23 mm, (2) 23,042 N at 131.25 mm, (3) 27,579 N at 140.05 mm, (4) 28, 913 N at 147.01 mm, (5) 27,578 N at 153.00 mm, and (6) 20,462 N at 160.10 mm. The maximum load is 28,913 N and the final data point occurred immediately prior to failure. (a) Plot the engineering stress strain curve. Determine (b) yield strength, (c) modulus of elasticity, and (d) tensile strength.

Solution: (a) Student exercise.

(b) From the plot, Y = **310.27 MPa.**

(c) First data point is prior to yielding.
Strain e = (125.23 - 125)/125 = 0.00184, E = 310.27/0.00184 = **168,625 MPa.**

(d) From the plot, TS = **462.6 MPa.** Also, TS = 28,913/62.5 = **462.6 MPa.**

Flow Curve

3.4 In Problem 3.3, determine the strength coefficient and the strain-hardening exponent in the flow curve equation. Be sure not to use data after the point at which necking occurred.

Solution: Starting volume of test specimen V = 125(62.5) = 7812.5 mm^3.
Select two data points: (1) F = 23042 N and L = 131.25 mm; (2) F = 28913 N and L = 147.01 mm.

(1) $A = V/L$ = 7812.5/131.25 = 59.524 mm^2.
Stress σ = 23042/59.524 = 387.1 MPa. Strain ε = ln(131.25/125) = 0.0488

(2) A = 7812.5/147.01 = 53.143 mm^2.
Stress σ = 28913/53.143 = 544.1 MPa. Strain ε = ln(147.01/125) = 0.1622

Substituting these values into the flow curve equation, we have
(1) $387.1 = K(0.0488)^n$ and (2) $544.1 = K(0.1622)^n$
$544.1/387.1 = (0.1622/0.0488)^n$
$1.4056 = (3.3238)^n$
$\ln(1.4056) = n \ln(3.3238)$ $\quad$ $0.3405 = 1.2011\, n$ $\quad$ ***n* = 0.283**

Substituting this value with the data back into the flow curve equation, we obtain the value of the strength coefficient K:
$K = 387.1/(0.0488)^{.283}$ = 909.9 MPa
$K = 544.1/(0.1622)^{.283}$ = 910.4 MPa $\quad$ Use average ***K* = 910.2 MPa**

The flow curve equation is: $\boldsymbol{\sigma = 910.2\, \varepsilon^{0.283}}$

3.5 In a tensile test on a metal specimen, true strain = 0.08 at a stress = 265 MPa. When true stress = 325 MPa, true strain = 0.27. Determine the strength coefficient and the strain-hardening exponent in the flow curve equation.

Solution: (1) $265 = K(0.08)^n$ and (2) $325 = K(0.27)^n$

$325/265 = (0.27/0.08)^n$ $\quad$ $1.2264 = (3.375)^n$
$n \ln(3.375) = \ln(1.2264)$ $\quad$ $1.2164\, n = 0.2041$ $\quad$ ***n* = 0.1678**

Substituting this value with the data back into the flow curve equation, we obtain the value of the strength coefficient K:
(1) $K = 265/(0.08)^{.1678}$ = **404.85 MPa**
(2) $K = 325/(0.27)^{.1678}$ = 404.85 MPa

The flow curve equation is: $\boldsymbol{\sigma = 404.85\, \varepsilon^{0.1678}}$

3.6 During a tensile test, a metal has a true strain = 0.10 at a true stress = 37,000 lb/in^2. Later, at a true stress = 55,000 lb/in^2, true strain = 0.25. Determine the strength coefficient and strain-hardening exponent in the flow curve equation.

Solution: (1) $37{,}000 = K(0.10)^n$ and (2) $55{,}000 = K(0.25)^n$

$55{,}000/37{,}000 = (0.25/0.10)^n$ $\quad$ $1.4865 = (2.5)^n$
$n \ln(2.5) = \ln(1.4865)$ $\quad$ $0.9163\, n = 0.3964$ $\quad$ ***n* = 0.4326**

Substituting this value with the data back into the flow curve equation, we obtain the value of the strength coefficient K:
(1) $K = 37{,}000/(0.10)^{0.4326}$ = 100,191 lb/in^2
(2) $K = 55{,}000/(0.25)^{0.4326}$ = 100,191 lb/in^2

The flow curve equation is: $\boldsymbol{\sigma = 100{,}191\, \varepsilon^{0.4326}}$

3.7 In a tensile test a metal begins to neck at a true strain = 0.28 with a corresponding true stress = 345.0 MPa. Without knowing any more about the test, can you estimate the strength coefficient and the strain-hardening exponent in the flow curve equation?

Solution: If we assume that $n = \varepsilon$ when necking starts, then $\boldsymbol{n} = \mathbf{0.28}$.
Using this value in the flow curve equation, we have $K = 345/(0.28)^{.28}$ = **492.7 MPa**

The flow curve equation is: $\boldsymbol{\sigma} = \mathbf{492.7\ \varepsilon^{0.28}}$

3.8 A tensile test for a certain metal provides flow curve parameters: strain-hardening exponent is 0.3 and strength coefficient is 600 MPa. Determine (a) the flow stress at a true strain = 1.0 and (b) true strain at a flow stress = 600 MPa.

Solution: (a) $Y_f = 600(1.0)^{.3}$ = **600 MPa**

(b) $\varepsilon = (600/600)^{1/.3} = (1.0)^{3.33}$ = **1.00**

3.9 The flow curve for a certain metal has a strain-hardening exponent of 0.22 and strength coefficient of 54,000 lb/in^2. Determine (a) the flow stress at a true strain = 0.45 and (b) the true strain at a flow stress = 40,000 lb/in^2.

Solution: (a) $Y_f = 54{,}000(0.45)^{.22}$ = **45,300 lb/in^2**

(b) $\varepsilon = (40{,}000/54{,}000)^{1/.22} = (0.7407)^{4.545}$ = **0.256**

3.10 A metal is deformed in a tension test into its plastic region. The starting specimen had a gage length = 2.0 in and an area = 0.50 in^2. At one point in the tensile test, the gage length = 2.5 in, and the corresponding engineering stress = 24,000 lb/in^2; at another point in the test prior to necking, the gage length = 3.2 in, and the corresponding engineering stress = 28,000 lb/in^2. Determine the strength coefficient and the strain-hardening exponent for this metal.

Solution: Starting volume $V = L_oA_o = 2.0(0.5) = 1.0$ in^3

(1) $A = V/L = 1.0/2.5 = 0.4$ in^2
So, true stress $\sigma = 24{,}000(0.5)/0.4 = 31{,}250$ lb/in^2 and $\varepsilon = \ln(2.5/2.0) = 0.223$

(2) $A = 1.0/3.2 = 0.3125$ in^2
So, true stress $\sigma = 28{,}000(0.5)/0.3125 = 44{,}800$ lb/in^2 and $\varepsilon = \ln(3.2/2.0) = 0.470$

These are two data points with which to determine the parameters of the flow curve equation.
(1) $31{,}250 = K(0.223)^n$ and (2) $44{,}800 = K(0.470)^n$
$44{,}800/31{,}250 = (0.470/0.223)^n$
$1.4336 = (2.1076)^n$
$\ln(1.4336) = n \ln(2.1076)$
$0.3602 = .7455\ n$ $\boldsymbol{n} = \mathbf{0.483}$

(1) $K = 31{,}250/(0.223)^{.483} = 64{,}513$ lb/in^2
(2) $K = 44{,}800/(0.470)^{.483} = 64{,}516$ lb/in^2 Use average $\boldsymbol{K} = \mathbf{64{,}515}$ **lb/in^2**

The flow curve equation is: $\boldsymbol{\sigma} = \mathbf{64{,}515\ \varepsilon^{0.483}}$

3.11 A tensile test specimen has a starting gage length = 75.0 mm. It is elongated during the test to a length = 110.0 mm before necking occurs. Determine (a) the engineering strain and (b) the true strain. (c) Compute and sum the engineering strains as the specimen elongates from: (1) 75.0 to 80.0 mm, (2) 80.0 to 85.0 mm, (3) 85.0 to 90.0 mm, (4) 90.0 to 95.0 mm, (5) 95.0 to 100.0 mm, (6) 100.0 to 105.0 mm, and (7) 105.0 to 110.0 mm. (d) Is the result closer to the answer to part (a) or part (b)? Does this help to show what is meant by the term true strain?

Solution: (a) Engineering strain $e = (110 - 75)/75 = 35/75$ = **0.4667**

(b) True strain ε = ln(110/75) = ln(1.4667) = **0.383**

(c) (1) L = 75 to 80 mm: e = (80 - 75)/75 = 5/75 = 0.0667
(2) L = 80 to 85 mm: e = (85 - 80)/80 = 5/80 = 0.0625
(3) L = 85 to 90 mm: e = (90 - 85)/85 = 5/85 = 0.0588
(4) L = 90 to 95 mm: e = (95 - 90)/90 = 5/90 = 0.0556
(5) L = 95 to 100 mm: e = (100 - 95)/95 = 5/95 = 0.0526
(6) L = 100 to 105 mm: e = (105 - 100)/100 = 5/100 = 0.0500
(7) L = 105 to 110 mm: e = (110 - 105)/105 = 5/105 = 0.0476

Sum of incremental engineering strain values = **0.3938**

(d) The resulting sum in (c) is close to the true strain value in (b). The summation process is an approximation of the integration over the range from 75 to 110 mm in (b). As the interval size is reduced, the summation becomes closer to the integration value.

3.12 A tensile specimen is elongated to twice its original length. Determine the engineering strain and true strain for this test. If the metal had been strained in compression, determine the final compressed length of the specimen such that (a) the engineering strain is equal to the same value as in tension (it will be negative value because of compression), and (b) the true strain would be equal to the same value as in tension (again, it will be negative value because of compression). Note that the answer to part (a) is an impossible result. True strain is therefore a better measure of strain during plastic deformation.

Solution: Engineering strain e = (2.0 - 1.0)/1.0 = 1.0
True strain ε = ln(2.0/1.0) = ln(2.0) = 0.693

(a) To be compressed to the same engineering strain (e = -1.0) the final height of the compression specimen would have to be zero, which is impossible.

(b) To be compressed to the same true strain value (e = -0.693) the final height of the compression specimen can be determined as follows:
$\varepsilon = -.693 = \ln(L_f/L_o)$
$L_f/L_o = \exp.(-0.693) = 0.500$ Therefore, $\boldsymbol{L_f = 0.5\ L_o}$

3.13 Derive an expression for true strain as a function of D and D_o for a tensile test specimen of round cross section, where D = the instantaneous diameter of the specimen and D_o is its original diameter.

Solution: Starting with the definition of true strain as $\varepsilon = \ln(L/L_o)$ and assuming constant volume, we have $V = A_oL_o = AL$
Therefore, $L/L_o = A_o/A$
$A = \pi D^2$ and $A_o = \pi D_o^2$
$A_o/A = \pi D_o^2/\pi D^2 = (D_o/D)^2$
$\boldsymbol{\varepsilon = \ln(D_o/D)^2 = 2\ln(D_o/D)}$

3.14 Show that true strain = ln(1 + e), where e = engineering strain.

Solution: Starting definitions: (1) $\varepsilon = \ln(L/L_o)$ and (2) $e = (L - L_o)/L_o$
Consider definition (2): $e = L/L_o - L_o/L_o = L/L_o - 1$
Rearranging, $1 + e = L/L_o$
Substituting this into definition (1), $\boldsymbol{\varepsilon = \ln(1 + e)}$

3.15 Based on results of a tensile test, the flow curve strain-hardening exponent = 0.40 and strength coefficient = 551.6 MPa. Based on this information, calculate the (engineering) tensile strength for the metal.

Solution: Tensile strength occurs at maximum value of load. Necking begins immediately thereafter. At necking, $n = \varepsilon$. Therefore, $\sigma = 551.6(0.4)^{0.4} = 382.3$ MPa. This is a true stress.
TS is defined as an engineering stress. From Problem 3.15, we know that $\varepsilon = 2\ \ln(D_o/D)$. Therefore,
$0.4 = 2\ \ln(D_o/D)$
$\ln(D_o/D) = .4/2 = 0.2$
$D_o/D = \exp(0.2) = 1.221$
Area ratio = $(D_o/D)^2 = (1.221)^2 = 1.4918$
The ratio between true stress and engineering stress would be the same ratio.
Therefore, $TS = 1.4918(382.3) =$ **570.3 MPa**

3.16 A copper wire of diameter 0.80 mm fails at an engineering stress = 248.2 MPa. Its ductility is measured as 75% reduction of area. Determine the true stress and true strain at failure.

Solution: Area reduction $AR = (A_o - A_f)/A_o = 0.75$
$A_o - A_f = 0.75\ A_o$
$A_o - 0.75A_o = 0.25\ A_o = A_f$
If engineering stress = 248.2 MPa, then true stress $\sigma = 248.2/0.25 =$ **992.8 MPa**
True strain $\varepsilon = \ln(L_f/L_o) = \ln(A_o/A_f) = \ln(4) =$ **1.386**. However, it should be noted that these values are associated with the necked portion of the test specimen.

3.17 A steel tensile specimen with starting gage length = 2.0 in and cross-sectional area = 0.5 in^2 reaches a maximum load of 37,000 lb. Its elongation at this point is 24%. Determine the true stress and true strain at this maximum load.

Solution: Elongation = $(L - L_o)/L_o = 0.24$
$L - L_o = 0.24\ L_o$
$L = 1.24\ L_o$
$A = A_o/1.24 = 0.8065\ A_o$
True stress $\sigma = 37{,}000/0.8065(0.5) =$ **91,754 lb/in^2**
True strain $\varepsilon = \ln(1.24) =$ **0.215**

Compression

3.18 A metal alloy has been tested in a tensile test with the following results for the flow curve parameters: strength coefficient = 620.5 MPa and strain-hardening exponent = 0.26. The same metal is now tested in a compression test in which the starting height of the specimen = 62.5 mm and its diameter = 25 mm. Assuming that the cross section increases uniformly, determine the load required to compress the specimen to a height of (a) 50 mm and (b) 37.5 mm.

Solution: Starting volume of test specimen $V = \pi h D_o^2/4 = 62.5\pi(25)^2/4 = 30679.6$ mm^3.

(a) At $h = 50$ mm, $\varepsilon = \ln(62.5/50) = \ln(1.25) = 0.223$
$Y_f = 620.5(.223)^{.26} = 420.1$ MPa
$A = V/L = 30679.6/50 = 613.6$ mm^2
$F = 420.1(613.6) =$ **257,770 N**

(b) At $h = 37.5$ mm, $\varepsilon = \ln(62.5/37.5) = \ln(1.667) = 0.511$
$Y_f = 620.5(0.511)^{.26} = 521.1$ MPa
$A = V/L = 30679.6\ /37.5 = 818.1$ mm^2
$F = 521.1(818.1) =$ **426,312 N**

3.19 The flow curve parameters for a certain stainless steel are strength coefficient = 1100 MPa and strain-hardening exponent = 0.35. A cylindrical specimen of starting cross-sectional area = 1000 mm^2 and height = 75 mm is compressed to a height of 58 mm. Determine the force required to achieve this compression, assuming that the cross section increases uniformly.

Solution: For h = 58 mm, ε = ln(75/58) = ln(1.293) = 0.257
$Y_f = 1100(.257)^{.35}$ = 683.7 MPa
Starting volume V = 75(1000) = 75,000 mm^3
At h = 58 mm, $A = V/L$ = 75,000/58 = 1293.1 mm^2
F = 683.7(1293.1) = **884,095 N.**

3.20 A steel test specimen (modulus of elasticity = 30 x 10^6 lb/in^2) in a compression test has a starting height = 2.0 in and diameter = 1.5 in. The metal yields (0.2% offset) at a load = 140,000 lb. At a load of 260,000 lb, the height has been reduced to 1.6 in. Determine (a) yield strength and (b) flow curve parameters (strength coefficient and strain-hardening exponent). Assume that the cross-sectional area increases uniformly during the test.

Solution: (a) Starting volume of test specimen $V = h\pi D^2/4 = 2\pi(1.5)^2/4$ = 3.534 in^3.
$A_o = \pi D_o/4 = \pi(1.5)^2/4$ = 1.767 in^2
Y = 140,000/1.767 = **79,224 lb/in^2**

(b) Elastic strain at Y = 79,224 lb/in^2 is $e = Y/E$ = 79,224/30,000,000 = 0.00264
Strain including offset = 0.00264 + 0.002 = 0.00464
Height h at strain = 0.00464 is h = 2.0(1 - 0.00464) = 1.9907 in.
Area A = 3.534/1.9907 = 1.775 in^2.
True strain σ = 140,000/1.775 = 78,862 lb/in^2.

At F = 260,000 lb, A = 3.534/1.6 = 2.209 in^2.
True stress σ = 260,000/2.209 = 117,714 lb/in^2.
True strain ε = ln(2.0/1.6) = 0.223

Given the two points: (1) σ = 78,862 lb/in^2 at ε = 0.00464, and (2) σ = 117,714 lb/in^2 at ε = 0.223.
$117,714/78,862 = (0.223/0.00464)^n$
$1.493 = (48.06)^n$
ln(1.493) = n ln(48.06)
0.4006 = 3.872 n $\qquad$ n = 0.103
$K = 117,714/(0.223)^{0.103}$ = 137,389 lb/in^2.

The flow curve equation is: $\boldsymbol{\sigma = 137,389\ \varepsilon^{103}}$

Bending and Shear

3.21 A bend test is used for a certain hard material. If the transverse rupture strength of the material is known to be 1000 MPa, what is the anticipated load at which the specimen is likely to fail, given that its width = 15 mm, thickness = 10 mm, and length = 60 mm?

Solution: $F = (TRS)(bt^2)/1.5L$ = 1000(15 x 10^2)/(1.5 x 60) = **16,667 N.**

3.22 A special ceramic specimen is tested in a bend test. Its width = 0.50 in and thickness = 0.25 in. The length of the specimen between supports = 2.0 in. Determine the transverse rupture strength if failure occurs at a load = 1700 lb.

Solution: $TRS = 1.5FL/bt^2$ = 1.5(1700)(2.0)/(0.5 x 0.25^2) = **163,200 lb/in^2.**

3.23 A torsion test specimen has a radius = 25 mm, wall thickness = 3 mm, and gage length = 50 mm. In testing, a torque of 900 N-m results in an angular deflection = 0.3°. Determine (a) the shear stress, (b) shear strain, and (c) shear modulus, assuming the specimen had not yet yielded. (d) If failure of the specimen occurs at a torque = 1200 N-m and a corresponding angular deflection = 10°, what is the shear strength of the metal?

Solution: (a) $\tau = T/(2\pi R^2 t)$ = (900 x 1000)/(2π(25)^2(3)) = **76.39 MPa.**

(b) $\gamma = R\alpha/L$, $\alpha = 0.3(2\pi/360)$ = 0.005236 radians

γ = 25(0.005236)/50 = **0.002618**

(c) $\tau = G\gamma$, $G = \tau/\gamma$ = 76.39/0.002618 = **29,179 MPa.**

(d) $S = (1200(10^3))/(2\pi(25)^2(3))$ = **101.86 MPa.**

3.24 In a torsion test, a torque of 5000 ft-lb is applied which causes an angular deflection = 1° on a thin-walled tubular specimen whose radius = 1.5 in, wall thickness = 0.10 in, and gage length = 2.0 in. Determine (a) the shear stress, (b) shear strain, and (c) shear modulus, assuming the specimen had not yet yielded. (d) If the specimen fails at a torque = 8000 ft-lb and an angular deflection = 23°, calculate the shear strength of the metal.

Solution: (a) $\tau = T/(2\pi R^2 t) = (5000 \text{ x } 12)/(2\pi(1.5)^2(0.1))$ = **42,441 lb/in^2.**

(b) $\gamma = R\alpha/L$, $\alpha = 1(2\pi/360)$ = 0.01745 rad., γ = 1.5(0.01745)/2.0 = **0.01309**

(c) $\tau = G\gamma$, $G = \tau/\gamma$ = 42,441/0.01309 = **3.24 x 10^6 lb/in^2.**

(d) $S = (8000 \text{ x } 12)/(2\pi(1.5)^2(0.1))$ = **67,906 lb/in^2.**

Hardness

3.25 In a Brinell hardness test, a 1500-kg load is pressed into a specimen using a 10-mm-diameter hardened steel ball. The resulting indentation has a diameter = 3.2 mm. (a) Determine the Brinell hardness number for the metal. (b) If the specimen is steel, estimate the tensile strength of the steel.

Solution: (a) $HB = 2(1500)/(10\pi(10 - (10^2 - 3.2^2)^{.5})) = 3000/(10\pi \text{ x } 0.5258)$ = **182 BHN**

(b) The estimating formula is: $TS = 500(HB)$.
For a tested hardness of HB = 182, TS = 500(182) = **91,000 lb/in^2.**

3.26 One of the inspectors in the quality control department has frequently used the Brinell and Rockwell hardness tests, for which equipment is available in the company. He claims that all hardness tests are based on the same principle as the Brinell test, which is that hardness is always measured as the applied load divided by the area of the impressions made by an indentor. (a) Is he correct? (b) If not, what are some of the other principles involved in hardness testing, and what are the associated tests?

Solution: (a) No, the claim is not correct. Not all hardness tests are based on the applied load divided by area, but many of them are.

(b) Some of the other hardness tests and operating principles include: (1) Rockwell hardness test, which measures the depth of indentation of a cone resulting from an applied load; (2) Scleroscope, which measures the rebound height of a hammer dropped from a certain distance against a surface specimen; and (3) Durometer, which measures elastic deformation by pressing an indentor into the surface of rubber and similar soft materials.

3.27 A batch of annealed steel has just been received from the vendor. It is supposed to have a tensile strength in the range 60,000 - 70,000 lb/in^2. A Brinell hardness test in the receiving department yields a value of HB = 118. (a) Does the steel meet the specification on tensile strength? (b) Estimate the yield strength of the material.

Solution: (a) $TS = 500(HB)$ = 500(118) = **59,000 lb/in^2.** This lies outside the specified range of 60,000 to 70,000 lb/in^2. However, from a legal standpoint, it is unlikely that the batch can be rejected on the basis of its measured Brinell hardness number without using an actual tensile test to measure TS. The formula for converting from Brinell hardness number to tensile strength is only an approximating equation.

(b) Based on Table 3.2 in the text, the ratio of Y to TS for low carbon steel = 25,000/45,000 = 0.555. Using this ratio, we can estimate the yield strength to be Y = 0.555(59,000) = **32,700 lb/in^2.**

Viscosity of Fluids

3.28 Two flat plates, separated by a space of 4 mm, are moving relative to each other at a velocity of 5 m/sec. The space between them is occupied by a fluid of unknown viscosity. The motion of the plates is resisted by a shear stress of 10 Pa due to the viscosity of the fluid. Assuming that the velocity gradient of the fluid is constant, determine the coefficient of viscosity of the fluid.

Solution: Shear rate = (5 m/s x 1000 mm/m)/(4 mm) = 1250 s^{-1}
η = (10N/m^2)/(1250 s^{-1}) = **0.008 N-s/m^2 = 0.008 Pa-s**

3.29 Two parallel surfaces, separated by a space of 0.5 in that is occupied by a fluid, are moving relative to each other at a velocity of 25 in/sec. The motion is resisted by a shear stress of 0.3 lb/in^2 due to the viscosity of the fluid. If the velocity gradient in the space between the surfaces is constant, determine the viscosity of the fluid.

Solution: Shear rate = (25 in/sec)/(0.5 in) = 50 sec^{-1}
η = (0.3 lb/in^2)/(50 sec^{-1}) = **0.0006 lb-sec/in^2.**

3.30 A 125.0-mm-diameter shaft rotates inside a stationary bushing whose inside diameter = 125.6 mm and length = 50.0 mm. In the clearance between the shaft and the bushing is a lubricating oil whose viscosity = 0.14 Pa-s. The shaft rotates at a velocity of 400 rev/min; this speed and the action of the oil are sufficient to keep the shaft centered inside the bushing. Determine the magnitude of the torque due to viscosity that acts to resist the rotation of the shaft.

Solution: Bushing internal bearing area $A = \pi(125.6)^2$ x 50/4 = 19729.6 mm^2 = 19729.2(10^{-6}) m^2
d = (125.6 - 125)/2 = 0.3 mm
v = (125π mm/rev)(400 rev/min)(1 min/60 sec) = 2618.0 mm/s
Shear rate = 2618/0.3 = 8726.6 s^{-1}
τ = (0.14)(8726.6) = 1221.7 Pa = 1221.7 N/mm^2
Force on surface between shaft and bushing = (1221.7 N/mm^2)(19729.2(10^{-6})) = 24.1 N
Torque T = 24.1 N x 125/2 mm = **1506.4 N-mm = 1.506 N-m**

4 PHYSICAL PROPERTIES OF MATERIALS

Review Questions

4.1 Define density as a material property.

Answer. Density is the weight per unit volume of a material.

4.2 What is the difference in melting characteristics between a pure metal element and an alloy metal?

Answer. A pure metal element melts at one temperature (the melting point), while an alloy begins melting at a certain temperature called the solidus and finally completes the transformation to the molten state at a higher temperature called the liquidus. Between the solidus and liquidus, the metal is a mixture of solid and liquid.

4.3 Describe the melting characteristics of a noncrystalline material such as glass.

Answer. In the heating of a noncrystalline material such as glass, the material begins to soften as temperature increases, finally converting to a liquid at a temperature defined for these materials as the melting point.

4.4 Define specific heat as a material property.

Answer. Specific heat is defined as the quantity of heat required to raise the temperature of a unit mass of the material by one degree.

4.5 What is thermal conductivity as a material property?

Answer. Thermal conductivity is the capacity of a material to transfer heat energy through itself by thermal movement only (no mass transfer).

4.6 Define thermal diffusivity.

Answer. Thermal diffusivity is the thermal conductivity divided by the volumetric specific heat.

4.7 What are the important variables that affect mass diffusion?

Answer. According to Fick's first law, mass diffusion depends on the diffusion coefficient of the material, which increases rapidly with temperature (so temperature could be listed as an important variable), concentration gradient, contact area, and time.

4.8 Define resistivity as a material property.

Answer. Resistivity is the material's capacity to resist the flow of electric current.

4.9 Why are metals better conductors of electricity than ceramics and polymers?

Answer. Metals are better conductors because of metallic bonding, which permits electrons to move easily within the metal. Ceramics and polymers have covalent and ionic bonding, in which the electrons are tightly bound to particular molecules.

4.10 What is dielectric strength as a material property?

Answer. Dielectric strength is defined as the electrical potential required to break down the insulator per unit thickness.

4.11 What is an electrolyte?

Answer. An electrolyte is an ionized solution capable of conducting electric current by movement of the ions.

Multiple Choice Quiz

There are 12 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

4.1 Which one of the following metals has the lowest density: (a) aluminum, (b) copper, (c) magnesium, or (d) tin?

Answer. (c).

4.2 The thermal expansion properties of polymers are generally (a) greater than, (b) less than, or (c) the same as those of metals?

Answer. (a).

4.3 In the heating of most metal alloys, melting begins at a certain temperature and concludes at a higher temperature. In these cases, which of the following temperatures marks the beginning of melting: (a) liquidus or (b) solidus?

Answer. (b).

4.4 Which one of the following materials has the highest specific heat: (a) aluminum, (b) concrete, (c) polyethylene, or (d) water?

Answer. (d).

4.5 Copper is generally considered easy to weld because of its high thermal conductivity: (a) true or (b) false?

Answer. (b). The high thermal conductivity of copper makes it difficult to weld because the heat flows away from the joint rather than being concentrated to permit melting of the metal.

4.6 The mass diffusion rate dm/dt across a boundary between two different metals is a function of which of the following variables (four best answers): (a) concentration gradient dc/dx, (b) contact area, (c) density, (d) melting point, (e) thermal expansion, (f) temperature, and (g) time?

Answer. (a), (b), (f), and (g). This is perhaps a tricky question. Choices (a) and (b) are included in Eq. (4.5). Temperature (f) has a strong influence on the diffusion coefficient. Time (g) figures into the process because it affects the concentration gradient; as time elapses, the concentration gradient is reduced so that the rate of diffusion is reduced.

4.7 Which of the following pure metals is the best conductor of electricity: (a) aluminum, (b) copper, (c) gold, or (d) silver?

Answer. (d).

4.8 A superconductor is characterized by which of the following (one best answer): (a) high conductivity, (b) resistivity properties between those of conductors and semiconductors, (c) very low resistivity, or (d) zero resistivity?

Answer. (d).

4.9 In an electrolytic cell, the anode is the electrode that is (a) positive or (b) negative.

Answer. (a).

Problems

4.1 The starting diameter of a shaft is 25.00 mm. This shaft is to be inserted into a hole in an expansion fit assembly operation. To be readily inserted, the shaft must be reduced in diameter by cooling. Determine the temperature to which the shaft must be reduced from room temperature (20°C) in order to reduce its diameter to 24.98 mm. Refer to Table 4.1.

Solution: For steel, $\alpha = 12(10^{-6})$ mm/mm/°C according to Table 4.1.
Revise Eq. (4.1) to $D_2 - D_1 = \alpha D_1 (T_2 - T_1)$.
$24.98 - 25.00 = 12(10^{-6})(25.00)(T_2 - 20)$
$-0.02 = 300(10^{-6})(T_2 - 20)$
$-0.02 = 0.0003(T_2 - 20) = 0.0003T_2 - 0.006$
$-.02 + 0.006 = 0.0003T_2$
$-0.014 = 0.0003T_2$ $\qquad$ $T_2 = \mathbf{-46.67°C}$

4.2 A bridge built with steel girders is 500 m in length and 12 m in width. Expansion joints are provided to compensate for the change in length in the support girders as the temperature fluctuates. Each expansion joint can compensate for a maximum of 40 mm of change in length. From historical records it is estimated that the minimum and maximum temperatures in the region will be -35°C and 38°C, respectively. What is the minimum number of expansion joints required?

Solution: Assume L_1 =500 m at -35 C, α=12x10^{-6}/C
$L_2 - L_1 = \alpha L_1(T_2 - T_1)$
$L_2 - L_1 = 12\text{x}10^{-6}(500)(38 - (-35))$
$L_2 - L_1 = 0.42$ m
Each expansion joint will control 40 mm = 0.04 m of expansion.
10 joints will provide 0.40 m of expansion. 11 joints will provide 0.45 m of expansion. Therefore, a **minimum of 11 joints** are needed for coverage of the total length. Each bridge section will be 500/11 = 45.5 m long.

4.3 Aluminum has a density of 2.70 g/cm^3 at room temperature (20°C). Determine its density at 650°C, using data in Table 4.1 as a reference.

Solution: Assume a 1 cm^3 cube, 1 cm on each side.
From Table 4.1, $\alpha = 24(10^{-6})$ mm/mm/°C
$L_2 - L_1 = \alpha L_1 (T_2 - T_2)$.
$L_2 = 1.0 + 24(10^{-6})(1.0)(650 - 20) = 1.01512$ cm
$(L_2)^3 = (1.01512)^3 = 1.04605$ cm^3
Assume weight remains the same; thus ρ at 650°C = 2.70/1.04605 = **2.581 g/cm^3**

4.4 With reference to Table 4.1, determine the increase in length of a steel bar whose length = 10.0 in, if the bar is heated from room temperature of 70°F to 500°F.

Solution: Increase = (6.7 x 10^{-6} in/in/F)(10.0 in)(500°F - 70°F) = **0.0288 in**.

4.5 With reference to Table 4.2, determine the quantity of heat required to increase the temperature of an aluminum block that is 10 cm x 10 cm x 10 cm from room temperature (21°C) to 300°C.

Solution. Heat = (0.21 cal/g-°C)(10^3 cm^3)(2.70 g/cm^3)(300°C - 21°C) = **158,193 cal**.
Conversion: 1.0 cal = 4.184J, so heat = **662,196 J**.

4.6 What is the resistance R of a length of copper wire whose length = 10 m and whose diameter = 0.10 mm? Use Table 4.3 as a reference.

Solution: $R = rL/A$, $A = \pi(0.1)^2/4 = 0.007854$ mm^2 = 0.007854(10^{-6}) m^2
From Table 4.3, $r = 1.7 \times 10^{-8}$ Ω-m^2/m

$R = (1.7 \times 10^{-8}\ \Omega\text{-m}^2/\text{m})(10\ \text{m})/(0.007854(10^{-6})\ \text{m}^2) = 2164.5(10^{-2})\ \Omega = \mathbf{21.65\ \Omega}$

4.7 A 16 gage nickel wire (0.0508-in diameter) connects a solenoid to a control circuit that is 32.8 ft away. (a) What is the resistance of the wire? Use Table 4.3 as a reference. (b) If a current was passed through the wire, it would heat up. How does this affect the resistance?

Solution: (a) $L = 32.8$ ft = 393.6 in
Area $A = \pi(0.0508)^2/4 = 0.00203$ in^2
$R = r\ (L/A) = 6.8 \times 10^{-8}\ (39.4)(393.6/0.00203) =$ **0.520 ohm**

(b) If a current is passed through the wire causing the wire to heat up, the resistivity of the wire would change. Since nickel is a metal, the resistivity would increase, causing the resistance to increase. This, in turn, would cause slightly more heat to be generated.

4.8 Aluminum wiring was used in many homes in the 1960s due to the high cost of copper at the time. Aluminum wire that was 12 gauge (a measure of cross-sectional area) was rated at 15 A of current. If copper wire of the same gauge were used to replace the aluminum wire, what current should the wire be capable of carrying if all factors except resistivity are considered equal? Assume that the resistance of the wire is the primary factor that determines the current it can carry and the cross-sectional area and length are the same for the aluminum and copper wires.

Solution: The area and length are constant between the types of wires. The overall change in resistance is due to the change in resistivity of the materials. From Table 4.3:
For Aluminum $r = 2.8 \times 10^{-8}$
For Copper $r = 1.7 \times 10^{-8}$
The resistance will reduce by $1.7\text{x}10^{-8}/2.8\text{x}10^{-8} = 0.61$
Since $I = E/R$ and $R_{cu}=0.61(R_{al})$, then $I_{cu} = 1/0.61{*}I_{al} = 15/0.61=$ **25 A**
Note that the code value is actually 20 A due to several factors including heat dissipation and rounding down to the nearest 5 amp value.

5 DIMENSIONS, SURFACES, AND THEIR MEASUREMENT

Review Questions

5.1 What is a tolerance?

Answer. A tolerance is defined as the total amount by which a specified dimension is permitted to vary.

5.2 What is the difference between a bilateral tolerance and a unilateral tolerance?

Answer. A bilateral tolerance allows variation in both positive and negative directions from the nominal dimension, whereas a unilateral tolerance allows the variation from the nominal dimension to be either positive or negative, but not both.

5.3 What is accuracy in measurement?

Answer. Accuracy is the degree to which the measured value agrees with the true value of the quantity of interest. It is a measurement procedure that is absent of systematic errors.

5.4 What is precision in measurement?

Answer. Precision in measurement is the degree to which random errors are minimized.

5.5 What is meant by the term graduated measuring device?

Answer. A graduated measuring device has markings (called graduations) on a linear or angular scale to measure an object's feature of interest (e.g., length).

5.6 What are some of the reasons why surfaces are important?

Answer. The reasons why surfaces are important include: aesthetics, safety, friction and wear, effect of surface on mechanical and physical properties, mating of components in assembly, and electrical contacts.

5.7 Define nominal surface.

Answer. The nominal surface is the ideal part surface represented on an engineering drawing. It is assumed perfectly smooth; perfectly flat if referring to a planar surface; perfectly round if referring to a round surface, etc.

5.8 Define surface texture.

Answer. Surface texture is the random and repetitive deviations from the nominal surface, including roughness, waviness, lay, and flaws.

5.9 How is surface texture distinguished from surface integrity?

Answer. Surface texture refers only to the surface geometry; surface integrity includes not only surface but the subsurface layer beneath the surface and the changes in it.

5.10 Within the scope of surface texture, how is roughness distinguished from waviness?

Answer. Roughness consists of the finely-spaced deviations from the nominal surface, while waviness refers to the deviations of larger spacing. Roughness deviations lie within waviness deviations.

5.11 Surface roughness is a measurable aspect of surface texture; what does ***surface roughness*** mean?

Answer. Surface roughness is defined as the average value of the vertical deviations from the nominal surface over a specified surface length.

5.12 Indicate some of the limitations of using surface roughness as a measure of surface texture.

Answer. Surface roughness provides only a single measure of surface texture. Among its limitations are: (1) it varies depending on direction; (2) it does not indicate lay; (3) its value depends on the roughness width cutoff used to measure the average.

5.13 Identify some of the changes and injuries that can occur at or immediately below the surface of a metal.

Answer. The changes and injuries include: cracks, craters, variations in hardness near the surface, metallurgical changes resulting from heat, residual stresses, intergranular attack, etc. (see Table 5.1).

5.14 What causes the various types of changes that occur in the altered layer just beneath the surface?

Answer. Energy input to the surface resulting from the manufacturing process used to generate the surface. The energy forms can be any of several types, including mechanical, thermal, chemical, and electrical.

5.15 What are the common methods for assessing surface roughness?

Answer. Common methods for assessing surface roughness are (1) comparison of the specimen surface with standard test blocks having known surface roughness values and (2) stylus-type electronic instruments which measure average roughness.

5.16 Name some manufacturing processes that produce very poor surface finishes.

Answer. Processes that produce poor surfaces include sand casting, hot rolling, sawing, and thermal cutting (e.g., flame cutting).

5.17 Name some manufacturing processes that produce very good or excellent surface finishes.

Answer. Processes that produced very good and excellent surfaces include honing, lapping, polishing, and superfinishing.

5.18 (**Video**) Based on the video about vernier calipers, are the markings on the vernier plate (moveable scale) the same spacing, slightly closer, or slightly further apart compared to the stationary bar?

Answer: The markings are slightly closer. The 50 markings on the vernier plate fit in place of 49 markings on the stationary bar.

5.19 (**Video**) Based on the video about vernier calipers, explain how to read the scale on a vernier caliper.

Answer: The object is inserted between the jaws. The distance between the zero on the stationary bar and the zero on the vernier plate (moveable scale) is added to the number that corresponds to the line that exactly lines up on the vernier plate. Only one mark on the veriner plate will line up with a mark on the stationary bar.

5.20 (**Video**) Based on the video about micrometers, explain the primary factor that makes an English micrometer different from a metric micrometer.

Answer: The thread pitch determines the linear motion of the micrometer for each rotation of the barrel. A metric micrometer will use a different pitch than an English micrometer.

Multiple Choice Quiz

There are 19 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

5.1 A tolerance is which one of the following: (a) clearance between a shaft and a mating hole, (b) measurement error, (c) total permissible variation from a specified dimension, or (d) variation in manufacturing?

Answer. (c).

5.2 Which of the following two geometric terms have the same meaning: (a) circularity, (b) concentricity, (c) cylindricity, and (d) roundness?

Answer. (a) and (d).

5.3 A surface plate is most typically made of which one of the following materials: (a) aluminum oxide ceramic, (b) cast iron, (c) granite, (d) hard polymers, or (e) stainless steel?

Answer. (c).

5.4 An outside micrometer would be appropriate for measuring which of the following (two correct answers): (a) hole depth, (b) hole diameter, (c) part length, (d) shaft diameter, and (e) surface roughness?

Answer. (c) and (d).

5.5 In a GO/NO-GO gage, which one of the following best describes the function of the GO gage: (a) checks limit of maximum tolerance, (b) checks maximum material condition, (c) checks maximum size, (d) checks minimum material condition, or (e) checks minimum size?

Answer. (b).

5.6 Which of the following are likely to be GO/NO-GO gages (three correct answers): (a) gage blocks, (b) limit gage, (c) master gage, (d) plug gage, and (e) snap gage?

Answer. (b), (d), and (e).

5.7 Surface texture includes which of the following characteristics of a surface (three correct answers): (a) deviations from the nominal surface, (b) feed marks of the tool that produced the surface, (c) hardness variations, (d) oil films, and (e) surface cracks?

Answer. (a), (b), and (e).

5.8 Surface texture is included within the scope of surface integrity: (a) true or (b) false?

Answer. (a).

5.9 Thermal energy is normally associated with which of the following changes in the altered layer (three best answers): (a) cracks, (b) hardness variations, (c) heat affected zone, (d) plastic deformation, (e) recrystallization, or (f) voids?

Answer. (b), (c), and (e).

5.10 Which one of the following manufacturing processes will likely result in the best surface finish: (a) arc welding, (b) grinding, (c) machining, (d) sand casting, or (e) sawing?

Answer. (b).

5.11 Which one of the following manufacturing processes will likely result in the worst surface finish: (a) cold rolling, (b) grinding, (c) machining, (d) sand casting, or (e) sawing?

Answer. (d). Also, sawing (e) will yield a poor finish. Either answer is acceptable.

Problems

5.1 Design the nominal sizes of a GO/NO-GO plug gage to inspect a 1.500 ± 0.030 in diameter hole. There is a wear allowance applied only to the GO side of the gage. The wear allowance is 2% of the entire tolerance band for the inspected feature. Determine (a) the nominal size of the GO gage including the wear allowance and (b) the nominal size of the NO-GO gage.

Solution: (a) The tolerance band is 0.060 in. Wear allowance = 0.02(0.060) = 0.0012 in.
GO gage will inspect the minimum hole diameter = 1.500 – 0.030 = 1.470 in.
As the gage wears, the dimension will decrease and allow unacceptable parts, so the wear allowance is added to it.
Nominal GO Size = 1.470 + 0.0012 = **1.4712 in**

(b) NO-GO gage will inspect the maximum hole diameter = 1.500 + 0.030 = **1.530 in**.
No wear allowance is added because this gage should not fit in the hole and wear away.

5.2 Design the nominal sizes of a GO/NO-GO snap gage to inspect the diameter of a shaft that is 1.500 ± 0.030. A wear allowance of 2% of the entire tolerance band is applied to the GO side. Determine (a) the nominal size of the GO gage including the wear allowance and (b) the nominal size of the NO-GO gage.

Solution: (a) The tolerance band is 0.060 in. Wear allowance = 0.02(0.060) = 0.0012 in.
GO gage will inspect the maximum shaft diameter = 1.500 + 0.030 = 1.530 in.
As the gage wears, the dimension will increase allowing unacceptable parts, so the wear allowance is subtracted from it.
Nominal GO Size = 1.530 – 0.0012 = **1.5288 in**

(b) NO-GO gage will inspect the minimum shaft diameter = 1.500 – 0.030 = **1.470 in**.
No wear allowance is added because this gage should not fit in the hole and wear away.

5.3 Design the nominal sizes of a GO/NO-GO plug gage to inspect a 30.00 ± 0.18 mm diameter hole. There is a wear allowance applied only to the GO side of the gage. The wear allowance is 3% of the entire tolerance band for the inspected feature. Determine (a) the nominal size of the GO gage including the wear allowance and (b) the nominal size of the NO-GO gage.

Solution: (a) The tolerance band is 0.36 mm. Wear allowance = 0.03(0.36) = 0.0108 mm
GO gage will inspect the minimum hole diameter = 30.00 – 0.18 = 29.82 mm
As the gage wears, the dimension will decrease and allow unacceptable parts, so the wear allowance is added to it
Nominal GO Size = 29.82 + 0.0108 = **29.8308 mm**

(b) NO-GO gage will inspect the maximum hole diameter = 30.00 + 0.18 = **30.18 mm**.
No wear allowance is added because this gage should not fit in the hole and wear away.

5.4 Design the nominal sizes of a GO/NO-GO snap gage to inspect the diameter of a shaft that is 30.00 ± 0.18 mm. A wear allowance of 3% of the entire tolerance band is applied to the GO side. Determine (a) the nominal size of the GO gage including the wear allowance and (b) the nominal size of the NO-GO gage.

Solution: (a) The tolerance band is 0.36 mm. Wear allowance = 0.03(0.36) = 0.0108 mm
GO gage will inspect the maximum shaft diameter = 30.00 + 0.18 = 30.18 mm
As the gage wears, the dimension will increase allowing unacceptable parts, so the wear allowance is subtracted from it.
Nominal GO Size = 30.18 – 0.0108 = **30.1692 mm**

(b) NO-GO gage will inspect the minimum shaft diameter = 30.00 – 0.18 = **29.82 mm**.
No wear allowance is added because this gage should not fit in the hole and wear away.

5.5 A sine bar is used to determine the angle of a part feature. The length of the sine bar is 6.000 in. The rolls have a diameter of 1.000 in. All inspection is performed on a surface plate. In order for the sine bar to match the angle of the part, the following gage blocks must be stacked: 2.0000, 0.5000, 0.3550. Determine the angle of the part feature.

Solution: H = 2.0000+0.5000 + 0.3550 = 2.8550 in
$A = \sin^{-1}(H/L) = \sin^{-1}(2.8550/6.000) = \sin^{-1}(0.4758) =$ **28.41°**

5.6 A 200.00 mm sine bar is used to inspect an angle on a part. The angle has a dimension of 35.0 ± 1.8°. The sine bar rolls have a diameter of 30.0 mm. A set of gage blocks is available that can form any height from 10.0000 to 199.9975 mm in increments of 0.0025 mm. Determine (a) the height of the gage block stack to inspect the minimum angle, (b) height of the gage block stack to inspect the maximum angle, and (c) smallest increment of angle that can be setup at the nominal angle size. All inspection is performed on a surface plate.

Solution: (a) $\sin A = (H/L)$; $H = L \sin A$ = 200.00 Sin (35.0-1.8)
= 200.00 sin 33.2 = 109.51264 = **109.5150 mm** (must round up to insure angle is in tolerance.

(b) $H = L \sin A$ = 200.00 sin (35.0 + 1.8) = 200.00 sin (36.8) = 119.80472 = **119.8025 mm** (must round down to insure angle within dimensions)

(c) H at nominal angle = $L \sin A$ = 200.00 Sin (35.0) = 114.7152 mm
Closest angle to nominal is at H=114.7150; $A = \sin^{-1}(H/L) = \sin^{-1}(114.7150/200.000)$
$A = \sin^{-1}(0.573575) = 34.99989953°$
At one increment above, H=114.7175; $A = \sin^{-1}(H/L) = \sin^{-1}(114.7175/200.000) =$
$A = \sin^{-1}(0.5735875) = 35.00077385°$
Change in A = 35.00077385 – 34.9989953 = **0.0008743°**

6 METALS

Review Questions

6.1 What are some of the general properties that distinguish metals from ceramics and polymers?

Answer. Typical metallic properties include: high strength and stiffness, good electrical and thermal conductivity, and higher density than ceramics or polymers.

6.2 What are the two major groups of metals? Define them.

Answer. Ferrous metals, which are based on iron; and nonferrous, which includes all others.

6.3 What is an alloy?

Answer. An alloy is a metal comprised of two or more elements, at least one of which is metallic.

6.4 What is a solid solution in the context of alloys?

Answer. A solid solution is an alloy in which one of the metallic elements is dissolved in another to form a single phase.

6.5 Distinguish between a substitutional solid solution and an interstitial solid solution.

Answer. A substitutional solid solution is where the atoms of the dissolved element replace atoms of the solution element in the lattice structure of the metal. An interstitial solid solution is where the dissolved atoms are small and fit into the vacant spaces (the interstices) in the lattice structure of the solvent metal.

6.6 What is an intermediate phase in the context of alloys?

Answer. An intermediate phase is an alloy formed when the solubility limit of the base metal in the mixture is exceeded and a new phase, such as a metallic compound (e.g., Fe_3C) or intermetallic compound (e.g., Mg_2Pb) is formed.

6.7 The copper-nickel system is a simple alloy system, as indicated by its phase diagram. Why is it so simple?

Answer. The Cu-Ni alloy system is simple because it is a solid solution alloy throughout its entire composition range.

6.8 What is the range of carbon percentages which defines an iron-carbon alloy as a steel?

Answer. The carbon content ranges from 0.02% to 2.11%.

6.9 What is the range of carbon percentages which defines an iron-carbon alloy as cast iron?

Answer. The carbon content ranges from 2.11% to about 5%.

6.10 Identify some of the common alloying elements other than carbon in low alloy steels.

Answer. The common alloying elements in low alloy steel are Cr, Mn, Mo, Ni, and V.

6.11 What are some of the mechanisms by which the alloying elements other than carbon strengthen steel?

Answer. All of the alloying elements other than C strengthen the steel by solid solution alloying. Cr, Mn, Mo, and Ni increase hardenability during heat treatment. Cr and Mo improve hot hardness. Several of the alloying elements (Cr, Mo, V) form hard carbides with C, which increases wear resistance. Vanadium inhibits grain growth during heat treatment which improves strength and toughness.

6.12 What is the predominant alloying element in all of the stainless steels?

Answer. Chromium.

6.13 Why is austenitic stainless steel called by that name?

Answer. It is called austenitic because this alloy exists in its austenitic phase at room temperature. The reason is that nickel has the effect of enlarging the austenitic temperature range to include room temperature.

6.14 Besides high carbon content, what other alloying element is characteristic of the cast irons?

Answer. Silicon.

6.15 Identify some of the properties for which aluminum is noted?

Answer. Aluminum is noted for its low density, high electrical and thermal conductivity, formability, good corrosion resistance due to the formation of a tough oxide film on its surface, and ability to be alloyed and strengthened to achieve good strength-to-weight ratios.

6.16 What are some of the noteworthy properties of magnesium?

Answer. Magnesium is noted for its very low density (lightest of the structural metals), propensity to oxidize (which can cause problems in processing), and low strength; however, it can be alloyed and strengthened by methods similar to those used for aluminum alloys to achieve respectable strength-to-weight ratios.

6.17 What is the most important engineering property of copper that determines most of its applications?

Answer. Its high electrical conductivity (low resistivity).

6.18 What elements are traditionally alloyed with copper to form (a) bronze and (b) brass?

Answer. The elements are (a) tin and (b) zinc, respectivley.

6.19 What are some of the important applications of nickel?

Answer. The important applications of Ni are (1) as an alloying ingredient in steel, e.g., stainless steel; (2) for plating of steel to resist corrosion; and (3) to form nickel-based alloys noted for high-temperature performance and corrosion resistance.

6.20 What are the noteworthy properties of titanium?

Answer. Titanium is noted for its high strength-to-weight ratio, corrosion resistance (due to the formation of a thin but tough oxide film), and high temperature strength.

6.21 Identify some of the important applications of zinc.

Answer. The important applications of Zn are (1) die castings - zinc is an easy metal to cast; (2) as a coating in galvanized steel; (3) as an alloying element with copper to form brass.

6.22 What important alloy is formed from lead and tin?

Answer. Solder.

6.23 (a) Name the important refractory metals. (b) What does the term refractory mean?

Answer. (a) The refractory metals include columbium (Cb), molybdenum (Mo), tantalum (Ta), and tungsten (W). Mo and W are the most important. (b) Refractory means the capability to withstand high temperature service.

6.24 (a) Name the four principal noble metals. (b) Why are they called noble metals?

Answer. (a) The principal noble metals are copper, gold, platinum, and silver. (b) Nobel metals are so-named because they are chemically inactive.

6.25 The superalloys divide into three basic groups, according to the base metal used in the alloy. Name the three groups.

Answer. The three groups are (1) iron-based alloys, (2) nickel-based alloys, and (3) cobalt-based alloys.

6.26 What is so special about the superalloys? What distinguishes them from other alloys?

Answer. The superalloys are generally distinguished by their strength and resistance to corrosion and oxidation at elevated temperatures.

6.27 What are the three basic methods by which metals can be strengthened?

Answer. The three basic methods are (1) alloying to form solid solutions and two-phase structures which are stronger than the elemental metals; (2) cold working, in which the strain-hardened metal is stronger and harder than the unstrained metal; and (3) heat treatment - most of the commercial heat treatments are designed to increase the strength of the metal.

Multiple Choice Quiz

There are 20 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

6.1 Which of the following properties or characteristics are inconsistent with the metals (two correct answers): (a) good thermal conductivity, (b) high strength, (c) high electrical resistivity, (d) high stiffness, and (e) ionic bonding?

Answer. (c) and (e).

6.2 Which one of the metallic elements is the most abundant on the earth: (a) aluminum, (b) copper, (c) iron, (d) magnesium, or (e) silicon?

Answer. (a).

6.3 The predominant phase in the iron-carbon alloy system for a composition with 99% Fe at room temperature is which one of the following: (a) austenite, (b) cementite, (c) delta, (d) ferrite, or (e) gamma?

Answer. (d).

6.4 A steel with 1.0% carbon is known as which one of the following: (a) eutectoid, (b) hypoeutectoid, (c) hypereutectoid, or (d) wrought iron?

Answer. (c).

6.5 The strength and hardness of steel increases as carbon content (a) increases or (b) decreases?

Answer. (a).

6.6 Plain carbon steels are designated in the AISI code system by which of the following: (a) 01XX, (b) 10XX, (c) 11XX, (d) 12XX, or (e) 30XX?

Answer. (b).

6.7 Which one of the following elements is the most important alloying ingredient in steel: (a) carbon, (b) chromium, (c) nickel, (d) molybdenum, or (e) vanadium?

Answer. (a).

6.8 Which one of the following is not a common alloying ingredient in steel: (a) chromium, (b) manganese, (c) nickel, (d) vanadium, (e) zinc?

Answer. (e).

6.9 Solid solution alloying is the principal strengthening mechanism in high-strength low-alloy (HSLA) steels: (a) true or (b) false?

Answer. (a).

6.10 Which of the following alloying elements are most commonly associated with stainless steel (two best answers): (a) chromium, (b) manganese, (c) molybdenum, (d) nickel, and (e) tungsten?

Answer. (a) and (d).

6.11 Which of the following is the most important cast iron commercially: (a) ductile cast iron, (b) gray cast iron, (c) malleable iron, or (d) white cast iron?

Answer. (b).

6.12 Which one of the following metals has the lowest density: (a) aluminum, (b) magnesium, (c) tin, or (d) titanium.?

Answer. (b).

6.13 Which of the following metals has the highest density: (a) gold, (b) lead, (c) platinum, (d) silver, or (e) tungsten?

Answer. (c).

6.14 From which of the following ores is aluminum derived: (a) alumina, (b) bauxite, (c) cementite, (d) hematite, or (e) scheelite?

Answer. (b).

6.15 Which of the following metals is noted for its good electrical conductivity (one best answer): (a) copper, (b) gold, (c) iron, (d) nickel, or (e) tungsten?

Answer. (a).

6.16 Traditional brass is an alloy of which of the following metallic elements (two correct answers): (a) aluminum, (b) copper, (c) gold, (d) tin, and (e) zinc?

Answer. (b) and (e).

6.17 Which one of the following metals has the lowest melting point: (a) aluminum, (b) lead, (c) magnesium, (d) tin, or (e) zinc?

Answer. (d).

Problems

6.1 For the copper-nickel phase diagram in Figure 6.2, find the compositions of the liquid and solid phases for a nominal composition of 70% Ni and 30% Cu at 1371°C (2500°F).

Solution: From Fig 6.2, the compositions are observed as follows:
Liquid phase composition = **65% Ni - 35% Cu.**
Solid phase composition = **83% Ni - 17% Cu.**

6.2 For the preceding problem, use the inverse lever rule to determine the proportions of liquid and solid phases present in the alloy.

Solution: From Fig 6.2, measured values of CL and CS are: CL = 5 mm, CS = 12 mm.
Liquid phase proportion = 12/(12 + 5) = 12/17 = **0.71**
Solid phase proportion = 5/17 = **0.29**

6.3 Using the lead-tin phase diagram in Figure 6.3, determine the liquid and solid phase compositions for a nominal composition of 40% Sn and 60% Pb at 204°C (400°F).

Solution: From Fig 6.3, the compositions are observed as follows:
Liquid phase composition = **56% Sn - 44% Pb.**
α phase composition = **18% Sn - 82% Pb.**

6.4 For the preceding problem, use the inverse lever rule to determine the proportions of liquid and solid phases present in the alloy.

Solution: From Fig 6.3, measured values of CL and CS are: CL = 10.5 mm, CS = 15 mm.
Liquid phase proportion = 15/(15 + 10.5) = 15/25.5 = **0.59**
α phase proportion = 10.5/25.5 = **0.41**

6.5 Using the lead-tin phase diagram in Figure 6.3, determine the liquid and solid phase compositions for a nominal composition of 90% Sn and 10% Pb at 204°C (400°F).

Solution: From Fig 6.3, the compositions are observed as follows:
Liquid phase composition = **78% Sn - 22% Pb**.
β phase composition = **98% Sn - 2% Pb.**

6.6 For the preceding problem, use the inverse lever rule to determine the proportions of liquid and solid phases present in the alloy.

Solution: From Fig 6.3, measured values of CL and CS are: CL = 7.8 mm, CS = 4.2 mm.
Liquid phase proportion = 4.2/(13) = **0.32**
α phase proportion = 7.8/13 = **0.68**

6.7 In the iron-iron carbide phase diagram of Figure 6.4, identify the phase or phases present at the following temperatures and nominal compositions: (a) 650°C (1200°F) and 2% Fe_3C, (b) 760°C (1400°F) and 2% Fe_3C, and (c) 1095°C (2000°F) and 1% Fe_3C.

Solution: (a) Alpha + iron carbide, (b) gamma + iron carbide, and (c) gamma.

7 CERAMICS

Review Questions

7.1 What is a ceramic?

Answer. A ceramic is an inorganic compound, consisting of a metal (or semi-metal) and one or more non-metals.

7.2 What are the four most common elements in the earth's crust?

Answer. Oxygen, silicon, aluminum, and iron.

7.3 What is the difference between the traditional ceramics and the new ceramics?

Answer. Traditional ceramics are based primarily on clay products (e.g., pottery, bricks) while new ceramics are more recently developed ceramics which are generally simpler in chemical composition (e.g., oxides, carbides).

7.4 What is the feature that distinguishes glass from the traditional and new ceramics?

Answer. Glass is noncrystalline (amorphous), while most other ceramics assume a crystalline structure.

7.5 What are the general mechanical properties of ceramic materials?

Answer. Typical mechanical properties include high hardness, brittleness, and no ductility.

7.6 What are the general physical properties of ceramic materials?

Answer. Typical physical properties include electrical and thermal insulating, medium density (mostly below the density of metals), high melting temperatures, and thermal expansion usually less than metals.

7.7 What type of atomic bonding characterizes the ceramics?

Answer. Covalent and ionic bonding.

7.8 What do bauxite and corundum have in common?

Answer. They are both minerals of alumina.

7.9 What is clay, used in making ceramic products?

Answer. Clay most commonly consists of hydrous aluminum silicate; for example, kaolinite ($Al_2(Si_2O_5)(OH)_4$) is a common clay.

7.10 What is glazing, as applied to ceramics?

Answer. Glazing involves the application of a surface coating of oxides such as alumina and silica, usually to a porous ceramic product such as earthenware, to make the product more impervious to moisture and more attractive.

7.11 What does the term refractory mean?

Answer. Refractories are heat resistant ceramic materials. The term is sometimes also applied to metals that are heat resistant.

7.12 What are some of the principal applications of cemented carbides, such as WC-Co?

Answer. Important applications of WC-Co include cutting tool inserts, drawing dies, rock drilling bits, dies for powder metallurgy, and other applications where hardness is a critical factor.

7.13 What is one of the important applications of titanium nitride, as mentioned in the text?

Answer. As a thin coating on cutting tools to prolong tool life.

7.14 What are the elements in the ceramic material Sialon?

Answer. Sialon consists of the elements silicon, aluminum, oxygen, and nitrogen.

7.15 Define glass.

Answer. Glass is an inorganic, nonmetallic material that cools to a rigid solid without crystallization.

7.16 What is the primary mineral in glass products?

Answer. Silica, or silicon dioxide (SiO_2).

7.17 What are some of the functions of the ingredients that are added to glass in addition to silica? Name at least three.

Answer. The functions of the additional ingredients include: (1) acting as flux (promoting fusion) during heating; (2) increasing fluidity in the molten glass during processing; (3) retarding devitrification, which is the tendency to crystallize from the glassy state; (4) reducing thermal expansion in the final product; (5) increasing the chemical resistance against attack by acids, basic substances, or water; (6) adding color to the glass; and (7) altering the index of refraction for optical applications (e.g., lenses).

7.18 What does the term devitrification mean?

Answer. Devitrification is the transformation from the glassy state into a polycrystalline state.

7.19 What is graphite?

Answer. Graphite is carbon in the form of hexagonal crystalline layers, in which covalent bonding exists between atoms in the layers, and the (parallel) layers are bonded by van der Waals forces, thus leading to highly anisotropic properties.

Multiple Choice Quiz

There are 17 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

7.1 Which one of the following is the most common element in the earth's crust: (a) aluminum, (b) calcium, (c) iron, (d) oxygen, or (e) silicon?

Answer. (d).

7.2 Glass products are based primarily on which one of the following minerals: (a) alumina, (b) corundum, (c) feldspar, (d) kaolinite, or (e) silica?

Answer. (e).

7.3 Which of the following contains significant amounts of aluminum oxide (three correct answers): (a) alumina, (b) bauxite, (c) corundum, (d) feldspar, (e) kaolinite, (f) quartz, (g) sandstone, and (h) silica?

Answer. (a), (b), and (c).

7.4 Which of the following ceramics are commonly used as abrasives in grinding wheels (two best answers): (a) aluminum oxide, (b) calcium oxide, (c) carbon monoxide, (d) silicon carbide, and (e) silicon dioxide?

Answer. (a) and (d).

7.5 Which one of the following is generally the most porous of the clay-based pottery ware: (a) china, (b) earthenware, (c) porcelain, or (d) stoneware?

Answer. (b).

7.6 Which one of the following is fired at the highest temperatures: (a) china, (b) earthenware, (c) porcelain, or (d) stoneware?

Answer. (c).

7.7 Which one of the following comes closest to expressing the chemical composition of clay: (a) Al_2O_3, (b) $Al_2(Si_2O_5)(OH)_4$, (c) $3AL_2O_3$-$2SiO_2$, (d) MgO, or (e) SiO_2?

Answer. (b).

7.8 Glass ceramics are polycrystalline ceramic structures that have been transformed into the glassy state: (a) true or (b) false?

Answer. (b). Glass ceramics are glasses that have been transformed into a mostly crystalline form through heat treatment.

7.9 Which one of the following materials is closest to diamond in hardness: (a) aluminum oxide, (b) carbon dioxide, (c) cubic boron nitride, (d) silicon dioxide, or (e) tungsten carbide?

Answer. (c).

7.10 Which of the following best characterizes the structure of glass-ceramics: (a) 95% polycrystalline, (b) 95% vitreous, or (b) 50% polycrystalline?

Answer. (a).

7.11 Properties and characteristics of the glass-ceramics include which of the following (two best answers): (a) efficiency in processing, (b) electrical conductor, (c) high thermal expansion, and (d) strong, relative to other glasses?

Answer. (a) and (d).

7.12 Diamond is the hardest material known: (a) true or (b) false?

Answer. (a).

7.13 Synthetic diamonds date to (a) ancient times, (b) 1800s, (c) 1950s, or (d) 1980.

Answer. (c).

8 POLYMERS

Review Questions

8.1 What is a polymer?

Answer. A polymer is a compound comprised of long-chain molecules that consist of repeating units, called mers, connected end to end.

8.2 What are the three basic categories of polymers?

Answer. The categories are (1) thermoplastics, (2) thermosetting polymers, and (3) elastomers.

8.3 How do the properties of polymers compare with those of metals?

Answer. In general, polymers have lower strength, hardness, stiffness, density, and temperature resistance compared to metals. In addition, polymers have low electrical and thermal conductivity.

8.4 What does the degree of polymerization indicate?

Answer. The degree of polymerization indicates the average number of mers or repeating units in the polymer molecule.

8.5 What is cross-linking in a polymer, and what is its significance?

Answer. Cross-linking is the formation of connections between the long-chain molecules in a polymer. It causes the polymer structure to be permanently altered. If the amount of cross-linking is low, the polymer is transformed into an elastomer; if cross-linking is significant, the polymer is transformed into a thermoset.

8.6 What is a copolymer?

Answer. A copolymer is a polymer made up of two different types of mers, such as ethylene and propylene.

8.7 Copolymers can possess four different arrangements of their constituent mers. Name and briefly describe the four arrangements.

Answer. The four possible arrangements of the mers along the chain are (1) alternating, in which the mers repeat every other position; (2) random, in which the mers are in random order; (3) block, in which mers of each type group themselves into long segments along the chain; and (4) graft, in which mers of one type are attached as branches to a main backbone of mers of the other type.

8.8 What is a terpolymer?

Answer. A terpolymer is a polymer with three different mer types. An example is ABS (acrylonitrile-butadiene-styrene) plastic.

8.9 How are a polymer's properties affected when it takes on a crystalline structure?

Answer. Density, stiffness, and melting temperature increase.

8.10 Does any polymer ever become 100% crystalline?

Answer. No.

8.11 What are some of the factors that influence a polymer's tendency to crystallize?

Answer. The factors that influence a polymer's tendency to crystallize are the following: (1) only linear polymers can form crystals; (2) copolymers do not form crystals; (3) stereoregularity - isotactic polymers always form crystals, atactic polymers never form crystals, and syndiotactic polymers sometimes form crystals; (4) slow cooling from the molten states promotes crystal formation; (5) plasticizers inhibit crystal formation; and (6) stretching the polymer tends to promote crystallization.

8.12 Why are fillers added to a polymer?

Answer. Fillers are added to increase strength or simply to reduce the cost of the polymer.

8.13 What is a plasticizer?

Answer. A plasticizer is a chemical added to the polymer to make it softer and more flexible. It is often added to improve the polymer's flow characteristics for shaping.

8.14 In addition to fillers and plasticizers, what are some other additives used with polymers?

Answer. Other additives include (1) lubricants - to reduce friction and improve flow; (2) flame retardents; (3) colorants; (4) cross-linking agents, (5) antioxidants, and (6) ultraviolet light absorbers.

8.15 Describe the difference in mechanical properties as a function of temperature between a highly crystalline thermoplastic and an amorphous thermoplastic.

Answer. A highly crystalline TP retains rigidity during heating until just before its T_m is reached. An amorphous TP shows a significant drop in deformation resistance as its T_g as temperature is reached; it becomes increasingly like a liquid as temperature continues to increase.

8.16 What is unique about the polymer cellulose?

Answer. Cellulose is a polymer that grows in nature. Wood fiber contains about 50% cellulose and cotton fiber is about 95% cellulose.

8.17 The nylons are members of which polymer group?

Answer. Polyamides.

8.18 What is the chemical formula of ethylene, the monomer for polyethylene?

Answer. The chemical formula of ethylene is C_2H_4.

8.19 What is the basic difference between low-density and high-density polyethylene?

Answer. LDPE has a branched structure and is amorphous. HDPE is linear and highly crystalline. These differences account for HDPE having higher density, stiffness, and melting point.

8.20 How do the properties of thermosetting polymers differ from those of thermoplastics?

Answer. Thermosets are more rigid, brittle, capable of higher service temperatures, and cannot be remelted.

8.21 Cross-linking (curing) of thermosetting plastics is accomplished by one of three ways. Name the three ways.

Answer. The three ways are (1) temperature-activated systems, in which elevated temperatures accomplish curing; (2) catalyst-activated systems, in which small amounts of a catalyst cause cross-linking; and (3) mixing-activated systems, in which two reactive components are mixed and curing occurs by their chemical reaction.

8.22 Elastomers and thermosetting polymers are both cross-linked. Why are their properties so different?

Answer. Elastomers are lightly cross-linked, whereas thermosets are highly cross-linked. Light cross-linking allows extensibility; a highly cross-linked structure makes the polymer rigid.

8.23 What happens to an elastomer when it is below its glass transition temperature?

Answer. An elastomer becomes hard and brittle when its temperature is below its T_g.

8.24 What is the primary polymer ingredient in natural rubber?

Answer. The primary polymer ingredient in natural rubber is polyisoprene whose mer has the chemical formula C_5H_8.

8.25 How do thermoplastic elastomers differ from conventional rubbers?

Answer. TPEs are different in two basic ways: (1) they exhibit thermoplastic properties, and (2) their extensibility derives from physical connections between different phases in the polymer rather than cross-linking.

Multiple Choice Quiz

There are 20 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

8.1 Of the three polymer types, which one is the most important commercially: (a) thermoplastics, (b) thermosets, or (c) elastomers?

Answer. (a).

8.2 Which one of the three polymer types is not normally considered to be a plastic: (a) thermoplastics, (b) thermosets, or (c) elastomers?

Answer. (c).

8.3 Which one of the three polymer types does not involve cross-linking: (a) thermoplastics, (b) thermosets, or (c) elastomers?

Answer. (a).

8.4 As the degree of crystallinity in a given polymer increases, the polymer becomes denser and stiffer, and its melting temperature decreases: (a) true or (b) false?

Answer. (b). Melting temperature increases with higher degree of crystallinity.

8.5 Which one of the following is the chemical formula for the repeating unit in polyethylene: (a) CH_2, (b) C_2H_4, (c) C_3H_6, (d) C_5H_8, or (e) C_8H_8?

Answer. (b).

8.6 Degree of polymerization is which one of the following: (a) average number of mers in the molecule chain; (b) proportion of the monomer that has been polymerized; (c) sum of the molecule weights of the mers in the molecule; or (d) none of the above?

Answer. (a).

8.7 A branched molecular structure is stronger in the solid state and more viscous in the molten state than a linear structure for the same polymer: (a) true or (b) false?

Answer. (a).

8.8 A copolymer is a mixture of the macromolecules of two different homopolymers: (a) true or (b) false?

Answer. (b).

8.9 As the temperature of a polymer increases, its density (a) increases, (b) decreases, or (c) remains fairly constant?

Answer. (b).

8.10 Which of the following plastics has the highest market share: (a) phenolics, (b) polyethylene, (c) polypropylene, (d) polystyrene, or (e) polyvinylchloride?

Answer. (b).

8.11 Which of the following polymers are normally thermoplastic (four best answers): (a) acrylics, (b) cellulose acetate, (c) nylon, (d) phenolics, (e) polychloroprene, (f) polyesters, (g) polyethylene, (h) polyisoprene, and (i) polyurethane?

Answer. (a), (b), (c), and (g).

8.12 Polystyrene (without plasticizers) is amorphous, transparent, and brittle: (a) true or (b) false?

Answer. (a).

8.13 The fiber rayon used in textiles is based on which one of the following polymers: (a) cellulose, (b) nylon, (c) polyester, (d) polyethylene, or (e) polypropylene?

Answer. (a).

8.14 The basic difference between low-density polyethylene and high-density polyethylene is that the latter has a much higher degree of crystallinity: (a) true or (b) false?

Answer. (a).

8.15 Among the thermosetting polymers, the most widely used commercially is which one of the following: (a) epoxies, (b) phenolics, (c) silicones, or (d) urethanes?

Answer. (b).

8.16 The chemical formula for polyisoprene in natural rubber is which of the following: (a) CH_2, (b) C_2H_4, (c) C_3H_6, (d) C_5H_8, or (e) C_8H_8?

Answer. (d).

8.17 The leading commercial synthetic rubber is which one of the following: (a) butyl rubber, (b) isoprene rubber, (c) polybutadiene, (d) polyurethane, (e) styrene-butadiene rubber, or (f) thermoplastic elastomers?

Answer. (e).

9 COMPOSITE MATERIALS

Review Questions

9.1 What is a composite material?

Answer. A composite material is a material system consisting of two or more distinct phases whose combination results in properties that differ from those of its constituents.

9.2 Identify some of the characteristic properties of composite materials.

Answer. Typical properties include (1) high strength-to-weight and stiffness-to-weight ratios; (2) good fatigue properties and toughness; (3) anisotropic properties in many cases; and (4) other properties and features that are difficult or impossible to obtain with metals, ceramics, or polymers alone.

9.3 What does the term anisotropic mean?

Answer. Anisotropic means that the properties of a material vary depending on the direction in which they are measured.

9.4 How are traditional composites distinguished from synthetic composites?

Answer. Traditional composites have been used for decades or centuries; some of them are obtained from sources in nature, such as wood. Synthetic composites are manufactured.

9.5 Name the three basic categories of composite materials.

Answer. Metal matrix composites (MMCs), ceramic matrix composites (CMCs), and polymer matrix composites (PMCs).

9.6 What are the common forms of the reinforcing phase in composite materials?

Answer. The forms are: (1) fibers, (2) particles and flakes, and (3) an infiltrated phase in skeletal structures.

9.7 What is a whisker?

Answer. A whisker is a thin, hairlike crystal of very high strength.

9.8 What are the two forms of sandwich structure among laminar composite structures? Briefly describe each.

Answer. The two forms are (1) foamed-core sandwich, in which the core is polymer foam between two solid skins; and (2) honeycomb, in which the core is a honeycomb structure sandwiched between two solid skins.

9.9 Give some examples of commercial products which are laminar composite structures.

Answer. Examples given in Table 9.2 are automotive tires, honeycomb sandwich structures, fiber reinforced polymer structures such as boat hulls, plywood, printed circuit boards, snow skis made from fiber reinforced polymers, and windshield glass.

9.10 What are the three general factors that determine the properties of a composite material?

Answer. Three factors are given in the text: (1) the component materials; (2) the geometric shapes of the constituents - the reinforcing phase in particular - and the resulting structure of the material; and (3) the interaction of the phases.

9.11 What is the rule of mixtures?

Answer. The rule of mixtures applies to certain properties of composite materials; it states that the property value is a weighted average of the property values of the components, the weighting being by proportions of the components in the composite.

9.12 What is a cermet?

Answer. A cermet is a composite material consisting of a ceramic and a metal. In the text, it is defined as a composite consisting of ceramic grains imbedded in a metallic matrix.

9.13 Cemented carbides are what class of composites?

Answer. A cemented carbide is a cermet; although the cemented carbide industry does not generally think of cemented carbides as cermets, they fit within the definition.

9.14 What are some of the weaknesses of ceramics that might be corrected in fiber-reinforced ceramic matrix composites?

Answer. Weaknesses of ceramics include low tensile strength, poor toughness, and susceptibility to thermal cracking.

9.15 What is the most common fiber material in fiber-reinforced plastics?

Answer. E-glass.

9.16 What does the term advanced composites mean?

Answer. An advanced composite is a PMC in which carbon, Kevlar, or boron fibers are used as the reinforcing material.

9.17 What is a hybrid composite?

Answer. A hybrid composite is a fiber-reinforced PMC in which two or more fibers materials are combined in the FRP.

9.18 Identify some of the important properties of fiber-reinforced plastic composite materials.

Answer. Properties include high strength-to-weight ratio, high modulus-to-weight ratio, low density, good fatigue strength, good corrosion resistance, and low thermal expansion for many FRPs.

9.19 Name some of the important applications of FRPs.

Answer. FRPs are used in modern aircraft as skin parts, automobile body panels, printed circuit boards, tennis rackets, boat hulls, and a variety of other items.

9.20 What is meant by the term interface in the context of composite materials?

Answer. The interface is the boundary between the component phases in a composite material.

Multiple Choice Quiz

There are 19 correct answers in the following multiple-choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

9.1 Anisotropic means which one of the following: (a) composite materials with composition consisting of more than two materials, (b) properties are the same in every direction, (c) properties vary depending on the direction in which they are measured, or (d) strength and other properties are a function of curing temperature?

Answer. (c).

9.2 The reinforcing phase is the matrix within which the secondary phase is imbedded: (a) true or (b) false?

Answer. (b).

9.3 Which one of the following reinforcing geometries offers the greatest potential for strength and stiffness improvement in the resulting composite material: (a) fibers, (b) flakes, (c) particles, or (d) infiltrated phase?

Answer. (a).

9.4 Wood is which one of the following composite types: (a) CMC, (b) MMC, or (c) PMC?

Answer. (c).

9.5 Which of the following materials are used as fibers in fiber-reinforced plastics (four best answers): (a) aluminum oxide, (b) boron, (c) cast iron, (d) E-glass, (e) epoxy, (f) Kevlar 49, (g) polyester, and (h) silicon?

Answer. (a), (b), (d), and (f).

9.6 Which of the following metals are used as the matrix material in fiber-reinforced MMCs (two best answers): (a) aluminum, (b) copper, (c) iron, (d) magnesium, and (e) zinc?

Answer. (a) and (d).

9.7 Which of the following metals are used as the matrix metals in nearly all WC cemented carbides and TiC cermets (two correct answers): (a) aluminum, (b) chromium, (c) cobalt, (d) lead, (e) nickel, (f) tungsten, and (g) tungsten carbide?

Answer. (c) and (e).

9.8 Ceramic matrix composites are designed to overcome which of the following weaknesses of ceramics (two best answers): (a) compressive strength, (b) hardness, (c) hot hardness, (d) modulus of elasticity, (e) tensile strength, and (f) toughness?

Answer. (e) and (f).

9.9 Which one of the following polymer types are most commonly used in polymer matrix composites: (a) elastomers, (b) thermoplastics, or (c) thermosets?

Answer. (c).

9.10 Which of the following materials are not composites (two correct answers): (a) cemented carbide, (b) phenolic molding compound, (c) plywood, (d) Portland cement, (e) rubber in automobile tires, (f) wood, and (g) 1020 steel?

Answer. (d) and (g).

In the Boeing 787 Dreamliner, what percentage of the aircraft consist of composite materials (two correct answers): (a) 12% be volume, (b) 20% by volume, (c) 50% by volume, (d) 80% by volume, (e) 12% by weight, (f) 20% by weight, (g) 50% by weight, and (h) 80% by weight?

Answer. (d) and (g).

Problems

9.1 A fiberglass composite is composed of a matrix of vinyl ester and reinforcing fibers of E-glass. The volume fraction of E-glass is 35%. The remainder is vinyl ester. The density of the vinyl ester is 0.882 g/cm^3, and its modulus of elasticity is 3.60 GPa. The density of E-glass is 2.60 g/cm^3, and its modulus of elasticity is 76.0 GPa. A section of composite 1.00 cm by 50.00 cm by 200.00 cm is fabricated with the E-glass fibers running longitudinal along the 200-cm direction. Assume there are no voids in the composite. Determine the (a) mass of vinyl ester in the section, (b) mass of E-glass fibers in the section, and (c) the density of the composite.

Solution: Volume V = (1.00 cm)(50.00 cm)(200.00 cm) = 10,000 cm^3

(a) $V_m = f_m (V_c) = 0.650(10{,}000\ cm^3) = 6{,}500\ cm^3$
$m_m = 6500\ cm^3\ (0.882\ g/cm^3) = 5733$ g

(b) $V_r = f_r (V_c) = 0.350(10{,}000\ cm^3) = 3{,}500\ cm^3$
$m_r = 3500\ cm^3\ (2.60\ g/cm^3) = 9100$ g

(c) $\rho_c = = f_m\, \rho_m + f_r\, \rho_r = 0.650(0.882) + 0.350(2.60) =$ **1.48 g/cm^3**

9.2 For problem 9.1, determine the modulus of elasticity in (a) the longitudinal direction of the glass fibers and (b) the perpendicular direction to the glass fibers.

Solution: $f_m = 0.650$, $f_r = 0.350$, $E_m = 3.60$ GPa, and $E_r = 76.0$ GPa

(a) $E_c = f_mE_m + f_rE_r$
$E_c = 0.650(3.60) + 0.350(76.0) =$ **28.9 GPa**

(b) $E_c' = E_mE_r/(f_mE_r + f_rE_m)$
$E_c' = 3.60(76.0)/(0.650(76.0) + 0.350(3.60)) =$ **5.40 GPa**

9.3 A composite sample of carbon reinforced epoxy has dimensions of 12 in by 12 in by 0.25 in and mass of 1.8 lb. The carbon fibers have a modulus of elasticity of $50(10^6)$ lb/in^2 and a density of 0.069 lb/in^3. The epoxy matrix has modulus of elasticity of $0.61(10^6)$ lb/in^2 and a density of 0.042 lb/in^3. What is the volume fraction of (a) the carbon fibers and (b) the epoxy matrix in the sample? Assume there are no voids in the sample.

Solution: $V_c = 12(12)(0.25) = 36$ in^3
$\rho_c = m_c/V_c = 1.8/36 = 0.050$ lb/in^3

(a) $f_m = 1 - f_r$
$\rho_c = f_m\rho_m + f_r\rho_r$
$\rho_c = (1\text{-}f_r)\rho_m + f_r\rho_r$
$\rho_c = \rho_m - f_r\rho_m + f_r\rho_r = \rho_m - f_r(\rho_m - \rho_r)$
$f_r = (\rho_m - \rho_c)/(\rho_m - \rho_r) = (0.042 - 0.050)/(0.042 - 0.069) =$ **0.30 = 30%**

(b) $f_m = 1 - f_r$ $\quad$ $f_m = 1\text{-}\ 0.30 =$ **0.70 = 70%**

9.4 In problem 9.3, what is the predicted value for the modulus of elasticity (a) in the longitudinal direction and (b) the perpendicular to the carbon fibers?

Solution: $f_m = 0.70$, $f_r = 0.30$, $E_m = 0.61\text{x}10^6$ lb/in^2, and $E_r = 50.0\text{x}10^6$ lb/in^2

(a) $E_c = f_mE_m + f_rE_r$ $\quad$ $E_c = 0.70(0.61\text{x}10^6) + 0.30(50.0\text{x}10^6) =$ **15 x 10^6 lb/in^2**

(b) $E_c' = E_mE_r/(f_mE_r + f_rE_m)$
$E_c' = 0.61(10^6)(50.0(10^6)/(0.70(50.0\text{x}10^6) + 0.30(0.61\text{x}10^6)) =$ **0.87 x 10^6 lb/in^2**

9.5 A composite has a matrix of polyester with Kevlar-29 fibers. The volume fractions of polyester and Kevlar are 60% and 40%, respectively. The Kevlar fibers have a modulus of elasticity of 60 GPa in the longitudinal direction and 3 GPa in the transverse direction. The polyester matrix has a modulus of elasticity of 5.6 GPa in both directions. (a) Determine the modulus of elasticity for the composite in the longitudinal direction. (b) Determine the modulus of elasticity in the transverse direction.

Solution: $f_m = 0.60$, $f_r = 0.40$, $E_m = 5.6$ GPa, and $E_r = 60$ GPa

(a) $E_c = f_mE_m + f_rE_r$ $\quad$ $E_c = 0.60(5.6) + 0.40(60) =$ **27.4 GPa**

(b) $E_c' = E_m E_r/(f_m E_r + f_r E_m)$ $E_c' = 5.6(60)/(0.60(60) + 0.40(5.6)) =$ **8.79 GPa**

10 FUNDAMENTALS OF METAL CASTING

Review Questions

10.1 Identify some of the important advantages of shape-casting processes.

Answer. Advantages include (1) complex part geometries are possible; (2) some casting operations are net shape processes, meaning that no further manufacturing operations are needed to accomplish the final part shape; (3) very large parts are possible; (4) they are applicable to any metal that can be melted; and (5) some casting processes are suited to mass production.

10.2 What are some of the limitations and disadvantages of casting?

Answer. Disadvantages include (1) limitations on mechanical strength properties; (2) porosity; (3) poor dimensional accuracy; (4) safety hazards due to handling of hot metals; and (5) environmental problems.

10.3 What is a factory that performs casting operations usually called?

Answer. A foundry.

10.4 What is the difference between an open mold and a closed mold?

Answer. An open mold is open to the atmosphere at the top; it is an open container in the desired shape which must be flat at the top. A closed mold has a cavity that is entirely enclosed by the mold, with a passageway (called the gating system) leading from the outside to the cavity. Molten metal is poured into this gating system to fill the mold.

10.5 Name the two basic mold types that distinguish casting processes.

Answer. The two mold types are (1) expendable molds and (2) permanent molds.

10.6 Which casting process is the most important commercially?

Answer. Sand casting is the most important casting process.

10.7 What is the difference between a pattern and a core in sand molding?

Answer. The pattern determines the external shape of the cast part, while a core determines its internal geometry if the casting includes a cavity.

10.8 What is meant by the term superheat?

Answer. Superheat is the temperature difference above the melting point at which the molten metal is poured. The term also refers to the amount of heat that is removed from the molten metal between pouring and solidification.

10.9 Why should turbulent flow of molten metal into the mold be avoided?

Answer. Turbulence causes the following problems: (1) it accelerates formation of oxides in the solidified metal, and (2) it causes mold erosion or gradual wearing away of the mold due to impact of molten metal.

10.10 What is the continuity law as it applies to the flow of molten metal in casting?

Answer. The continuity law, or continuity equation, indicates that the volumetric flow rate is constant throughout the liquid flow.

10.11 What are some of the factors that affect the fluidity of a molten metal during pouring into a mold cavity?

Answer. The factors include (1) pouring temperature above the melting point, (2) metal alloy composition, (3) viscosity of the liquid metal, and (4) heat transfer to the surroundings.

10.12 What does heat of fusion mean in casting?

Answer. Heat of fusion is the amount of heat energy required to transform the metal from solid state to liquid state.

10.13 How does solidification of alloys differ from solidification of pure metals?

Answer. Pure metals solidify at a single temperature equal to the melting point. Most alloys (exceptions are eutectic alloys) start to solidify at the liquidus and complete solidification occurs at the solidus, where the liquidus is a higher temperature than the solidus.

10.14 What is a eutectic alloy?

Answer. A eutectic alloy is a particular composition in an alloy system for which the solidus and liquidus temperatures are equal. The temperature is called the eutectic temperature. Hence, solidification occurs at a single temperature, rather than over a temperature range.

10.15 What is the relationship known as Chvorinov's rule in casting?

Answer. Chvorinov's rule is summarized: $T_{TS} = C_m(V/A)^2$, where T_{TS} = total solidification time, C_m = mold constant, V = volume of casting, and A = surface area of casting.

10.16 Identify the three sources of contraction in a metal casting after pouring.

Answer. The three contractions occur due to (1) contraction of the molten metal after pouring, (2) solidification shrinkage during transformation of state from liquid to solid, and (3) thermal contraction in the solid state.

10.17 What is a chill in casting?

Answer. A chill is a heat sink placed to encourage rapid freezing in certain regions of the casting.

Multiple Choice Quiz

There are 15 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

10.1 Sand casting is which of the following types: (a) expendable mold or (b) permanent mold?

Answer. (a).

10.2 The upper half of a sand-casting mold is called which of the following: (a) cope or (b) drag?

Answer. (a).

10.3 In casting, a flask is which one of the following: (a) beverage bottle for foundrymen, (b) box which holds the cope and drag, (c) container for holding liquid metal, or (d) metal which extrudes between the mold halves?

Answer. (b).

10.4 In foundry work, a runner is which one of the following: (a) channel in the mold leading from the downsprue to the main mold cavity, (b) foundryman who moves the molten metal to the mold, or (c) vertical channel into which molten metal is poured into the mold?

Answer. (a).

10.5 Turbulence during pouring of the molten metal is undesirable for which of the following reasons (two best answers): (a) it causes discoloration of the mold surfaces, (b) it dissolves the binder used to hold together the sand mold, (c) it increases erosion of the mold surfaces, (d) it increases the formation of metallic oxides that can become entrapped during solidification, (e) it increases the mold filling time, and (f) it increases total solidification time?

Answer: (c) and (d).

10.6 Total solidification time is defined as which one of the following: (a) time between pouring and complete solidification, (b) time between pouring and cooling to room temperature, (c) time between solidification and cooling to room temperature, or (d) time to give up the heat of fusion?

Answer. (a).

10.7 During solidification of an alloy when a mixture of solid and liquid metals is present, the solid-liquid mixture is referred to as which one of the following: (a) eutectic composition, (b) ingot segregation, (c) liquidus, (d) mushy zone, or (e) solidus?

Answer. (d).

10.8 Chvorinov's rule states that total solidification time is proportional to which one of the following quantities: (a) $(A/V)^n$, (b) H_f, (c) T_m, (d) V, (e) V/A, or (f) $(V/A)^2$; where A = surface area of casting, H_f = heat of fusion, T_m = melting temperature, and V = volume of casting?

Answer. (f).

10.9 A riser in casting is described by which of the following (three correct answers): (a) an insert in the casting that inhibits buoyancy of the core, (b) gating system in which the sprue feeds directly into the cavity, (c) metal that is not part of the casting, (d) source of molten metal to feed the casting and compensate for shrinkage during solidification, and (e) waste metal that is usually recycled?

Answer. (c), (d), and (e).

10.10 In a sand-casting mold, the V/A ratio of the riser should be (a) equal to, (b) greater than, or (c) smaller than the V/A ratio of the casting itself?

Answer. (b).

10.11 Which of the following riser types are completely enclosed within the sand mold and connected to the main cavity by a channel to feed the molten metal (two correct answers): (a) blind riser, (b) open riser, (c) side riser, and (d) top riser?

Answer. (a) and (c).

Problems

Heating and Pouring

10.1 A disk 40 cm in diameter and 5 cm thick is to be cast of pure aluminum in an open mold casting operation. The melting temperature of aluminum = 660°C, and the pouring temperature will be 800°C. Assume that the amount of aluminum heated will be 5% more than what is needed to fill the mold cavity. Compute the amount of heat that must be added to the metal to heat it to the pouring temperature, starting from a room temperature of 25°C. The heat of fusion of aluminum = 389.3 J/g. Other properties can be obtained from Tables 4.1 and 4.2 in the text. Assume the specific heat has the same value for solid and molten aluminum.

Solution: Volume $V = \pi D^2h/4 = \pi(40)^2(5)/4 = 6283.2$ cm^3
Volume of aluminum to be heated = 6283.2(1.05) = 6597.3 cm^3
From Table 4.1 and 4.2, density $\rho = 2.70$ g/cm^3 and specific heat C = 0.21 Cal/g-°C = 0.88 J/g-°C

Heat required = 2.70(6597.3){0.88(660-25) + 389.3 + 0.88(800-660)}
= 17,812.71{558.8 + 389.3 + 123.2} = **19,082,756 J**

10.2 A sufficient amount of pure copper is to be heated for casting a large plate in an open mold. The plate has dimensions: length = 20 in, width = 10 in, and thickness = 3 in. Compute the amount of heat that must be added to the metal to heat it to a temperature of 2150°F for pouring. Assume that the amount of metal heated will be 10% more than what is needed to fill the mold cavity. Properties of the metal are: density = 0.324 lbm/in^3, melting point = 1981°F, specific heat of the metal = 0.093 Btu/lbm-F in the solid state and 0.090 Btu/lbm-F in the liquid state, and heat of fusion = 80 Btu/lbm.

Solution: Volume V = (20 x 10 x 3)(1 + 10%) = 600(1.1) = 660.0 in^3
Assuming T_o = 75 °F and using Eq. (10.1),
H = 0.324 x 660{0.093(1981 - 75) + 80 + 0.090(2150 - 1981)} = 213.84{177.26 + 80 + 15.21}
***H* = 58,265 Btu**

10.3 The downsprue leading into the runner of a certain mold has a length = 175 mm. The cross-sectional area at the base of the sprue is 400 mm^2. The mold cavity has a volume = 0.001 m^3. Determine (a) the velocity of the molten metal flowing through the base of the downsprue, (b) the volume rate of flow, and (c) the time required to fill the mold cavity.

Solution: (a) Velocity v = (2 x 9815 x 175)$^{0.5}$ = (3,435,096)$^{0.5}$ = **1853 mm/s**
(b) Volume flow rate $Q = vA$ = 1853 x 400 = **741,200 mm^3/s**
(c) Time to fill cavity $T_{MF} = V/Q$ = 1,000,000/741,200 = **1.35 s**

10.4 A mold has a downsprue of length = 6.0 in. The cross-sectional area at the bottom of the sprue is 0.5 in^2. The sprue leads into a horizontal runner which feeds the mold cavity, whose volume = 75 in^3. Determine (a) the velocity of the molten metal flowing through the base of the downsprue, (b) the volume rate of flow, and (c) the time required to fill the mold cavity.

Solution: (a) Velocity v = (2 x 32.2 x 12 x 6.0)$^{0.5}$ = (4636.8)$^{0.5}$ = **68.1 in/sec**
(b) Volume flow rate $Q = vA$ = 68.1 x 0.5 = **34.05 in^3/sec**
(c) Time to fill cavity $T_{MF} = V/Q$ = 75.0/34.05 = **2.2 sec.**

10.5 The flow rate of liquid metal into the downsprue of a mold = 1 liter/sec. The cross-sectional area at the top of the sprue = 800 mm^2, and its length = 175 mm. What area should be used at the base of the sprue to avoid aspiration of the molten metal?

Solution: Flow rate Q = 1.0 l/s = 1,000,000 mm^3/s
Velocity v = (2 x 9815 x 175)$^{0.5}$ = 1854 mm/s
Area at base A = 1,000,000/1854 = **540 mm^2**

10.6 The volume rate of flow of molten metal into the downsprue from the pouring cup is 50 in^3/sec. At the top where the pouring cup leads into the downsprue, the cross-sectional area = 1.0 in^2. Determine what the area should be at the bottom of the sprue if its length = 8.0 in. It is desired to maintain a constant flow rate, top and bottom, in order to avoid aspiration of the liquid metal.

Solution: Velocity at base $v = (2gh)^{0.5}$ = (2 x 32.2 x 12 x 8)$^{0.5}$ = 78.6 in/sec
Assuming volumetric continuity, area at base A = (50 in/sec)/(78.6 in/sec) = **0.636 in^2**

10.7 Molten metal can be poured into the pouring cup of a sand mold at a steady rate of 1000 cm^3/s. The molten metal overflows the pouring cup and flows into the downsprue. The cross section of the sprue is round, with a diameter at the top = 3.4 cm. If the sprue is 25 cm long, determine the proper diameter at its base so as to maintain the same volume flow rate.

Solution: Velocity at base $v = (2gh)^{0.5}$ = (2 x 981 x 25)$^{0.5}$ = 221.5 cm/s
Assuming volumetric continuity, area at base A = (1000 cm/s)/(221.5 cm/s) = 4.51 cm^2
Area of sprue $A = \pi D^2/4$; rearranging, $D^2 = 4A/\pi = 4(4.51)/\pi$ = 5.74 cm^2

***D* = 2.39 cm**

10.8 During pouring into a sand mold, the molten metal can be poured into the downsprue at a constant flow rate during the time it takes to fill the mold. At the end of pouring the sprue is filled and there is negligible metal in the pouring cup. The downsprue is 6.0 in long. Its cross-sectional area at the top = 0.8 in^2 and at the base = 0.6 in^2. The cross-sectional area of the runner leading from the sprue also = 0.6 in^2, and it is 8.0 in long before leading into the mold cavity, whose volume = 65 in^3. The volume of the riser located along the runner near the mold cavity = 25 in^3. It takes a total of 3.0 sec to fill the entire mold (including cavity, riser, runner, and sprue. This is more than the theoretical time required, indicating a loss of velocity due to friction in the sprue and runner. Find (a) the theoretical velocity and flow rate at the base of the downsprue; (b) the total volume of the mold; (c) the actual velocity and flow rate at the base of the sprue; and (d) the loss of head in the gating system due to friction.

Solution: (a) Velocity $v = (2 \times 32.2 \times 12 \times 6.0)^{0.5}$ = **68.1 in/sec**
Flow rate $Q = 68.1 \times 0.60$ = **40.8 in^3/sec**

(b) Total $V = 65.0 + 25.0 + 0.5(0.8 + 0.6)(6.0) + 0.6(8.0)$ = **99.0 in^3**

(c) Actual flow rate $Q = 99.0/3$ = **33.0 in^3/sec**
Actual velocity $v = 33.0/0.6$ = **55.0 in/sec**

(d) $v = (2 \times 32.2 \times 12 \times h)^{0.5} = 27.8\ h^{0.5} = 55.0$ in/sec.
$h^{0.5} = 55.0/27.8 = 1.978$
$h = 1.978^2 = 3.914$ in
Head loss = 6.0 - 3.914 = **2.086 in**

Shrinkage

10.9 Determine the shrink rule to be used by pattern makers for white cast iron. Using the shrinkage value in Table 10.1, express your answer in terms of decimal fraction inches of elongation per foot of length compared to a standard one-foot scale.

Solution: For white cast iron, shrinkage 2.1% from Table 10.1.
Thus, linear contraction = 1.0 – 0.021 = 0.979.
Shrink rule elongation = $(0.979)^{-1} = 1.02145$
For a 12-inch rule, L = 1.02145(12) = 12.257 in
Elongation per foot of length = **0.257 in**

10.10 Determine the shrink rule to be used by mold makers for die casting of zinc. Using the shrinkage value in Table 10.1, express your answer in terms of decimal mm of elongation per 300 mm of length compared to a standard 300-mm scale.

Solution: For zinc, shrinkage 2.6% from Table 10.1.
Thus, linear contraction = 1.0 – 0.026 = 0.974.
Shrink rule elongation = $(0.974)^{-1} = 1.0267$
For a 300-mm rule, L = 1.0267(300) = 308.008 mm
Elongation per 300 mm of length = **8.008 mm**

10.11 A flat plate is to be cast in an open mold whose bottom has a square shape that is 200 mm by 200 mm. The mold is 40 mm deep. A total of 1,000,000 mm^3 of molten aluminum is poured into the mold. Solidification shrinkage is known to be 6.0%. Table 10.1 lists the linear shrinkage due to thermal contraction after solidification to be 1.3%. If the availability of molten metal in the mold allows the square shape of the cast plate to maintain its 200 mm by 200 mm dimensions until solidification is completed, determine the final dimensions of the plate.

Solution: The initial volume of liquid metal = 1,000,000 mm^3. When poured into the mold it takes the shape of the open mold, which is 200 mm by 200 mm square, or 40,000 mm^2. The starting height of the molten metal is 1,000,000 / 40,000 = 25 mm.
Volumetric solidification shrinkage is 6%, so when the aluminum has solidified its volume = 1,000,000(0.94) = 940,000 mm^3. Because its base still measures 200 mm by 200 mm due to the flow of liquid metal before solidification, its height has been reduced to 940,000 / 40,000 = 23.5 mm. Thermal contraction causes a further shrinkage of 1.6%. Thus the final dimensions of the plate are 200(0.984) by 200(0.984) by 23.5(0.984) = **196.8 mm by 196.8 mm by 23.124 mm**.

Solidification Time and Riser Design

10.12 In the casting of steel under certain mold conditions, the mold constant in Chvorinov's rule is known to be 4.0 min/cm^2, based on previous experience. The casting is a flat plate whose length = 30 cm, width = 10 cm, and thickness = 20 mm. Determine how long it will take for the casting to solidify.

Solution: Volume V = 30 x 10 x 2 = 600 cm^3
Area A = 2(30 x 10 + 30 x 2 + 10 x 2) = 760 cm^2
Chvorinov's rule: $T_{TS} = C_m (V/A)^2 = 4(600/760)^2 =$ **2.49 min**

10.13 Solve for total solidification time in the previous problem only using an exponent value of 1.9 in Chvorinov's rule instead of 2.0. What adjustment must be made in the units of the mold constant?

Solution: Chvorinov's rule: $T_{TS} = C_m (V/A)^{1.9} = 4(600/760)^{1.9} =$ **2.55 min**
The units for C_m become min/in$^{1.9}$ - strange units but consistent with Chvorinov's empirical rule.

10.14 A disk-shaped part is to be cast out of aluminum. The diameter of the disk = 500 mm and its thickness = 20 mm. If the mold constant = 2.0 sec/mm^2 in Chvorinov's rule, how long will it take the casting to solidify?

Solution: Volume $V = \pi D^2 t/4 = \pi(500)^2(20)/4 = 3{,}926{,}991$ mm^3
Area $A = 2\pi D^2/4 + \pi Dt = \pi(500)^2/2 + \pi(500)(20) = 424{,}115$ mm^2
Chvorinov's rule: $T_{TS} = C_m (V/A)^2 = 2.0(3{,}926{,}991/424{,}115)^2 =$ **171.5 s = 2.86 min**

10.15 In casting experiments performed using a certain alloy and type of sand mold, it took 155 sec for a cube-shaped casting to solidify. The cube was 50 mm on a side. (a) Determine the value of the mold constant in Chvorinov's rule. (b) If the same alloy and mold type were used, find the total solidification time for a cylindrical casting in which the diameter = 30 mm and length = 50 mm.

Solution: (a) Volume $V = (50)^3 = 125{,}000$ mm^3
Area $A = 6 \times (50)^2 = 15{,}000$ mm^2
$(V/A) = 125{,}000/15{,}000 = 8.333$ mm
$C_m = T_{TS}/(V/A)^2 = 155/(8.333)^2 =$ **2.232 s/mm^2**

(b) Cylindrical casting with D = 30 mm and L = 50 mm.
Volume $V = \pi D^2 L/4 = \pi(30)^2(50)/4 = 35{,}343$ mm^3
Area $A = 2\pi D^2/4 + \pi DL = \pi(30)^2/2 + \pi(30)(50) = 6126$ mm^2
$V/A = 35{,}343/6126 = 5.77$
$T_{TS} = 2.232\ (5.77)^2 =$ **74.3 s = 1.24 min.**

10.16 A steel casting has a cylindrical geometry with 4.0 in diameter and weighs 20 lb. This casting takes 6.0 min to completely solidify. Another cylindrical-shaped casting with the same diameter-to-length ratio weighs 12 lb. This casting is made of the same steel, and the same conditions of mold and pouring were used. Determine: (a) the mold constant in Chvorinov's rule, (b) the dimensions, and (c) the total solidification time of the lighter casting. The density of steel = 490 lb/ft^3.

Solution: (a) For steel, ρ = 490 lb/ft^3 = 0.2836 lb/in^3
Weight $W = \rho V$, $V = W/\rho = 20/0.2836 = 70.53$ in^3

Volume $V = \pi D^2L/4 = \pi(4)^2L/4 = 4\pi L = 70.53$ in^3
Length $L = 70.53/4\pi = 5.61$ in
Area $A = 2\pi D^2/4 + \pi DL = 2\pi(4)^2/4 + \pi(4)(5.61) = 95.63$ in^2
$(V/A) = 70.53/95.63 = 0.7375$
$C_m = 6.0/(0.7353)^2 =$ **11.03 min/in^2**

(b) Find dimensions of smaller cylindrical casting with same D/L ratio and $w = 12$ lb.
Weight is proportional to volume: $V = (12/20)(70.53) = 42.32$ in^3
D/L ratio = 4.0/5.61 = 0.713; thus $L = 1.4025$D
Volume $V = \pi D^2L/4 = \pi(D)^2(1.4025D)/4 = 1.1015D^3$
$D^3 = (42.32 \text{ in}^3)/1.1015 = 38.42$ in^3
$D = (38.42)^{0.333} =$ **3.374 in**
$L = 1.4025(3.374) =$ **4.732 in**

(c) $V = \pi D^2L/4 = \pi(3.374)^2(4.732)/4 = 42.32$ in^3
$A = 2\pi D^2/4 + \pi DL = 0.5\pi(3.374)^2 + \pi(3.374)(4.732) = 68.04$ in^2
$V/A = 42.32/68.04 = 0.622$ in.
$T_{TS} = 11.03(.622)^2 =$ **4.27 min**.

10.17 The total solidification times of three casting shapes are to be compared: (1) a sphere with diameter = 10 cm, (2) a cylinder with diameter and length both = 10 cm, and (3) a cube with each side = 10 cm. The same casting alloy is used in the three cases. (a) Determine the relative solidification times for each geometry. (b) Based on the results of part (a), which geometric element would make the best riser? (c) If the mold constant = 3.5 min/cm^2 in Chvorinov's rule, compute the total solidification time for each casting.

Solution: For ease of computation, make the substitution 10 cm = 1 decimeter (1 dm)

(a) Chvorinov's rule: $T_{TS} = C_m(V/A)^2$
(1) Sphere volume $V = \pi D^3/6 = \pi(1)^3/6 = \pi/6$ dm^3
Sphere surface area $A = \pi D^2 = \pi(1)^2 = \pi$ dm^2
$V/A = (\pi/6)/\pi = 1/6 = 0.1667$ dm
Chvorinov's rule $T_{TS} = (0.1667)^2C_m =$ **$0.02778C_m$**

(2) Cylinder volume $V = \pi D^2H/4 = \pi(1)^2(1)/4 = \pi/4 = 0.25\pi$ dm^3
Cylinder area $A = 2\pi D^2/4 + \pi DL = 2\pi(1)^2/4 + \pi(1)(1) = \pi/2 + \pi = 1.5\pi$ dm^2
$V/A = 0.25\pi/1.5\pi = 0.1667$ dm
Chvorinov's rule $T_{TS} = (0.1667)^2C_m =$ **$0.02778C_m$**

(3) Cube: $V = L^3 = (1)^3 = 1.0$ dm^3
Cube area = $6L^2 = 6(1)^2 = 6.0$ dm^2
$V/A = 1.0/6.0 = 0.1667$ dm
Chvorinov's rule $T_{TS} = (0.1667)^2C_m =$ **$0.02778C_m$**

(b) All three shapes are equivalent as risers.

(c) If $C_m = 3.5$ min/cm^2 = 350 min/dm^2, then $T_{TS} = 0.02778(350) =$ **9.723 min.** Note, however, that the volumes of the three geometries are different: (1) sphere $V = 0.524$ dm^3 = 524 cm^3, cylinder $V = 0.25\pi = 0.7854$ dm^3 = 785.4 cm^3, and (3) cube $V = 1.0$ dm^3 = 1000cm^3. Accordingly, we might revise our answer to part (b) and choose the sphere on the basis that it wastes less metal than the other shapes.

10.18 The total solidification times of three casting shapes are to be compared: (1) a sphere, (2) a cylinder, in which the length-to-diameter ratio = 1.0, and (3) a cube. For all three geometries, the volume = 1000 cm^3. The same casting alloy is used in the three cases. (a) Determine the relative solidification times for each geometry. (b) Based on the results of part (a), which geometric element would make the best riser? (c) If the mold constant = 3.5 min/cm^2 in Chvorinov's rule, compute the total solidification time for each casting.

Solution: For ease of computation, make the substitution 10 cm = 1 decimeter (1 dm). Thus 1000 cm^3 = 1.0 dm^3.

(1) Sphere volume $V = \pi D^3/6 = 1.0$ dm^3. $D^3 = 6/\pi = 1.910$ dm^3. $D = (1.910)^{0.333} = 1.241$ dm
Sphere area $A = \pi D^2 = \pi(1.241)^2 = 4.836$ dm^2
$V/A = 1.0/4.836 = 0.2067$ dm
Chvorinov's rule $T_{TS} = (0.2067)^2 C_m = \mathbf{0.0428} \boldsymbol{C_m}$

(2) Cylinder volume $V = \pi D^2 H/4 = \pi D^3/4 = 1.0$ dm^3. $D^3 = 4/\pi = 1.273$ dm^3
Therefore, $D = H = (1.273)^{0.333} = 1.084$ dm
Cylinder area $A = 2\pi D^2/4 + \pi DL = 2\pi(1.084)^2/4 + \pi(1.084)(1.084) = 5.536$ dm^2
$V/A = 1.0/5.536 = 0.1806$ dm
Chvorinov's rule $T_{TS} = (0.1806)^2 C_m = \mathbf{0.0326} \boldsymbol{C_m}$

(3) Cube: $V = L^3 = 1.0$ dm^3. $L = 1.0$ dm
Cube area $= 6L^2 = 6(1)^2 = 6.0$ dm^2
$V/A = 1.0/6.0 = 0.1667$ dm
Chvorinov's rule $T_{TS} = (0.1667)^2 C_m = \mathbf{0.02778} \boldsymbol{C_m}$

(b) Sphere would be the best riser, since V/A ratio is greatest.

(c) Given that $C_m = 3.5$ min/cm^2 = 350 min/dm^3
Sphere: $T_{TS} = 0.0428(350) =$ **14.98 min**
Cylinder: $T_{TS} = 0.0326(350) =$ **11.41 min**
Cube: $T_{TS} = 0.02778(350) =$ **9.72 min**

10.19 A cylindrical riser is to be used for a sand-casting mold. For a given cylinder volume, determine the diameter-to-length ratio that will maximize the time to solidify.

Solution: To maximize T_{TS}, the V/A ratio must be maximized.
Cylinder volume $V = \pi D^2 L/4$. $L = 4V/\pi D^2$
Cylinder area $A = 2\pi D^2/4 + \pi DL$
Substitute the expression for L from the volume equation in the area equation:
$A = \pi D^2/2 + \pi DL = \pi D^2/2 + \pi D(4V/\pi D^2) = \pi D^2/2 + 4\ V/D$
Differentiate the area equation with respect to D:
$dA/dD = \pi D - 4\ V/D^2 = 0$ Rearranging, $\pi D = 4V/D^2$
$D^3 = 4\ V/\pi$
$D = (4\ V/\pi)^{0.333}$
From the previous expression for L, substituting in the equation for D that we have developed,
$L = 4V/\pi D^2 = 4V/\pi(4V/\pi)^{0.667} = (4V/\pi)^{0.333}$
Thus, optimal values are $D = L = (4V/\pi)^{0.333}$, and therefore the **optimal *D/L* ratio = 1.0**

10.20 A riser in the shape of a sphere is to be designed for a sand casting mold. The casting is a rectangular plate, with length = 200 mm, width = 100 mm, and thickness = 18 mm. If the total solidification time of the casting itself is known to be 3.5 min, determine the diameter of the riser so that it will take 25% longer for the riser to solidify.

Solution: Casting volume $V = LWt = 200(100)(18) = 360{,}000$ mm^3
Casting area $A = 2(200 \times 100 + 200 \times 18 + 100 \times 18) = 50{,}800$ mm^2
$V/A = 360{,}000/50{,}800 = 7.0866$
Casting $T_{TS} = C_m(7.0866)^2 = 3.50$ min
$C_m = 3.5/(7.0866)^2 = 0.0697$ min/mm^2
Riser volume $V = \pi D^3/6 = 0.5236D^3$

Riser area $A = \pi D^2 = 3.1416D^2$
$V/A = 0.5236D^3/3.1416D^2 = 0.1667D$
$T_{TS} = 1.25(3.5) = 4.375$ min $= 0.0697(0.1667D)^2 = 0.001936D^2$
$D^2 = 4.375/0.001936 = 2259.7$ mm^2
$\boldsymbol{D}$ **= 47.5 mm**

10.21 A cylindrical riser is to be designed for a sand casting mold. The length of the cylinder is to be 1.25 times its diameter. The casting is a square plate, each side = 10 in and thickness = 0.75 in. If the metal is cast iron, and the mold constant = 16.0 min/in^2 in Chvorinov's rule, determine the dimensions of the riser so that it will take 30% longer for the riser to solidify.

Solution: Casting volume $V = tL^2 = 0.75(10.0)^2 = 75$ in^3
Casting area $A = 2L^2 + 4Lt = 2(10.0)^2 + 4(10.0)(0.75) = 230.0$ in^2
$V/A = 75/230 = 0.3261$ Casting $T_{TS} = 16(0.3261)^2 = 1.70$ min
Riser $T_{TS} = 1.30(1.70) = 2.21$ min
Riser volume $V = \pi D^2H/4 = 0.25\pi D^2(1.25D) = 0.3125\pi D^3$
Riser area $A = 2\pi D^2/4 + \pi DH = 0.5\pi D^2 + 1.25\pi D^2 = 1.75\pi D^2$
$V/A = 0.3125\pi D^3/1.75\pi D^2 = 0.1786D$
Riser $T_{TS} = 16.0(0.1786D)^2 = 16.0(0.03189)D^2 = 0.5102D^2 = 2.21$ min
$D^2 = 2.21/0.5102 = 4.3316$
$D = (4.3316)^{0.5} =$ **2.081 in**
$H = 1.25(2.081) =$ **2.602 in.**

10.22 A cylindrical riser with diameter-to-length ratio = 1.0 is to be designed for a sand casting mold. The casting geometry is illustrated in Figure P10.25, in which the units are inches. If the mold constant in Chvorinov's rule = 19.5 min/in^2, determine the dimensions of the riser so that the riser will take 0.5 min longer to freeze than the casting itself.

Solution: Casting volume $V = V$(5 in x 10 in rectangular plate) + V(5 in. half disk) + V(upright tube) - V(3 in x 6 in rectangular cutout).
V(5 in x 10 in rectangular plate) = 5 x 12.5 x 1.0 = 62.5 in^3
V(5 in. half disk) = $0.5\pi(5)^2(1)/4 = 9.817$ in^3
V(upright tube) = $3.0\pi(2.5)^2/4 - 4\pi(1.5)^2/4) = 7.657$ in^3
V(3 in x 6 in rectangular cutout) = 3 x 6 x 1 = 18.0 in^3
Total $V = 62.5 + 9.817 + 7.657 - 18.0 = 61.974$ in^3
Total $A = 1 \times 5 + 1(12.5 + 2.5\pi + 12.5) + 2(6+3) + 2(5 \times 12.5 - 3 \times 6) + 2(.5\pi(5)^2/4) - 2(1.5)^2\pi/4 + 2.5\pi(3) + 1.5\pi(3+1) = 203.36$ in^2
$V/A = 61.974/203.36 = 0.305$ in
Casting $T_{TS} = 19.5(0.305)^2 = 1.81$ min
Riser design: specified $T_{TS} = 1.81 + 0.5 = 2.31$ min
Riser volume $V = \pi D^2\mathrm{L}/4 = \pi D^3/4 = 0.25\pi D^3$
Riser area $A = \pi DL + 2\pi D^2/4 = \pi D^2 + 0.5\pi D^2 = 1.5\pi D^2$
$V/A = 0.25\pi D^3/1.5\pi D^2 = D/6$
$T_{TS} = C_m(V/A)^2$
$2.31 = 19.5(D/6)^2 = 0.5417D^2$
$D^2 = 2.31/0.5417 = 4.266$ in^2 $\boldsymbol{D}$ **= 2.065 in** and $\boldsymbol{L}$ **= 2.065 in**

11 METAL CASTING PROCESSES

Review Questions

11.1 Name the two basic categories of casting processes.

Answer. The two categories are (1) expendable mold processes, and (2) permanent mold processes.

11.2 There are various types of patterns used in sand casting. What is the difference between a split pattern and a match-plate pattern?

Answer. A split pattern is a pattern that consists of two pieces; a match-plate pattern consists of the two split patterns attached to opposite sides of a plate.

11.3 What is a chaplet?

Answer. Chaplets are metal supports of various designs used to hold the core in place in the sand mold.

11.4 What properties determine the quality of a sand mold for sand casting?

Answer. The usual properties are (1) strength - ability to maintain shape in the face of the flowing metal, (2) permeability - ability of the mold to allow hot air and gases to escape from the cavity, (3) thermal stability - ability to resist cracking and buckling when in contact with the molten metal, (4) collapsibility - ability of the mold to give way during shrinkage of the solidified casting, and (5) reusability - can the sand be reused to make other molds?

11.5 What is the Antioch process?

Answer. The Antioch process refers to the making of the mold. The mold is 50% sand and 50% plaster heated in an autoclave and then dried. This mold has greater permeability than a plaster mold.

11.6 What is the difference between vacuum permanent-mold casting and vacuum molding?

Answer. Vacuum permanent-mold casting is a form of low-pressure casting in which a vacuum is used to draw molten metal into the cavity. Vacuum molding is sand casting in which the sand mold is held together by vacuum pressure rather than by a chemical binder.

11.7 What are the most common metals used in die casting?

Answer. Common die-casting metals include zinc, tin, lead, aluminum, brass, and magnesium.

11.8 Which die-casting machines usually have a higher production rate, cold-chamber or hot-chamber, and why?

Answer. Hot-chamber machines are faster because cold-chamber die casting machines require molten metal to be ladled into the chamber from an external source. Ladling takes more time than injecting the molten metal into the die as in the hot-chamber operation.

11.9 What is flash in die casting?

Answer. Flash is a thin portion of metal at the exterior of a casting that results from molten metal being squeezed into the spaces between the die halves of the mold at the parting line, or into the clearances around the cores and ejector pins.

11.10 What is the difference between true centrifugal casting and semicentrifugal casting?

Answer. In true centrifugal casting, a tubular mold is used and a tubular part is produced. In semicentrifugal casting, the shape is solid; an example is a railway wheel. The mold is rotated so that centrifugal force is used to distribute the molten metal to the exterior of the mold so that the density of the final metal is greater at the outer sections.

11.11 What is a cupola?

Answer. A cupola is a vertical cylindrical furnace equipped with a tapping spout near its base. Cupolas are used for melting cast irons.

11.12 What are some of the operations required in sand casting after the casting is removed from the mold?

Answer. The operations include (1) trimming, in which the sprues, runners, risers, and flash are removed, (2) core removal, (3) surface cleaning, (4) inspection, (5) repair if needed, (6) heat treatment, and (7) machining.

11.13 What are some of the general defects encountered in casting processes? Name and briefly describe three.

Answer. General defects include: (1) misruns, in which the casting solidifies before filling the mold cavity; (2) cold shuts, in which two portions of metal flow together but there is lack of fusion at the joint; (3) cold shots, where solid globules of cast metal become entrapped in the casting; (4) shrinkage cavity, which is a depression on the casting surface or an internal void in the casting caused by solidification shrinkage; (5) microporosity, which is a network of small voids throughout the casting caused by localized solidification shrinkage; and (6) hot tearing, which is a crack in the casting caused by a mold that does not yield to the metal during the early stages of solidification shrinkage.

11.14 (**Video**) What is the composition of green sand in the green-sand molding process?

Answer: The sand is composed of silica sand, clay, and water.

11.15 (**Video**) What are the advantages and disadvantages of sand casting over investment casting?

Answer: Sand casting provides low production cost for a wide variety of metals, shapes and sizes. The size of the casting is unlimited. The disadvantage is the surface finish and dimensional control are not very good.

11.16 (**Video**) Explain the difference between horizontal and vertical die-casting machines. Which is more popular?

Answer: The direction in the machine indicates the direction from which the metal is injected. Horizontal is injected from the side and vertical from the top. Horizontal is the most common type used in industry.

11.17 (**Video**) Why are aluminum and copper alloys unsuitable for use in hot chamber die casting?

Answer: Molten aluminum and copper alloys attack the metal pot used to hold the shot for the next casting. Over time, they would chemically attack and erode the die casting feeding mechanism.

11.18 (**Video**) According to the die casting video, what materials are most common for die-casting dies?

Answer: Common materials for die casting dies are hot-work tool steels, mold steels, maraging steels, and refractory metals such as tungsten alloys or molybdenum alloys.

Multiple Choice Quiz

There are 27 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and

each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

11.1 Which one of the following casting processes is the most widely used: (a) centrifugal casting, (b) die casting, (c) investment casting, (d) sand casting, or (e) shell casting?

Answer. (d).

11.2 In sand casting, the volumetric size of the pattern is (a) bigger than, (b) same size as, or (c) smaller than the cast part?

Answer. (a).

11.3 Silica sand has which one of the following compositions: (a) Al_2O_3, (b) SiO, (c) SiO_2, or (d) $SiSO_4$?

Answer. (c).

11.4 For which one of the following reasons is a green mold named: (a) green is the color of the mold, (b) moisture is contained in the mold, (c) mold is cured, or (d) mold is dry?

Answer. (b).

11.5 Given that W_m = weight of the molten metal displaced by a core and W_c = weight of the core, the buoyancy force is which one of the following: (a) downward force = $W_m + W_c$, (b) downward force = $W_m - W_c$, (c) upward force = $W_m + W_c$, or (d) upward force = $W_m - W_c$?

Answer. (d).

11.6 Which of the following casting processes are expendable mold operations (four correct answers): (a) centrifugal casting, (b) die casting, (c) investment casting, (d) low pressure casting, (e) sand casting, (f) shell molding, (g) slush casting, and (h) vacuum molding?

Answer. (c), (e), (f), and (h).

11.7 Shell molding is best described by which one of the following: (a) casting operation in which the molten metal has been poured out after a thin shell has been solidified in the mold, (b) casting process in which the mold is a thin shell of sand bonded by a thermosetting resin, (c) sand-casting operation in which the pattern is a shell rather than a solid form, or (d) casting operation used to make artificial sea shells?

Answer. (b).

11.8 Investment casting is also known by which one of the following names: (a) fast-payback molding, (b) full-mold process, (c) lost-foam process, (d) lost-pattern process, or (e) lost-wax process?

Answer. (e).

11.9 In plaster mold casting, the mold is made of which one of the following materials: (a) Al_2O_3, (b) $CaSO_4$-H_2O, (c) SiC, or (d) SiO_2?

Answer. (b).

11.10 Which of the following qualifies as a precision-casting process (two correct answers): (a) ingot casting, (b) investment casting, (c) plaster-mold casting, (d) sand casting, and (e) shell molding?

Answer. (b) and (c).

11.11 Which of the following casting processes are permanent mold operations (three correct answers): (a) centrifugal casting, (b) die casting, (c) expanded polystyrene process, (d) sand casting, (e) shell molding, (f) slush casting, and (g) vacuum molding.

Answer. (a), (b), and (f).

11.12 Which of the following metals would typically be used in die casting (three best answers): (a) aluminum, (b) cast iron, (c) steel, (d) tin, (e) tungsten, and (f) zinc?

Answer. (a), (d), and (f).

11.13 Which of the following are advantages of die casting over sand casting (four best answers): (a) better surface finish, (b) closer tolerances, (c) higher melting temperature metals, (d) higher production rates, (e) larger parts can be cast, and (f) mold can be reused?

Answer. (a), (b), (d), and (f).

11.14 Cupolas are furnaces used to melt which of the following metals (one best answer): (a) aluminum, (b) cast iron, (c) steel, or (d) zinc?

Answer. (b).

11.15 A misrun is which one of the following defects in casting: (a) globules of metal becoming entrapped in the casting, (b) metal is not properly poured into the downsprue, (c) metal solidifies before filling the cavity, (d) microporosity, and (e) "pipe" formation?

Answer. (c).

11.16 Which one of the following casting metals is most important commercially: (a) aluminum and its alloys, (b) bronze, (c) cast iron, (d) cast steel, or (e) zinc alloys?

Answer. (c).

Problems

Buoyancy Force

11.1 An 92% aluminum-8% copper alloy casting is made in a sand mold using a sand core that weighs 20 kg. Determine the buoyancy force in Newtons tending to lift the core during pouring.

Solution: Sand density = 1.6 g/cm^3 = 0.0016 kg/cm^3
Core volume V = 20/0.0016 = 12,500 cm^3
Density of aluminum-copper alloy ρ = 2.81 g/cm^3 = 0.00281 kg/cm^3 (Table 11.1).
Weight of displaced Al-Cu W = 12,500(0.00281) = 35.125 kg
$F_b = W_m - W_c$
Difference = (35.125 - 20) x 9.815 = **148.5 N**

11.2 A sand core located inside a mold cavity has a volume of 157.0 in^3. It is used in the casting of a cast iron pump housing. Determine the buoyancy force that will tend to lift the core during pouring.

Solution: Sand density = 0.058 lb/in^3
W_c = 157(0.058) = 9.11 lb
From Table 13.1, density of cast iron ρ = 0.26 lb/in^3
W_m = 157(0.26) = 40.82 lb
$F_b = W_m - W_c$
F_b = 40.82 - 9.11 = **31.71 lb**

11.3 Caplets are used to support a sand core inside a sand mold cavity. The design of the caplets and the manner in which they are placed in the mold cavity surface allows each caplet to sustain a force of 10 lb. Several caplets are located beneath the core to support it before pouring; and several other caplets are placed above the core to resist the buoyancy force during pouring. If the volume of the core = 325 in.^{3}, and the metal poured is brass, determine the minimum number of caplets that should be placed (a) beneath the core, and (b) above the core.

Solution: Sand density = 0.058 lb/in^3. From Table 11.1, density of brass ρ = 0.313 lb/in^3.

(a) W_c = 325(0.058) = **18.85 lb**
At least **2 caplets** are required beneath to support the weight of the core. Probably 3 or 4 caplets would be better to achieve stability.

(b) W_m = 325(.313) = 101.73 lb
F_b = 101.73 - 18.85 = **82.88 lb**
A total of **9 caplets** are required above the core to resist the buoyancy force.

11.4 A sand core used to form the internal surfaces of a steel casting experiences a buoyancy force of 23 kg. The volume of the mold cavity forming the outside surface of the casting = 5000 cm^3. What is the weight of the final casting? Ignore considerations of shrinkage.

Solution: Sand density = 1.6 g/cm^3, steel casting density ρ = 7.82 g/cm^3
$F_b = W_m - W_c$ = 7.82V - 1.6V = 6.22V = 23 kg = 23,000 g V = 3698 cm^3.
Cavity volume V = 5000 cm^3
Volume of casting V = 5000 - 3698 = 1302 cm^3.
Weight of the final casting W = 1302(7.82) = 10,184 g = **10.184 kg**

Centrifugal Casting

11.5 A horizontal true centrifugal casting operation will be used to make copper tubing. The lengths will be 1.5 m with outside diameter = 15.0 cm, and inside diameter = 12.5 cm. If the rotational speed of the pipe = 1000 rev/min, determine the G-factor.

Solution: From Eq. (11.4), $GF = R(\pi N/30)^2/g = 7.5(\pi(1000)/30)^2/981$ = **83.8**

11.6 A true centrifugal casting operation is to be performed in a horizontal configuration to make cast iron pipe sections. The sections will have a length = 42.0 in, outside diameter = 8.0 in, and wall thickness = 0.50 in. If the rotational speed of the pipe = 500 rev/min, determine the G-factor. Is the operation likely to be successful?

Solution: Using outside wall of casting, R = 0.5(8)/12 = 0.333 ft.
$v = \pi RN/30 = \pi(0.333)(500)/30$ = 17.45 ft/sec.
$GF = v^2/Rg = (17.45)^2/(0.333 \times 32.2)$ = **28.38**
Since the G-factor is less than 60, the rotational speed is not sufficient, and the operation is likely to be unsuccessful.

11.7 A horizontal true centrifugal casting process is used to make brass bushings with the following dimensions: length = 10 cm, outside diameter = 15 cm, and inside diameter = 12 cm. (a) Determine the required rotational speed in order to obtain a G-factor of 70. (b) When operating at this speed, what is the centrifugal force per square meter (Pa) imposed by the molten metal on the inside wall of the mold?

Solution: (a) Using the outside wall diameter of the casting, which is equal to the inside wall diameter of the mold, D = 15 cm
$N = (30/\pi)(2g \times 70/15)^{.5}$ = **913.7 rev/min.**

(b) Use 1.0 cm of mold wall length as basis of area calculations.
Area of this length of mold wall $A = \pi D_o L = \pi(15\text{ cm})(1\text{ cm}) = 15\pi\text{ cm}^2 = 15\pi(10^{-4})\text{ m}^2$
Volume of cast metal $V = \pi(R_o^2 - R_i^2)(1.0) = \pi((7.5)^2 - (6)^2)(1.0) = 63.62\text{ cm}^3$
Mass $m = (8.62g/\text{cm}^3)(63.62\text{ cm}^3) = 548.4\ g$ = 0.5484 kg
$v = \pi RN/30$ Use mean radius R = (7.5 + 6.0)/2 = 6.75 cm
$v = \pi(6.75)(913.7)/30$ = 645.86 cm/s = 6.4585 m/s
Centrifugal force per square meter on mold wall = F_c/A where $F_c = mv^2/R$
$F_c = (0.5484\text{ kg})(6.4586\text{ m/s})^2/(6.75 \times 10^{-2}\text{ m}) = 338.9\text{ kg-m/s}^2$
Given that 1 N = 9.81 kg-m/s^2, F_c = 338.9/9.81 = 34.55 N

F_c/A = (34.55 N)/(15π x 10^{-4} m^2) = **0.7331(10^4) N/m^2 = 7331 Pa**

11.8 True centrifugal casting is performed horizontally to make large diameter copper tube sections. The tubes have a length = 1.0 m, diameter = 0.25 m, and wall thickness = 15 mm. (a) If the rotational speed of the pipe = 700 rev/min, determine the G-factor on the molten metal. (b) Is the rotational speed sufficient to avoid "rain?" (c) What volume of molten metal must be poured into the mold to make the casting if solidification shrinkage and contraction after solidification are considered? Solidification shrinkage for copper = 4.5%, and solid thermal contraction = 7.5%.

Solution: (a) $GF = v^2/Rg$ g = 9.8 m/s^2
$v = \pi RN/30 = \pi(.125)(700)/30$ = 9.163 m/s
GF = (9.163)^2/(0.125 x 9.8) = **68.54**

(b) G-factor is sufficient for a successful casting operation.

(c) Volume of final product after solidification and cooling is
$V = (0.25^2 - (0.25-.03)^2)\pi \times 1.0/4 = 0.25\pi(0.25^2 - 0.22^2) = 0.011074$ m^3
Given: solidification shrinkage = 4.5% and solid thermal contraction = 7.5% for copper. Taking these factors into account,
Volume of molten metal V = 0.011074/(1 - 0.045)(1 - 0.075) = **0.01254 m^3**

11.9 If a true centrifugal casting operation were to be performed in a space station circling the Earth, how would weightlessness affect the process?

Solution: The mass of molten metal would be unaffected by the absence of gravity, but its weight would be zero. Thus, in the G-factor equation ($GF = v^2/Rg$), GF would theoretically go to infinity if g = 0. Thus, it should be possible to force the metal against the walls of the mold in centrifugal casting without the nuisance of "raining" inside the cavity. However, this all assumes that the metal is inside the mold and rotating with it. In the absence of gravity, there would be a problem in pouring the molten metal into the mold cavity and getting it to adhere to the mold wall as the mold begins to rotate. With no gravity the liquid metal would not be forced against the lower surface of the mold to initiate the centrifugal action.

11.10 A horizontal true centrifugal casting process is used to make aluminum rings with the following dimensions: length = 5 cm, outside diameter = 65 cm, and inside diameter = 60 cm. (a) Determine the rotational speed that will provide a G-factor = 60. (b) Suppose that the ring were made out of steel instead of aluminum. If the rotational speed computed in part (a) were used in the steel casting operation, determine the G-factor and (c) centrifugal force per square meter (Pa) on the mold wall. (d) Would this rotational speed result in a successful operation?

Solution: (a) Use inside diameter of mold in Eq. (11.5), $D = D_o$ = 65 cm. Use g = 981 cm/s^2,
$N = 30(2g \times GF/D)^{.5}/\pi = 30(2 \times 981 \times 60/65)^{.5}/\pi$ = **406.4 rev/min.**

(b) Rotational speed would be the same as in part (a) because mass does not enter the computation of rotational speed. N = **406.4 rev/min**

(c) Use 5 cm ring length as basis of area calculations.
Area of this length of mold wall $A = \pi D_o L = \pi$(65 cm)(5 cm) = 1021 cm^2 = 0.1021 m^2
Volume of cast metal $V = \pi(R_o^2 - R_i^2)(L) = \pi((65/2)^2 - (60/2)^2)(5.0)$ = 2454.4 cm^3
Density of steel ρ = 7.87 g/cm^3
Mass m = (7.87g/cm^3)(2454.4 cm^3) = 19,315.9 g = 19.316 kg
$v = \pi RN/30$ Use mean radius R = (65 + 60)/4 = 31.25 cm = 0.3125 m
$v = \pi(31.25)(406.4)/30$ = 1329.9 cm/s = 13.299 m/s
Centrifugal force per square meter on mold wall = F_c/A where $F_c = mv^2/R$
F_c = (19.316 kg)(13.299 m/s)^2/(0.3125 m) = 10,932.1 kg-m/s^2
Given that 1 N = 9.81 kg-m/s^2, F_c = 10,932.1/9.81 = 1114.4 N

F_c/A = (1114.4 N)/(0.1021 m^2) = **10,914.7 N/m² = 10,914.7 Pa**

(d) The G-factor of 60 would probably result in a successful casting operation.

11.11 For the steel ring of preceding Problem 11.10(b), determine the volume of molten metal that must be poured into the mold, given that the liquid shrinkage is 0.5%, solidification shrinkage = 3%, and solid contraction after freezing = 7.2%.

Solution: Volume of final casting $V = \pi(R_o^2 - R_i^2)L = \pi(32.5^2 - 30^2)(5) = 2454.4$ cm³
Given that the molten metal shrinkage = 0.5%, and from Table 10.1, the solidification shrinkage for steel = 3% and the solid contraction during cooling = 7.2%, the total volumetric contraction is (1-0.005)(1-0.03)(1-0.072) = 0.8957
The required starting volume of molten metal V = 2454.4/(0.8957) = **2740.2 cm³**

11.12 A horizontal true centrifugal casting process is used to make lead pipe for chemical plants. The pipe has length = 0.5 m, outside diameter = 70 mm, and wall thickness = 6.0 mm. Determine the rotational speed that will provide a G-factor = 60.

Solution: D = 70 mm = 0.07 m. g = 9.8 m/s²
$N = 30(2g \text{ x } GF/D)^{.5}/\pi = 30(2 \text{ x } 9.8 \text{ x } 60/.07)^{.5}/\pi$ = **1237.7 rev/min.**

11.13 A vertical true centrifugal casting process is used to make tube sections with length = 10.0 in and outside diameter = 6.0 in. The inside diameter of the tube = 5.5 in at the top and 5.0 in at the bottom. At what speed must the tube be rotated during the operation in order to achieve these specifications?

Solution: Use Eq. (11.6) to make the computation of N: $N = (30/\pi)(2gL/(R_t^2\text{-}R_b^2)^{.5}$
L = 10 in = 0.8333 ft
R_t = 5.5/2 = 2.75 in = 0.22917 ft
R_b = 5.0/2 = 2.50 in = 0.20833 ft
$N = (30/\pi)(2 \text{ x } 32.2 \text{ x } .8333/(0.22917^2 - 0.20833^2)^{.5} = 9.5493(5888)^{.5}$ = **732.7 rev/min**

11.14 A vertical true centrifugal casting process is used to produce bushings that are 200 mm long and 200 mm in outside diameter. If the rotational speed during solidification is 500 rev/min, determine the inside diameter at the top of the bushing if the inside diameter at the bottom is 150 mm.

Solution: L = 200 mm = 0.2 m. R_b = 150/2 = 75 mm = 0.075 m.
$N = (30/\pi)(2gL/(R_t^2\text{-}R_b^2)^{.5} = (30/\pi)(2 \text{ x } 9.8 \text{ x } 0.2/(R_t^2 - 0.075^2))^{.5}$
$N = (30/\pi)(3.92/(R_t^2 - 0.005625))^{.5}$ = 500 rev/min
$(3.92/(R_t^2\text{-}\ 0.005625))^{.5} = 500\pi/30 = 52.36$
$3.92/(R_t^2\text{-}.005625) = (52.36)^2 = 2741.56$
$R_t^2\text{-}.005625 = 3.92/2741.56 = 0.00143$
$R_t^2 = .005625 + 0.001430 = 0.007055$
$R_t = (0.007055)^{.5} = .08399$ m = 83.99 mm.
D_t = 2(83.99) = **167.98 mm**.

11.15 A vertical true centrifugal casting process is used to cast brass tubing that is 15.0 in long and whose outside diameter = 8.0 in. If the speed of rotation during solidification is 1000 rev/min, determine the inside diameters at the top and bottom of the tubing if the total weight of the final casting = 75.0 lbs.

Solution: For brass, density ρ = 0.313 lb/in³ (Table 11.1).
Volume of casting V = 75.0/.313 = 239.6 in³
Assume the inside wall of the casting is straight from top to bottom (an approximation of the parabolic shape). The average inside radius $R_i = (R_t + R_b)/2$
Volume $V = \pi(R_o^2 - R_i^2)L = \pi(4.0^2 - R_i^2)(15.0) = 239.6$ in³
$(4.0^2 - R_i^2) = 239.6/15\pi = 5.085$
$R_i^2 = 16.0 - 5.085 = 10.915$ in² R_i = 3.304 in

Let $R_t = R_i + y = 3.304 + y$ and $R_b = R_i - y = 3.304 - y$, where y = one-half the difference between R_t and R_b.

$N = (30/\pi)(2gL/(R_t^2-R_b^2)^{.5} = (30/\pi)(2 \text{ x } 32.2 \text{ x } 12 \text{ x } 15/((3.304+y)^2-(3.304-y)^2))^{.5}$

Given N = 1000 rev/min, thus

$1000\pi/30 = (11592/((3.304+y)^2-(3.304-y)^2))^{.5}$

$((3.304+y)^2-(3.304-y)^2)^{.5} = 30(11592)^{.5}/1000\pi = 1.02814$

$(3.304^2 + 6.608y + y^2 - (3.304^2 - 6.608y + y^2))^{.5} = 1.02814$

$(3.304^2 + 6.608y + y^2 - 3.304^2 + 6.608y - y^2)^{.5} = 1.02814$

$(2 \text{ x } 6.608y)^{.5} = (13.216y)^{.5} = 1.02814$

$3.635 (y)^{.5} = 1.02814$ $\qquad$ $y = .080$ in.

$R_t = 3.304 + 0.080 = 3.384$ in. $\qquad$ $\boldsymbol{D_t = 6.768}$ **in.**

$R_b = 3.304 - 0.080 = 3.224$ in. $\qquad$ $\boldsymbol{D_b = 6.448}$ **in.**

Defects and Design Considerations

11.16 The housing for a certain machinery product is made of two components, both aluminum castings. The larger component has the shape of a dish sink, and the second component is a flat cover that is attached to the first component to create an enclosed space for the machinery parts. Sand casting is used to produce the two castings, both of which are plagued by defects in the form of misruns and cold shuts. The foreman complains that the parts are too thin, and that is the reason for the defects. However, it is known that the same components are cast successfully in other foundries. What other explanation can be given for the defects?

Solution: Misruns and cold shuts result from low fluidity. One possible reason for the defects in this case is that the thickness of the casting cross sections is too small. However, given that the casting of these parts is successfully accomplished at other foundries, two other possible explanations are (1) the pouring temperature is too low, and (2) the pouring operation is performed too slowly.

11.17 A large steel sand casting shows the characteristic signs of penetration defect: a surface consisting of a mixture of sand and metal. (a) What steps can be taken to correct the defect? (b) What other possible defects might result from taking each of these steps?

Solution: (a) What are the possible corrective steps? (1) Reduce pouring temperature. (2) Increase the packing of the mold sand to resist penetration. (3) Treat the mold cavity surface to make it harder.

(b) What possible defects might result from each of these steps? In the case of step (1), the risk is for cold shuts and misruns. Steps (2) and (3) would reduce permeability of the sand, thus increasing the risk of sand blows and pin holes.

12 GLASSWORKING

Review Questions

12.1 Glass is classified as a ceramic material; yet glass is different from the traditional and new ceramics. What is the difference?

Answer. Glass is vitreous - it is in the glassy state, whereas traditional and new ceramics are, by and large, polycrystalline materials.

12.2 What is the predominant chemical compound in almost all glass products?

Answer. Silica - SiO_2.

12.3 What are the three basic steps in the glassworking sequence?

Answer. (1) raw materials preparation and melting, (2) shaping, and (3) heat treatment. Finishing operations (e.g., grinding, polishing, etching) are performed on some glass products, if needed.

12.4 Melting furnaces for glassworking can be divided into four types. Name three of the four types.

Answer. The four types are: (1) pot furnaces, (2) day tanks, (3) continuous tank furnaces, and (4) electric furnaces.

12.5 Describe the spinning process in glassworking.

Answer. Spinning in glassworking is similar to centrifugal casting in metalworking. A gob of molten glass is dropped into a conical mold which spins, causing centrifugal force to spread the glass upward onto the mold surface.

12.6 What is the main difference between the press-and-blow and the blow-and-blow shaping processes in glassworking?

Answer. In the press-and-blow process, the initial forming step is pressing of the part, while the first step in the blow-and-blow process is blowing.

12.7 There are several ways of shaping plate or sheet glass. Name and briefly describe one of them.

Answer. The methods described in this text are (1) rolling, in which the hot glass is squeezed between opposing cylindrical rolls; and (2) the float process, in which the melted glass flows onto a molten tin surface to achieve uniform thickness and smoothness.

12.8 Describe the Danner process.

Answer. In the Danner process, molten glass flows around a rotating hollow mandrel through which air is blown while the glass is being drawn. The temperature of the air and its volumetric flow rate as well as the drawing velocity determine the diameter and wall thickness of the tubular cross-section. During hardening, the glass tube is supported by a series of rollers extending beyond the mandrel.

12.9 Two processes for forming glass fibers are discussed in the text. Name and briefly describe one of them.

Answer. The two processes in the text are (1) drawing, in which fine glass fibers are pulled through small orifices in a heated plate; and (2) centrifugal spraying, in which molten glass is forced to flow through small orifices in a rapidly rotating bowl to form glass fibers.

12.10 What is the purpose of annealing in glassworking?

Answer. Annealing is performed on glass to remove internal stresses that result from shaping and solidification.

12.11 Describe how a piece of glass is heat treated to produce tempered glass.

Answer. The glass is heated to a temperature above the annealing temperature and the surfaces are then quenched by air jets to cool and harden them while the interior of the piece remains plastic; as the interior cools and contracts, it puts the previously hardened surfaces in compression, which strengthens the glass product.

12.12 Describe the type of material that is commonly used to make windshields for automobiles.

Answer. Laminated glass, in which two sheets of glass are laminated on either side of a polymer sheet. This has good impact resistance and does not splinter when broken.

12.13 What are some of the design recommendations for glass parts?

Answer. The guidelines include the following: (1) Subject ceramic parts to compressive, not tensile loads. (2) Ceramics are brittle, so avoid impact loading. (3) Use large radii on inside and outside corners. (4) Screw threads should be course.

Multiple Choice Quiz

There are 10 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

12.1 Which one of the following terms refers to the glassy state of a material: (a) crystalline, (b) devitrified, (c) polycrystalline, (d) vitiated, or (e) vitreous?

Answer. (e).

12.2 Besides helping to preserve the environment, the use of recycled glass as an ingredient of the starting material in glassmaking serves what other useful purpose (one answer): (a) adds coloring variations to the glass for aesthetic value, (b) makes the glass easier to melt, (c) makes the glass stronger, or (d) reduces odors in the plant?

Answer. (b).

12.3 The charge in glassworking is which one of the following: (a) the duration of the melting cycle, (b) the electric energy required to melt the glass, (c) the name given to the melting furnace, or (d) the starting materials in melting?

Answer. (d).

12.4 Typical glass melting temperatures are in which of the following ranges: (a) 400°C to 500°C, (b) 900°C to 1000°C, (c) 1500°C to 1600°C, or (d) 2000°C to 2200°C?

Answer. (c).

12.5 Casting is a glassworking process used for (a) high production, (b) low production, or (c) medium production?

Answer. (b). Casting is used in glassworking for large components like giant telescope lenses in small lot sizes. It is a slow process for these large products.

12.6 Which one of the following processes or processing steps is not applicable in glassworking: (a) annealing, (b) pressing, (c) quenching, (d) sintering, and (e) spinning?

Answer. (d). Sintering is used to cause bonding of particulate materials such as metal and ceramic powders.

12.7 The press-and-blow process is best suited to the production of (narrow-necked) beverage bottles, while the blow-and-blow process is more appropriate for producing (wide-mouthed) jars: (a) true, or (b) false?

Answer. (b). It's the reverse.

12.8 Which one of the following processes is used to produce glass tubing: (a) Danner process, (b) pressing, (c) rolling, or (d) spinning?

Answer. (a).

12.9 If a glass part with a wall thickness of 5 mm (0.20 in) takes 10 minutes to anneal, how much time would a glass part of similar geometry but with a wall thickness of 7.5 mm (0.30 in) take to anneal (choose the one closest answer): (a) 10 minutes, (b) 15 minutes, (c) 20 minutes, or (c) 30 minutes?

Answer. (c). The rule is that annealing time varies as the square of the wall thickness. That would indicate an annealing time of $(0.30/0.20)^2 = 2.25$ times 10 minutes or 22.5 minutes. 20 minutes is closest.

12.10 A lehr is which of the following: (a) a lion's den, (b) a melting furnace, (c) a sintering furnace, (d) an annealing furnace, or (e) none of the above?

Answer. (d).

13 SHAPING PROCESSES FOR PLASTICS

Review Questions

13.1 What are some of the reasons why plastic shaping processes are important?

Answer. The reasons include (1) many of the processes are net shape processes; (2) in general, less energy is employed than in metalworking processes; (3) lower temperatures are required to process plastics than metals or ceramics; (4) there is great flexibility in geometry; and (5) painting and other finishing processes are generally not required.

13.2 Identify the main categories of plastics shaping processes, as classified by the resulting product geometry.

Answer. The categories are (1) extrusion, (2) molding, (3) forming of continuous sheets and films, (4) fibers, (5) foamed products, and (6) discrete formed sheets and films.

13.3 Viscosity is an important property of a polymer melt in plastics shaping processes. Upon what parameters does viscosity depend?

Answer. Viscosity of a polymer melt depends on (1) temperature and (2) shear rate. Also, (3) the molecular weight of the polymer affects viscosity.

13.4 How does the viscosity of a polymer melt differ from most fluids that are Newtonian.

Answer. A polymer melt exhibits pseudoplasticity, which means that its value decreases with increasing shear rate.

13.5 What does viscoelasticity mean, when applied to a polymer melt?

Answer. Viscoelasticity is a combination of viscous and elastic properties which cause the melt to exhibit memory - the tendency to return to its previous shape, as exhibited by die swell in extrusion.

13.6 Define die swell in extrusion.

Answer. Die swell is the tendency of the extrudate to expand in cross-sectional dimensions immediately on exiting the die orifice. It results from the viscoelastic properties of the polymer melt.

13.7 Briefly describe the plastic extrusion process.

Answer. In plastic extrusion, a polymer melt is compressed to flow through a die orifice and thus the continuous length of the plastic assumes a cross-sectional shape that is approximately the same as that of the orifice.

13.8 The barrel and screw of an extruder are generally divided into three sections; identify the sections.

Answer. The sections are (1) the feed section, in which the feed stock is fed from the hopper and heated; (2) the compression section, in which the polymer changes to a viscous fluid; and (3) the metering section, in which pressure is developed to pump the plastic through the die orifice.

13.9 What are the functions of the screen pack and breaker plate at the die end of the extruder barrel?

Answer. The functions are to (1) filter dirt and lumps, (2) build pressure, (3) straighten the flow and remove memory of the polymer melt.

13.10 What are the various forms of extruded shapes and corresponding dies?

Answer. The shapes are (1) solid profiles, such as rounds and L-shapes; (2) hollow profiles, such as tubes; (3) wire and cable coating; (4) sheet and film; and (5) filaments (continuous fibers).

13.11 What is the distinction between plastic sheet and film?

Answer. The distinction is based on thickness. Sheet stock has a thickness greater than 0.020 in (0.5 mm), while film stock is less than 0.020 in (0.5 mm) thick.

13.12 What is the blown-film process for producing film stock?

Answer. The blown-film process is a widely used process for making thin polyethylene film for packaging. It combines extrusion and blowing to produce a tube of thin film. The process begins with the extrusion of a tube that is immediately drawn upward while still molten and simultaneously expanded in size by air inflated into it through the die mandrel.

13.13 Describe the calendering process.

Answer. Calendering is a process for producing sheet and film stock out of rubber or rubbery thermoplastics such as plasticized PVC. In the process, the initial feedstock is passed through a series of rolls to work the material and reduce its thickness to the desired gage.

13.14 Polymer fibers and filaments are used in several applications; what is the most important application commercially?

Answer. Textiles.

13.15 Technically, what is the difference between a fiber and a filament?

Answer. A fiber is a long, thin strand of material whose length is at least 100 times its diameter; a filament is a fiber of continuous length.

13.16 Among the synthetic fiber materials, which are the most important?

Answer. Polyester is the most important commercially, followed by nylon, acrylics, and rayon.

13.17 Briefly describe the injection molding process.

Answer. Injection molding is a process in which a polymer is heated to a highly plastic state and forced to flow under high pressure into a mold cavity, where it solidifies. The molding is then removed from the cavity.

13.18 An injection-molding machine is divided into two principal components. Name them.

Answer. The components of an injection-molding machine are (1) the injection unit and (2) the clamping unit.

13.19 What are the two basic types of clamping units?

Answer. The clamping units are: (1) mechanical toggle clamp and (2) hydraulic. In addition, there are hydromechanical units which combine hydraulic and mechanical actuations.

13.20 What is the function of gates in injection molds?

Answer. The function of gates in an injection mold is to constrict the flow of molten plastic into the cavity, which increases the shear rate and reduces the viscosity of the polymer melt.

13.21 What are the advantages of a three-plate mold over a two-plate mold in injection molding?

Answer. As the mold opens, the three-plate mold automatically separates the molded part(s) from the runner system.

13.22 Discuss some of the defects that can occur in plastic injection molding.

Answer. The defects include (1) short shots, in which the polymer melt solidifies before filling the cavity; (2) flashing, in which the polymer melt is squeezed into the parting surfaces between the mold halves and around ejection pins; (3) sink marks, in which the surface is drawn into the molding by contraction of internal material; and (4) weld lines where the melt has flowed around a core or other convex detail in the mold cavity and met from opposite directions, thus resulting in mechanical properties that are inferior to those in the rest of the part.

13.23 Describe structural-foam molding.

Answer. Structural-foam molding is an injection molding process in which a gas or gas-producing ingredient is mixed with the polymer melt prior to injection into the mold cavity; this results in the part having a tough outer skin surrounded by a foam core.

13.24 What are the significant differences in the equipment and operating procedures between injection molding of thermoplastics and injection molding of thermosets?

Answer. The differences in injection molding of thermosets are (1) shorter barrel length, (2) lower temperatures in the barrel, these first two reasons to prevent premature curing; and (3) use of a heated mold to cause cross-linking of the TS polymer.

13.25 What is reaction injection molding?

Answer. Reaction injection molding involves the mixing of two highly reactive liquid ingredients and immediately injecting the mixture into a mold cavity where chemical reactions leading to solidification occur. The two ingredients form the components used in catalyst-activated or mixing-activated thermoset systems.

13.26 What kinds of products are produced by blow molding?

Answer. Blow molding is used to produce hollow, seamless containers, such as bottles.

13.27 What is the form of the starting material in thermoforming?

Answer. Thermoforming starts with a thermoplastic sheet or film.

13.28 What is the difference between a positive mold and a negative mold in thermoforming?

Answer. A positive mold has a convex shape; a negative mold has a concave cavity.

13.29 Why are the molds generally more costly in mechanical thermoforming than in pressure or vacuum thermoforming?

Answer. In mechanical thermoforming, matching mold halves are required; while in other thermoforming processes, only one mold form is required.

13.30 What are the processes by which polymer foams are produced?

Answer. There are several foaming processes: (1) mechanical agitation - mixing a liquid resin with air, then hardening the polymer by means of heat or chemical reaction; (2) mixing a physical blowing agent with the polymer - a gas such as nitrogen (N_2) or pentane (C_5H_{12}) which can be dissolved in the polymer melt under pressure, so that the gas comes out of solution and expands when the pressure is subsequently reduced; and (3) mixing the polymer with chemical compounds, called chemical blowing agents, that decompose at elevated temperatures to liberate gases such as CO_2 or N_2 within the melt.

13.31 What are some of the general considerations that product designers must keep in mind when designing components out of plastics?

Answer. Some of the general considerations are the following: (1) Plastics are not as strong or stiff as metals and should not be used in applications where high stresses will be encountered. (2) Impact resistance of plastics is general good, better than many ceramics. (3) Service temperatures of plastics are limited relative to engineering metals and ceramics. (4) Thermal expansion is greater for plastics than metals; so dimensional changes due to temperature variations are much more significant than for metals. (5) Many types of plastics degrade from sunlight and certain other forms of radiation.

Also, some plastics degrade in oxygen and ozone atmospheres. Finally, plastics are soluble in many common solvents.

13.32 (**Video**) According to the injection molding videos, what are the four primary elements that influence the injection molding process?

Answer: The four primary elements that influence the injection molding process are the molder, material, injection machine, and the mold.

13.33 (**Video**) According to the injection molding video, name the four types of mold design most common in industry.

Answer: The four types of mold design most common in industry are (1) cold runner two-plate mold, (2) cold runner three-plate mold, (3) hot runner mold, also known as runnerless mold, and (4) insulated runner mold.

13.34 (**Video**) According to the injection molding video, what is the most common type of injection molding machine used in industry?

Answer: The most common injection-molding machine used in industry is a hydraulic, three-platen system.

13.35 (**Video**) According to the blow molding video, what materials are used in blow molding? Name three.

Answer: Materials are used in blow molding are high density polyethylene (HDPE), medium and low density polyethylene (MDPE, LDPE), polyethylene terephthalate (PET), polypropylene (PP), polyvinyl chloride (PVC), thermoplastic elastomers (TPE), polystyrene (PS), polycarbonate (PC), fluoropolymers (PTFE), and polyimide/nylon.

13.36 (**Video**) List the four most common blow-molding processes according to the video on blow molding.

Answer: The four most common blow-molding processes are (1) extrusion blow molding, (2) injection blow molding, (3) biaxial stretch blow molding, and (4) co-extrusion blow molding.

13.37 (**Video**) List the stages of extrusion blow molding according to the video.

Answer: The stages of extrusion blow molding are (1) plasticizing the resin, (2) parison production (or preform production in biaxial stretch blow molding), (3) parison or preform inflation and cooling, (4) ejection from the blow mold, and (5) finishing and trimming.

13.38 (**Video**) Name the four types of finishing operations performed on plastics, according to the plastics finishing video.

Answer: The four types of finishing operations performed on plastics are degating, deflashing, cleaning, and decorating.

13.39 (**Video**) What are the different processes that can be used to apply decorations to plastic parts according to the plastics finishing video?

Answer: The processes that can be used to apply decorations to plastic parts include painting, plating, vacuum metallization, pad printing, hot stamping, silk screening, and fill and wipe.

Multiple Choice Quiz

There are 29 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and

each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

13.1 The forward movement of polymer melt in an extruder barrel is resisted by drag flow, which is caused by the resistance to flow through the die orifice: (a) true or (b) false?

Answer. (b). Drag flow is the forward motion of the melt caused by the Archimedian screw principle in the barrel. The resistance to forward flow is called back pressure flow.

13.2 Which of the following are sections of a conventional extruder barrel for thermoplastics (three best answers): (a) compression section, (b) die section, (c) feed section, (d) heating section, (e) metering section, and (f) shaping section?

Answer. (a), (c), and (e).

13.3 Which of the following processes are associated with the production of plastic sheet and film (three correct answers): (a) blown-film extrusion process, (b) calendering, (c) chill-roll extrusion, (d) doctor blade method, (e) spinning, (f) thermoforming, and (g) transfer molding?

Answer. (a), (b), and (c).

13.4 The principal components of an injection molding machine are which two of the following: (a) clamping unit, (b) hopper, (c) injection unit, (d) mold, and (e) part ejection unit?

Answer. (a) and (c).

13.5 The parting line in injection molding is which one of the following: (a) the lines formed where polymer melt meets after flowing around a core in the mold, (b) the narrow gate sections where the parts are separated from the runner, (c) where the clamping unit is joined to the injection unit in the molding machine, or (d) where the two mold halves come together?

Answer. (d).

13.6 The function of the ejection system is which one of the following: (a) move polymer melt into the mold cavity, (b) open the mold halves after the cavity is filled, (c) remove the molded parts from the runner system after molding, or (d) separate the part from the cavity after molding?

Answer. (d).

13.7 A three-plate mold offers which of the following advantages when compared to a two-plate mold (two best answers): (a) automatic separation of parts from runners, (b) gating is usually at the base of the part to reduce weld lines, (c) sprue does not solidify, and (d) stronger molded parts?

Answer. (a) and (b).

13.8 Which of the following defects or problems is associated with injection molding (three correct answers): (a) bambooing, (b) die swell, (c) drag flow, (d) flash, (e) melt fracture, (f) short shots, or (g) sink marks?

Answer. (d), (f), and (g).

13.9 In rotational molding, centrifugal force is used to force the polymer melt against the surfaces of the mold cavity where solidification occurs: (a) true or (b) false?

Answer. (b). It is the force of gravity in the doubly rotating mold that forces the polymer against the mold surfaces.

13.10 Use of a parison is associated with which one of the following plastic shaping processes: (a) bi-injection molding, (b) blow molding, (c) compression molding, (d) pressure thermoforming, or (e) sandwich molding?

Answer. (b).

13.11 A thermoforming mold with a convex form is called which one of the following: (a) a die, (b) a negative mold, (c) a positive mold, or (d) a three-plate mold?

Answer. (c).

13.12 The term encapsulation refers to which one of the following plastics shaping processes: (a) casting, (b) compression molding, (c) extrusion of hollow forms, (d) injection molding in which a metal insert is encased in the molded part, or (e) vacuum thermoforming using a positive mold?

Answer. (a).

13.13 The two most common polymer foams are which of the following: (a) polyacetal, (b) polyethylene, (c) polystyrene, (d) polyurethane, and (e) polyvinylchloride?

Answer. (c) and (d).

13.14 In which of the following properties do plastic parts often compare favorably with metals (two best answers): (a) impact resistance, (b) resistance to ultraviolet radiation, (c) stiffness, (d) strength, (e) strength-to-weight ratio, and (f) temperature resistance?

Answer. (a) and (e).

13.15 Which of the following processes are generally limited to thermoplastic polymers (two best answers): (a) blow molding, (b) compression molding, (c) reaction injection molding, (d) thermoforming, (e) transfer molding, and (f) wire coating?

Answer. (a) and (d).

13.16 Which of the following processes would be applicable to produce hulls for small boats (three best answers): (a) blow molding, (b) compression molding, (c) injection molding, (d) rotational molding, and (e) vacuum thermoforming?

Answer. (a), (d), and (e).

Problems

Extrusion

13.1 The diameter of an extruder barrel is 65 mm and its length = 1.75 m. The screw rotates at 55 rev/min. The screw channel depth = 5.0 mm, and the flight angle = 18°. The head pressure at the die end of the barrel is 5.0 x 10^6 Pa. The viscosity of the polymer melt is given as 100 Pa-s. Find the volume flow rate of the plastic in the barrel.

Solution: $Q_d = 0.5\pi^2(65\text{x}10^{-3})^2(55/60)(5\text{x}10^{-3})\sin 18 \cos 18 = 95{,}560\text{x}10^{-9}(0.3090)(0.9510)$
$= 28.081 \text{ x } 10^{-6} \text{ m}^3/\text{s}$
$p = 5 \text{ MPa} = 5\text{x}10^6 \text{ n/m}^2$
$Q_b = \pi(5\text{x}10^6)(65\text{x}10^{-3})(5\text{x}10^{-3})^3(\sin 18)^2/12(100)(1.75) = 5.804(10^{-6}) \text{ m}^3/\text{s}$
$Q_x = 28.081 - 5.804 = \mathbf{22.277 \text{ x } 10^{-6} \text{ m}^3/\text{s}.}$

13.2 An extruder has a diameter of 5.0 in and a length to diameter ratio of 26. The barrel heats the polypropylene melt to 450°F, which provides a melt viscosity of 0.0025 lb-s/in^2. The pitch of the screw is 4.2 in and the channel depth is 0.15 in. In operation the screw rotates at 50 rev/min and a head pressure of 450 lb/in^2 is generated. What is the volume flow rate of polypropylene from the die at the end of the barrel?

Solution:
$A = \tan^{-1}(p/(\pi D)) = \tan^{-1}(4.2/(5\pi)) = 15°$
$Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5\pi^2 (5.0^2)(50/60)\ 0.15 \sin 15 \cos 15 = 3.9 \text{ in}^3/\text{sec}$
$Q_b = p\pi D d_c^3 \sin^2 A/(12\eta L) = 450\pi(5.0)(0.15^3)\sin^2 15/(12(0.0025)(5.0)(26)) = 0.41 \text{ in}^3/\text{sec}$
$Q_x = Q_d - Q_b = 3.9 - 0.41 = \mathbf{3.5 \text{ in}^3/\text{sec}}$

13.3 An extruder barrel has a diameter of 110 mm and a length of 3.0 m. The screw channel depth = 7.0 mm, and its pitch = 95 mm. The viscosity of the polymer melt is 105 Pa-s, and the head pressure in the barrel is 4.0 MPa. What rotational speed of the screw is required to achieve a volumetric flow rate of 90 cm^3/s?

Solution: $A = \tan^{-1}(p/(\pi D)) = \tan^{-1}(95/110\pi) = 15.37°$
$Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5\pi^2(0.110)^2(N)(7.0\text{x}10^{-3})\sin 15.37 \cos 15.37$
$= 106.8\ N \text{ x } 10^{-6}\ m^3/s$
$Q_b = \pi(4\text{x}10^6)(0.110)(7\text{x}10^{-3})^3(\sin 15.37)^2/12(105)(3.0) = 8.81 \text{ x } 10^{-6}\ m^3/s$
$Q_x = Q_d - Q_b = 106.8\ N \text{ x } 10^{-6} - 8.81 \text{ x } 10^{-6} = 90 \text{ x } 10^{-6}\ m^3/s$
$106.8\ N = 90.0 + 8.81 = 98.81$
$N = 98.81/106.8 =$ **0.9252 rev/s = 55.51 rev/min.**

13.4 An extruder has a barrel diameter of 2.5 in and a length of 6.0 ft. The screw has a channel depth of 0.25 in, a flight angle of 20°, and rotates at 55 rev/min. The material being extruded is polypropylene. At the present settings, the volumetric flow rate of the polymer melt is 1.50 in^3/sec and the head pressure is 500 lb/in^2. (a) Under these operating characteristics, what is the viscosity of the polypropylene? (b) Using Figure 13.2, approximate the temperature in °F of the polypropylene.

Solution: (a) $Q_d = 0.5\pi^2 D^2 N d_c \sin A \cos A = 0.5\pi^2(2.5^2)(55/60)(0.25)\sin 20 \cos 20$
$Q_d = 2.27\ in^3/sec$
$Q_b = Q_d - Q_x = 2.27 - 1.50 = 0.78\ in^3/sec$
$\eta = p\pi D d_c^3\ in^2 A/(12\ Q_b L) = 500\pi(2.5)(0.25^3)\sin^2(20)/(12(0.78)(6)(12)) =$ **0.011 lb-s/in²**

(b) X-axis is Log scale. Therefore LOG(0.011) = -1.96
This is very close to –2, which is at the 10^{-2} hash mark on the y-axis. This yields about 410°F.

13.5 An extruder has diameter = 80 mm and length = 2.0 m. Its screw has a channel depth = 5 mm, flight angle = 18 degrees, and it rotates at 1 rev/sec. The plastic melt has a shear viscosity = 150 Pa-s. Determine the extruder characteristic by computing Q_{max} and p_{max} and then finding the equation of the straight line between them.

Solution: $Q_{max} = Q_d = 0.5\pi^2(0.08)^2(1)(5\text{x}10^{-3})\sin 18 \cos 18 = 0.158 \text{ x } 10^{-3}(0.3090)(0.9510)$
$= 46.4 \text{ x } 10^{-6}\ m^3/s$
$p_{max} = 6\pi(0.08)(1)(2)(150)(\cot 18)/(5\text{x}10^{-3})^2 = 452.4(3.077)/25\text{x}10^{-6} = 55 \text{ x } 10^6$ Pa = 55 MPa
$Q_x = 46.4 \text{ x } 10^{-6} - (46.4\text{x}10^{-6}/55)p$
$\boldsymbol{Q_x = 46.4 \text{ x } 10^{-6} - 0.8436 \text{ x } 10^{-6}\ p}$, where p has units of MPa

13.6 Determine the helix angle A such that the screw pitch p is equal to the screw diameter D. This is called the "square" angle in plastics extrusion - the angle that provides a flight advance equal to one diameter for each rotation of the screw.

Solution: Assume flight land = zero.
From Eq. (15.4), $\tan A = \text{pitch}/\pi D$
If pitch = D, then $A = \tan^{-1}(1/\pi)$ **= 17.66°**

13.7 An extruder barrel has a diameter of 2.5 in. The screw rotates at 60 rev/min; its channel depth = 0.20 in, and its flight angle = 17.5°. The head pressure at the die end of the barrel is 800 lb/in^2 and the length of the barrel is 50 in. The viscosity of the polymer melt is 122 x 10^{-4} lb-sec/in^2. Determine the volume flow rate of the plastic in the barrel.

Solution: $Q_d = 0.5\pi^2(2.5)^2(1)(.2)\sin 17.5 \cos 17.5 = 0.5(12.337)(0.3007)(0.9537) = 1.769\ in^3/sec$
$Q_b = \pi(800)(2.5)(.2)^3(\sin 17.5)^2/12(122\text{x}10^{-4})(50) = 0.621\ in^3/sec$
$Q_x = 1.769 - 0.621 =$ **1.148 in³/sec.**

13.8 An extruder barrel has a diameter of 4.0 in and an L/D ratio of 28. The screw channel depth = 0.25 in, and its pitch = 4.8 in. It rotates at 60 rev/min. The viscosity of the polymer melt is 100 x 10^{-4} lb-sec/in^2. What head pressure is required to obtain a volume flow rate = 150 in^3/min?

Solution: $A = \tan^{-1}(\text{pitch}/\pi D) = \tan^{-1}(4.8/4\pi) = 20.9°$
$Q_d = 0.5\pi^2(4)^2(1)(0.25)\sin 20.9 \cos 20.9 = 19.74(0.3567)(0.9342) = 6.578$ in^3/sec = 394.66 in^3/min
$Q_x = Q_d - Q_b = 394.66 - Q_d = 150$
$Q_b = 394.66 - 150 = 244.66$ in^3/min = 4.078 in^3/sec
$L = 4(28) = 112$ in.
$Q_b = \pi p(4)(0.25)^3(\sin 20.9)^2/(12(100\text{x}10^{-4})(112)) = 4.078$
$0.0018592\ p = 4.078$
$\boldsymbol{p = 2193.4}$ **lb/in^2**

13.9 An extrusion operation produces continuous tubing with outside diameter = 2.0 in and inside diameter = 1.7 in. The extruder barrel has a diameter = 4.0 in and length = 10 ft. The screw rotates at 50 rev/min; it has a channel depth = 0.25 in and flight angle = 16°. The head pressure has a value of 350 lb/in^2 and the viscosity of the polymer melt is 80 x 10^{-4} lb-sec/in^2. Under these conditions, what is the production rate in length of tube/min, assuming the extrudate is pulled at a rate that eliminates the effect of die swell (i.e., the tubing has the same OD and ID as the die profile)?

Solution: $Q_d = 0.5\pi^2(4)^2(50/60)(.25)\sin 16 \cos 16 = 16.45(0.2756)(0.9613) = 4.358$ in^3/sec
$Q_b = \pi(350)(4)(.25)^3(\sin 16)^2/(12(80\text{x}10^{-4})(120)) = 0.453$ in^3/sec
$Q_x = 4.358 - 0.453 = 3.905$ in^3/sec.
$A_x = 0.25\pi(2^2 - 1.7^2) = 0.872$ in^2
$v_x = 3.905/0.872 =$ **4.478 in/sec = 22.39 ft/min.**

13.10 Continuous tubing is produced in a plastic extrusion operation through a die orifice whose outside diameter = 2.0 in and inside diameter = 1.5 in. The extruder barrel diameter = 5.0 in and length = 12 ft. The screw rotates at 50 rev/min; it has a channel depth = 0.30 in and flight angle = 16°. The head pressure has a value of 350 lb/in^2 and the viscosity of the polymer melt is 90 x 10^{-4} lb-sec/in^2. Under these conditions, what is the production rate in length of tube/min, given that the die swell ratio is 1.25.

Solution: $Q_d = 0.5\pi^2(5)^2(50/60)(.3)\sin 16 \cos 16 = 30.84(0.2756)(0.9613) = 8.171$ in^3/sec
$Q_b = \pi(350)(5)(.3)^3(\sin 16)^2/(12(90\text{x}10^{-4})(144)) = 0.725$ in^3/sec
$Q_x = 8.171 - 0.725 = 7.446$ in^3/sec
Die swell ratio applied to OD and ID: OD = 2(1.25) = 2.5, ID = 1.5(1.25) = 1.875
$A_x = 0.25\pi(2.5^2 - 1.875^2) = 2.1476$ in^2
$v_x = 7.446/2.1476 =$ **3.467 in/sec = 17.34 ft/min**

13.11 An extruder has barrel diameter and length of 100 mm and 2.8 m, respectively. The screw rotational speed = 50 rev/min, channel depth = 7.5 mm, and flight angle = 17°. The plastic melt has a shear viscosity = 175 Pa-s. Determine: (a) the extruder characteristic, (b) the shape factor K_s for a circular die opening with diameter = 3.0 mm and length = 12.0 mm, and (c) the operating point (Q and p).

Solution: $Q_{max} = Q_d = 0.5\pi^2(.1)^2(50/60)(7.5\text{x}10^{-3}) \sin 17 \cos 17 = 308.4 \text{ x } 10^{-6}(0.2924)(0.9563)$
$= 86.2 \text{ x } 10^{-6}$ m^3/s
$p_{max} = 6\pi(.1)(50/60)(2.8)(175)(\cot 17)/(7.5\text{x}10^{-3})^2 = 44.75 \text{ x } 10^6$ Pa =44.75 MPa
$\boldsymbol{Q_x = 86.2 \text{ x } 10^{-6} - 1.926 \text{ x } 10^{-12}\ p}$, where p has units of Pa

(b) Given: $D_d = 3$ mm, $L_d = 12$ mm.
$K_s = \pi(3 \text{ x } 10^{-3})^4/(128(175)(12 \text{ x } 10^{-3})) =$ **0.9467 x 10^{-12}**

(c) $0.9467 \text{ x } 10^{-12}\ p = 86.2 \text{ x } 10^{-6} - 1.926 \text{ x } 10^{-12}\ p$
$2.8727 \text{ x } 10^{-12}\ p = 86.2 \text{ x } 10^{-6}$

p = **30.0 x 10^6 Pa = 30 MPa**
$Q_x = 0.9467 \times 10^{-12} (30 \times 10^6)$ = **28.4 x 10^{-6} m³/s**

Check with extruder characteristic: $Q_x = 86.2 \times 10^{-6} - 1.926 \times 10^{-12} (30 \times 10^6) = 28.4 \times 10^{-6}$ m³/s.

13.12 For Problem 13.11, assume the material is acrylic. (a) Using Figure 13.2, determine the temperature of the polymer melt. (b) If the temperature is lowered 20°C, estimate the resulting viscosity of the polymer melt. (Hint: the *y*-axis of Figure 13.2 is a log scale, not linear).

Solution: (a) When viscosity = 175 Pa-s, Log(175) = 2.243, and temperature is approximately 260°C.

(b) At 240°C, Log(viscosity) is approximately 2.7 and viscosity = $10^{2.7}$ = 500 Pa-s. (Note: due to the log scale, small changes in the estimate will result in large changes in viscosity.

13.13 Consider an extruder in which the barrel diameter = 4.5 in and length = 11 ft. The extruder screw rotates at 60 rev/min; it has channel depth = 0.35 in and flight angle = 20°. The plastic melt has a shear viscosity = 125 x 10^{-4} lb-sec/in². Determine: (a) $Q_{\max}$ and $p_{\max}$; (b) the shape factor K_s for a circular die opening in which D_d = 0.312 in and L_d = 0.75 in; and (c) the values of Q and p at the operating point.

Solution: (a) $Q_{max} = 0.5\pi^2(4.5)^2(1)(0.35)\sin 20 \cos 20 = 34.975(0.342)(0.9397) = 11.24$ in³/sec
$p_{max} = 6\pi(4.5)(1)(132)(0.0125)(\cot 20)/(0.35)^2$ = **3139 lb/in²**

(b) Given: D_d = 0.312 in., L_d = 0.75 in.
$K_s = \pi(0.312)^4/128(0.0125)(0.75)$ = **0.024808**

(c) From (a), $Q_x = Q_{max} - (Q_{max}/p_{max})p = 11.24 - 0.003581p$
From (b), $Q_x = 0.024808p$
Combining, $.024808p = 11.24 - .003581p$
$0.02839p = 11.24$ $\qquad$ $p = 395.9$ lb/in²
$Q_x = 11.24 - 0.003581(395.9)$ = **9.82 in³/sec**

13.14 An extruder has a barrel diameter = 5.0 in and length = 12 ft. The extruder screw rotates at 50 rev/min; it has channel depth = 0.30 in and flight angle = 17.7°. The plastic melt has a shear viscosity = 100 x 10^{-4} lb-sec/in². Find: (a) the extruder characteristic, (b) the values of Q and p at the operating point, given that the die characteristic is $Q_x = 0.00150\ p$.

Solution: (a) $Q_{max} = 0.5\pi^2(5)^2(50/60)(0.3)\sin 17.7 \cos 17.7 = 30.84(0.3040)(0.9527) = 8.93$ in³/sec
$p_{max} = 6\pi(5)(50/60)(144)(0.01)(\cot 17.7)/(0.3)^2 = 3937.6$ lb/in²
$Q_x = Q_{max} - (Q_{max}/p_{max})p$ = **$8.93 - 0.002268p$**

(b) Given: die characteristic $Q_x = 0.0015p$
$Q_x = 8.93 - 0.002268p = 0.0015p$
$0.00377p = 8.93$ $\qquad$ p = **2370 lb/in²**
$Q_x = 8.93 - 0.002268(2370)$ = **3.55 in³/sec**

13.15 Given the data in Problem 13.14, except that the flight angle of the extruder screw is a variable instead of a constant 17.7°. Use a spreadsheet calculator to determine the value of the flight angle that maximizes the volumetric flow rate Q_x. Explore values of flight angle between 10° and 20°. Determine the optimum value to the nearest tenth of a degree.

Solution: The author's spreadsheet computations returned an optimum value of 13.5°.

13.16 An extruder has a barrel diameter of 3.5 in and a length of 5.0 ft. It has a screw channel depth of 0.16 in and a flight angle of 22°. The extruder screw rotates at 75 rev/min. The polymer melt has a shear viscosity = 65 x 10^{-4} lb-sec/in² at the operating temperature of 525°F. The specific gravity of the polymer is 1.2 and its tensile strength is 8000 lb/in². A T-shaped cross section is extruded at a rate of

0.11 lb/sec. The density of water is 62.5 lb/ft^3. (a) Find the equation for the extruder characteristic. (b) Find the operating point (Q and p), and (c) the die characteristic that is indicated by the operating point.

Solution: (a) $Q_{max} = 0.5\pi^2 D^2 N d_c \sin A \cos A$
$= 0.5\pi^2(3.5)^2(75/60)(0.16)\sin 22 \cos 22 = 4.199$ in^3/sec
$p_{max} = 6\pi DNL\eta \cot A/d_c^2 = 6\pi(3.5)(75/60)(60)(0.0065)(\cot 22)/(0.16)^2 = 989.8$ lb/in^2
$Q_x = Q_{max} - (Q_{max}/p_{max})p = \mathbf{4.199 - 0.004242}\boldsymbol{p}$

(b) Given: T-shaped cross section extruded at 0.14 lb/sec.
Density of polymer ρ = specific gravity of polymer x ρ_{water} =1.2(62.4 lb/ft^3) = 75 lb/ft^3
Convert to lb/in^3: ρ= 75 lb/ft^3 /(12^3 in^3/ft^3) = 0.0433 lb/in^3
Q_x = 0.11/0.0433 = 2.540 in^3/sec.
2.540 = 4.199 - 0.004242p
0.004242p = 4.199 – 2.540 = 1.659
***p* = 391.1 lb/in^2**

(c) $Q_x = K_s p$
$K_s = Q_x/p$ = 2.540/391.1 = 0.00649
$\mathbf{Q_x = 0.00649}\ \boldsymbol{p}$

Injection Molding

13.17 Compute the percentage volumetric contraction of a polyethylene molded part, based on the value of shrinkage given in Table 13.1.

Solution: S = 0.025 for polyethylene from Table 13.1.
Volumetric contraction = 1.0 - (1 - .025)^3 = 1.0 - 0.92686 = **0.07314 = 7.314%**

Note that we are not using the parameter S from Table 13.1 in the way it was intended to be used. Its intended use is to compute the oversized dimension of a mold cavity in injection molding. Instead, we are using the shrinkage term to calculate the amount of (volumetric) reduction in size of the part after the polymer is injected into the cavity. In fact, a slightly different shrinkage parameter value may apply in this case.

13.18 The specified dimension = 225.00 mm for a certain injection molded part made of ABS. Compute the corresponding dimension to which the mold cavity should be machined, using the value of shrinkage given in Table 13.1.

Solution: S = 0.006 for ABS from Table 13.1.
D_c = 225.00 + 225.00(0.006) + 225.00(0.006)^2 = 225.00 + 1.35 + 0.0081 = **226.36 mm.**

13.19 The part dimension for a certain injection molded part made of polycarbonate is specified as 3.75 in. Compute the corresponding dimension to which the mold cavity should be machined, using the value of shrinkage given in Table 13.1.

Solution: S = 0.007 for polycarbonate from Table 13.1.
D_c = 3.75 + 3.75(0.007) + 3.75 (0.007)^2 = 3.75 + 0.0263 + 0.0002 = **3.7765 in.**

13.20 The foreman in the injection molding department says that a polyethylene part produced in one of the operations has greater shrinkage than the calculations indicate it should have. The important dimension of the part is specified as 112.5 ±0.25 mm. However, the actual molded part measures 112.02 mm. (a) As a first step, the corresponding mold cavity dimension should be checked. Compute the correct value of the mold dimension, given that the shrinkage value for polyethylene is 0.025 (from Table 13.1). (b) What adjustments in process parameters could be made to reduce the amount of shrinkage?

Solution: (a) Given: S = 0.025, D_c = 112.5 + 112.5(.025) + 112.5(.025)^2 = **115.383 mm**

(b) Adjustments to reduce shrinkage include: (1) increase injection pressure, (2) increase compaction time, and (3) increase molding temperatures.

13.21 An injection molded polyethylene part has a dimension of 2.500 in. A new material, polycarbonate, is used in the same mold. What is the expected corresponding dimension of the polycarbonate molding?

Solution: For polyethylene the shrinkage is 0.025 in/in (from Table 13.1).
Die Cavity = $D_c = D_p + D_pS + D_pS^2 = 2.500 + 2.500(0.025) + 2.500(0.025)^2 = 2.564$ in
For polycarbonate, the shrinkage is 0.007 in/in
Part dimension = $D_c/(1 + S + S^2) = 2.564/(1 + 0.007 + 0.007^2)$ = **2.546 in**

Other Molding Operations and Thermoforming

13.22 The extrusion die for a polyethylene parison used in blow molding has a mean diameter of 18.0 mm. The size of the ring opening in the die is 2.0 mm. The mean diameter of the parison is observed to swell to a size of 21.5 mm after exiting the die orifice. If the diameter of the blow molded container is to be 150 mm, determine (a) the corresponding wall thickness of the container and (b) the wall thickness of the parison.

Solution: (a) $r_s = D_p/D_d = 21.5/18.0 = 1.194$
$t_m = t_p\, D_p/D_m = r_s\, t_d\, D_p/D_m = (1.194)(2.0)(21.5)/150.0$ = **0.342 mm**

(b) $t_p = r_s\, t_d = (1.194)(2.0)$ = **2.388 mm**

13.23 A parison is extruded from a die with outside diameter = 11.5 mm and inside diameter = 7.5 mm. The observed die swell is 1.25. The parison is used to blow mold a beverage container whose outside diameter = 112 mm (a standard size 2-liter soda bottle). (a) What is the corresponding wall thickness of the container? (b) Obtain an empty 2-liter plastic soda bottle and (carefully) cut it across the diameter. Using a micrometer, measure the wall thickness to compare with your answer in (a).

Solution: (a) $D_d = (11.5 + 7.5)/2 = 9.5$ mm, and $t_d = (11.5 - 7.5)/2 = 2.0$ mm
$t_m = (1.25)^2(2.0)(9.5)/112$ = **0.265 mm (= 0.010 in)**

(b) Measured value should be close to calculated value. Some wall thicknesses are less.

13.24 A blow-molding operation is used to produce a bottle with a diameter of 2.250 in and a wall thickness of 0.045 in. The parison has a thickness of 0.290 in. The observed die swell ratio is 1.30. (a) What is the required diameter of the parison? (b) What is the diameter of the die?

Solution: (a) $D_p = t_mD_m/t_p = (0.045)(2.250)/0.290$ = **0.349 in**

(b) $D_d = D_p/r_s = 0.349/1.30$ = **0.268 in**

13.25 An extrusion operation is used to produce a parison whose mean diameter = 27 mm. The inside and outside diameters of the die that produced the parison are 18 mm and 22 mm, respectively. If the minimum wall thickness of the blow-molded container is to be 0.40 mm, what is the maximum possible diameter of the blow mold?

Solution: $D_d = (22 + 18)/2 = 20$ mm, and $t_d = (22 - 18)/2 = 2$ mm
$r_s = 27/20 = 1.35$
Rearranging Eq. (13.22) in text, $D_m = r_{sd}{}^3 t_dD_d/t_m = (1.35)^2(2)(20)/(0.40)$ = **182.25 mm**

13.26 A rotational molding operation is to be used to mold a hollow playing ball out of polypropylene. The ball will be 1.25 ft in diameter and its wall thickness should be 3/32 in. What weight of PP powder should be loaded into the mold in order to meet these specifications? The specific gravity of the PP grade is 0.90, and the density of water is 62.4 lb/ft^3.

Solution: Density ρ = specific gravity of polymer x $\rho_{water} = 0.90(62.4\text{ lb/ft}^3) = 56.2\text{ lb/ft}^3$

Convert to lb/in^3: ρ = 56.2 lb/ft^3 /(1728 in^3/ft^3) = 0.0325 lb/in^3

Volume = $\pi(D_o^3 - D_i^3)/6 = 0.16667\pi[(1.25x12)^3 - (1.25x12 - 3/16)^3]$ = 10.91 in^3

Weight W = (10.91)(0.0325) = **0.355 lb.**

13.27 The problem in a certain thermoforming operation is that there is too much thinning in the walls of the large cup-shaped part. The operation is conventional pressure thermoforming using a positive mold, and the plastic is an ABS sheet with an initial thickness of 3.2 mm. (a) Why is thinning occurring in the walls of the cup? (b) What changes could be made in the operation to correct the problem?

Solution: (a) As the starting flat sheet is draped over the convex cup-shaped mold, the portion contacting the base of the cup experiences little stretching. However, the remaining portions of the sheet must be stretched significantly to conform to the sides of the cup. Hence, thinning in these sides results.

(b) The problem could be solved by either: (1) fabricating a negative mold to replace the current positive mold, since a negative mold will distribute the material more uniformly and result in approximately equal thinning throughout the sheet; or (2) prestretch the sheet as in Figure 13.38 in the text.

14 RUBBER PROCESSING TECHNOLOGY

Review Questions

14.1 How is the rubber industry organized?

Answer. The rubber industry is organized into three parts: (1) rubber growing plantations produce natural rubber, (2) the petrochemical industry produces synthetic rubber, and (3) fabricators take the NR and SR and produce finished rubber goods.

14.2 How is raw rubber recovered from the latex that is tapped from a rubber tree?

Answer. The rubber is usually recovered as follows: (1) the latex is collected into tanks and diluted to half natural concentration; (2) formic or acetic or other acid is added to the solution which causes the rubber to coagulate; (3) the coagulum is then squeezed through rolls to drive off water; and (4) the resulting sheets are dried in smokehouses for several days. The resulting raw rubber is called ribbed smoked sheet.

14.3 What is the sequence of processing steps required to produce finished rubber goods?

Answer. The typical sequence is (1) production of the raw rubber, (2) compounding, (3) mixing, (4) shaping, and (5) vulcanization.

14.4 What are some of the additives that are combined with rubber during compounding?

Answer. The additives include vulcanizing chemicals, reinforcing fillers, extenders to reduce cost, antioxidants, coloring pigments, plasticizers to soften the rubber, and blowing agents to make foam rubber.

14.5 Name the four basic categories of processes used to shape rubber.

Answer. The categories are (1) extrusion, (2) calendering, (3) coating, and (4) molding.

14.6 What does vulcanization do to the rubber?

Answer. Vulcanization causes cross-linking of the rubber molecules; this strengthens and stiffens the rubber while extensibility is retained.

14.7 Name the three basic tire constructions and briefly identify the differences in their construction.

Answer. The three basic tire constructions are (a) diagonal ply, (b) belted bias, and (c) radial ply. Diagonal ply and belted bias both have their carcass plys running in a diagonal direction relative to the tire circumference. Radial ply has its carcass plies running in a radial direction. Belted bias and radial ply tires use belts, which are additional plies around the outside circumference of the tire; whereas diagonal ply tires do not have these belts.

14.8 What are the three basic steps in the manufacture of a pneumatic tire?

Answer. The three steps are (1) preform the components, (2) building the carcass and adding the rubber for the sidewall and treads, and (3) molding and curing.

14.9 What is the purpose of the bead coil in a pneumatic tire?

Answer. The bead coil provides a rigid support for the tire when it is mounted onto the wheel rim.

14.10 What is a TPE?

Answer. TPE stands for thermoplastic elastomer; it is a thermoplastic polymer that behaves like a rubber.

14.11 Many of the design guidelines that are applicable to plastics are also applicable to rubber. However, the extreme flexibility of rubber results in certain differences. What are some examples of these differences?

Answer. Examples include the following: (1) No draft is needed on a molded rubber part for removal from the mold. (2) Holes should be molded into rubber parts rather than machined, whereas holes can be machined or molded in a plastic part. (3) Screw threads are quite uncommon on rubber parts, whereas they are not uncommon on plastic parts.

Multiple Choice Quiz

There are 10 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

14.1 The most important rubber product is which one of the following: (a) footwear, (b) conveyor belts, (c) pneumatic tires, or (d) tennis balls?

Answer. (c).

14.2 The chemical name of the ingredient recovered from the latex of the rubber tree is which one of the following: (a) polybutadiene, (b) polyisobutylene, (c) polyisoprene, or (d) polystyrene?

Answer. (c).

14.3 Of the following rubber additives, which one would rank as the single most important: (a) antioxidants, (b) carbon black, (c) clays and other hydrous aluminum silicates, (d) plasticizers and softening oils, or (e) reclaimed rubber?

Answer. (b).

14.4 Which one of the following molding processes is the most important in the production of products made of conventional rubber: (a) compression molding, (b) injection molding, (c) thermoforming, or (d) transfer molding?

Answer. (a).

14.5 Which of the following ingredients do not contribute to the vulcanizing process (two correct answers): (a) calcium carbonate, (b) carbon black, (c) stearic acid, (d) sulfur, and (e) zinc oxide?

Answer. (a) and (b).

14.6 How many minutes are required to cure (vulcanize) a modern passenger car tire: (a) 5, (b) 15, (c) 25, or (d) 45?

Answer. (b).

14.7 When is the tread pattern imprinted onto the circumference of the tire: (a) during preforming, (b) while building the carcass, (c) during molding, or (d) during curing?

Answer. (c).

14.8 Which of the following are not normally used in the processing of thermoplastic elastomers (two correct answers): (a) blow molding, (b) compression molding, (c) extrusion, (d) injection molding, or (e) vulcanization?

Answer. (b) and (e).

15 SHAPING PROCESSES FOR POLYMER MATRIX COMPOSITES

Review Questions

15.1 What are the principal polymers used in fiber-reinforced polymers?

Answer. Principal polymer matrices in FRPs are unsaturated polyesters and epoxies.

15.2 What is the difference between a roving and a yarn?

Answer. A roving consists of untwisted filaments, while a yarn consists of twisted fibers.

15.3 In the context of fiber reinforcement, what is a mat?

Answer. A mat is a felt consisting of randomly oriented fibers held loosely together in a binder.

15.4 Why are particles and flakes members of the same basic class of reinforcing material?

Answer. Flakes are simply particles that possess very low width-to-thickness ratios.

15.5 What is sheet molding compound (SMC)?

Answer. SMC consists of TS polymer resin, fillers, and chopped glass fibers, all rolled into a sheet of typical thickness = 6.5 mm (0.250 in).

15.6 How is a prepreg different from a molding compound?

Answer. Prepregs have continuous fibers rather than chopped fibers as in molding compounds.

15.7 Why are laminated FRP products made by the spray-up method not as strong as similar products made by hand lay-up?

Answer. Because in hand lay-up, orientation of the fibers is controlled; whereas in spray-up, the fibers in each layer are randomly oriented.

15.8 What is the difference between the wet lay-up approach and the prepreg approach in hand lay-up?

Answer. In wet lay-up, the layer of fiber reinforcement is placed into the mold dry, and the uncured resin is then applied to it to form the composite laminate. In the prepreg approach, layers of fiber preimpregnated with resin are laid into the mold.

15.9 What is an autoclave?

Answer. An autoclave is an enclosed chamber which can supply heat and/or pressure at controlled levels.

15.10 What are some of the advantages of the closed mold processes for PMCs relative to open mold processes?

Answer. The advantages of a closed mold are (1) good finish on all part surfaces, (2) higher production rates, (3) closer control over tolerances, and (4) more complex three-dimensional shapes are possible.

15.11 Identify some of the different forms of polymer matrix composite molding compounds.

Answer. PMC molding compounds include sheet molding compounds, thick molding compounds (a.k.a. dough molding compounds), and bulk molding compounds.

15.12 What is preform molding?

Answer. Preform molding is a compression molding process in which a precut mat is placed into the lower half of a mold together with a charge of thermosetting resin; the materials are then pressed between heated molds to cure the resin and produce a fiber-reinforced molding.

15.13 Describe reinforced reaction injection molding (RRIM).

Answer. RRIM involves the injection of resins that cure by chemical reaction together with reinforcing fibers into a closed mold. The resulting part is a fiber-reinforced (usually glass fiber) plastic molding.

15.14 What is filament winding?

Answer. Filament winding is a process in which resin-impregnated continuous fibers are wrapped around a rotating mandrel with the internal shape of the FRP product; the resin is cured and the mandrel is removed.

15.15 Describe the pultrusion process.

Answer. Pultrusion is a process in which continuous fibers are dipped into a resin and pulled through a shaping die (somewhat like an extrusion die) where the resin cures. The resulting sections are similar to extruded parts except that they are reinforced with continuous fibers.

15.16 How does pulforming differ from pultrusion?

Answer. Pulforming is pultrusion with the added operation of a shape change in the length (straight length becomes curved) and cross section (different cross sections throughout the length).

15.17 With what kinds of products is tube rolling associated?

Answer. Typical products include bicycle frames and space trusses.

15.18 How are FRPs cut?

Answer. Uncured FRPs are cut by methods that include knives, scissors, power shears, steel-rule blanking dies, laser beam cutting, and water jet cutting. Cured FRPs are cut by cemented carbides and HSS cutting tools, diamond cutting tools, and water jet cutting.

15.20 (**Video**) According to the video on composites, list the primary purpose of the matrix and the reinforcement in a composite.

Answer: The primary purpose of the matrix is to transfer the load or stress to the reinforcement. A secondary purpose of the matrix is to protect the reinforcement from the environment. The primary purpose of the reinforcement is to improve the mechanical properties of the composite. The reinforcement is the main load bearing element in the composite.

15.21 (**Video**) List the primary methods of fiber reinforced thermoset polymer composite production according to the composite video.

Answer: The methods of fiber-reinforced thermoset polymer composite production identified in the video are (1) manual lay-up, (2) automated lay-up, (3) spray-up, (4) filament winding, (5) pultrusion, and (6) resin transfer molding.

15.22 (**Video**) What are the advantages and disadvantages of using prepreg material for lay-up of composites according to the composite video?

Answer: The advantages are that prepreg eliminates the separate handling of the matrix and resin, reduces resin consumption, and can improve part quality by providing more consistent proportions of resin and reinforcement content. The disadvantage of prepreg is that it must be stored in a refrigerator so the resin does not cure.

Multiple Choice Quiz

There are 14 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

15.1 Which one of the following is the most common polymer type in fiber-reinforced polymer composites: (a) elastomers, (b) thermoplastics, or (c) thermosets?

Answer. (c).

15.2 Most rubber products are properly classified into which of the following categories (three best answers): (a) elastomer reinforced with carbon black, (b) fiber-reinforced composite, (c) particle-reinforced composite, (d) polymer matrix composite, (e) pure elastomer, and (f) pure polymer?

Answer. (a), (c), and (d).

15.3 Other names for open mold processes include which of the following (two best answers): (a) compression molding, (b) contact lamination, (c) contact molding, (d) filament winding, (e) matched die molding, (f) preform molding, and (g) pultrusion?

Answer. (b) and (c).

15.4 Hand lay-up is classified in which of the following general categories of PMC shaping processes (two best answers): (a) closed mold process, (b) compression molding, (c) contact molding, (d) filament winding, or (e) open mold process?

Answer. (c) and (e).

15.5 A positive mold with a smooth surface will produce a good finish on which surface of the laminated product in the hand lay-up method: (a) inside surface or (b) outside surface?

Answer. (a).

15.6 A molding operation that uses sheet-molding compound (SMC) is a form of which one of the following: (a) compression molding, (b) contact molding, (c) injection molding, (d) open mold processing, (e) pultrusion, or (f) transfer molding?

Answer. (a).

15.7 Filament winding involves the use of which one of the following fiber reinforcements: (a) continuous filaments, (b) fabrics, (c) mats, (d) prepregs, (e) short fibers, or (f) woven rovings?

Answer. (a).

15.8 In filament winding, when the continuous filament is wound around the cylindrical mandrel at a helix angle close to 90°, it is called which of the following (one best answer): (a) bi-axial winding, (b) helical winding, (c) hoop winding, (d) perpendicular winding, (e) polar winding, or (f) radial winding?

Answer. (c).

15.9 Pultrusion is most similar to which one of the following plastic shaping processes: (a) blow-molding, (b) extrusion, (c) injection molding, or (d) thermoforming?

Answer. (b).

15.10 Water jet cutting is one of several ways of cutting or trimming uncured or cured FRPs; in the case of cured FRPs, the process is noted for its reduction of dust and noise: (a) true or (b) false?

Answer. (a).

16 POWDER METALLURGY

Review Questions

16.1 Name some of the reasons for the commercial importance of powder metallurgy technology.

Answer. PM is important because (1) parts can be made to net or near net shape, (2) parts can be made with a controlled level of porosity, (3) certain metals difficult to process by other methods can be processed by PM, and (4) PM allows the formulation of unusual alloys not easily obtained by traditional alloying methods.

16.2 What are some of the disadvantages of PM methods?

Answer. Disadvantages include (1) high tooling costs, (2) metal powders are expensive, (3) difficulties in storing and handling metallic powders, (4) certain limitations on part geometry imposed by the uniaxial press methods, and (5) variations in density in a PM component can be troublesome.

16.3 In the screening of powders for sizing, what is meant by the term mesh count?

Answer. The mesh count of the screen is the number of openings per linear inch.

16.4 What is the difference between open pores and closed pores in a metallic powders?

Answer. Open pores are air spaces between particles, while closed pores are voids internal to a particle.

16.5 What is meant by the term aspect ratio for a metallic particle?

Answer. The aspect ratio of a particle is the ratio of the maximum dimension to the minimum dimension of the given particle.

16.6 How would one measure the angle of repose for a given amount of metallic powder?

Answer. One measure would be to let the powders flow through a small funnel and measure the angle taken by the resulting pile of powders relative to the horizontal.

16.7 Define bulk density and true density for metallic powders.

Answer. Bulk density refers to the weight per volume of the powders in the loose state, while true density is the weight per volume of the true volume of metal in the powders (the volume that would result if the powders were melted).

16.8 What are the principal methods used to produce metallic powders?

Answer. The powder production methods are (1) atomization - the conversion of molten metal into droplets which solidify into powders; (2) chemical reduction - reducing metallic oxides by use of reducing agents which combine with the oxygen to free the metals in the form of powders; and (3) electrolysis - use of an electrolytic cell to deposit particles of the metal onto the cathode in the cell.

16.9 What are the three basic steps in the conventional powder metallurgy shaping process?

Answer. The steps are (1) blending and/or mixing, (2) pressing, and (3) sintering.

16.10 What is the technical difference between mixing and blending in powder metallurgy?

Answer. Mixing refers to the combining of metal powders of different chemistries, while blending means combining particles of the same chemistry but different sizes.

16.11 What are some of the ingredients usually added to the metallic powders during blending and/or mixing?

Answer. The additives include (1) lubricants, (2) binders, and (3) deflocculants.

16.12 What is meant by the term green compact?

Answer. The green compact is the pressed but not yet sintered PM part.

16.13 Describe what happens to the individual particles during compaction.

Answer. Starting with the initial powder arrangement, the particles are first repacked into a more efficient arrangement, followed by deformation of the particles as pressure is increased.

16.14 What are the three steps in the sintering cycle in PM?

Answer. The three steps in the cycle are (1) preheat, in which lubricants and binders are burned off, (2) sintering, and (3) cool down.

16.15 What are some of the reasons why a controlled atmosphere furnace is desirable in sintering?

Answer. Some of the purposes of a controlled atmosphere furnace are (1) to protect against oxidation, (2) to provide a reducing atmosphere to remove existing oxides, (3) to provide a carburizing atmosphere, and (4) to remove lubricants and binders from pressing.

16.16 What are the advantages of infiltration in PM?

Answer. Advantages of infiltration are (1) the resulting structure is nonporous structure and (2) toughness and strength are improved.

16.17 What is the difference between powder injection molding and metal injection molding?

Answer. Metal injection molding is a subset of powder injection molding, in which the powders are metallic. The more general term includes powders of ceramic.

16.18 How is isostatic pressing distinguished from conventional pressing and sintering in PM?

Answer. Isostatic pressing applies hydrostatic pressure to all sides of the mold, whereas conventional pressing is uniaxial.

16.19 Describe liquid phase sintering.

Answer. Liquid phase sintering occurs when two metals of different melting temperatures are sintered at a temperature between their melting points. Accordingly, one metal melts, thoroughly wetting the solid particles and creating a strong bonding between the metals upon solidification.

16.20 What are the two basic classes of metal powders as far as chemistry is concerned?

Answer. The two classes are (1) elemental powders - powders of pure metal such as iron or copper, and (2) pre-alloyed powders - powders of alloys such as stainless steel or brass.

16.21 Why is PM technology so well suited to the production of gears and bearings?

Answer. The reasons are (1) the geometries of these parts lend themselves to conventional PM pressing, which consists of pressing in one direction, and (2) the porosity allows impregnation of the PM parts with lubricants.

16.22 (**Video**) List the most common methods for forming the pressed parts in powder metallurgy according to the powder metallurgy video.

Answer: Common methods for forming the pressed parts in powder metallurgy are (1) mechanical pressing, (2) injection molding, and (3) isostatic pressing.

16.23 (**Video**) List the types of environments that can be present during the sintering process according to the powder metallurgy video.

Answer: The types of environments that can be present during the sintering process are (1) endothermic (hyrdrogen, nitrogen, carbon monoxide mixtures), (2) exothermic (nitrogen), (3) dissociated ammonia (hydrogen and nitrogen), (3) hydrogen, (4) vacuum, and (5) inert gas.

Multiple Choice Quiz

There are 19 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

16.1 The particle size that can pass through a screen is obtained by taking the reciprocal of the mesh count of the screen: (a) true or (b) false?

Answer. (b). The given description neglects consideration of the screen wire thickness.

16.2 For a given weight of metallic powders, the total surface area of the powders is increased by which of the following (two best answers): (a) larger particle size, (b) smaller particle size, (c) higher shape factor, and (d) smaller shape factor?

Answer. (b) and (c).

16.3 As particle size increases, interparticle friction (a) decreases, (b) increases, or (c) remains the same?

Answer. (a).

16.4 Which of the following powder shapes would tend to have the lowest interparticle friction: (a) acicular, (b) cubic, (c) flakey, (d) spherical, and (e) rounded?

Answer. (d).

16.5 Which of the following statements is correct in the context of metallic powders (three correct answers): (a) porosity + packing factor = 1.0, (b) packing factor = 1/porosity, (c) packing factor = 1.0 - porosity, (d) packing factor = - porosity, (e) packing factor = bulk density/true density?

Answer. (a), (c), and (e).

16.22 Which of the following most closely typifies the sintering temperatures in PM? (a) 0.5 T_m, (b) 0.8 T_m, (c) T_m, where T_m = melting temperature of the metal?

Answer. (b).

16.6 Repressing refers to a pressworking operation used to compress a sintered part in a closed die to achieve closer sizing and better surface finish: (a) true or (b) false?

Answer. (a).

16.7 Impregnation refers to which of the following (two best answers): (a) filling the pores of the PM part with a molten metal, (b) putting polymers into the pores of a PM part, (c) soaking oil by capillary action into the pores of a PM part, and (d) something that should not happen in a factory?

Answer. (b) and (c).

16.8 In cold isostatic pressing, the mold is most typically made of which one of the following: (a) rubber, (b) sheetmetal, (c) textile, (d) thermosetting polymer, or (e) tool steel?

Answer. (a).

16.9 Which of the following processes combines pressing and sintering of the metal powders (three best answers): (a) hot isostatic pressing, (b) hot pressing, (c) metal injection molding, (d) pressing and sintering, and (e) spark sintering?

Answer. (a), (b), and (e).

16.10 Which of the following design features would be difficult or impossible to achieve by conventional pressing and sintering (three best answers): (a) outside rounded corners, (b) side holes, (c) threaded holes, (d) vertical stepped holes, and (e) vertical wall thickness of 1/8 inch (3 mm)?

Answer. (a), (b), and (c).

Problems

Characterization of Engineering Powders

16.1 A screen with 325 mesh count has wires with a diameter of 0.001377 in. Determine (a) the maximum particle size that will pass through the wire mesh and (b) the proportion of open space in the screen.

Solution: (a) By Eq. (16.1), particle size $PS = 1/MC - t_w = 1/325 - 0.001377$
$= 0.003077 - 0.001377 = \mathbf{0.00170\ in}$

(b) There are 325 x 325 = 105,625 openings in one square inch of the mesh. By inference from part (a), each opening is 0.00170 inch on a side, thus each opening is $(0.0017)^2 = 0.000002889\ in^2$. The total open area in one square inch of mesh = $105{,}625(0.000002889\ in^2) = 0.30523\ in^2$. This is total open space. Therefore, the percent open space in one square inch of mesh = **30.523%.**

16.2 A screen with 10 mesh count has wires with a diameter of 0.0213 in. Determine (a) the maximum particle size that will pass through the wire mesh and (b) the proportion of open space in the screen.

Solution: (a) By Eq. (16.1), particle size $PS = 1/MC - t_w = 1/10 - 0.0213 = $ **0.0787 in.**

(b) There are 10 x 10 = 100 openings in one square inch of the mesh. By inference from part (a), each opening is 0.0787 inch on a side, thus each opening is $(0.0787)^2 = 0.00619\ in^2$. The total open area in one square inch of mesh = $100(0.00619\ in^2) = 0.619\ in^2$. This is total open space. Therefore, the percent open space in one square inch of mesh = **61.9%.**

16.3 What is the aspect ratio of a cubic particle shape?

Solution: The aspect ratio is the ratio of the maximum dimension to the minimum dimension of the particle shape. The minimum dimension is the edge of any face of the cube; call it L. The maximum dimension is the cube diagonal, which is given by $(L^2 + L^2 + L^2)^{0.5} = (3\,L^2)^{0.5} = (3)^{0.5}\,L = 1.732\,L$. Thus, the **aspect ratio = 1.732:1.**

16.4 Determine the shape factor for metallic particles of the following ideal shapes: (a) sphere, (b) cubic, (c) cylindrical with length-to-diameter ratio of 1:1, (d) cylindrical with length-to-diameter ratio of 2:1, and (e) a disk-shaped flake whose thickness-to-diameter ratio is 1:10.

Solution: (a) Sphere: $K_s = 6.0$ as shown in the text, Eq. (16.5).

(b) Cube: Let L = edge of one face. For a cube, $A = 6L^2$ and $V = L^3$
Find diameter D of a sphere of equivalent volume.
$V = \pi D^3/6 = L^3$
$D^3 = 6L^3/\pi = 1.90986\,L^3$
$D = (1.90986\,L^3)^{0.333} = 1.2407\,L$
$K_s = AD/V = (6L^2)(1.2407\,L)/L^3 = \mathbf{7.444}$

(c) Cylinder with $L/D = 1.0$. For this cylinder shape, $L = D$. Thus, $A = 2\pi D^2/4 + \pi DL = 0.5\pi L^2 + \pi L^2 = 1.5\pi L^2$, and $V = (\pi D^2/4)L = 0.25\pi L^3$.

Find diameter D of a sphere of equivalent volume.
$V = \pi D^3/6 = 0.25\pi L^3$
$D^3 = 6(0.25\pi L^3)/\pi = 1.5L^3$
$D = (1.5\ L^3)^{0.333} = 1.1447$ L
$K_s = AD/V = (1.5\pi L^2)(1.1447\ L)/0.25\pi L^3 = \mathbf{6.868}$

(d) Cylinder with $L/D = 2.0$. For this cylinder shape, $0.5L = D$. Thus, $A = 2\pi D^2/4 + \pi DL = 0.5\pi(0.5L)^2 + \pi(0.5L)L = 0.125\pi L^2 + 0.5\pi L^2 = 0.625\pi L^2$, and $V = (\pi D^2/4)L = 0.25\pi(0.5L)^2\ L = 0.0625\pi L^3$
Find diameter D of a sphere of equivalent volume.
$V = \pi D^3/6 = 0.0625\pi L^3$
$D^3 = 6(0.0625\pi L^3)/\pi = 0.375L^3$
$D = (0.375\ L^3)^{0.333} = 0.721\ L$
$K_s = A\ D/V = (0.625\pi L^2)(0.721\ L)/0.0625\pi L^3 = \mathbf{7.211}$

(e) Disk with $L/D = 0.10$. For this shape, $10L = D$. Thus, $A = 2\pi D^2/4 + \pi DL = 0.5\pi(10L)^2 + \pi(10L)L = 50\pi L^2 + 10\pi L^2 = 60\pi L^2$, and $V = (\pi D^2/4)L = 0.25\pi(10L)^2\ L = 25\pi L^3$
Find diameter D of a sphere of equivalent volume.
$V = \pi D^3/6 = 25\pi L^3$
$D^3 = 6(25\pi L^3)/\ \pi = 150L^3$
$D = (150\ L^3)^{0.333} = 5.313\ L$
$K_s = A\ D/V = (60\pi L^2)(5.313\ L)/25\pi L^3 = \mathbf{12.75}$

16.5 A pile of iron powder weighs 2 lb. The particles are spherical in shape and all have the same diameter of 0.002 in. (a) Determine the total surface area of all the particles in the pile. (b) If the packing factor = 0.6, determine the volume taken by the pile. Note: the density of iron = 0.284 lb/in^3.

Solution: (a) For a spherical particle of $D = 0.002$ in, $V = \pi D^3/6 = \pi(0.002)^3/6$
$= 0.00000000418 = 4.18 \times 10^{-9}$ in^3/particle
Weight per particle $W = \rho V = 0.284(4.18 \times 10^{-9}\ \text{in}^3) = 1.19 \times 10^{-9}$ lb/particle
Number of particles in 2 lb = $2.0/(1.19 \times 10^{-9}) = 1.681 \times 10^9$
$A = \pi D^2 = \pi(0.002)^2 = 0.00001256\ \text{in}^2 = 12.56 \times 10^{-6}\ \text{in}^2$
Total surface area = $(1.681 \times 10^9)(12.56 \times 10^{-6}) = \mathbf{21.116 \times 10^3\ in^2}$

(b) With a packing factor of 0.6, the total volume taken up by the pile = (2.0/0.284)/0.6 = **11.74 in^3**

16.6 Solve Problem 16.5, except that the diameter of the particles is 0.004 in. Assume the same packing factor.

Solution: (a) For a spherical particle of $D = 0.004$ in, $V = \pi D^3/6 = \pi(0.004)^3/6$
$= 0.00000003351 = 33.51 \times 10^{-9}$ in^3/particle
Weight per particle $W = \rho V = 0.284(33.51 \times 10^{-9}\ \text{in}^3) = 9.516 \times 10^{-9}$ lb/particle
Number of particles in 2 lb = $2.0/(9.516 \times 10^{-9}) = 0.2102 \times 10^9$
$A = \pi D^2 = \pi(0.004)^2 = 0.00005027\ \text{in}^2 = 50.27 \times 10^{-6}\ \text{in}^2$
Total surface area = $(0.2102 \times 10^9)(50.27 \times 10^{-6}) = \mathbf{10.565 \times 10^3\ in^2}$

(b) With a packing factor of 0.6, the total volume taken up by the pile = (2.0/0.284)/0.6 = **11.74 in^3**

16.7 Suppose in Problem 16.5 that the average particle diameter = 0.002 in; however, the sizes vary, forming a statistical distribution as follows: 25% of the particles by weight are 0.001 in, 50% are 0.002 in, and 25% are 0.003 in. Given this distribution, what is the total surface area of all the particles in the pile?

Solution: For a spherical particle of $D = 0.001$ in, $V = \pi D^3/6 = \pi(0.001)^3/6$
$= 0.5236 \times 10^{-9}$ in^3/particle

Weight per particle $W = \rho V = 0.284(0.5236 \times 10^{-9}\ in^3) = 0.1487 \times 10^{-9}$ lb/particle
Particles of size $D = 0.001$ in constitute 25% of total 2 lb. = 0.5 lb
Number of particles in 0.5 lb = $0.5/(0.1487 \times 10^{-9}) = 3.362 \times 10^9$
$A = \pi D^2 = \pi(0.001)^2 = 3.142 \times 10^{-6}\ in^2$/particle
Total surface area of particles of $D = 0.001$ in = $(3.362 \times 10^9)(3.142 \times 10^{-6}) = 10.563 \times 10^3\ in^2$

For a spherical particle of $D = 0.002$ in, $V = \pi(0.002)^3/6 = 4.18 \times 10^{-9}\ in^3$/particle
Weight per particle $W = \rho V = 0.284(4.18 \times 10^{-9}\ in^3) = 1.19 \times 10^{-9}$ lb/particle
Particles of size $D = 0.002$ in constitute 50% of total 2 lb. = 1.0 lb
Number of particles in 1 lb = $1.0/(1.19 \times 10^{-9}) = 0.8406 \times 10^9$
$A = \pi D^2 = \pi(0.002)^2 = 12.56 \times 10^{-6}\ in^2$
Total surface area of particles of $D = 0.002$ in = $(0.8406 \times 10^9)(12.566 \times 10^{-6}) = 10.563 \times 10^3\ in^2$

For a spherical particle of $D = 0.003$ in, $V = \pi(0.003)^3/6 = 14.137 \times 10^{-9}\ in^3$/particle
Weight per particle $W = \rho V = 0.284(14.137 \times 10^{-9}\ in^3) = 4.015 \times 10^{-9}$ lb/particle
Particles of size $D = 0.003$ in constitute 25% of total 2 lb. = 0.5 lb
Number of particles in 0.5 lb = $0.5/(4.015 \times 10^{-9}) = 0.124 \times 10^9$
$A = \pi D^2 = \pi(0.003)^2 = 28.274 \times 10^{-6}\ in^2$
Total surface area of particles of $D = 0.003$ in = $(0.124 \times 10^9)(28.274 \times 10^{-6}) = 3.506 \times 10^3\ in^2$

Total surface area of all particles = $10.563 \times 10^3 + 10.563 \times 10^3 + 3.506 \times 10^3 = 24.632 \times 10^3\ in^2$.

16.8 A solid cube of copper with each side = 1.0 ft is converted into metallic powders of spherical shape by gas atomization. What is the percentage increase in total surface area if the diameter of each particle is 0.004 in (assume that all particles are the same size)?

Solution: Area of initial cube $A = 6(1\ ft)^2 = 6\ ft^2 = 864\ in^2$
Volume of cube $V = (1\ ft)^3 = 1728\ in^3$
Surface area of a spherical particle of $D = 0.004$ in is $A = \pi D^2 = \pi(0.004)^2$
$= 50.265 \times 10^{-6}\ in^3$/particle
Volume of a spherical particle of $D = 0.004$ in is $V = \pi D^3/6 = \pi(0.004)^3/6$
$= 33.51 \times 10^{-9}\ in^3$/particle
Number of particles in 1 ft^3 = $1728/33.51 \times 10^{-9} = 51.567 \times 10^9$
Total surface area = $(51.567 \times 10^9)(50.265 \times 10^{-6}\ in^3) = 2{,}592 \times 10^3 = 2{,}592{,}000\ in^2$
Percent increase = 100(2,592,000 - 864)/864 = **299,900%**

16.9 A solid cube of aluminum with each side = 1.0 m is converted into metallic powders of spherical shape by gas atomization. How much total surface area is added by the process if the diameter of each particle is 100 microns (assume that all particles are the same size)?

Solution: Area of starting cube $A = 6(1\ m)^2 = 6\ m^2$
Volume of starting cube $V = (1\ m)^3 = 1\ m^3$
$D = 100\ \mu m = 0.1\ mm = 0.1 \times 10^{-3}\ m$
Surface area of a sphere of $D = 0.1 \times 10^{-3}$ m is $A = \pi D^2 = \pi(0.1 \times 10^{-3})^2$
$= 3.142 \times 10^{-8}\ m^3$/particle
Volume of a sphere of $D = 0.1 \times 10^{-3}$ m is $V = \pi D^3/6 = \pi(0.1 \times 10^{-3})^3/6$
$= 0.5236 \times 10^{-12}\ m^3$/particle
Number of particles in 1 m^3 = $1.0/0.5236 \times 10^{-12} = 1.91 \times 10^{12}$
Total surface area = $(1.91 \times 10^{12})(0.5236 \times 10^{-12}\ m^3) = 5.9958 \times 10^4 = 59{,}958\ m^2$
Added surface area = 59,958 - 6 = **59,952 m²**

16.10 Given a large volume of metallic powders, all of which are perfectly spherical and having the same exact diameter, what is the maximum possible packing factor that the powders can take?

Solution: The maximum packing factor is achieved when the spherical particles are arranged as a face-centered cubic unit cell, similar to the atomic structure of FCC metals; see Figure 2.8(b). The unit cell of the FCC structure contains 8 spheres at the corners of the cube and 6 spheres on each face. Our approach to determine the packing factor will consist of: (1) finding the volume of the spheres and portions thereof that are contained in the cell, and (2) finding the volume of the unit cell cube. The ratio of (1) over (2) is the packing factor.

(1) Volume of whole and/or partial spheres contained in the unit cell. The unit cell contains 6 half spheres in the faces of the cube and 8 one-eighth spheres in corners. The equivalent number of whole spheres = 6(.5) + 8(.125) = 4 spheres. Volume of 4 spheres = $4\pi D^3/6 = 2.0944\ D^3$ where D = diameter of a sphere.

(2) Volume of the cube of one unit cell. Consider that the diagonal of any face of the unit cell contains one full diameter (the sphere in the center of the cube face) and two half diameters (the spheres at the corners of the face). Thus, the diagonal of the cube face = $2D$. Accordingly, the face is a square with each edge = $D\sqrt{2} = 1.414D$. The volume of the unit cell is therefore $(1.414D)^3$ = $2.8284\ D^3$.

The packing factor = 2.0944/2.8284 = **0.7405 = 74.05%**

Compaction and Design Considerations

16.11 In a certain pressing operation, the metallic powder fed into the open die has a packing factor of 0.5. The pressing operation reduces the powders to 2/3 of their starting volume. In the subsequent sintering operation, shrinkage amounts to 10% on a volume basis. Given that these are the only factors that affect the structure of the finished part, determine its final porosity.

Solution: Packing factor = bulk density / true density
Density = (specific volume)$^{-1}$
Packing factor = true specific volume / bulk specific volume
Pressing reduces bulk specific volume to 2/3 = 0.667
Sintering further reduces the bulk specific volume to 0.90 of value after pressing.
Let true specific volume = 1.0
Thus for a packing factor of 0.5, bulk specific volume = 2.0.
Packing factor after pressing and sintering = 1.0/(2.0 x .667 x .90) = 1.0/1.2 = 0.833
By Eq. (18.7), porosity = 1 - 0.833 = **0.167**

16.12 A bearing of simple geometry is to be pressed out of bronze powders, using a compacting pressure of 207 MPa. The outside diameter = 44 mm, the inside diameter = 22 mm, and the length of the bearing = 25 mm. What is the required press tonnage to perform this operation?

Solution: Projected area of part $A_p = 0.25\pi(D_o^2 - D_i^2) = 0.25\pi(44^2 - 22^2) = 1140.4\ \text{mm}^2$
$F = A_p p_c = 1140.4(207) =$ **236,062 N**

16.13 The part shown in Figure P16.13 is to be pressed of iron powders using a compaction pressure of 75,000 lb/in^2. Dimensions are inches. Determine (a) the most appropriate pressing direction, (b) the required press tonnage to perform this operation, and (c) the final weight of the part if the porosity is 10%. Assume shrinkage during sintering can be neglected.

Solution: (a) Most appropriate pressing direction is parallel to the part axis.

(b) Press tonnage $F = A_p p_c$
Projected area of part $A_p = 0.25\pi(D_o^2 - D_i^2) = 0.25\pi(2.8^2 - 0.875^2) = 5.556\ \text{in}^2$
$F = A_p p_c = 5.556(75{,}000) =$ **416,715 lb = 208 tons.**

(c) $V = 0.25\pi(2.8^2 - 0.875^2)(0.5) + 0.25\pi(2.8^2 - 1.5^2)(1.25 - 0.5) = 0.25\pi(3.5372 + 4.1925)$
$= 6.071\ \text{in}^3$

From Table 4.1, density of iron $\rho = 0.284$ lb/in^3.
At 10% porosity, part weight $W = 6.071(0.284)(0.90) =$ **1.55 lb**.

16.14 For each of the four part drawings in Figure P16.14, indicate which PM class the parts belong to, whether the part must be pressed from one or two directions, and how many levels of press control will be required? Dimensions are mm.

Solution: (a) Class II, 2 directions because of axial thickness, one level of press control.

(b) Class I, one direction part is relatively thin, one level of press control.

(c) Class IV, 2 directions of pressing, 3 levels of press control required.

(d) Class IV, 2 directions of pressing, 4 or 5 levels of press control due to multiple steps in part design.

17 PROCESSING OF CERAMICS AND CERMETS

Review Questions

17.1 What is the difference between the traditional ceramics and the new ceramics, as far as raw materials are concerned?

Answer. The traditional ceramics are based on hydrous aluminum silicates (clay), whereas the new ceramics are based on simpler compounds such as oxides, nitrides, and carbides.

17.2 List the basic steps in the traditional ceramics processing sequence.

Answer. The sequence is (1) preparation of raw materials, (2) shaping, (3) drying, and (4) firing.

17.3 What is the technical difference between crushing and grinding in the preparation of traditional ceramic raw materials?

Answer. Crushing is performed to reduce large lumps of mineral to smaller size. Grinding is a secondary process which further reduces the particle size to fine powder.

17.4 Describe the slip casting process in traditional ceramics processing.

Answer. In slip casting, a slurry of clay is poured into a plaster of Paris mold, whereupon water is absorbed from the slurry into the plaster to form a clay layer against the mold wall. The remaining slurry is usually poured out to leave a hollow part.

17.5 List and briefly describe some of the plastic forming methods used to shape traditional ceramic products.

Answer. The plastic forming methods include (1) hand modeling, molding, and throwing; (2) jiggering, which is a mechanized extension of hand throwing used to manufacture bowls and plates; (3) plastic pressing, in which a clay slug is pressed in a mold; and (4) extrusion, in which the clay is compressed through a die opening to make long pieces of uniform cross section.

17.6 What is the process of jiggering?

Answer. Jiggering is a clay forming process that uses a convex mold on a potters wheel. The clay is first pressed into rough shape and then rotated and formed with a jigger tool to final shape. It is suited to the manufacture of flatware (e.g., dinner plates).

17.7 What is the difference between dry pressing and semi-dry pressing of traditional ceramic parts?

Answer. The difference is in the starting clay. For semi-dry pressing, the clay has a typical water content of 10% to 15%. For dry pressing, the water content is usually less than 5%. Dry clay has virtually no plasticity, and so this imposes certain limitations on part geometry in dry pressing.

17.8 What happens to a ceramic material when it is sintered?

Answer. Sintering of green ceramics (or powdered metals) causes bonding between the ceramic grains, which is accompanied by densification and reduction of porosity.

17.9 What is the name given to the furnace used to fire ceramic ware?

Answer. Kiln.

17.10 What is glazing in traditional ceramics processing?

Answer. Glazing refers to the process of putting a ceramic coating on the surface of the ceramic piece. The coating, usually consisting of ceramic oxides, is referred to as a glaze.

17.11 Why is the drying step, so important in the processing of traditional ceramics, usually not required in processing of new ceramics?

Answer. Because water is usually not one of the ingredients in the new ceramics during forming. Drying is only needed when the green piece contains water.

17.12 Why is raw material preparation more important in the processing of new ceramics than for traditional ceramics?

Answer. Because the requirements on the strength of the finished product are usually more demanding for new ceramics.

17.13 What is the freeze drying process used to make certain new ceramic powders?

Answer. In freeze drying, salts are dissolved in water and sprayed into small droplets that are immediately frozen; the water is then removed from the droplets in a vacuum chamber, and the freeze-dried salt is decomposed by heating to form the ceramic powders.

17.14 Describe the doctor-blade process.

Answer. In the doctor-blade process, a ceramic slurry is flowed onto a moving film which passes under a wiper blade, so that the resulting ceramic is in the form of a thin green sheet which is dried and reeled onto a spool for subsequent shaping and sintering.

17.15 Liquid phase sintering is used for WC-Co compacts, even though the sintering temperatures are below the melting points of either WC or Co. How is this possible?

Answer. The melting point of cobalt is reduced when WC is dissolved in it. At the sintering temperatures used for WC-Co, WC gradually dissolves in the cobalt, reducing its melting point to the sintering temperature. Thus does liquid phase sintering occur in the WC-Co system.

17.16 What are some design recommendations for ceramic parts?

Answer. The guidelines include the following: (1) subject ceramic parts to compressive stresses, not tensile stresses; (2) ceramics are brittle, so avoid impact loading; (3) part geometries should be simple; (4) use large radii on inside and outside corners; (5) take into account shrinkage; and (6) no screw threads.

Multiple Choice Quiz

There are 16 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

17.1 The following equipment is used for crushing and grinding of minerals in the preparation of traditional ceramics raw materials. Which of the pieces listed is used for grinding (two correct answers): (a) ball mill, (b) hammer mill, (c) jaw crusher, (d) roll crusher, and (e) roller mill?

Answer. (a) and (e).

17.2 Which one of the following compounds becomes a plastic and formable material when mixed with suitable proportions of water: (a) aluminum oxide, (b) hydrogen oxide, (c) hydrous aluminum silicate, or (d) silicon dioxide?

Answer. (c).

17.3 At which one of the following water contents does clay become a suitably plastic material for the traditional ceramics plastic forming processes: (a) 5%, (b) 10%, (c) 20%, or (d) 40%?

Answer. (c).

17.4 Which of the following processes are not plastic forming methods used in the shaping of traditional ceramics (three correct answers): (a) dry pressing, (b) extrusion, (c) jangling, (d) jiggering, (e) jolleying, (f) slip casting, and (g) spinning?

Answer. (b), (d), and (e).

17.5 The term green piece in ceramics refers to a part that has been shaped but not yet fired: (a) true or (b) false?

Answer. (a).

17.6 In the final product made of a polycrystalline new ceramic material, strength increases with grain size: (a) true or (b) false?

Answer. (b).

17.7 Which one of the following processes for the new ceramic materials accomplishes shaping and sintering simultaneously: (a) doctor-blade process, (b) freeze drying, (c) hot pressing, (d) injection molding, or (e) isostatic pressing?

Answer. (c).

17.8 Which of the following are the purposes of finishing operations used for parts made of the new ceramics (two best answers): (a) apply a surface coating, (b) electroplate the surface, (c) improve surface finish, (d) increase dimensional accuracy, and (e) work harden the surface?

Answer. (c) and (d).

17.9 Which of the following terms describes what a cemented carbide is (one best answer): (a) ceramic, (b) cermet, (c) composite, (d) metal, (e) new ceramic, or (f) traditional ceramic?

Answer. (b).

17.10 Which of the following geometric features should be avoided if possible in the design of structural components made of new ceramics (three best answers): (a) deep holes, (b) rounded inside corners, (c) rounded outside corners, (d) sharp edges, (e) thick sections, and (f) threads?

Answer. (a), (d), and (f).

18 FUNDAMENTALS OF METAL FORMING

Review Questions

18.1 What are the differences between bulk deformation processes and sheet metal processes?

Answer. In bulk deformation, the shape changes are significant, and the workparts have a low area-to-volume ratio. In sheet metal processes, the area-to-volume ratio is high.

18.2 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.

18.3 Why is the term pressworking often used for sheet metal processes?

Answer. The term pressworking is used because most sheet metal operations are performed on presses.

18.4 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.

18.5 Indicate the mathematical equation for the flow curve.

Answer. The flow curve is defined in Eq. (18.1) as $Y_f = K\varepsilon^n$.

18.6 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.

18.7 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.

18.8 What is isothermal forming?

Answer. An isothermal forming operation is performed in such a way as to eliminate surface cooling and thermal gradients in the workpart. This is accomplished by preheating the forming tools.

18.9 Describe the effect of strain rate in metal forming.

Answer. Increasing strain rate tends to increase the resistance to deformation. The tendency is especially prominent in hot forming operations.

18.10 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.

18.11 What is sticking friction in metalworking?

Answer. Sticking friction is when the work surface adheres to the surface of the tool rather than slides against it; it occurs when the friction stress is greater than the shear flow stress of the metal.

Multiple Choice Quiz

There are 13 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

18.1 Which of the following are bulk deformation processes (three correct answers): (a) bending, (b) deep drawing, (c) extrusion, (d) forging, (e) rolling, and (f) shearing?

Answer. (c), (d), and (e).

18.2 Which of the following is typical of the starting work geometry in sheet metal processes: (a) high volume-to-area ratio or (b) low volume-to-area ratio?

Answer. (b).

18.3 The flow curve expresses the behavior of a metal in which of the following regions of the stress-strain curve: (a) elastic region or (b) plastic region?

Answer. (b).

18.4 The average flow stress is the flow stress multiplied by which of the following factors: (a) n, (b) $(1+n)$, (c) $1/n$, or (d) $1/(1+n)$, where n is the strain-hardening exponent?

Answer. (d).

18.5 Hot working of metals refers to which one of the following temperature regions relative to the melting point of the given metal on an absolute temperature scale: (a) room temperature, (b) $0.2T_m$, (c) $0.4T_m$, or (d) $0.6T_m$?

Answer. (d).

18.6 Which of the following are advantages and characteristics of hot working relative to cold working (four correct answers): (a) fracture of workpart is less likely, (b) friction is reduced, (c) increased strength properties, (d) isotropic mechanical properties, (e) less overall energy is required, (f) lower deformation forces is required, (g) more significant shape changes are possible, and (h) strain-rate sensitivity is reduced?

Answer. (a), (d), (f), and (g).

18.7 Increasing strain rate tends to have which one of the following effects on flow stress during hot forming of metal: (a) decreases flow stress, (b) has no effect, or (c) increases flow stress?

Answer. (c).

18.8 The coefficient of friction between the part and the tool in cold working tends to be (a) higher, (b) lower, or (c) no different relative to its value in hot working?

Answer. (b).

Problems

Flow Curve in Forming

18.1 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 MPa.**

Average flow stress $\bar{Y}_f = 550(0.85)^{0.22}/1.22 =$ **435 MPa.**

18.2 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 MPa.**
Average flow stress $\bar{Y}_f = 850(0.451)^{0.30}/1.30 =$ **514.9 MPa.**

18.3 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 lb/in^2.**
Average flow stress $\bar{Y}_f = 35{,}000(0.501)^{0.26}/1.26 =$ **23,206 lb/in^2.**

18.4 The strength coefficient and strain-hardening exponent of a certain test metal are 40,000 lb/in^2 and 0.19, respectively. A cylindrical specimen of the metal with starting diameter = 2.5 in and length = 3.0 in is compressed to a length of 1.5 in. Determine the flow stress at this compressed length and the average flow stress that the metal has experienced during deformation.

Solution: $\varepsilon = \ln(1.5/3.0) = \ln 0.5 = -0.69315$
Flow stress $Y_f = 40{,}000(0.69315)^{0.19} =$ **37,309 lb/in^2.**
Average flow stress $\bar{Y}_f = 40{,}000(0.69315)^{0.19}/1.19 =$ **31,352 lb/in^2.**

18.5 Derive the equation for average flow stress, Eq. (18.2) in the text.

Solution: Flow stress equation [Eq. (18.1)]: $Y_f = K\varepsilon^n$
$\bar{Y}_f$ over the range $\varepsilon = 0$ to $\varepsilon = \varepsilon$ is given by $\int K\varepsilon^n\, d\varepsilon = K \int\varepsilon^n\, d\varepsilon = K\varepsilon^{n+1}/\varepsilon(n+1) = \boldsymbol{K\varepsilon^n/(n+1)}$

18.6 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: $Y_f = K = 700 = K\varepsilon^n = 700\varepsilon^{.27}$
ε must be equal to 1.0.
$\bar{Y}_f = 700(1.0)^{.27}/1.27 = 700/1.27 =$ **551.2 MPa**

18.7 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: $\bar{Y}_f = 0.75\, Y_f$
$K\varepsilon^n/(1+n) = 0.75\, K\varepsilon^n$
$1/(1+n) = 0.75$
$1 = 0.75(1+n) = 0.75 + 0.75n$
$0.25 = 0.75n$ $\boldsymbol{n = 0.333}$

18.8 The strength coefficient = 35,000 lb/in^2 and strain-hardening exponent = 0.40 for a metal used in a forming operation in which the workpart is reduced in cross-sectional area by stretching. If the average flow stress on the part is 20,000 lb/in^2, determine the amount of reduction in cross-sectional area experienced by the part.

Solution: $\overline{Y}_f = K\varepsilon^n/(1+n)$
$20{,}000 = 35{,}000\ \varepsilon^4/(1.4)$
$1.4(20{,}000) = 35{,}000\ \varepsilon^4$
$28{,}000/35{,}000 = 0.8 = \varepsilon^4$
$0.4 \ln \varepsilon = \ln (0.8) = -0.22314$
$\ln \varepsilon = -0.22314/0.4 = -0.55786$
$\varepsilon = 0.5724$
$\varepsilon = \ln(A_o/A_f) = 0.5724$
$A_o/A_f = 1.7726$
$\boldsymbol{A_f = A_o/1.7726 = 0.564A_o}$

18.9 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) $\ln K = \ln 259 – n \ln 0.68$
(1) $\ln K = 5.3799 – (-1.0498)n = 5.3799 + 1.0498\ n$
(2) $\ln K = 5.5568 – (-0.3857)n = 5.5568 + 0.3857\ n$
$5.3799 + 1.0498\ n = 5.5568 + 0.3857\ n$
$1.0498\ n – 0.3857\ n = 5.5568 – 5.3799$
$0.6641\ n = 0.1769$ $\boldsymbol{n = 0.2664}$
$\ln K = 5.3799 + 1.0498\ (0.2664) = 5.6596$ $\boldsymbol{K = 287}$ **MPa**

18.10 The following stress and strain values were measured in the plastic region during a tensile test carried out on a new experimental metal: (1) true stress = 43,608 lb/in^2 and true strain = 0.27 in/in, and (2) true stress = 52,048 lb/in^2 and true strain = 0.85 in/in. Based on these data points, determine the strength coefficient and strain-hardening exponent.

Solution: Solve two equations, two unknowns: $\ln K = \ln \sigma - n \ln \varepsilon$
(3) $\ln K = \ln 43{,}608 – n \ln 0.27$
(4) $\ln K = \ln 52{,}048 – n \ln 0.85$
(3) $\ln K = 10.6830 – (-1.3093)n = 10.6830 + 1.3093\ n$
(4) $\ln K = 10.8600 – (-0.1625)n = 10.8600 + 0.1625\ n$
(5) $10.6830 + 1.3093\ n = 10.8600 + 0.1625\ n$
$1.3093\ n – 0.1625\ n = 10.8600 – 10.6830$
$1.1468\ n = 0.1769$ $\boldsymbol{n = 0.1543}$
$\ln K = 10.6830 + 1.3093\ (0.1543) = 10.885$ $\boldsymbol{K = 53{,}374}$ **lb/in^2**

Strain Rate

18.11 The gage length of a tensile test specimen = 150 mm. It is subjected to a tensile test in which the grips holding the end of the test specimen are moved with a relative velocity = 0.1 m/s. Construct a plot of the strain rate as a function of length as the specimen is pulled to a length = 200 mm.

Solution: The following values are calculated for the plot:
At L = 150 mm, strain rate $\dot{\varepsilon} = 0.1/0.15 = 0.667$ s^{-1}
At L = 160 mm, strain rate $\dot{\varepsilon} = 0.1/0.16 = 0.625$ s^{-1}
At L = 170 mm, strain rate $\dot{\varepsilon} = 0.1/0.17 = 0.588$ s^{-1}
At L = 180 mm, strain rate $\dot{\varepsilon} = 0.1/0.18 = 0.555$ s^{-1}
At L = 190 mm, strain rate $\dot{\varepsilon} = 0.1/0.19 = 0.526$ s^{-1}
At L = 200 mm, strain rate $\dot{\varepsilon} = 0.1/0.20 = 0.500$ s^{-1}

18.12 A specimen with 6.0 in starting gage length is subjected to a tensile test in which the grips holding the end of the test specimen are moved with a relative velocity = 1.0 in/sec. Construct a plot of the strain rate as a function of length as the specimen is pulled to a length = 8.0 in.

Solution: The following values are calculated for the plot:
At L = 6.0 in, strain rate $\dot{\varepsilon}$ = 1/6.0 = 0.1667 sec^{-1}
At L = 6.5 in, strain rate $\dot{\varepsilon}$ = 1/6.5 = 0.1538 sec^{-1}
At L = 7.0 in, strain rate $\dot{\varepsilon}$ = 1/7.0 = 0.1429 sec^{-1}
At L = 7.5 in, strain rate $\dot{\varepsilon}$ = 1/7.5 = 0.1333 sec^{-1}
At L = 8.0 in, strain rate $\dot{\varepsilon}$ = 1/8.0 = 0.1250 sec^{-1}

18.13 A workpart with starting height h = 100 mm is compressed to a final height of 50 mm. During the deformation, the relative speed of the plattens compressing the part = 200 mm/s. Determine the strain rate at (a) h = 100 mm, (b) h = 75 mm, and (c) h = 51 mm.

Solution: (a) strain rate $\dot{\varepsilon}$ = 200/100 = **2.0 s^{-1}**

(b) strain rate $\dot{\varepsilon}$ = 200/75 = **2.667 s^{-1}**

(c) strain rate $\dot{\varepsilon}$ = 200/51 = **3.922 s^{-1}**

18.14 A hot working operation is carried out at various speeds. The strength constant = 30,000 lb/in^2 and the strain-rate sensitivity exponent = 0.15. Determine the flow stress if the strain rate is (a) 0.01/sec (b) 1.0/sec, (c) 100/sec.

Solution: (a) $Y_f = C(\dot{\varepsilon})^m = 30{,}000(0.01)^{.15}$ = **15,036 lb/in^2**

(b) $Y_f = 30{,}000(1.0)^{0.15}$ = **30,000 lb/in^2**

(c) $Y_f = 30{,}000(100)^{0.15}$ = **59,858 lb/in^2**

18.15 A tensile test is performed to determine the strength constant C and strain-rate sensitivity exponent m in Eq. (18.4) for a certain metal. The temperature at which the test is performed = 500°C. At a strain rate = 12/s, the stress is measured at 160 MPa; and at a strain rate = 250/s, the stress = 300 MPa. (a) Determine C and m. (b) If the temperature were 600°C, what changes would you expect in the values of C and m?

Solution: (a) Two equations: (1) $160 = C(12)^m$ and (2) $300 = C(250)^m$
(1) $\ln 160 = \ln C + m \ln 12$ or $\ln 160 - m \ln 12 = \ln C$
(2) $\ln 300 = \ln C + m \ln 250$ or $\ln 300 - m \ln 250 = \ln C$
(1) and (2): $\ln 160 - m \ln 12 = \ln 300 - m \ln 250$
$5.0752 – 2.4849\, m = 5.7038 – 5.5215\, m$
$(5.5215 – 2.4849)m = 5.7038 – 5.0752$
3.0366 m = 0.6286 **m = 0.207**
(1) C = $160/(12)^{0.207}$ = 160.1.6726 = 95.658
(2) C = $300/(250)^{0.207}$ = 300/3.1361 = 95.660
Averaging these values, **C = 95.659**

(b) If temperature were 600°C, the strength constant C would decrease and the strain-rate sensitivity exponent m would increase.

18.16 A tensile test is carried out to determine the strength constant C and strain-rate sensitivity exponent m for a certain metal at 1000°F. At a strain rate = 10/sec, the stress is measured at 23,000 lb/in^2; and at a strain rate = 300/sec, the stress = 45,000 lb/in^2. (a) Determine C and m. (b) If the temperature were 900°F, what changes would you expect in the values of C and m?

Solution: (a) Two equations: (1) $23{,}000 = C(10)^m$ and (2) $45{,}000 = C(300)^m$
$45{,}000/23{,}000 = 1.9565 = (300/10)^m = (30)^m$

ln 1.9656 = m ln 30

0.67117 = 3.4012 m **m = 0.1973**

(1) $C = 23000/10^{0.1973} = 23000/1.5752 = 14{,}601.4$

(2) $C = 45000/300^{0.1973} = 45000/3.0819 = 14{,}601.4$ **C = 14,601.4**

(b) If temperature were decreased to 900°F, the strength constant C would increase and the strain-rate sensitivity exponent m would decrease.

19 BULK DEFORMATION PROCESSES IN METALWORKING

Review Questions

19.1 What are the reasons why the bulk deformation processes are important commercially and technologically?

Answer. Reasons why the bulk deformation processes are important include the following: (1) they are capable of significant shape change when hot working is used, (2) they have a positive effect on part strength when cold working is used, and (3) most of the processes produce little material waste; some are net shape processes.

19.2 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.

19.3 What is rolling in the context of the bulk deformation processes?

Answer. Rolling is a deformation process in which the thickness of the workpiece is reduced by compressive forces exerted by two opposing rolls. The rolls rotate, thus pulling and simultaneously squeezing the workpiece between them.

19.4 In rolling of steel, what are the differences between a bloom, a slab, and a billet?

Answer. A bloom is a rolled steel workpiece with a square cross section of about 150 mm by 150 mm. The starting work unit for a bloom is an ingot heated in a soaking pit. A slab is rolled from an ingot or a bloom and has a rectangular cross section of about 250 mm by 40 mm. A billet is rolled from a bloom and has a square cross section of about 40 mm by 40 mm.

19.5 List some of the products produced on a rolling mill.

Answer. Rolled products include flat sheet and plate stock, round bar and rod stock, rails, structural shapes such as I-beams and channels.

19.6 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.

19.7 What is sticking in a hot rolling operation?

Answer. Sticking is a condition in hot rolling in which the surface of the workpiece adheres to the rolls as the piece passes between the rolls, causing severe deformation of the metal below the surface in order to allow passage through the roll gap.

19.8 Identify some of the ways in which force in flat rolling can be reduced.

Answer. Ways to reduce force in flat rolling include (1) use hot rolling, (2) reduce draft in each pass, and (3) use smaller diameter rolls.

19.9 What is a two-high rolling mill?

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

19.10 What is a reversing mill in rolling?

Answer. A reversing mill is a two-high rolling mill in which the direction of rotation of the rolls can be reversed to allow the work to pass through from either side.

19.11 Besides flat rolling and shape rolling, identify some additional bulk forming processes that use rolls to effect the deformation.

Answer. Some other processes that use rolls are ring rolling, thread rolling, gear rolling, roll piercing, and roll forging.

19.12 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.

19.13 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.

19.14 Why is flash desirable in impression die forging?

Answer. Because its presence constrains the metal in the die to fill the details of the die cavity.

19.15 What is a trimming operation in the context of impression die forging?

Answer. Trimming is a shearing operation used to remove the flash on the workpiece after impression die forging.

19.16 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.

19.17 What is isothermal forging?

Answer. Isothermal forging is a hot forging operation in which the die surfaces are heated to reduce heat transfer from the work into the tooling.

19.18 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.

19.19 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.

19.20 Name some products that are produced by extrusion.

Answer. Products produced by continuous extrusion include structural shapes (window frames, shower stalls, channels), tubes and pipes, and rods of various cross sections. Products made by discrete extrusion include toothpaste tubes, aluminum beverage cans, and battery cases.

19.21 Why is friction a factor in determining the ram force in direct extrusion but not a factor in indirect extrusion?

Answer. Friction is a factor in direct extrusion because the work billet is squeezed against the walls of the container so that friction resists the movement of the billet toward the die opening. In indirect extrusion, the billet does not move relative to the container walls, and thus there is no friction.

19.22 What does the centerburst defect in extrusion have in common with the roll piercing process?

Answer. They are both examples of how compressive stresses applied to the outside surface of a solid cylindrical cross section can create high tensile stresses in the interior of the cylinder.

19.23 What is 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.

19.24 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.

19.25 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.

19.26 (**Video**) According to the video on forming, what is the primary factor that makes the mechanical performance of forged parts better than cast parts in many situations?

Answer: The mechanical performance of forged or wrought parts is usually better because of the microstructure changes and the directional grain flow imparted during the forging process.

19.27 (**Video**) List the accessory tools that can be used during open die forging according to the video on forging.

Answer: Accessory tools that can be used during open-die forging are (1) saddles, (2) blocks, (3) rings, (4) mandrels, and (5) punches.

19.28 (**Video**) List the preforming operations discussed in the forming video.

Answer: The preforming operations discussed in the forming video are (1) edging – to increase the cross section of the work and (2) blocking – to refine the shape. Then, (3) finish forging is used to complete the shape.

Multiple Choice Quiz

There are 27 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

19.1 The starting workpiece in steel hot rolling of plate and sheet stock is which of the following (one best answer): (a) bar stock, (b) billet, (c) bloom, (d) slab, or (e) wire stock?

Answer. (d).

19.2 The maximum possible draft in a rolling operation depends on which of the following parameters (two correct answers): (a) coefficient of friction between roll and work, (b) roll diameter, (c) roll velocity, (d) stock thickness, (e) strain, and (f) strength coefficient of the work metal?

Answer. (a) and (b).

19.3 Which of the following stress or strength parameters is used in the computation of rolling force (one best answer): (a) average flow stress, (b) compression strength, (c) final flow stress, (d) tensile strength, or (e) yield strength?

Answer. (a).

19.4 Which of the following rolling mill types are associated with relatively small diameter rolls in contact with the work (two correct answers): (a) cluster mill, (b) continuous rolling mill, (c) four-high mill, (d) reversing mill, and (e) three-high configuration?

Answer. (a) and (c).

19.5 Production of pipes and tubes is associated with which of the following bulk deformation processes (three correct answers): (a) extrusion, (b) hobbing, (c) ring rolling, (d) roll forging, (e) roll piercing, (f) tube sinking, and (g) upsetting?

Answer. (a), (e), and (f).

19.6 Which of the following stress or strength parameters is used in the computation of the maximum force in a forging operation (one best answer): (a) average flow stress, (b) compression strength, (c) final flow stress, (d) tensile strength, or (e) yield strength?

Answer. (c).

19.7 Which of the following operations are closely related to open-die forging (three best answers): (a) cogging, (b) flashless forging, (c) fullering, (d) impression-die forging, (e) Mannesmann process, (f) precision forging, (g) soaking, and (h) upsetting?

Answer. (a), (c), and (h).

19.8 Flash in impression die forging serves no useful purpose and is undesirable because it must be trimmed from the part after forming: (a) true or (b) false?

Answer. (b). Flash causes build-up of pressure inside the die, which forces the work metal to fill the die cavity.

19.9 Which of the following are classified as forging operations (four correct answers): (a) coining, (b) fullering, (c) impact extrusion, (d) roll piercing, (e) swaging, (f) thread rolling, (g) trimming, and (h) upsetting?

Answer. (a), (b), (e), and (h). Trimming, answer (g), although associated with forging, is a cutting operation.

19.10 Which of the following are alternative names for indirect extrusion (two correct answers): (a) backward extrusion, (b) direct extrusion, (c) forward extrusion, (d) impact extrusion, and (e) reverse extrusion?

Answer. (a) and (e).

19.11 The production of tubing is possible in indirect extrusion but not in direct extrusion: (a) true or (b) false?

Answer. (b). Tube and pipe cross sections can be produced by either direct or indirect extrusion.

19.12 Which of the following stress or strength parameters is used in the computation of the force in an extrusion operation (one best answer): (a) average flow stress, (b) compression strength, (c) final flow stress, (d) tensile strength, or (e) yield strength?

Answer. (a).

19.13 In which of the following extrusion operations is friction a factor in determining the extrusion force (one best answer): (a) direct extrusion or (b) indirect extrusion?

Answer. (a).

19.14 Theoretically, the maximum reduction possible in a wire drawing operation, under the assumptions of a perfectly plastic metal, no friction, and no redundant work, is which of the following (one answer): (a) zero, (b) 0.63, (c) 1.0, or (d) 2.72?

Answer. (b).

19.15 Which of the following bulk deformation processes are involved in the production of nails for lumber construction (three best answers): (a) bar and wire drawing, (b) extrusion, (c) flashless forging, (d) impression die forging, (e) rolling, and (f) upsetting?

Answer. (a), (c), and (d). Bar stock is rolled, and then drawn into wire stock. Upset forged is used to form the nail head.

19.16 Johnson's formula is associated with which one of the four bulk deformation processes: (a) bar and wire drawing, (b) extrusion, (c) forging, and (d) rolling?

Answer. (b).

Problems

Rolling

19.1 A 42.0-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. Determine (a) the minimum required coefficient of friction that would make this rolling operation possible, (b) exit velocity of the plate, and (c) forward slip.

Solution: (a) Maximum draft $d_{max} = \mu^2 R$
Given that $d = t_o - t_f = 42 - 34 = 8.0$ mm,
$\mu^2 = 8/325 = 0.0246$
$\mu = (0.0246)^{0.5} = \mathbf{0.157}$

(b) Plate widens by 4%.
$t_o w_o v_o = t_f w_f v_f$
$w_f = 1.04\ w_o$
$42(w_o)(15) = 34(1.04w_o)v_f$
$v_f = 42(w_o)(15)/\ 34(1.04w_o) = 630/35.4 =$ **17.8 m/min**

(c) $v_r = \pi\ r^2N= \pi(0.325)^2(49.0) = 16.26$ m/min

$s = (v_f - v_r)/v_r = (17.8 – 16.26)/16.26 = \mathbf{0.0947}$

19.2 A 2.0-in-thick slab is 10.0 in wide and 12.0 ft long. Thickness is to be reduced in three steps in a hot rolling operation. Each step will reduce the slab to 75% of its previous thickness. It is expected that for this metal and reduction, the slab will widen by 3% in each step. If the entry speed of the slab in the first step is 40 ft/min, and roll speed is the same for the three steps, determine: (a) length and (b) exit velocity of the slab after the final reduction.

Solution: (a) After three passes, $t_f = (0.75)(0.75)(0.75)(2.0) = 0.844$ in
$w_f = (1.03)(1.03)(1.03)(10.0) = 10.927$ in
$t_o w_o L_o = t_f w_f L_f$
$(2.0)(10.0)(12 \text{ x } 12) = (0.844)(10.927)L_f$
$L_f = (2.0)(10.0)(12 \text{ x } 12)/(0.844)(10.927) = 312.3$ in = **26.025 ft**

(b) Given that roll speed is the same at all three stands and that $t_o w_o v_o = t_f w_f v_f$,

Step 1: v_f = (2.0)(10.0)(40)/(0.75 x 2.0)(1.03 x 10.0) = 51.78 ft/min
Step 2: v_f = (0.75 x 2.0)(1.03 x 10.0)(40)/(0.75^2 x 2.0)(1.03^2 x 10.0) = 51.78 ft/min
Step 3: v_f = (0.75^2 x 2.0)(1.03^2 x 10.0)(40)/(0.75^3 x 2.0)(1.03^3 x 10.0) = **51.78 ft/min**

19.3 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. 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 $d_{max} = \mu^2 R = (0.15)^2 (350) = 7.875$ mm
Minimum number of passes = $(t_o - t_f)/d_{max}$ = (50 - 25)/7.875 = **3.17 → 4 passes**

(b) Draft per pass d = (50 - 25)/4 = **6.25 mm**

19.4 In the previous problem, suppose that the percent reduction were specified to be equal for each pass, rather than the draft. (a) What is the minimum number of passes required? (b) What is the draft for each pass?

Solution: (a) Maximum possible draft occurs on first pass: $d_{max} = \mu^2 R = (0.15)^2 (350) = 7.875$ mm
This converts into a maximum possible reduction x = 7.875/50 = 0.1575
Let x = fraction reduction per pass, and n = number of passes. The number of passes must be an integer. To reduce from t_o = 50 mm to t_o = 25 mm in n passes, the following relationship must be satisfied:
$50(1 - x)^n = 25$
$(1 - x)^n = 25/50 = 0.5$
$(1 - x) = 0.5^{1/n}$
Try n = 4: $(1 - x) = (0.5)^{1/4} = 0.8409$
x = 1 - 0.8409 = 0.1591, which exceeds the maximum possible reduction of 0.1575.
Try n = 5: $(1 - x) = (0.5)^{1/5} = 0.87055$
x = 1 - 0.87055 = **0.12945**, which is within the maximum possible reduction of 0.1575.

(b) Pass 1: d = 50(0.12945) = **6.47 mm**, t_f = 50 - 6.47 = **43.53 mm**
Pass 2: d = 43.53(0.12945) = **5.63 mm**, t_f = 43.53 - 5.63 = **37.89 mm**
Pass 3: d = 37.89(0.12945) = **4.91 mm**, t_f = 37.89 - 4.91 = **32.98 mm**
Pass 4: d = 32.98(0.12945) = **4.27 mm**, t_f = 32.98 - 4.27 = **28.71 mm**
Pass 5: d = 28.71(0.12945) = **3.71 mm**, t_f = 28.71 - 3.71 = **25.00 mm**

19.5 A continuous hot rolling mill has two stands. Thickness of the starting plate = 25 mm and width = 300 mm. Final thickness is to be 13 mm. Roll radius at each stand = 250 mm. Rotational speed at the first stand = 20 rev/min. Equal drafts of 6 mm are to be taken at each stand. The plate is wide enough relative to its thickness that no increase in width occurs. Under the assumption that the forward slip is equal at each stand, determine (a) speed v_r at each stand, and (b) forward slip s. (c) Also, determine the exiting speeds at each rolling stand, if the entering speed at the first stand = 26 m/min.

Solution: (a) Let t_o = entering plate thickness at stand 1. t_o = 25 mm. Let t_1 = exiting plate thickness at stand 1 and entering thickness at stand 2. t_1 = 25 - 6 = 19 mm.
Let t_2 = exiting plate thickness at stand 2. t_2 = 19 - 6 = 13 mm.
Let v_o = entering plate speed at stand 1.
Let v_1 = exiting plate speed at stand 1 and entering speed at stand 2.
Let v_2 = exiting plate speed at stand 2.
Let v_{r1} = roll speed at stand 1. $v_{r1} = \pi DN_r = \pi(2 \text{ x } 250)(10^{-3})(20)$ = **31.42 m/min**
Let v_{r2} = roll speed at stand 2. v_{r2} = ?

Forward slip $s = (v_f - v_r)/v_r$
$sv_r = v_f - v_r$
$(1 + s)v_r = v_f$

At stand 1, $(1 + s)v_{r1} = v_1$ (Eq. 1)
At stand 2, $(1 + s)v_{r2} = v_2$ (Eq. 2)
By constant volume, $t_ow_ov_o = t_1w_1v_1 = t_2w_2v_2$
Since there is no change in width, $w_o = w_1 = w_2$
Therefore, $t_ov_o = t_1v_1 = t_2v_2$
$1.0v_o = 0.75v_1 = 0.50v_2$
$v_2 = 1.5v_1$ (Eq. 3)
Combining (Eqs. 2 and 3), $(1 + s)v_{r2} = v_2 = 1.5v_1$
Substituting (Eq. 1), $(1 + s)v_{r2} = 1.5(1 + s)v_{r1}$, thus $v_{r2} = 1.5v_{r1}$
$v_{r2} = 1.5(31.42) =$ **47.1 m/min**

(b) $25v_o = 19v_1$
$v_1 = 25(26)/19 = 34.2$ m/min
(Eq. 1): $(1 + s)v_{r1} = v_1$
$(1 + s)(31.4) = 34.2$
$(1 + s) = 34.2/31.4 = 1.089$
$\boldsymbol{s = 0.089}$

(c) $v_1 =$ **34.2 m/min,** previously calculated in (b)
$v_2 = 1.5v_1 = 1.5(34.2) =$ **51.3 m/min**

19.6 A continuous hot rolling mill has eight stands. The dimensions of the starting slab are: thickness = 3.0 in, width = 15.0 in, and length = 10 ft. The final thickness is to be 0.3 in. Roll diameter at each stand = 36 in, and rotational speed at stand number 1 = 30 rev/min. It is observed that the speed of the slab entering stand 1 = 240 ft/min. Assume that no widening of the slab occurs during the rolling sequence. Percent reduction in thickness is to be equal at all stands, and it is assumed that the forward slip will be equal at each stand. Determine (a) percent reduction at each stand, (b) rotational speed of the rolls at stands 2 through 8, and (c) forward slip. (d) What is the draft at stands 1 and 8? (e) What is the length and exit speed of the final strip exiting stand 8?

Solution: (a) To reduce from $t_o = 3.0$ in to $t_f = 0.3$ in over 8 stands, $3.0(1 - x)^8 = 0.3$
$(1 - x)^8 = 0.3/3.0 = 0.10$
$(1 - x) = (0.10)^{1/8} = 0.74989$
$x = 1 - 0.74989 =$ ***r* = 0.2501 = 25.01% at each stand.**

(b) Forward slip $s = (v_f - v_r)/v_r$
$sv_r = v_f - v_r$
$(1 + s)v_r = v_f$
At stand 1: $(1 + s)v_{r1} = v_1$, where v_{r1} = roll speed, v_1 = exit speed of slab.
At stand 2: $(1 + s)v_{r2} = v_2$, where v_{r2} = roll speed, v_2 = exit speed of slab.
Etc.
At stand 8: $(1 + s)v_{r8} = v_8$, where v_{r8} = roll speed, v_8 = exit speed of slab.
By constant volume, $t_ow_ov_o = t_1w_1v_1 = t_2w_2v_2 = . . . = t_8w_8v_8$
Since there is no change in width, $w_o = w_1 = w_2 = . . . w_8$
Therefore, $t_ov_o = t_1v_1 = t_2v_2 = . . . = t_8v_8$
$t_o = 3.0$,
$3v_o = 3(1 - r)v_1 = 3(1 - r)^2v_2 = . . . 3(1 - r)^8v_8$, where $r = 0.2501$ as determined in part (a).
Since s is a constant, $v_{r1} : v_{r2} : . . . : v_{r8} = v_1 : v_2 : . . . : v_8$
Given that $N_{r1} = 30$ rev/min, $v_{r1} = \pi DN_{r1} = (2\pi \text{ x } 18/12)(30) = 282.78$ ft/min
In general $N_r = (30/282.78) = 0.10609v_r$
$N_{r2} = 0.10609 \text{ x } 282.78/(1-r) = 0.10609 \text{ x } 282.78/(1-0.2501) =$ **40 rev/min**
$N_{r3} = 0.10609 \text{ x } 282.78/(1-r)^2 =$ **53.3 rev/min**
$N_{r4} = 0.10609 \text{ x } 282.78/(1-r)^3 =$ **71.1 rev/min**
$N_{r5} = 0.10609 \text{ x } 282.78/(1-r)^4 =$ **94.9 rev/min**

N_{r6} = 0.10609 x 282.78/(1-r)^5 = **126.9.3 rev/min**
N_{r7} = 0.10609 x 282.78/(1-r)^6 = **168.5 rev/min**
N_{r8} = 0.10609 x 282.78/(1-r)^7 = **224.9 rev/min**

(c) Given v_o = 240 ft/min
v_1 = 240/(1-r) = 240/0.74989 = 320 ft/min
v_2 = 320/0.74989 = 426.8 ft/min
From equations for forward slip, (1 + s)v_{r1} = v_1
(1 + s)(282.78) = 320
(1 + s) = 320/282.78 = 1.132 **s = 0.132**
Check with stand 2: given v_2 = 426.8 ft/min from above
N_{r2} = 0.10609v_{r2}
Rearranging, v_{r2} = N_{r2}/0.10609 = 9.426N_{r2} = 0.426(40) = 377.04 ft/min
(1 + s)(377.04) = 426.8
(1 + s) = 426.8/377.14 = 1.132 s = 0.132, as before

(d) Draft at stand 1 d_1 = 3.0(0.2501) = **0.7503 in**
Draft at stand 8 d_8 = 3.0(1 - 0.2501)^7(0.2501) = **0.10006 in**

(e) Length of final strip L_f = L_8
$t_o w_o L_o = t_8 w_8 L_8$
Given that $w_o = w_8$, $t_o L_o = t_8 L_8$
3.0(10 ft) = 0.3L_8 $\boldsymbol{L_8}$ **= 100 ft**
$t_o w_o v_o = t_8 w_8 v_8$
$t_o v_o = t_8 v_8$
v_8 = 240(3/0.3) = **2400 ft/min**

19.7 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 mm,
Contact length L = (500 x 5)$^{.5}$ = 50 mm
True strain ε = ln(25/20) = ln 1.25 = 0.223
$\bar{Y}_f$ = 240(0.223)$^{0.20}$/1.20 = 148.1 MPa
Rolling force F = 148.1(250)(50) = **1,851,829 N**

(b) Torque T = 0.5(1,851,829)(50 x 10^{-3}) = **46,296 N-m**

(c) N = (30 m/min)/(2π x 0.500) = 9.55 rev/min = 0.159 rev/s
Power P = 2π(0.159)(1,851,829)(50 x 10^{-3}) = 92,591 N-m/s = **92,591 W**

19.8 Solve Problem 19.7 using a roll radius = 250 mm.

Solution: (a) Draft d = 25 - 20 = 5 mm,
Contact length L = (250 x 5)$^{.5}$ = 35.35 mm
True strain ε = ln(25/20) = ln 1.25 = 0.223
$\bar{Y}_f$ = 240(0.223)$^{0.20}$/1.20 = 148.1 MPa
Rolling force F = 148.1(250)(35.35) = **1,311,095 N**

(b) Torque T = 0.5(1,311,095)(35.35 x 10^{-3}) = **23,174 N-m**

(c) N = (30 m/min)/(2π x 0.250) = 19.1 rev/min = 0.318 rev/s
Power P = 2π(0.318)(1,311,095)(35.35 x 10^{-3}) = 92,604 N-m/s = **92,604 W**

Note that the force and torque are reduced as roll radius is reduced, but that the power remains the same (within calculation error) as in the previous problem.

19.9 Solve Problem 19.7, only assume a cluster mill with working rolls of radius = 50 mm. Compare the results with the previous two problems, and note the important effect of roll radius on force, torque and power.

Solution: (a) Draft d = 25 - 20 = 5 mm,
Contact length $L = (50 \times 5)^{.5} = 15.81$ mm
True strain $\varepsilon = \ln(25/20) = \ln 1.25 = 0.223$
$\bar{Y}_f = 240(0.223)^{0.20}/1.20 = 148.1$ MPa
Rolling force F = 148.1(250)(15.81) = **585,417 N**

(b) Torque $T = 0.5(585{,}417)(15.81 \times 10^{-3})$ = **4,628 N-m**

(c) N = (30 m/min)/(2π x 0.050) = 95.5 rev/min = 1.592 rev/s
Power $P = 2\pi(1.592)(585{,}417)(15.81 \times 10^{-3})$ = 92,554 N-m/s = **92,554 W**

Note that this is the same power value (within calculation error) as in Problems 19.7 and 19.8. In fact, power would probably increase because of lower mechanical efficiency in the cluster type rolling mill.

19.10 A 4.50-in-thick slab that is 9 in wide and 24 in long is to be reduced in a single pass in a two-high rolling mill to a thickness of 3.87 in. The roll rotates at a speed of 5.50 rev/min and has a radius of 17.0 in. The work material has a strength coefficient = 30,000 lb/in^2 and a strain hardening exponent = 0.15. Determine (a) roll force, (b) roll torque, and (c) power required to accomplish this operation.

Solution: (a) Draft d = 4.50 – 3.87 = 0.63 in,
Contact length $L = (17.0 \times 0.63)^{0.5} = 3.27$ in
True strain $\varepsilon = \ln(4.5/3.87) = \ln 1.16 = 0.1508$
$\bar{Y}_f = 30{,}000(0.1508)^{0.15}/1.15 = 19{,}642$ lb/in^2
Rolling force $F = \bar{Y}_f wL$ = 16,414(9.0)(3.27) = **483,000 lb**

(b) Torque $T = 0.5FL$ = 0.5(483000)(3.27) = **789,700 in-lb.**

(c) N = 5.50 rev/min
Power P = 2π(5.50)(483000)(3.27) = 54,580,500 in-lb/min
HP = (54,580,500 in-lb/min)/(396,000) = **138 hp**

19.11 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 strength coefficient = 0.22. Determine (a) roll force, (b) roll torque, and (c) power required for this operation.

Solution: (a) Draft d = 20 - 18 = 2.0 mm,
Contact length $L = (250 \times 2)^{.5} = 11.18$ mm = 0.0112 m
True strain $\varepsilon = \ln(20/18) = \ln 1.111 = 0.1054$
$\bar{Y}_f = 600(0.1054)^{0.22}/1.22 = 300$ MPa
Rolling force F = 300(0.0112)(0.2) = **0.672 MN = 672,000 N**

(b) Torque T = 0.5(672,000)(0.0112) **= 3,720 N-m**

(c) Given that N = 12 rev/min
Power P = 2π(12/60)(672,000)(0.0112) = **37,697 W**

19.12 A hot rolling mill has rolls of diameter = 24 in. It can exert a maximum force = 400,000 lb. The mill has a 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/in^2 and a strain hardening exponent = zero. Determine (a) maximum possible draft, (b) associated true strain, and (c) maximum speed of the rolls for the operation.

Solution: (a) Assumption: maximum possible draft is determined by the force capability of the rolling mill and not by coefficient of friction between the rolls and the work.
Draft $d = 1.5 - t_f$
Contact length $L = (12\text{d})^{0.5}$
$\bar{Y}_f = 20{,}000(\varepsilon)^0/1.0 = 20{,}000$ lb/in^2
Force $F = 20{,}000(10)\,(12d)^{0.5} = 400{,}000$ (the limiting force of the rolling mill)
$(12d)^{0.5} = 400{,}000/200{,}000 = 2.0$
$12\,d = 2.0^2 = 4$
$\boldsymbol{d = 4/12 = 0.333}$ **in**

(b) True strain $\varepsilon = \ln(1.5/t_f)$
$t_f = t_o - d = 1.5 - 0.333 = 1.167$ in
$\varepsilon = \ln(1.5/1.167) = \ln 1.285 = \mathbf{0.251}$

(c) Given maximum possible power HP = 100 hp = 100 x 396000 (in-lb/min)/hp = 39,600,000 in-lb/min
Contact length $L = (12 \times 0.333)^{0.5} = 2.0$ in
$P = 2\pi N(400{,}000)(2.0) = 5{,}026{,}548\text{N}$ in-lb/min
$5{,}026{,}548N = 39{,}600{,}000$
$N = 7.88$ rev/min
$v_r = 2\pi RN = 2\pi(12/12)(7.88) =$ **49.5 ft/min**

19.13 Solve Problem 19.12 except that the operation is warm rolling and the strain-hardening exponent is 0.18. Assume the strength coefficient remains at 20,000 lb/in^2.

Solution: (a) Assumption (same as in previous problem): maximum possible draft is determined by the force capability of the rolling mill and not by coefficient of friction between the rolls and the work.
Draft $d = 1.5 - t_f$
Contact length $L = (12d)^{0.5}$
$\varepsilon = \ln(1.5/t_f)$
$\bar{Y}_f = 20{,}000(\varepsilon)^{0.18}/1.18 = 16{,}949\varepsilon^{.18}$
$F = \bar{Y}_f\,(10)(12d)^{0.5} = 34.641\,\bar{Y}_f\,(d)^{0.5} = 400{,}000$ (as given)
$\bar{Y}_f\,(d)^{0.5} = 400{,}000/34.641 = 11{,}547$
Now use trial-and-error to values of $\bar{Y}_f$ and d that fit this equation.
Try $d = 0.3$ in, $t_f = 1.5 - 0.3 = 1.2$ in
$\varepsilon = \ln(1.5/1.2) = \ln 1.25 = 0.223$
$\bar{Y}_f = 16{,}949(0.223)^{.18} = 13{,}134$ lb/in^2.
$(d)^{0.5} = 11{,}547/13{,}134 = 0.8791$
$d = 0.773$, which does not equal the initial trial value of $d = 0.3$

Try d = 0.5 in, $t_f = 1.5 - 0.5 = 1.0$ in
$\varepsilon = \ln(1.5/1.0) = \ln 1.50 = 0.4055$
$\bar{Y}_f = 16{,}949(0.4055)^{.18} = 14{,}538$ lb/in^2.
$(d)^{0.5} = 11{,}547/14{,}538 = 0.7942$
$d = 0.631$, which does not equal the trial value of $d = 0.5$

Try d = 0.6 in, t_f = 1.5 - 0.6= 0.9 in
ε = ln(1.5/0.9) = 0.5108
$\bar{Y}_f$ = 16,949(0.5108)$^{.18}$ = 15,120 lb/in^2.
$(d)^{0.5}$ = 11,547/15,120 = 0.7637
d = 0.583, which is too much compared to d = 0.6

Try d = 0.58 in, t_f = 1.5 - 0.58 = 0.92 in
ε = ln(1.5/0.92) = ln 1.579 = 0.489
$\bar{Y}_f$ = 16,949(0.489)$^{.18}$ = 15,007 lb/in^2.
$(d)^{0.5}$ = 11,547/15,007 = 0.769
d = 0.592, which is close but still above the trial value of d = 0.55

Try d = 0.585 in, t_f = 1.50 - 0.585 = 0.915 in
ε = ln(1.5/0.915) = 0.494
$\bar{Y}_f$ = 16,949(0.494)$^{.18}$ = 15,036 lb/in^2.
$(d)^{0.5}$ = 11,547/15,036 = 0.768
d = 0.590, which is close but still above the trial value of d = 0.585.

Try d = 0.588 in, t_f = 1.50 - 0.588 = 0.912 in
ε = ln(1.5/0.912) = 0.498
$\bar{Y}_f$ = 16,949(0.498)$^{.18}$ = 15,053 lb/in^2.
$(d)^{0.5}$ = 11,547/15,053 = 0.767
d = 0.588, which is almost the same as the trial value of ***d* = 0.588.**

(b) True strain ε = ln(1.5/0.912) = **0.498**

(c) Given maximum possible power HP = 100 hp = 100 x 396000 (in-lb/min)/hp
= 39,600,000 in-lb/min
Contact length $L = (12 \times 0.588)^{0.5}$ = 2.66 in
$P = 2\pi N$(400,000)(2.66) = 6,685,000N in-lb/min
6,486,000N = 39,600,000
N = 5.92 rev/min
$v_r = 2\pi RN = 2\pi$(12/12)(5.92) = **37.2 ft/min**

Forging

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

(b) Given h = 35, ε = ln(40/35) = ln 1.143 = 0.1335
$Y_f = 600(0.1335)^{0.12}$ = 471.2 MPa
V = 63,617 mm^3 from part (a) above.
At h = 35, $A = V/h$ = 63617/35 = 1818 mm^2

Corresponding D = 48.1 mm (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 N**

(c) Given h = 30, $\varepsilon = \ln(40/30) = \ln 1.333 = 0.2877$
$Y_f = 600(0.2877)^{0.12} = 516.7$ 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 $A = \pi D^2/4$)
$K_f = 1 + 0.4(0.2)(51.96)/30 = 1.138$
$F = 1.138(516.7)(2120.6) =$ **1,247,536 N**

(d) Given h = 25, $\varepsilon = \ln(40/25) = \ln 1.6 = 0.4700$
$Y_f = 600(0.470)^{0.12} = 548.0$ 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 $A = \pi D^2/4$)
$K_f = 1 + 0.4(0.2)(56.9)/25 = 1.182$
$F = 1.182(548.0)(2545) =$ **1,649,000 N**

19.15 A cylindrical workpart with D = 2.5 in and h = 2.5 in is upset forged in an open die to a height = 1.5 in. Coefficient of friction at the die-work interface = 0.10. The work material has a flow curve defined by: K = 40,000 lb/in^2 and n = 0.15. Yield strength = 15,750 lb/in^2. Determine the instantaneous force in the operation (a) just as the yield point is reached (yield at strain = 0.002), (b) at height h = 2.3 in, (c) h = 2.1 in, (d) h = 1.9 in, (e) h = 1.7 in, and (f) h = 1.5 in. Use of a spreadsheet calculator is recommended.

Solution: (a) $V = \pi D^2L/4 = \pi(2.5)^2(2.5)/4 = 12.273$ in^3
Given $\varepsilon = 0.002$, $Y_f = 40{,}000(0.002)^{0.15} = 15{,}748$ lb/in^2 and $h = 2.5 - 2.5(0.002) = 2.495$
$A = V/h = 12.273/2.495 = 4.92$ in^2
$K_f = 1 + 0.4(0.1)(2.5)/2.495 = 1.04$
$F = 1.04(15{,}748)(4.92) =$ **80,579 lb**

(b) Given h = 2.3, $\varepsilon = \ln(2.5/2.3) = \ln 1.087 = 0.0834$
$Y_f = 40{,}000(0.0834)^{0.15} = 27{,}556$ lb/in^2
V = 12.273 in^3 from part (a) above.
At h = 2.3, $A = V/h$ = 12.273/2.3 = 5.34 in^2
Corresponding D = 2.61 (from $A = \pi D^2/4$)
$K_f = 1 + 0.4(0.1)(2.61)/2.3 = 1.045$
$F = 1.045(27{,}556)(5.34) =$ **153,822 lb**

(c) Given h = 2.1, $\varepsilon = \ln(2.5/2.1) = \ln 1.191 = 0.1744$
$Y_f = 40{,}000(0.1744)^{0.15} = 30{,}780$ lb/in^2
V = 12.273 in^3 from part (a) above.
At h = 2.1, $A = V/h$ = 12.273/2.1 = 5.84 in^2
Corresponding D = 2.73 (from $A = \pi D^2/4$)
$K_f = 1 + 0.4(0.1)(2.73)/2.1 = 1.052$
$F = 1.052(30{,}780)(5.84) =$ **189,236 lb**

(d) Given h = 1.9, $\varepsilon = \ln(2.5/1.9) = \ln 1.316 = 0.274$
$Y_f = 40{,}000(0.274)^{0.15} = 32{,}948$ lb/in^2
V = 12.273 in^3 from part (a) above.
At h = 1.9, $A = V/h$ = 12.273/1.9 = 6.46 in^2
Corresponding D = 2.87 (from $A = \pi D^2/4$)

$K_f = 1 + 0.4(0.1)(2.87)/1.9 = 1.060$
$F = 1.060(32{,}948)(6.46) =$ **225,695 lb**

(e) Given $h = 1.7$, $\varepsilon = \ln(2.5/1.7) = \ln 1.471 = 0.386$
$Y_f = 40{,}000(0.386)^{0.15} = 34{,}673$ lb/in^2
$V = 12.273$ in^3 from part (a) above.
At $h = 1.7$, $A = V/h = 12.273/1.7 = 7.22$ in^2
Corresponding $D = 3.03$ (from $A = \pi D^2/4$)
$K_f = 1 + 0.4(0.1)(3.03)/1.7 = 1.071$
$F = 1.071(34{,}673)(7.22) =$ **268,176 lb**

(f) Given $h = 1.5$, $\varepsilon = \ln(2.5/1.5) = \ln 1.667 = 0.511$
$Y_f = 40{,}000(0.511)^{0.15} = 36{,}166$ lb/in^2
$V = 12.273$ in^3 from part (a) above.
At $h = 1.5$, $A = V/h = 12.273/1.5 = 8.182$ in^2
Corresponding $D = 3.23$ (from $A = \pi D^2/4$)
$K_f = 1 + 0.4(0.1)(3.23)/1.5 = 1.086$
$F = 1.086(36{,}166)(8.182) =$ **321,379 lb**

19.16 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. Coefficient of friction at 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. Determine the plot of force vs. work height. Use of a spreadsheet calculator is recommended.

Solution: Volume of cylinder $V = \pi D^2 L/4 = \pi(2.5)^2(4.0)/4 = 19.635$ in^3
We will compute the force F at selected values of height h: h = (a) 4.0, (b) 3.75, (c) 3.5, (d) 3.25, (e) 3.0, (f) 2.75, and (g) 2.5. These values can be used to develop the plot. The shape of the plot will be similar to Figure 21.13 in the text.

At ***h* = 4.0**, we assume yielding has just occurred and the height has not changed significantly. Use $\varepsilon = 0.002$ (the approximate yield point of metal).
At $\varepsilon = 0.002$, $Y_f = 25{,}000(0.002)^{0.22} = 6{,}370$ lb/in^2
Adjusting the height for this strain, $h = 4.0 - 4.0(0.002) = 3.992$
$A = V/h = 19.635/3.992 = 4.92$ in^2
$K_f = 1 + 0.4(0.1)(2.5)/3.992 = 1.025$
$F = 1.025(6{,}370)(4.92) =$ **32,125 lb**

At ***h* = 3.75**, $\varepsilon = \ln(4.0/3.75) = \ln 1.0667 = 0.0645$
$Y_f = 25{,}000(0.0645)^{0.22} = 13{,}680$ lb/in^2
$V = 19.635$ in^3 calculated above.
At $h = 3.75$, $A = V/h = 19.635/3.75 = 5.236$ in^2
Corresponding $D = 2.582$ (from $A = \pi D^2/4$)
$K_f = 1 + 0.4(0.1)(2.582)/3.75 = 1.028$
$F = 1.028(13{,}680)(5.236) =$ **73,601 lb**

At ***h* = 3.5**, $\varepsilon = \ln(4.0/3.5) = \ln 1.143 = 0.1335$
$Y_f = 25{,}000(0.1335)^{0.22} = 16{,}053$ lb/in^2
At $h = 3.5$, $A = V/h = 19.635/3.5 = 5.61$ in^2
Corresponding $D = 2.673$ (from $A = \pi D^2/4$)
$K_f = 1 + 0.4(0.1)(2.673)/3.5 = 1.031$
$F = 1.031(16{,}053)(5.61) =$ **92,808 lb**

At ***h* = 3.25**, $\varepsilon = \ln(4.0/3.25) = \ln 1.231 = 0.2076$
$Y_f = 25{,}000(0.2076)^{0.22} = 17{,}691$ lb/in^2
At $h = 3.25$, $A = V/h = 19.635/3.25 = 6.042$ in^2

Corresponding $D = 2.774$ (from $A = \pi D^2/4$)
$K_f = 1 + 0.4(0.1)(2.774)/3.25 = 1.034$
$F = 1.034(17{,}691)(6.042) =$ **110,538 lb**

At ***h* = 3.0**, $\varepsilon = \ln(4.0/3.0) = \ln 1.333 = 0.2874$
$Y_f = 25{,}000(0.2874)^{0.22} = 19{,}006$ lb/in^2
At $h = 3.0$, $A = V/h = 19.635/3.0 = 6.545$ in^2
Corresponding $D = 2.887$ (from $A = \pi D^2/4$)
$K_f = 1 + 0.4(0.1)(2.887)/3.0 = 1.038$
$F = 1.038(19{,}006)(6.545) =$ **129,182 lb**

At ***h* =2.75**, $\varepsilon = \ln(4.0/2.75) = \ln 1.4545 = 0.3747$
$Y_f = 25{,}000(0.3747)^{0.22} = 20{,}144$ lb/in^2
$V = 19.635$ in^3 calculated above.
At $h = 2.75$, $A = V/h = 19.635/2.75 = 7.140$ in^2
Corresponding $D = 3.015$ (from $A = \pi D^2/4$)
$K_f = 1 + 0.4(0.1)(3.015)/2.75 = 1.044$
$F = 1.044(20{,}144)(7.140) =$ **150,136 lb**

19.17 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 $V = \pi D_f^2 h_f/4 = \pi(9.5)^2(1.6)/4 = 113.4$ mm^3.
$A_o = \pi D_o^2/4 = \pi(4.75)^2/4 = 19.6$ mm^2
$h_o = V/A_o = 113.4/19.6 =$ **5.78 mm**

(b) $\varepsilon = \ln(5.78/1.6) = \ln 3.61 = 1.2837$
$Y_f = 600(1.2837)^{0.22} = 634$ MPa
$A_f = \pi(9.5)^2/4 = 70.9$ mm^2
$K_f = 1 + 0.4(0.14)(9.5/1.6) = 1.33$
$F = 1.33(634)(70.9) =$ **59,886 N**

19.18 Obtain a large common nail (flat head). Measure the head diameter and thickness, as well as the diameter of the nail shank. (a) What stock length must project out of the die in order to provide sufficient material to produce the nail? (b) Using appropriate values for strength coefficient and strain hardening exponent for the metal out of which the nail is made (Table 3.4), compute the maximum force in the heading operation to form the head.

Solution: Student exercise. Calculations similar to those in the preceding problem for the data developed by the student.

19.19 A hot upset forging operation is performed in an open die. The initial size of the workpart is: $D_o = 25$ mm, and $h_o = 50$ mm. The part is upset to a 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) $\varepsilon = \ln(50/12.5) = \ln 4 = 1.3863$

$Y_f = 85(1.3863)^0 = 85$ MPa
Force is maximum at largest area value, $A_f = 1963.5$ mm^2
$D = (4 \times 1963.5/\pi)^{0.5} = 50$ mm
$K_f = 1 + 0.4(0.4)(50/12.5) = 1.64$
$F = 1.64(85)(1963.5) =$ **273,712 N**

19.20 A hydraulic forging press is capable of exerting a maximum force = 1,000,000 N. A cylindrical workpart is to be cold upset forged. The starting part has diameter = 30 mm and height = 30 mm. The flow curve of the metal is defined by $K = 400$ MPa and $n = 0.2$. Determine the maximum reduction in height to which the part can be compressed with this forging press, if the coefficient of friction = 0.1. Use of a spreadsheet calculator is recommended.

Solution: Volume of work $V = \pi D_o^2 h_o/4 = \pi(30)^2(30)/4 = 21{,}206$ mm^3.
Final area $A_f = 21{,}206/h_f$
$\varepsilon = \ln(30/h_f)$
$Y_f = 400\varepsilon^{0.2} = 400(\ln 30/h_f)^{0.2})$
$K_f = 1 + 0.4\mu(D_f/h_f) = 1 + 0.4(0.1)(D_f/h_f)$
Forging force $F = K_f Y_f A_f = (1 + 0.04D_f/h_f)(\ 400(\ln 30/h_f)^{0.2})(\ 21{,}206/h_f)$

Requires trial and error solution to find the value of $\boldsymbol{h_f}$ that will match the force of **1,000,000 N**.
(1) Try $h_f = 20$ mm
$A_f = 21{,}206/20 = 1060.3$ mm^2
$\varepsilon = \ln(30/20) = \ln 1.5 = 0.405$
$Y_f = 400(0.405)^{0.2} = 333.9$ MPa
$D_f = (4 \times 1060.3/\pi)^{0.5} = 36.7$ mm
$K_f = 1 + 0.04(36.7/20) = 1.073$
$F = 1.073(333.9)(1060.3) =$ **380,050 N**
Too low. Try a smaller value of h_f to increase F.

(2) Try $h_f = 10$ mm.
$A_f = 21{,}206/10 = 2120.6$ mm^2
$\varepsilon = \ln(30/10) = \ln 3.0 = 1.099$
$Y_f = 400(1.099)^{0.2} = 407.6$ MPa
$D_f = (4 \times 2120.6/\pi)^{0.5} = 51.96$ mm
$K_f = 1 + 0.04(51.96/10) = 1.208$
$F = 1.208(407.6)(2120.6) =$ **1,043,998 N**
Slightly high. Need to try a value of h_f between 10 and 20, closer to 10.

(3) Try $h_f = 11$ mm
$A_f = 21{,}206/11 = 1927.8$ mm^2
$\varepsilon = \ln(30/11) = \ln 2.7273 = 1.003$
$Y_f = 400(1.003)^{0.2} = 400.3$ MPa
$D_f = (4 \times 1927.8/\pi)^{0.5} = 49.54$ mm
$K_f = 1 + 0.04(51.12/11) = 1.18$
$F = 1.18(400.3)(1927.8) =$ **910,653 N**

(4) By linear interpolation, try $h_f = 10 + (44/133) = 10.33$ mm
$A_f = 21{,}206/10.33 = 2052.8$ mm^2
$\varepsilon = \ln(30/10.33) = \ln 2.9042 = 1.066$
$Y_f = 400(1.066)^{0.2} = 405.16$ MPa
$D_f = (4 \times 2052.8/\pi)^{0.5} = 51.12$ mm
$K_f = 1 + 0.04(51.12/10.33) = 1.198$
$F = 1.198(405.16)(2052.8) =$ **996,364 N**

(5) By further linear interpolation, try $h_f = 10 + (44/48)(0.33) = 10.30$
$A_f = 21{,}206/10.30 = 2058.8$ mm^2
$\varepsilon = \ln(30/10.30) = \ln 2.913 = 1.069$
$Y_f = 400(1.069)^{0.2} = 405.38$ MPa
$D_f = (4 \times 2058.8/\pi)^{0.5} = 51.2$ mm
$K_f = 1 + 0.04(51.2/10.3) = 1.199$
$F = 1.199(405.38)(2058.8) =$ **1,000,553 N**
Close enough! Maximum height reduction = 30.0 - 10.3 = **19.7 mm**

Using a spreadsheet calculator, the author's program (written in Excel) obtained a value of h = 19.69603 mm to achieve a force of 1,000,000 lb within one pound.

19.21 A part is designed to be hot forged in an impression die. The projected area of the part, including flash, is 16 in^2. After trimming, the part has a projected area of 10 in^2. Part geometry is complex. As heated the work material yields at 10,000 lb/in^2, and has no tendency to strain harden. At room temperature, the material yields at 25,000 lb/in^2 Determine the maximum force required to perform the forging operation.

Solution: Since the work material has no tendency to work harden, $n = 0$.
From Table 19.1, choose $K_f = 8.0$.
$F = 8.0(10{,}000)(16) =$ **1,280,000 lb.**

19.22 A connecting rod is designed to be hot forged in an impression die. The projected area of the part is 6,500 mm^2. The design of the die will cause flash to form during forging, so that the area, including flash, will be 9,000 mm^2. The part geometry is considered to be complex. As heated the work material yields at 75 MPa, and has no tendency to strain harden. Determine the maximum force required to perform the operation.

Solution: Since the work material has no tendency to work harden, $n = 0$.
From Table 19.1, choose $K_f = 8.0$.
$F = 8.0(75)(9{,}000) =$ **5,400,000 N.**

Extrusion

19.23 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°. The Johnson equation has $a = 0.8$ and $b = 1.4$, and the flow curve for the work metal has a strength coefficient of 800 MPa and strain hardening exponent of 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) $\overline{Y}_f = 800(1.833)^{0.13}/1.13 = 766.0$ MPa
$p = 766.0(3.366) =$ **2578 MPa**

(e) $A_o = \pi D_o^2/4 = \pi(50)^2/4 = 1963.5$ mm^2
$F = 2578(1963.5) =$ **5,062,000 N**

19.24 A 3.0-in-long cylindrical billet whose diameter = 1.5 in is reduced by indirect extrusion to a diameter = 0.375 in. Die angle = 90°. In the Johnson equation, $a = 0.8$ and $b = 1.5$. In the flow curve for the work metal, K = 75,000 lb/in^2 and $n = 0.25$. Determine (a) extrusion ratio, (b) true strain (homogeneous deformation), (c) extrusion strain, (d) ram pressure, (e) ram force, and (f) power if the ram speed = 20 in/min.

Solution: (a) $r_x = A_o/A_f = D_o^2/D_f^2 = (1.5)^2/(0.375)^2 = 4^2 =$ **16.0**

(b) $\varepsilon = \ln r_x = \ln 16 =$ **2.773**

(c) $\varepsilon_x = a + b \ln r_x = 0.8 + 1.5(2.773) =$ **4.959**

(d) $\overline{Y}_f = 75{,}000(2.773)^{0.25}/1.25 = 77{,}423$ lb/in^2
$p = 77{,}423(4.959) =$ **383,934 lb/in²**

(e) $A_o = \pi D_o^2/4 = \pi(1.5)^2/4 = 1.767$ in^2
$F = (383{,}934)(1.767) =$ **678,411 lb.**

(f) $P = 678{,}411(20) =$ **13,568,228 in-lb/min**
$HP = 13{,}568{,}228/396{,}000 =$ **34.26 hp**

19.25 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 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 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) $\overline{Y}_f = 600(1.119)^{0.25}/1.25 = 493.7$ MPa
$A_o = \pi(35)^2/4 = 962.1$ 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 mm to L = 70 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: $R_1 = 0.5D_o = 17.5$ mm and $R_2 = 0.5D_f = 10$ mm, and $h = (R_1 - R_2)/\tan 75 = 7.5/\tan 75 = 2.01$ mm
Frustum volume $V = 0.333\pi h(R_1^2 + R_1R_2 + R_2^2) = 0.333\pi(2.01)(17.5^2 + 10 \text{ x } 17.5 + 10^2) = 1223.4$ mm^3. Compare this with the volume of the portion of the cylindrical billet between L = 75 mm and L = 70 mm.
$V = \pi D_o^2\, h/4 = 0.25\pi(35)^2(75 - 70) = 4810.6$ 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 mm**: pressure p = 493.7(2.367 + 2 x 70/35) = **3143.4 MPa**
Force F = 3143.4(962.1) = **3,024, 321 N**
***L* = 60 mm**: pressure p = 493.7(2.367 + 2 x 60/35) = **2861.3 MPa**
Force F = 2861.3(962.1) = **2,752,890 N**
***L* = 50 mm**: pressure p = 493.7(2.367 + 2 x 50/35) = **2579.2 MPa**
Force F = 2579.2(962.1) = **2,481,458 N**
***L* = 40 mm**: pressure p = 493.7(2.367 + 2 x 40/35) = **2297.1 MPa**
Force F = 2297.1(962.1) = **2,210,027 N**
***L* = 30 mm**: pressure p = 493.7(2.367 + 2 x 30/35) = **2014.9 MPa**
Force F = 2014.9(962.1) = **1,938,595 N**
***L* = 20 mm**: pressure p = 493.7(2.367 + 2 x 20/35) = **1732.8 MPa**
Force F = 1732.8(962.1) = **1,667,164 N**
***L* = 10 mm**: pressure p = 493.7(2.367 + 2 x 10/35) = **1450.7 MPa**
Force F = 1450.7(962.1) = **1,395,732 N**

19.26 A 2.0-in-long billet with diameter = 1.25 in is direct extruded to a diameter of 0.50 in. The extrusion die angle = 90°. For the work metal, K = 45,000 lb/in^2, and n = 0.20. In the Johnson extrusion strain equation, a = 0.8 and b = 1.5. Determine (a) extrusion ratio, (b) true strain (homogeneous deformation), (c) extrusion strain, and (d) ram pressure at L = 2.0, 1.5, 1.0, 0.5 and zero in. Use of a spreadsheet calculator is recommended for part (d).

Solution: (a) $r_x = A_o/A_f = D_o^2/D_f^2 = (1.25)^2/(0.5)^2 =$ **6.25**

(b) $\varepsilon = \ln r_x = \ln 6.25 =$ **1.8326**

(c) $\varepsilon_x = a + b \ln r_x = 0.8 + 1.5(1.8326) =$ **3.549**

(d) $\overline{Y}_f = 45{,}000(1.8326)^{0.20}/1.20 = 42{,}330$ lb/in^2

$A_o = \pi(1.25)^2/4 = 1.227$ in^2

Unlike the previous problem, the die angle α = 90°, so metal is forced through the die opening as soon as the billet starts to move forward in the chamber.

***L* = 2.0 in**: pressure p = 42,330(3.549 + 2 x 2.0/1.25) = **285,677 lb/in^2**
Force F = 285,677(1.227) = **350,579 lb**
***L* = 1.5 in**: pressure p = 42,330(3.549 + 2 x 1.5/1.25) = **251,813 lb/in^2**
Force F = 251,813(1.227) = **309,022 lb**
***L* = 1.0 in**: pressure p = 42,330(3.549 + 2 x 1.0/1.25) = **217,950 lb/in^2**
Force F = 217,950(1.227) = **267,465 lb**
***L* = 0.5 in**: pressure p = 42,330(3.549 + 2 x 0.5/1.25) = **184,086 lb/in^2**
Force F = 184,086(1.227) = **225,908 lb**
***L* = 0.0 in**: pressure p = 42,330(3.549 + 2 x 0.0/1.25) = **150,229 lb/in^2**
Force F = 150,229(1.227) = **184,351 lb**
These last values for L = 0 are not possible because of the increase in pressure and force due to the butt remaining in the extruder container at the end of the operation.

19.27 A direct extrusion operation is performed on a cylindrical billet with an initial diameter of 2.0 in and an initial length of 4.0 in. The die angle = 60° and orifice diameter is 0.50 in. In the Johnson extrusion strain equation, a = 0.8 and b = 1.5. The operation is carried out hot and the hot metal yields at 13,000 lb/in^2 and does not strain harden when hot. (a) What is the extrusion ratio? (b) Determine the ram position at the point when the metal has been compressed into the cone of the die and starts to extrude through the die opening. (c) What is the ram pressure corresponding to this position? (d) Also determine the length of the final part if the ram stops its forward movement at the start of the die cone.

Solution: (a) $r_x = A_o/A_f = D_o^2/D_f^2 = (2.0)^2/(0.5)^2 =$ **16.0**

(b) The portion of the billet that is compressed into the die cone forms a frustum with $R_1 = 0.5D_o$ = 1.0 in and $R_2 = 0.5D_f$ = 0.25 in. The height of the frustum h = $(R_1 - R_2)$/tan 65 = (1.0 - 0.25)/tan 60 = 0.433 in. The volume of the frustum is

$V = 0.333\pi h(R_1^2 + R_1R_2 + R_2^2) = 0.333\pi(0.433)(1.0^2 + 1.0 \times 0.25 + 0.25^2) = 0.595$ in^3

The billet has advanced a certain distance by the time this frustum is completely filled and extrusion through the die opening is therefore initiated. The volume of billet compressed forward to fill the frustum is given by:

$V = \pi R_1^2(L_o - L_1) = \pi(1.0)^2(L_o - L_1)$

Setting this equal to the volume of the frustum, we have

$\pi(L_o - L_1) = 0.595$ in^3

$(L_o - L_1) = 0.595/\pi = 0.189$ in

$L_1 = 4.0 - 0.189 =$ **3.811 in**

(c) $\varepsilon = \ln r_x = \ln 16 = 2.7726$

$\varepsilon_x = a + b \ln r_x = 0.8 + 1.5(2.7726) = 4.959$
$\bar{Y}_f = 13{,}000(2.7726)^0/1.0 = 13{,}000$ lb/in^2
$p = 13{,}000(4.959 + 2 \text{ x } 3.811/2.0) =$ **114,000 lb/in^2**

(d) Length of extruded portion of billet = 3.811 in. With a reduction $r_x = 16$, the final part length, excluding the cone shaped butt remaining in the die is $L = 3.811(16) =$ **60.97 in.**

19.28 An indirect extrusion process starts with an aluminum billet with diameter = 2.0 in and length = 3.0 in. Final cross section after extrusion is a square with 1.0 in on a side. The die angle = 90°. The operation is performed cold and the strength coefficient of the metal $K = 26{,}000$ lb/in^2 and strain-hardening exponent $n = 0.20$. In the Johnson extrusion strain equation, $a = 0.8$ and $b = 1.2$. (a) Compute the extrusion ratio, true strain, and extrusion strain. (b) What is the shape factor of the product? (c) If the butt left in the container at the end of the stroke is 0.5 in thick, what is the length of the extruded section? (d) Determine the ram pressure in the process.

Solution: (a) $r_x = A_o/A_f$
$A_o = \pi D_o^2/4 = \pi(2)^2/4 = 3.142$ in^2
$A_f = 1.0 \text{ x } 1.0 = 1.0$ in^2
$r_x = 3.142/1.0 =$ **3.142**
$\varepsilon = \ln 3.142 =$ **1.145**
$\varepsilon_x = 0.8 + 1.3(1.145) =$ **2.174**

(b) To determine the die shape factor we need to determine the perimeter of a circle whose area is equal to that of the extruded cross section, $A = 1.0$ in^2. The radius of the circle is $R = (1.0/\pi)^{0.5} =$ 0.5642 in, $C_c = 2\pi(0.5642) = 3.545$ in
The perimeter of the extruded cross section $C_x = 4(1.0) = 4.0$ in
$K_x = 0.98 + 0.02(4.0/3.545)^{2.25} =$ **1.006**

(c) Given that the butt thickness = 0.5 in
Original volume $V = (3.0)(\pi \text{ x } 2^2/4) = 9.426$ in^3
The final volume consists of two sections: (1) butt, and (2) extrudate. The butt volume $V_1 =$ $(0.5)(\pi 2^2/4) = 1.571$ in^3. The extrudate has a cross-sectional area $A_f = 1.0$ in^2. Its volume $V_2 = LA_f =$ $9.426 - 1.571 = 7.855$ in^3. Thus, length $L = 7.855/1.0 =$ **7.855 in**

(d) $\bar{Y}_f = 26{,}000(1.145)^{0.2}/1.2 = 22{,}261$ lb/in^3
$p = 1.006(22{,}261)(2.174) =$ **48,698 lb/in^2**

19.29 An L-shaped structural section is direct extruded from an aluminum billet in which $L_o = 500$ mm and $D_o = 100$ mm. Dimensions of the cross section are given in Figure P19.29. Die angle = 90°. Determine (a) extrusion ratio, (b) shape factor, and (c) length of the extruded section if the butt remaining in the container at the end of the ram stroke is 25 mm.

Solution: (a) $r_x = A_o/A_f$
$A_o = \pi(100)^2/4 = 7854$ mm^2
$A_f = 2(12 \text{ x } 50) = 1200$ mm^2
$r_x = 7854/1200=$ **6.545**

(b) To determine the die shape factor we need to determine the perimeter of a circle whose area is equal to that of the extruded cross section, $A = 1200$ mm^2. The radius of the circle is $R = (1200/\pi)^{0.5}$ $= 19.54$ mm, $C_c = 2\pi(19.54) = 122.8$ mm.
The perimeter of the extruded cross section $C_x = 62 + 50 + 12 + 38 + 50 + 12 = 224$ mm
$K_x = 0.98 + 0.02(224/122.8)^{2.25} =$ **1.057**

(c) Total original volume $V = 0.25\pi(100)^2(500) = 3{,}926{,}991$ mm^3

The final volume consists of two sections: (1) butt, and (2) extrudate. The butt volume V_1 = $0.25\pi(100)^2(25) = 196{,}350$ mm^3. The extrudate has a cross-sectional area A_f = 1200 mm^2. Its volume $V_2 = LA_f$ = 3,926,991 - 196,350 = 3,730,641 mm^3.
Thus, length L = 3,730,641/1200 = **3108.9 mm = 3.109 m**

19.30 The flow curve parameters for the aluminum alloy of Problem 19.29 are: K = 240 MPa and n = 0.16. If the die angle in this operation = 90°, and the corresponding Johnson strain equation has constants a = 0.8 and b = 1.5, compute the maximum force required to drive the ram forward at the start of extrusion.

Solution: From Problem 19.29, r_x = 5.068
ε = ln 5.068= 1.623
ε_x = 0.8 + 1.5(1.623) = 3.234
$\bar{Y}_f = 240(1.623)^{0.16}/1.16$ = 223.6 MPa
Maximum ram force occurs at beginning of stroke when length is maximum at L = 250 mm
$p = K_x\bar{Y}_f\ (\varepsilon_x + 2L/D_o)$ = 1.057(223.6)(3.234 + 2(250)/88) = 2107.2 MPa
$F = pA_o$ = 2107.2 (6082.1) = **12,816,267 N**

19.31 A cup-shaped part is backward extruded from an aluminum slug that is 50 mm in diameter. The final dimensions of the cup are: OD = 50 mm, ID = 40 mm, height = 100 mm, and thickness of base = 5 mm. Determine (a) extrusion ratio, (b) shape factor, and (c) height of starting slug required to achieve the final dimensions. (d) If the metal has flow curve parameters K = 400 MPa and n = 0.25, and the constants in the Johnson extrusion strain equation are: a = 0.8 and b = 1.5, determine the extrusion force.

Solution: (a) $r_x = A_o/A_f$
$A_o = 0.25\pi(50)^2$ = 1963.75 mm^2
$A_f = 0.25\pi(50^2 - 40^2)$ = 706.86 mm^2
r_x = 1963.75/706.86 = **2.778**

(b) To determine the die shape factor we need to determine the perimeter of a circle whose area is equal to that of the extruded cross section, A = 706.86 mm^2. The radius of the circle is R = $(706.86/\pi)^{0.5}$ = 15 mm, $C_c = 2\pi(15)$ = 94.25 mm.
The perimeter of the extruded cross section $C_x = \pi(50 + 40) = 90\pi$ = 282.74 mm.
$K_x = 0.98 + 0.02(282.74/94.25)^{2.25}$ = **1.217**

(c) Volume of final cup consists of two geometric elements: (1) base and (2) ring.
(1) Base t = 5 mm and D = 50 mm. $V_1 = 0.25\pi(50)^2(5)$ = 9817.5 mm^3
(2) Ring OD = 50 mm, ID = 40 mm, and h = 95 mm.
$V_2 = 0.25\pi(50^2 - 40^2)(95) = 0.25\pi(2500 - 1600)(95)$ = 67,151.5 mm^3
Total $V = V_1 + V_2$ = 9817.5 + 67,151.5 = 76,969 mm^3
Volume of starting slug must be equal to this value V = 76,969 mm^3
$V = 0.25\pi(50)^2(h) = 1963.5h$ = 76,969 mm^3
***h* = 39.2 mm**

(d) ε = ln 2.778 = 1.0218
ε_x = 0.8 + 1.5(1.0218) = 2.33
$\bar{Y}_f = 400(1.0218)^{0.25}/1.25$ = 321.73 MPa
$p = K_x\ \bar{Y}_f\ \varepsilon_x$ = 1.217(321.73)(2.33) = 912.3 MPa
$A_o = 0.25\pi(40)^2$ = 1256.6 mm^2
F = 912.3(1256.6) = **1,146,430 N**

19.32 Determine the shape factor for each of the extrusion die orifice shapes in Figure P19.32.

Solution: (a) A_x = 20 x 60 = 1200 mm, C_x = 2(20 + 60) = 160 mm
$A_o = \pi R^2 = 1200$
$R^2 = 1200/\pi = 381.97$, R = 19.544 mm, $C_c = 2\pi R = 2\pi(19.544)$ = 122.8 mm
$K_x = 0.98 + 0.02(160/122.8)^{2.25}$ = **1.016**

(b) $A_x = \pi R_o^{\,2} - \pi R_i^{\,2} = \pi(25^2 - 22.5^2) = 373.06$ mm^2
$C_x = \pi D_o + \pi D_i = \pi(50 + 45) = 298.45$ mm
$R^2 = 373.06/\pi = 118.75$, R = 10.897 mm, $C_c = 2\pi R = 2\pi(10.897)$ = 68.47 mm
$K_x = 0.98 + 0.02(298.45/68.47)^{2.25}$ = **1.53**

(c) A_x = 2(5)(30) + 5(60 - 10) = 300 + 250 = 550 mm^2
C_x = 30 + 60 + 30 + 5 + 25 + 50 + 25 + 5 = 230 mm
$A_o = \pi R^2 = 550$, $R^2 = 550/\pi = 175.07$, R = 13.23 mm
$C_c = 2\pi R = 2\pi(13.23)$ = 83.14 mm
$K_x = 0.98 + 0.02(230/83.14)^{2.25}$ = **1.177**

(d) A_x = 5(55)(5) + 5(85 - 5x5) = 1675 mm^2
C_x = 2 x 55 + 16 x 25 + 8 x 15 + 10 x 5 = 680 mm
$A_o = \pi R^2 = 1675$, $R^2 = 1675/\pi = 533.17$, R = 23.09 mm
$C_c = 2\pi R = 2\pi(23.09)$ = 145.08 mm
$K_x = 0.98 + 0.02(680/145.08)^{2.25}$ = **1.626**

19.33 A direct extrusion operation produces the cross section shown in Figure P19.32(a) from a brass billet whose diameter = 125 mm and length = 350 mm. The flow curve parameters of the brass are K = 700 MPa and n = 0.35. In the Johnson strain equation, a = 0.7 and b = 1.4. Determine (a) the extrusion ratio, (b) the shape factor, (c) the force required to drive the ram forward during extrusion at the point in the process when the billet length remaining in the container = 300 mm, and (d) the length of the extruded section at the end of the operation if the volume of the butt left in the container is 600,000 mm^3.

Solution: (a) $r_x = A_o/A_f$
$A_o = \pi(125)^2/4$ = 12,272 mm^2
$A_f = A_x$ = 20(60) = 1200 mm^2
r_x = 12272/1200 = **10.23**

(b) To determine the die shape factor we need to determine the perimeter of a circle whose area is equal to that of the extruded cross section, A_f = 1200 mm^2.
The radius of the circle is $R = (1200/\pi)^{0.5}$ = 19.544 mm, $C_c = 2\pi(19.544)$ = 122.8 mm.
The perimeter of the extruded cross section C_x = 2(20 + 60) = 160 mm
$K_x = 0.98 + 0.02(160/122.8)^{2.25}$ = **1.016**

(c) ε = ln 10.23 = 2.325
ε_x = 0.7 + 1.4(2.325) = 3.955
$\bar{Y}_f = 700(2.325)^{0.35}/1.35$ = 696.6 MPa

$p = K_x \bar{Y}_f\, \varepsilon_x$ = 1.016(696.6)(3.955 + 2(300)/125) = 6196.3 MPa
$F = pA_o$ = 6196.3(12,272) = **76,295,200 N**

(d) Total original volume $V = \pi(125)^2(350)/4$ = 4,295,200 mm^3
The final volume consists of two sections: (1) butt, and (2) extrudate.
The butt volume as given V_1 = 600,000 mm^3.
The extrudate has a cross-sectional area A_f = 1200 mm^2.
Its volume $V_2 = LA_f$ = 4,295,200 – 600,000 = 3,695,200 mm^3.
Thus, length L = 3,695,200/1200 = **3079.3 mm = 3.079 m**

19.34 In a direct extrusion operation the cross section shown in Figure P19.32(b) is produced from a copper billet whose diameter = 100 mm and length = 500 mm. In the flow curve for copper, the strength coefficient = 300 MPa and strain hardening exponent = 0.50. In the Johnson strain equation, a = 0.8 and b = 1.5. Determine (a) the extrusion ratio, (b) the shape factor, (c) the force required to drive the ram forward during extrusion at the point in the process when the billet length remaining in the container = 450 mm, and (d) the length of the extruded section at the end of the operation if the volume of the butt left in the container is 350,000 mm^3.

Solution: (a) $r_x = A_o/A_f$
$A_o = \pi(100)^2/4 = 7854$ mm^2
$A_f = A_x = \pi(50)^2/4 - \pi(45)^2/4 = 1963.5 – 1590.4 = 373.1$ mm^2
$r_x = 7854/373.1 =$ **21.05**

(b) To determine the die shape factor we need to determine the perimeter of a circle whose area is equal to that of the extruded cross section, $A_x = 373.1$ mm^2.
The radius of the circle is $R = (373.1/\pi)^{0.5} = 10.9$ mm, $C_c = 2\pi(10.9) = 68.5$ mm.
The perimeter of the extruded cross section $C_x = \pi(50) + \pi(45) = 298.5$ mm
$K_x = 0.98 + 0.02(298.5/68.5)^{2.25} =$ **1.53**

(c) $\varepsilon = \ln 21.05 = 3.047$
$\varepsilon_x = 0.8 + 1.5(3.047) = 5.37$
$\bar{Y}_f = 300(3.047)^{0.50}/1.50 = 349.1$ MPa
$p = K_x \bar{Y}_f\, \varepsilon_x = 1.53(349.1)(5.37 + 2(450)/100) = 7675.3$ MPa
$F = pA_o = 7675.3(7854) =$ **60,282,179 N**

(d) Total original volume $V = \pi(100)^2(500)/4 = 3,926,991$ mm^3
The final volume consists of two sections: (1) butt, and (2) extrudate.
The butt volume as given $V_1 = 350,000$ mm^3.
The extrudate has a cross-sectional area $A_f = 373.1$ mm^2.
Its volume $V_2 = LA_f = 3,926,991 – 350,000 = 3,576,991$ mm^3.
Thus, length $L = 3,576,991/373.1 =$ **9,587.2 mm = 9.587 m**

19.35 A direct extrusion operation produces the cross section shown in Figure P19.32(c) from an aluminum billet whose diameter = 150 mm and length = 500 mm. The flow curve parameters for the aluminum are K = 240 MPa and n = 0.16. In the Johnson strain equation, a = 0.8 and b = 1.2. Determine (a) the extrusion ratio, (b) the shape factor, (c) the force required to drive the ram forward during extrusion at the point in the process when the billet length remaining in the container = 400 mm, and (d) the length of the extruded section at the end of the operation if the volume of the butt left in the container is 600,000 mm^3.

Solution: (a) $r_x = A_o/A_f$
$A_o = \pi(150)^2/4 = 17,671.5$ mm^2
$A_f = A_x = 60(5) + 2(25)(5) = 300 + 250 = 550$ mm^2
$r_x = 17,671.5/550 =$ **32.1**

(b) To determine the die shape factor we need to determine the perimeter of a circle whose area is equal to that of the extruded cross section, $A_x = 550$ mm^2.
$C_x = 30 + 60 + 30 + 5 + 25 + 50 + 25 + 5 = 230$ mm
$A_o = \pi R^2 = 550$, $R^2 = 550/\pi = 175.07$, $R = 13.23$ mm
$C_c = 2\pi R = 2\pi(13.23) = 83.14$ mm
$K_x = 0.98 + 0.02(230/83.14)^{2.25} =$ **1.177**

(c) $\varepsilon = \ln 32.1 = 3.47$
$\varepsilon_x = 0.8 + 1.2(3.47) = 4.96$

$\overline{Y}_f = 240(3.47)^{0.16}/1.16 = 252.5$ MPa

$p = K_x\overline{Y}_f\ \varepsilon_x = 1.177(252.5)(4.96 + 2(400)/150) = 3059.1$ MPa

$F = pA_o = 3059.1(17{,}671.5) =$ **54,058,912 N**

(d) Total original volume $V = \pi(150)^2(500)/4 = 8{,}835{,}750$ mm^3
The final volume consists of two sections: (1) butt, and (2) extrudate.
The butt volume as given $V_1 = 600{,}000$ mm^3.
The extrudate has a cross-sectional area $A_f = 550$ mm^2.
Its volume $V_2 = LA_f = 8{,}835{,}750 – 600{,}000 = 8{,}235{,}750$ mm^3.
Thus, length $L = 8{,}835{,}750/550 =$ **14,974 mm = 14.974 m**

19.36 A direct extrusion operation produces the cross section shown in Figure P19.32(d) from an aluminum billet whose diameter = 150 mm and length = 900 mm. The flow curve parameters for the aluminum are $K = 240$ MPa and $n = 0.16$. In the Johnson strain equation, $a = 0.8$ and $b = 1.5$. Determine (a) the extrusion ratio, (b) the shape factor, (c) the force required to drive the ram forward during extrusion at the point in the process when the billet length remaining in the container = 850 mm, and (d) the length of the extruded section at the end of the operation if the volume of the butt left in the container is 600,000 mm^3.

Solution: (a) $r_x = A_o/A_f$
$A_o = \pi(150)^2/4 = 17{,}671.5$ mm^2
$A_f = A_x = 5(55)(5) + 5(85 – 5(5)) = 1675$ mm^2
$r_x = 17{,}671.5/1675 =$ **10.55**

(b) To determine the die shape factor we need to determine the perimeter of a circle whose area is equal to that of the extruded cross section, $A_x = 1675$ mm^2.
$C_x = 2 \text{ x } 55 + 16 \text{ x } 25 + 8 \text{ x } 15 + 10 \text{ x } 5 = 680$ mm
$A_o = \pi R^2 = 1675$, $R^2 = 1675/\pi = 533.17$, $R = 23.09$ mm
$C_c = 2\pi R = 2\pi(23.09) = 145.08$ mm
$K_x = 0.98 + 0.02(680/145.08)^{2.25} =$ **1.626**

(c) $\varepsilon = \ln 10.55 = 2.36$
$\varepsilon_x = 0.8 + 1.5(2.36) = 4.33$
$\overline{Y}_f = 240(2.36)^{0.16}/1.16 = 237.4$ MPa

$p = K_x\overline{Y}_f\ \varepsilon_x = 1.626(237.4)(4.33 + 2(850)/150) = 6046.2$ MPa

$F = pA_o = 6046.2(17{,}671.5) =$ **106,846,146 N**

(d) Total original volume $V = \pi(150)^2(900)/4 = 15{,}904{,}313$ mm^3
The final volume consists of two sections: (1) butt, and (2) extrudate.
The butt volume as given $V_1 = 600{,}000$ mm^3.
The extrudate has a cross-sectional area $A_f = 1675$ mm^2.
Its volume $V_2 = LA_f = 15{,}904{,}313 – 600{,}000 = 15{,}304{,}313$ mm^3.
Thus, length $L = 15{,}304{,}313/1675 =$ **9,137 mm = 9.137 m**

Drawing

19.37 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 angel 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) $r = (A_o - A_f)/A_o$
$A_o = 0.25\pi(2.50)^2 = 4.91$ mm^2

$A_f = 0.25\pi(2.1)^2 = 3.46$ mm^2
$r = (4.91 – 3.46)/4.91 =$ **0.294**

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

(c) Draw force F:
$F = A_f\, \sigma_d = 3.46(154.2) =$ **534.0 N**

19.38 Rod stock that has an initial diameter of 0.50 in is drawn through a draw die with an entrance angle of 13°. 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. Coefficient of friction at the work-die interface = 0.1. Determine (a) area reduction, (b) draw force for the operation, and (c) horsepower to perform the operation if the exit velocity of the stock = 2 ft/sec.

Solution: (a) $r = (A_o - A_f)/A_o$
$A_o = 0.25\pi(0.50)^2 = 0.1964$ in^2
$A_f = 0.25\pi(0.35)^2 = 0.1104$ in^2
$r = (0.1964 - 0.1104)/0.1964 =$ **0.4375**

(b) Draw force F:
$\varepsilon = \ln(0.1964/0.1104) = \ln 1.778 = 0.5754$
$\overline{Y}_f = 40{,}000(0.5754)^{0.20}/1.20 = 29{,}845$ lb/in^2
$\phi = 0.88 + 0.12(D/L_c)$
$D = 0.5(.50 + 0.375) = 0.438$
$L_c = 0.5(0.50 - 0.375)/\sin 13 = 0.2778$
$\phi = 0.88 + 0.12(0.438/0.2778) = 1.069$
$F = A_f\, \overline{Y}_f (1 + \mu/\tan \alpha)\phi(\ln A_o/A_f)$
$F = 0.1104(29{,}845)(1 + 0.1/\tan 13)(1.069)(0.5754) =$ **2907 lb**

(c) $P = 2907(2$ ft/sec x $60) = 348{,}800$ ft/lb/min
$HP = 348800/33{,}000 =$ **10.57 hp**

19.39 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) $r = (A_o - A_f)/A_o$
$A_o = 0.25\pi(90)^2 = 6361.7$ mm^2
$D_f = D_o - d = 90 - 15 = 75$ mm,
$A_f = 0.25\pi(75)^2 = 4417.9$ mm^2
$r = (6361.7 - 4417.9)/6361.7 =$ **0.3056**

(b) Draw stress σ_d:
$\varepsilon = \ln(6361.7 /4417.9) = \ln 1.440 = 0.3646$

$\overline{Y}_f = k = 105$ MPa
$\phi = 0.88 + 0.12(D/L_c)$
$D = 0.5(90 + 75) = 82.5$ mm
$L_c = 0.5(90 - 75)/\sin 18 = 24.3$ mm
$\phi = 0.88 + 0.12(82.5/24.3) = 1.288$
$\sigma_d = \overline{Y}_f\,(1 + \mu/\tan\,\alpha)\phi(\ln A_o/A_f) = 105(1 + 0.08/\tan 18)(1.288)(0.3646) =$ **61.45 MPa**

(c) $F = A_f\,\sigma_d = 4417.9\ (61.45) =$ **271,475 N**

(d) $P = 271{,}475(1$ m/min$) = 271{,}475$ N-m/min $= 4524.6$ N-m/s $=$ **4524.6 W**

19.40 Wire stock of initial diameter = 0.125 in is drawn through two dies each providing a 0.20 area reduction. The starting metal has a strength coefficient = 40,000 lb/in^2 and a strain hardening exponent = 0.15. Each die has an entrance angle of 12°, and the coefficient of friction at the work-die interface is estimated to be 0.10. The motors driving the capstans at the die exits can each deliver 1.50 hp at 90% efficiency. Determine the maximum possible speed of the wire as it exits the second die.

Solution: First draw: $D_o = 0.125$ in, $A_o = 0.25\pi(0.125)^2 = 0.012273$ in^2 009819 in^2
$\varepsilon = \ln(0.012273/0.009819) = \ln 1.250 = 0.2231$
$r = (A_o - A_f)/A_o$, $A_f = A_o(1 - r) = 0.012773(1 - 0.2) = 0.$
$\overline{Y}_f\ = 40{,}000(0.2231)^{0.15}/1.15 = 27{,}775$ lb/in^2
$\phi = 0.88 + 0.12(D/L_c)$
$D_f = 0.125(1 - r)^{0.5} = 0.125(0.8)^{.5} = 0.1118$ in
$D = 0.5(.125 + 0.1118) = 0.1184$
$L_c = 0.5(0.125 - 0.1118)/\sin 12 = 0.03173$
$\phi = 0.88 + 0.12(0.1184/0.03173) = 1.33$
$F = A_f\,\overline{Y}_f\,(1 + \mu/\tan\,\alpha)\phi(\ln A_o/A_f)$
$F = 0.09819(27{,}775)(1 + 0.1/\tan 12)(1.33)(0.2231) = 119$ lb
1.5 hp at 90% efficiency = 1.5 x 0.90(33,000 ft-lb/min)/60 = 742.5 ft-lb/sec
$P = Fv = 119v = 742.5$
$v = 742.5/119 =$ **6.24 ft/sec**

Second draw: $D_o = 0.1118$ in, $A_o = 0.25\pi(0.1118)^2 = 0.009819$ in^2
$r = (A_o - A_f)/A_o$, $A_f = A_o(1 - r) = 0.009819(1 - 0.2) = 0.007855$ in^2
$\varepsilon = \ln(0.009819/0.007855) = \ln 1.250 = 0.2231$
Total strain experienced by the work metal is the sum of the strains from the first and second draws:
$\varepsilon = \varepsilon_1 + \varepsilon_2 = 0.2231 + 0.2231 = 0.4462$
$\overline{Y}_f = 40{,}000(0.4462)^{0.15}/1.15 = 30{,}818$ lb/in^2
$\phi = 0.88 + 0.12(D/L_c)$
$D_f = 0.1118(1 - r)^{0.5} = 0.1118(.8)^{.5} = 0.100$ in
$D = 0.5(0.1118 + 0.100) = 0.1059$
$L_c = 0.5(0.1118 - 0.100)/\sin 12 = 0.0269$
$\phi = 0.88 + 0.12(0.1059/0.0269) = 1.35$
$F = A_f\,\overline{Y}_f\,(1 + \mu/\tan\,\alpha)\phi(\ln A_o/A_f)$
$F = 0.007855(30{,}818)(1 + 0.1/\tan 12)(1.35)(0.4462) = 214$ lb.
1.5 hp at 90% efficiency = 742.5 ft-lb/sec as before in the first draw.
$P = Fv = 214v = 742.5$
$v = 742.5/214 =$ **3.47 ft/sec**

Note: The calculations indicate that the second draw die is the limiting step in the drawing sequence. The first operation would have to be operated at well below its maximum possible speed; or the second draw die could be powered by a higher horsepower motor; or the reductions to achieve the two stages could be reallocated to achieve a higher reduction in the first drawing operation.

20 SHEET METALWORKING

Review Questions

20.1 Identify the three basic types of sheet metalworking operations.

Answer. The three basic types of sheet metalworking operations are (1) cutting, (2) bending, and (3) drawing.

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

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

20.3 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.

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

Answer. A cutoff operation separates parts from a strip by shearing one edge of each part in sequence. A parting operation cuts a slug between adjacent parts in the strip. See Figure 20.8.

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

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

20.6 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 20.12.

20.7 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.

20.8 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.

20.9 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.

20.10 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.

20.11 Distinguish between redrawing and reverse drawing.

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

20.12 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 20.3.4.

20.13 What is an embossing operation?

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

20.14 What is stretch forming?

Answer. Stretch forming of sheet metal consists of simultaneously stretching and bending the sheet-metal workpart to achieve shape change.

20.15 Identify the principal components of a stamping die that performs blanking.

Answer. The principal components are the punch and die, which perform the cutting operation. They are attached respectively to the punch holder (a.k.a. upper shoe) and die holder (a.k.a. lower shoe). Alignment of the punch and die during the stamping operation is achieved by means of guide pins and bushings in the punch holder and die holder.

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

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

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

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

20.18 What is the Guerin process?

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

20.19 Identify a major technical problem in tube bending?

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

20.20 Distinguish between roll bending and roll forming.

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

20.21 (**Video**) According to the video on sheet-metal shearing, what is the blade rake angle?

Answer: The Blade Rake Angle or Shear Angle is the angle between the two surfaces that come together to shear the material. An angle of zero means that the shearing takes place at the same time along the entire surface. A larger value of angle means that less surface is in contact with the shearing blades at any moment during the operation.

20.22 (**Video**) According to the video on sheet-metal bending, what are the principal terms used to describe bending on a press brake?

Answer: The principal terms used to describe bending on a press brake are bend allowance, bend angle, bend radius, and bend springback.

20.23 (**Video**) According to the video on sheet-metal stamping dies and processes, what are the factors that affect the formability of a metal?

Answer: Factors mentioned in the video clip that affect the formability of a metal are (1) part shape is the primary factor, (2) sheet metal's ductility, (3) die design, (4) stamping press, (5) press speed, (6) lubrication, (7) sheet-metal feeding mechanism, and (8) monitoring/control systems.

20.24 (**Video**) Name the four forming processes listed in the video clip on sheet-metal stamping dies and processes.

Answer: The four forming processes listed in the video clip are (1) drawing, (2) bending, (3) flanging, and (4) hemming.

20.25 (**Video**) List the factors that affect the hold down pressure in a drawing operation according to the video on sheet-metal stamping dies and processes.

Answer: Factors that affect the hold down pressure in a drawing operation include (1) draw reduction severity, (2) metal properties, (3) metal thickness, and (4) die lubrication.

Multiple Choice Quiz

There are 21 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

20.1 Most sheet metalworking operations are performed as which one of the following: (a) cold working, (b) hot working, or (c) warm working?

Answer. (a).

20.2 In a sheet-metal-cutting operation used to produce a flat part with a hole in the center, the part itself is called a blank, and the scrap piece that was cut out to make the hole is called a slug: (a) true or (b) false?

Answer. (a).

20.3 As sheet-metal stock hardness increases in a blanking operation, the clearance between punch and die should be (a) decreased, (b) increased, or (c) remain the same?

Answer. (b).

20.4 A circular sheet-metal slug produced in a hole punching operation will have the same diameter as (a) the die opening or (b) the punch?

Answer. (a).

20.5 The cutting force in a sheet-metal blanking operation depends on which mechanical property of the metal (one correct answer): (a) compressive strength, (b) modulus of elasticity, (c) shear strength, (d) strain rate, (e) tensile strength, or (f) yield strength?

Answer. (d).

20.6 Which of the following descriptions applies to a V-bending operation as compared to an edge-bending operation (two best answers): (a) costly tooling, (b) inexpensive tooling, (c) limited to 90° bends or less, (d) used for high production, (e) used for low production, and (f) uses a pressure pad to hold down the sheet metal?

Answer. (b) and (e).

20.7 Sheet-metal bending involves which of the following stresses and strains (two correct answers): (a) compressive, (b) shear, and (c) tensile?

Answer. (a) and (c).

20.8 Which one of the following is the best definition of bend allowance: (a) amount by which the die is larger than the punch, (b) amount of elastic recovery experienced by the metal after bending, (c) safety factor used in calculating bending force, or (d) length before bending of the straight sheet-metal section to be bent?

Answer. (d).

20.9 Springback in a sheet-metal-bending operation is the result of which one of the following: (a) elastic modulus of the metal, (b) elastic recovery of the metal, (c) overbending, (d) overstraining, or (e) yield strength of the metal?

Answer. (b).

20.10 Which of the following are variations of sheet-metal-bending operations (two best answers): (a) coining, (b) flanging, (c) hemming, (d) ironing, (e) notching, (f) shear spinning, (g) trimming, and (h) tube bending?

Answer. (b) and (c).

20.11 The following are measures of feasibility for several proposed cup-drawing operations; which of the operations are likely to be feasible (three best answers): (a) $DR = 1.7$, (b) $DR = 2.7$, (c) $r = 0.35$, (d) $r = 0.65$, and (e) $t/D = 2\%$?

Answer. (a), (c), and (e).

20.12 The holding force in drawing is most likely to be (a) greater than, (b) equal to, or (c) less than the maximum drawing force?

Answer. (c).

20.13 Which one of the following stamping dies is the most complicated: (a) blanking die, (b) combination die, (c) compound die, (d) edge-bending die, (e) progressive die, or (f) V-bending die?

Answer. (e).

20.14 Which one of the following press types is usually associated with the highest production rates in sheet-metal-stamping operations: (a) adjustable bed, (b) open back inclinable, (c) press brake, (d) solid gap, or (e) straight-sided?

Answer. (b).

20.15 Which of the following processes are classified as high-energy-rate forming processes (two best answers): (a) electrochemical machining, (b) electromagnetic forming, (c) electron beam cutting, (d) explosive forming, (e) Guerin process, (f) hydroforming, (g) redrawing, and (h) shear spinning?

Answer. (b) and (d).

Problems

Cutting Operations

20.1 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 20.1, $A_c = 0.060$. Thus, $c = A_c t = 0.060(4.75) =$ **0.285 mm**

20.2 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 20.1, $A_c = 0.075$. Thus, $c = 0.075(2.0) = 0.15$ mm.
Punch diameter = $D_b - 2c = 75.0 - 2(0.15) =$ **74.70 mm**.
Die diameter = $D_b =$ **75.0 mm.**

20.3 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 20.1, $A_c = 0.060$. 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**

20.4 A blanking die is to be designed to blank the part outline shown in Figure P20.4. The material is 4 mm thick stainless steel (half hard). Determine the dimensions of the blanking punch and the die opening.

Solution: From Table 20.1, $A_c = 0.075$. Thus, $c = 0.075(4.0) = 0.30$ mm
Blanking die: dimensions are the same as for the part in Figure P20.4.
Blanking punch: 85 mm length dimension = 85 - 2(0.3) = **84.4 mm**
50 mm width dimension = 50 - 2(0.3) = **49.4 mm**
Top and bottom 25 mm extension widths = 25 - 2(0.3) = **24.4 mm**
The 25 mm inset dimension remains the same.

20.5 Determine the blanking force required in Problem 20.2, if the shear strength of the steel = 325 MPa and the tensile strength is 450 MPa.

Solution: $F = StL$
$t = 2.0$ mm from Problem 20.2.
$L = \pi D = 75\pi = 235.65$ mm
$F = 325(2.0)(235.65) =$ **153,200 N**

20.6 Determine the minimum tonnage press to perform the blanking and punching operation in Problem 20.3. The aluminum sheet metal has a tensile strength = 310 MPa, a strength coefficient of 350 MPa, and a strain-hardening exponent of 0.12. (a) Assume that blanking and punching occur simultaneously. (b) Assume the punches are staggered so that punching occurs first, then blanking.

Solution: (a) $F = 0.7(TS)tL$
t =3.5 mm from Problem 20.3.
$L = 50\pi + 15\pi = 65\pi = 204.2$ mm
$F = 0.7(310)(3.5)(235.6) =$ **155,100 N =** 155,1000/(4.4482*2000) tons **= 17.4 tons => 18 ton press**

(b) Longest length will determine the minimum tonnage press required.
Punching length of cut, $L = 15\pi$, blanking length of cut, $L = 50\pi = 157.1$ mm (use blanking)
$F = 0.7(310)(3.5)(157.1) =$ **119,300 N =** 119,3000/(4.4482*2000) tons **= 13.4 tons => 14 ton press**

20.7 Determine the tonnage requirement for the blanking operation in Problem 20.4, given that the stainless steel has a yield strength = 500 MPa, a shear strength = 600 MPa, and a tensile strength = 700 MPa.

Solution: $F = StL$
$t = 4$ mm from Problem 20.4.
$L = 85 + 50 + 25 + 25 + 35 + 25 + 25 + 50 = 320$ mm
$F = 600(4.0)(320) =$ **768,000 N.** This is about **86.3 tons**

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

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

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

Bending

20.9 A bending operation is to be performed on 5.00 mm thick cold-rolled steel. The part drawing is given in Figure P20.9. Determine the blank size required.

Solution: From drawing, $\alpha' = 40°$, $R = 8.50$ mm
$\alpha = 180 - \alpha' = 140°$.
$A_b = 2\pi(\alpha/360)(R + K_{ba}t)$
$R/t = (8.5)/(5.00) = 1.7$, which is less than 2.0; therefore, $K_{ba} = 0.333$
$A_b = 2\pi(140/360)(8.5 + 0.333 \times 5.0) = 24.84$ mm
Dimensions of starting blank: $w =$ **35 mm,** $L = 58 + 24.84 + 46.5 =$ **129.34 mm**

20.10 Solve Problem 20.9 except that the bend radius $R = 11.35$ mm.

Solution: From drawing, $\alpha' = 40°$, $R = 11.35$ mm
$\alpha = 180 - \alpha' = 140°$.
$A_b = 2\pi(\alpha/360)(R + K_{ba}t)$
$R/t = (11.35)/(5.00) = 2.270$; therefore, $K_{ba} = 0.5$
$A_b = 2\pi(140/360)(11.35 + 0.5 \times 5.00) = 34.21$ mm
Dimensions of starting blank: $w =$ **35 mm,** $L = 58 + 34.21 + 46.5 =$ **138.71 mm**

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

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

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

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

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

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

One more iteration: The thickness of the stretched sheet is (0.3756/0.4084)(0.15625) = 0.1437 in, and recalculating the length of the bent section based on this value, we have 2π(90/360)(0.1875 + 0.5 x 0.1437) = 0.4074 in. The new final length of the neutral axis is L = 2(1.8122) + 0.4074 = **4.0318 in**. Close enough and only about 0.01 in different from our previous value of 4.0417 in.

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

20.12 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 α' = 30°, R = 6.0 mm, and t = 4.0 mm
α = 180 - α' = 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 = 2π(150/360)(6.0 + 0.333 x 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 2π(150/360)(6.0 + 0.5 x 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 = $2\pi(150/360)(6.0 + 0.5 \times 3.67)$ = 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**

20.13 Determine the bending force required in Problem 20.9 if the bend is to be performed in a V-die with a die opening dimension of 40 mm. The material has a tensile strength of 600 MPa and a shear strength of 430 MPa.

Solution: For V-bending, K_{bf} = 1.33.
$F = K_{bf}(TS)wt^2/D = 1.33(600)(35)(5.0)^2/40$ = **17,460 N**

20.14 Solve Problem 20.13 except that the operation is performed using a wiping die with die opening dimension = 28 mm.

Solution: For edge-bending in a wiping die, K_{bf} = 0.33.
$F = K_{bf}(TS)wt^2/D = 0.33(600)(35)(5.0)^2/28$ = **6,188 N**

20.15 Determine the bending force required in Problem 20.11 if the bend is to be performed in a V-die with a die opening width dimension = 1.25 in. The material has a tensile strength = 70,000 lb/in^2.

Solution: For V-bending, K_{bf} = 1.33.
$F = K_{bf}(TS)wt^2/D = 1.33(70{,}000)(1.5)(5/32)^2/1.25$ = **2728 lb.**

20.16 Solve Problem 20.15 except that the operation is performed using a wiping die with die opening dimension = 0.75 in.

Solution: For edge-bending in a wiping die, K_{bf} = 0.33.
$F = K_{bf}(TS)wt^2/D = 0.33(70{,}000)(1.5)(5/32)^2/0.75$ = **1128 lb.**

20.17 A sheet-metal part 3.0 mm thick and 20.0 mm long is bent to an included angle = 60° and a bend radius = 7.5 mm in a V-die. The metal has a yield strength = 220 MPa and a tensile strength = 340 MPa. Compute the required force to bend the part, given that the die opening dimension = 15 mm.

Solution: For V-bending, K_{bf} = 1.33.
$F = K_{bf}(TS)wt^2/D = 1.33(340)(20)(3)^2/15$ = **5426 N**

Drawing Operations

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

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

20.19 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 (a) drawing ratio, (b) reduction, and (c) thickness-to-diameter ratio. (d) Does the operation seem feasible?

Solution: (a) $DR = D_b/D_p = 225/100 = \mathbf{2.25}$

(b) $r = (D_b - D_p)/D_b = (225 - 100)/225 = 0.555 = \mathbf{55.5\%}$

(c) $t/D_b = 2/225 = 0.0089 = \mathbf{0.89\%}$

(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%).

20.20 Solve Problem 20.19 except that the starting blank size diameter = 175 mm.

Solution: (a) $DR = D_b/D_p = 175/100 = \mathbf{1.75}$

(b) $r = (D_b - D_p)/D_b = (175 - 100)/175 = 0.429 = \mathbf{42.9\%}$

(c) $t/D_b = 2/175 = 0.0114 = \mathbf{1.14\%}$

(d) Feasibility? $DR < 2.0$, $r < 50\%$, and $t/D > 1\%$. However, the operation is not feasible because the 175 mm diameter blank size does not provide sufficient metal to draw a 75 mm cup height. The actual cup height possible with a 175 mm diameter blank can be determined by comparing surface areas (one side only for convenience) between the cup and the starting blank. Blank area = $\pi D^2/4 = \pi(175)^2/4 = 24{,}053$ mm^2. To compute the cup surface area, 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. Thus, Cup area = $\pi D_p h + \pi D_p^2/4 = 100\pi h + \pi(100)^2/4 = 100\pi h + 2500\pi = 314.16h + 7854$. Set surface area of cup = surface are of starting blank:
$314.16h + 7854 = 24{,}053$
$314.16h = 16{,}199$
$h = 51.56$ mm. This is less than the specified 75 mm height.

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

Solution: (a) $DR = 7.7/4.25 = \mathbf{1.81}$

(b) $r = (D_b – D_p)/D_b = (7.7 – 4.25)/7.7 = 3.45/7.70 = 0.448 = \mathbf{44.8\%}$

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

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

20.22 Solve Problem 20.21 except that the stock thickness $t = 1/8$ in.

Solution: (a) $DR = 7.7/4.25 = \mathbf{1.81}$ (same as previous problem)

(b) $t/D_b = 0.125/7.7 = \mathbf{0.01623 = 1.623\%}$

(c) $F = \pi D_p t(TS)(D/D_p - 0.7) = \pi(4.25)(0.125)(65{,}000)(7.7/4.25 - 0.7) = \mathbf{120{,}600\ lb}$.

(d) $F_h = 0.015Y\pi(D^2 - (D_p + 2.2t + 2R_d)^2)$
$F_h = 0.015(32{,}000)\pi(7.7^2 - (4.25 + 2.2 \text{ x } 0.125 + 2 \text{ x } 0.15625)^2) = 0.015(32{,}000)\pi(7.7^2 - 4.8375^2)$
$\boldsymbol{F_h} = \mathbf{54{,}100\ lb}$

20.23 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. Determine (a) drawing ratio, (b) reduction, (c) drawing force, and (d) blankholder force.

Solution: (a) $DR = 150/80 = \mathbf{1.875}$

(b) $r = (D_b - D_p)/D_b = (150 - 80)/150 = 70/150 = \mathbf{0.46}$

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

(d) $F_h = 0.015Y\pi(D_b^2 - (D_p + 2.2t + 2R_d)^2)$
$F_h = 0.015(180)\pi(150^2 - (80 + 2.2 \text{ x } 3 + 2 \text{ x } 4)^2) = 0.015(180)\pi(150^2 - 94.6^2)$
$\boldsymbol{F_h} \mathbf{= 114{,}942\ N}$

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

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

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

20.25 Solve Problem 20.24 except use a punch radius = 0.375 in.

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

Test for feasibility: $DR = D_b/D_p = 9.89/5.0 = \mathbf{1.978}$, which is less than the limiting ratio of 2.0. The thickness to diameter ratio $t/D_b = 0.125/9.89 = 0.0126 = 1.26\%$, which is above the value of 1% used as a criterion of feasibility in cup drawing. Whereas the operation in Problem 20.23 was not feasible, the operation in the present problem seems feasible.

20.26 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 = $\pi D_p h + \pi D_p^2/4 = \pi(70)(50) + 0.25\pi(70)^2 = 14{,}846$ mm^2.
Blank area = $\pi D_b^2/4 = 0.7855 D_b^2$
Setting blank area = cup area: $0.7855 D_b^2 = 14{,}846$
$D_b^2 = 14{,}846/0.7855 = 18{,}900$
$\boldsymbol{D_b}$ **= 137.48 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.

20.27 Solve Problem 20.26 except that the height = 60 mm.

Solution: Cup area = wall area + base area
Cup area = $\pi D_p h + \pi D_p^2/4 = \pi(70)(60) + 0.25\pi(70)^2 = 17{,}045$ mm^2.
Blank area = $\pi D_b^2/4 = 0.7855 D_b^2$
Setting blank area = cup area: $0.7855 D_b^2 = 17{,}045$
$D_b^2 = 17{,}045/0.7855 = 21{,}700$
$\boldsymbol{D_b}$ **= 147.31 mm.**

Test for feasibility: $DR = D_b/D_p = 147.31/70 =$ **2.10;** $t/D_b = 3/147.31 = 0.0204 =$ **2.04%.** Since the DR is greater than 2.0, this operation is considered infeasible. Also, as in the previous problem, the punch radius $R_p = 0$ would render this operation difficult if not infeasible.

20.28 Solve Problem 20.27 except that the corner radius on the punch = 10 mm.

Solution: Use surface area computation, assuming thickness t remains constant. The surface area of the cup will be divided into three sections: (1) straight walls, whose height = 60 - 10 = 50 mm, (2) quarter toroid formed by the 0.375 radius at the base of the cup, and (3) base, which has a diameter = 70 - 2 x 10 = 50 mm.
$A_1 = \pi D_p h = \pi(70)(50) = 10{,}995.6$ mm^2
A_2 = length of the quarter circle at the base multiplied by the circumference of the circle described by the centroid (Pappus-Guldin Theorem): length of quarter circle = $2\pi R_p/4 = 0.25\pi(2 \text{ x } 10) = 15.71$ mm. The centroid is located at the center of the arc, which is 10 sin 45 = 7.071 beyond the center of the 0.375 in radius. Thus, the diameter of the circle described by the centroid is 50 + 2 x 7.071 = 64.142 mm.
$A_2 = 64.142\pi(15.71) = 3166.1$ mm^2
$A_3 = \pi(50)^2/4 = 1963.8$ mm^2
Total area of cup = 10,995.6 + 3166.1 + 1963.8 = 16,125.5 mm^2
Blank area = $\pi D_b^2/4 = 0.7855 D_b^2$
Setting blank area = cup area: $0.7855 D_b^2 = 16{,}125.5$
$D_b^2 = 16{,}125.5/0.7855 = 20{,}529.0$
$\boldsymbol{D_b}$ **= 143.28 mm**

Test for feasibility: $DR = D_b/D_p = 143.28/70 =$ **2.047**. Since the DR is greater than 2.0, this operation is considered infeasible.

20.29 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.

20.30 A cup-shaped part is to be drawn without a blankholder from sheet metal whose thickness = 0.25 in. The inside diameter of the cup = 2.5 in, its height = 1.5 in, and the corner radius at the base = 0.375 in. (a) What is the minimum starting blank diameter that can be used, according to Eq. (20.14)? (b) Does this blank diameter provide sufficient material to complete the cup?

Solution: (a) According to Eq. (22.14), $D_b - D_p < 5t$
$D_b < 5t + D_p = 5(0.25) + 2.5 =$ **3.75 in**

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

Other Operations

20.31 A 20-in-long sheet-metal workpiece is stretched in a stretch forming operation to the dimensions shown in Figure P20.31. The thickness of the beginning stock is 3/16 in and the width is 8.5 in. The metal has a flow curve defined by a strength coefficient of 75,000 lb/in^2 and a strain hardening exponent of 0.20. The yield strength of the material is 30,000 lb/in^2. (a) Find the stretching force F required near the beginning of the operation when yielding first occurs. Determine (b) true strain experienced by the metal, (c) stretching force F, and (d) die force F_{die} at the very end when the part is formed as indicated in Figure P20.31(b).

Solution: (a) Use $\varepsilon = 0.002$ as start of yielding.
$F = LtY_f$
$Y_f = 75{,}000(0.002)^{0.20} = 21{,}600 \text{ lb/in}^2$
$F = (8.5)(0.1875)(21{,}600) =$ **34,500 lb.**

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

(c) At the final length of 22.361 in, the thickness of the sheet metal has been reduced to maintain constant volume, assuming width L = 8.5 in remains the same during stretching.

t_f = 0.1875(20/22.361) = 0.168 in
Y_f = 75,000(0.1116)$^{0.20}$ = 48,400 lb/in^2
F = 8.5(0.168)(48,400) = **69,000 lb.**

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

20.32 Determine the starting disk diameter required to spin the part in Figure P20.32 using a conventional spinning operation. The starting thickness = 2.4 mm.

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

20.33 If the part illustrated in Figure P20.32 were made by shear spinning, determine (a) the wall thickness along the cone-shaped portion, and (b) the spinning reduction r.

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

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

20.34 Determine the shear strain that is experienced by the material that is shear spun in Problem 20.33.

Solution: Based on sidewise displacement of metal through a shear angle of 30°,
Shear strain γ = cot 30 = **1.732.**

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

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

21 THEORY OF METAL MACHINING

Review Questions

21.1 What are the three basic categories of material removal processes?

Answer. As organized in this text, the three basic categories of material removal processes are (1) conventional machining, (2) abrasive processes, and (3) nontraditional processes.

21.2 What distinguishes machining from other manufacturing processes?

Answer. In machining, material is removed from the workpart so that the remaining material is the desired part geometry.

21.3 Identify some of the reasons why machining is commercially and technologically important.

Answer. The reasons include the following: (1) it is applicable to most materials; (2) it can produce a variety of geometries to a part; (3) it can achieve closer tolerances than most other processes; and (4) it can create good surface finishes.

21.4 Name the three most common machining processes.

Answer. The three common machining processes are (1) turning, (2) drilling, and (3) milling.

21.5 What are the two basic categories of cutting tools in machining? Give two examples of machining operations that use each of the tooling types.

Answer. The two categories are (1) single-point tools, used in operations such as turning and boring; and (2) multiple-edge cutting tools, used in operations such as milling and drilling.

21.6 What are the parameters of a machining operation that are included within the scope of cutting conditions?

Answer. Cutting conditions include speed, feed, depth of cut, and whether or not a cutting fluid is used.

21.7 Explain the difference between roughing and finishing operations in machining.

Answer. A roughing operation is used to remove large amounts of material rapidly and to produce a part geometry close to the desired shape. A finishing operation follows roughing and is used to achieve the final geometry and surface finish.

21.8 What is a machine tool?

Answer. A machine tool can be defined as a power-driven machine that positions and moves a tool relative to the work to accomplish machining or other metal shaping process.

21.9 What is an orthogonal cutting operation?

Answer. Orthogonal cutting involves the use of a wedge- shaped tool in which the cutting edge is perpendicular to the direction of speed motion into the work material.

21.10 Why is the orthogonal cutting model useful in the analysis of metal machining?

Answer. Orthogonal cutting is useful in the analysis of metal machining because it simplifies the rather complex three-dimensional machining situation to two dimensions. In addition, the tooling in the orthogonal model has only two parameters (rake angle and relief angle), which is a simpler geometry than a single-point tool.

21.11 Name and briefly describe the four types of chips that occur in metal cutting.

Answer. The four types are (1) discontinuous, in which the chip is formed into separated segments; (2) continuous, in which the chip does not segment and is formed from a ductile metal; (3) continuous with built-up edge, which is the same as (2) except that friction at the tool-chip interface causes adhesion of a small portion of work material to the tool rake face, and (4) serrated, which are semi-continuous in the sense that they possess a saw-tooth appearance that is produced by a cyclical chip formation of alternating high shear strain followed by low shear strain.

21.12 Identify the four forces that act upon the chip in the orthogonal metal cutting model but cannot be measured directly in an operation.

Answer. The four forces that act upon the chip are (1) friction force, (2) normal force to friction, (3) shear force, and (4) normal force to friction.

21.13 Identify the two forces that can be measured in the orthogonal metal cutting model.

Answer. The two forces that can be measured in the orthogonal metal cutting model are (1) cutting force and (2) thrust force.

21.14 What is the relationship between the coefficient of friction and the friction angle in the orthogonal cutting model?

Answer. The relationship is that the coefficient of friction is the tangent of the friction angle ($\mu = \tan \beta$).

21.15 Describe in words what the Merchant equation tells us.

Answer. The Merchant equation states that the shear plane angle increases when rake angle is increased and friction angle is decreased.

21.16 How is the power required in a cutting operation related to the cutting force?

Answer. The power required in a cutting operation is equal to the cutting force multiplied by the cutting speed.

21.17 What is the specific energy in metal machining?

Answer. Specific energy is the amount of energy required to remove a unit volume of the work material.

21.18 What does the term size effect mean in metal cutting?

Answer. The size effect refers to the fact that the specific energy increases as the cross-sectional area of the chip (t_o x w in orthogonal cutting or f x d in turning) decreases.

21.19 What is a tool-chip thermocouple?

Answer. A tool-chip thermocouple is comprised of the tool and chip as the two dissimilar metals forming the thermocouple junction; as the tool-chip interface heats up during cutting, a small voltage is emitted from the junction that can be measured to indicate cutting temperature.

Multiple Choice Quiz

There are 17 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

21.1 Which of the following manufacturing processes are classified as material removal processes (two correct answers): (a) casting, (b) drawing, (c) extrusion, (d) forging, (e) grinding, (f) machining, (g) molding, (h) pressworking, and (i) spinning?

Answer. (e) and (f).

21.2 lathe A lathe is used to perform which one of the following manufacturing operations: (a) broaching, (b) drilling, (c) lapping, (d) milling, or (e) turning?

Answer. (e).

21.3 With which one of the following geometric forms is the drilling operation most closely associated: (a) external cylinder, (b) flat plane, (c) round hole, (d) screw threads, or (e) sphere?

Answer. (c).

21.4 If the cutting conditions in a turning operation are cutting speed = 300 ft/min, feed = 0.010 in/rev, and depth of cut = 0.100 inch, which one of the following is the material removal rate: (a) 0.025 in^3/min, (b) 0.3 in^3/min, (c) 3.0 in^3/min, or (d) 3.6 in^3/min?

Answer. (d).

21.5 A roughing operation generally involves which one of the following combinations of cutting conditions: (a) high v, f, and d; (b) high v, low f and d; (c) low v, high f and d; or (d) low v, f, and d, where v = cutting speed, f = feed, and d = depth?

Answer. (c).

21.6 Which of the following are characteristics of the orthogonal cutting model (three best answers): (a) a circular cutting edge is used, (b) a multiple-cutting-edge tool is used, (c) a single-point tool is used, (d) only two dimensions play an active role in the analysis, (e) the cutting edge is parallel to the direction of cutting speed, (f) the cutting edge is perpendicular to the direction of cutting speed, and (g) the two elements of tool geometry are rake and relief angle?

Answer. (d), (f), and (g).

21.7 The chip thickness ratio is which one of the following: (a) t_c/t_o, (b) t_o/t_c, (c) f/d, or (d) t_o/w, where t_c = chip thickness after the cut, t_o = chip thickness before the cut, f = feed, d = depth, and w = width of cut?

Answer. (b).

21.8 Which one of the four types of chip would be expected in a turning operation conducted at low cutting speed on a brittle work material: (a) continuous, (b) continuous with built-up edge, (c) discontinuous, or (d) serrated?

Answer. (c).

21.9 According to the Merchant equation, an increase in rake angle would have which of the following results, all other factors remaining the same (two best answers): (a) decrease in friction angle, (b) decrease in power requirements, (c) decrease in shear plane angle, (d) increase in cutting temperature, and (e) increase in shear plane angle?

Answer. (b) and (e).

21.10 In using the orthogonal cutting model to approximate a turning operation, the chip thickness before the cut t_o corresponds to which one of the following cutting conditions in turning: (a) depth of cut d, (b) feed f, or (c) speed v?

Answer. (b).

21.11 Which one of the following metals would usually have the lowest unit horsepower in a machining operation: (a) aluminum, (b) brass, (c) cast iron, or (d) steel?

Answer. (a).

21.12 For which one of the following values of chip thickness before the cut t_o would you expect the specific energy in machining to be the greatest: (a) 0.010 inch, (b) 0.025 inch, (c) 0.12 mm, or (d) 0.50 mm?

Answer. (c).

21.13 Which of the following cutting conditions has the strongest effect on cutting temperature: (a) feed or (b) speed?

Answer. (b).

Problems

Chip Formation and Forces in Machining

21.1 In an orthogonal cutting operation, the tool has a rake angle = 15°. The chip thickness before the cut = 0.30 mm and the cut yields a deformed chip thickness = 0.65 mm. Calculate (a) the shear plane angle and (b) the shear strain for the operation.

Solution: (a) $r = t_o/t_c$ = 0.30/0.65 = 0.4615
$\phi = \tan^{-1}(0.4615 \cos 15/(1 - 0.4615 \sin 15)) = \tan^{-1}(0.5062) =$ **26.85°**

(b) Shear strain $\gamma = \cot 26.85 + \tan (26.85 - 15) = 1.975 + 0.210 =$ **2.185**

21.2 In Problem 21.1, suppose the rake angle were changed to 0°. Assuming that the friction angle remains the same, determine (a) the shear plane angle, (b) the chip thickness, and (c) the shear strain for the operation.

Solution: From Problem 21.1, α = 15° and ϕ = 26.85°. Using the Merchant Equation, Eq. (21.16):
$\phi = 45 + \alpha/2 - \beta/2$; rearranging, $\beta = 2(45) + \alpha - 2\phi$
$\beta = 2(45) + \alpha - 2(\phi) = 90 + 15 – 2(26.85) = 51.3°$
Now, with $\alpha = 0$ and β remaining the same at 51.3°, $\phi = 45 + 0/2 – 51.3/2 =$ **19.35°**

(b) Chip thickness at $\alpha = 0$: $t_c = t_o/\tan \phi$ = 0.30/tan 19.35 = **0.854 mm**

(c) Shear strain $\gamma = \cot 19.35 + \tan (19.35 - 0) = 2.848 + 0.351 =$ **3.199**

21.3 In an orthogonal cutting operation, the 0.250 in wide tool has a rake angle of 5°. The lathe is set so the chip thickness before the cut is 0.010 in. After the cut, the deformed chip thickness is measured to be 0.027 in. Calculate (a) the shear plane angle and (b) the shear strain for the operation.

Solution: (a) $r = t_o/t_c$ = 0.010/0.027 = 0.3701
$\phi = \tan^{-1}(0.3701 \cos 5/(1 - 0.3701 \sin 5)) = \tan^{-1}(0.3813) =$ **20.9°**

(b) Shear strain $\gamma = \cot 20.9 + \tan (20.9 – 5) = 2.623 + 0.284 =$ **2.907**

21.4 In a turning operation, spindle speed is set to provide a cutting speed of 1.8 m/s. The feed and depth of cut of cut are 0.30 mm and 2.6 mm, respectively. The tool rake angle is 8°. After the cut, the deformed chip thickness is measured to be 0.49 mm. Determine (a) shear plane angle, (b) shear strain, and (c) material removal rate. Use the orthogonal cutting model as an approximation of the turning process.

Solution: (a) $r = t_o/t_c$ = 0.30/0.49 = 0.612
$\phi = \tan^{-1}(0.612 \cos 8/(1 – 0.612 \sin 8)) = \tan^{-1}(0.6628) =$ **33.6°**

(b) $\gamma = \cot 33.6 + \tan (33.6 - 8) = 1.509 + 0.478 =$ **1.987**

(c) R_{MR} = (1.8 m/s x 10^3 mm/m)(0.3)(2.6) = **1404 mm^3/s**

21.5 The cutting force and thrust force in an orthogonal cutting operation are 1470 N and 1589 N, respectively. The rake angle = 5°, the width of the cut = 5.0 mm, the chip thickness before the cut = 0.6, and the chip thickness ratio = 0.38. Determine (a) the shear strength of the work material and (b) the coefficient of friction in the operation.

Solution: (a) $\phi = \tan^{-1}(0.38 \cos 5/(1 - 0.38 \sin 5)) = \tan^{-1}(0.3916) = 21.38°$
F_s = 1470 cos 21.38 – 1589 sin 21.38 = 789.3 N
A_s = (0.6)(5.0)/sin 21.38 = 3.0/.3646 = 8.23 mm^2
S = 789.3/8.23 = 95.9 N/mm^2 = **95.9 MPa**

(b) $\phi = 45 + \alpha/2 - \beta/2$; rearranging, $\beta = 2(45) + \alpha - 2\phi$
$\beta = 2(45) + \alpha - 2(\phi) = 90 + 5 – 2(21.38) = 52.24°$
μ = tan 52.24 = **1.291**

21.6 The cutting force and thrust force have been measured in an orthogonal cutting operation to be 300 lb and 291 lb, respectively. The rake angle = 10°, width of cut = 0.200 in, chip thickness before the cut = 0.015, and chip thickness ratio = 0.4. Determine (a) the shear strength of the work material and (b) the coefficient of friction in the operation.

Solution: $\phi = \tan^{-1}(0.4 \cos 10/(1 - 0.4 \sin 10)) = \tan^{-1}(0.4233) = 22.94°$
F_s = 300 cos 22.94 - 291sin 22.94 = 162.9 lb.
A_s = (0.015)(0.2)/sin 22.94 = 0.0077 in^2
S = 162.9/0.0077 = **21,167 lb/in^2**
$\beta = 2(45) + \alpha - 2(\phi) = 90 + 10 - 2(22.94) = 54.1°$
μ = tan 54.1 = **1.38**

21.7 An orthogonal cutting operation is performed using a rake angle of 15°, chip thickness before the cut = 0.012 in and width of cut = 0.100 in. The chip thickness ratio is measured after the cut to be 0.55. Determine (a) the chip thickness after the cut, (b) shear angle, (c) friction angle, (d) coefficient of friction, and (e) shear strain.

Solution: (a) $r = t_o/t_c$, $t_c = t_o/r$ = 0.012/0.55 = **0.022 in**

(b) $\phi = \tan^{-1}(0.55 \cos 15/(1 - 0.55 \sin 15)) = \tan^{-1}(0.6194)$ = **31.8°**

(c) $\beta = 2(45) + \alpha - 2(\phi) = 90 + 15 - 2(31.8)$ = **41.5°**

(d) μ = tan 41.5 = **0.88**

(e) γ = cot 31.8 + tan(31.8 - 15) = 1.615 + 0.301 = **1.92**

21.8 The orthogonal cutting operation described in previous Problem 21.7 involves a work material whose shear strength is 40,000 lb/in^2. Based on your answers to the previous problem, compute (a) the shear force, (b) cutting force, (c) thrust force, and (d) friction force.

Solution: (a) A_s = (0.012)(0.10)/sin 31.8 = 0.00228 in^2.
$F_s = A_sS$ = 0.00228(40,000) = **91.2 lb**

(b) F_c = 91.2 cos (41.5 - 15)/cos (31.8 + 41.5 -15) = **155 lb**

(c) F_t = 91.2 sin (41.5 - 15)/cos (31.8 + 41.5 -15) = **77.2 lb**

(d) F = 155 sin 15 - 77.2 cos 15 = **115 lb**

21.9 In an orthogonal cutting operation, the rake angle = -5°, chip thickness before the cut = 0.2 mm and width of cut = 4.0 mm. The chip ratio = 0.4. Determine (a) the chip thickness after the cut, (b) shear angle, (c) friction angle, (d) coefficient of friction, and (e) shear strain.

Solution: (a) $r = t_o/t_c$, $t_c = t_o/r$ = 0.2/.4 = **0.5 mm**

(b) $\phi = \tan^{-1}(0.4 \cos(-5)/(1 - 0.4 \sin(-5))) = \tan^{-1}(0.3851) =$ **21.1°**

(c) $\beta = 2(45) + \alpha - 2(\phi) = 90 + (-5) - 2(21.8) =$ **42.9°**

(d) $\mu = \tan 42.9 =$ **0.93**

(e) $\gamma = \cot 31.8 + \tan(31.8 - 15) = 2.597 + 0.489 =$ **3.09**

21.10 The shear strength of a certain work material = 50,000 lb/in^2. An orthogonal cutting operation is performed using a tool with a rake angle = 20° at the following cutting conditions: cutting speed = 100 ft/min, chip thickness before the cut = 0.015 in, and width of cut = 0.150 in. The resulting chip thickness ratio = 0.50. Determine (a) the shear plane angle, (b) shear force, (c) cutting force and thrust force, and (d) friction force.

Solution: (a) $\phi = \tan^{-1}(0.5 \cos 20/(1 - 0.5 \sin 20)) = \tan^{-1}(0.5668) =$ **29.5°**

(b) $A_s = (0.015)(0.15)/\sin 29.5 = 0.00456$ in^2.
$F_s = A_sS = 0.00456(50{,}000) =$ **228 lb**

(c) $\beta = 2(45) + \alpha - 2(\phi) = 90 + 20 - 2(29.5) = 50.9°$
$F_c = 228 \cos(50.9 - 20)/\cos(29.5 + 50.9 - 20) =$ **397 lb**
$F_t = 228 \sin(50.9 - 20)/\cos(29.5 + 50.9 - 20) =$ **238 lb**

(d) $F = 397 \sin 20 + 238 \cos 20 =$ **359 lb**

21.11 Consider the data in Problem 21.10 except that rake angle is a variable, and its effect on the forces in parts (b), (c), and (d) is to be evaluated. (a) Using a spreadsheet calculator, compute the values of shear force, cutting force, thrust force, and friction force as a function of rake angle over a range of rake angles between the high value of 20° in Problem 21.10 and a low value of -10°. Use intervals of 5° between these limits. The chip thickness ratio decreases as rake angle is reduced and can be approximated by the following relationship: $r = 0.38 + 0.006\alpha$, where r = chip thickness and α = rake angle. (b) What observations can be made from the computed results?

Solution: (a) The author's spreadsheet calculations (using Excel) returned the following results:

α	r	F_s (lb)	F_c (lb)	F_t (lb)	F (lb)
20	0.5	228	397	238	359
15	0.47	245	435	309	411
10	0.44	265	480	399	476
5	0.41	288	531	515	559
0	0.38	317	592	667	667
-5	0.35	351	665	870	809
-10	0.32	393	754	1150	1001

(b) Observations: (1) All forces increase as rake angle decreases. (2) The change in forces with rake angle increases at an accelerating rate as rake angle is reduced. (3) Thrust force is less than cutting force at high rake angles (e.g., 20°) but increases at a faster rate than cutting force so that its value is greater at low and negative rake angles. (4) Chip thickness ratio decreases with decreasing rake angle, as indicated by the given relationship $r = 0.38 + 0.006\alpha$.

21.12 Solve previous Problem 21.10 except that the rake angle has been changed to -5° and the resulting chip thickness ratio = 0.35.

Solution: (a) $\phi = \tan^{-1}(0.35 \cos(-5)/(1 - 0.35 \sin(-5))) = \tan^{-1}(0.3384) =$ **18.7°**

(b) $A_s = (0.015)(0.15)/\sin 18.7 = 0.00702$ in^2.
$F_s = A_sS = 0.00702(50{,}000) =$ **351 lb**

(c) $\beta = 2(45) + \alpha - 2(\phi) = 90 + (-5) - 2(18.7) = 47.6°$
F_c = 351 cos(47.6 - (-5))/cos(18.7 + 47.6 - (-5)) = **665 lb**
F_t = 351 sin(47.6 - (-5))/cos(18.7 + 47.6 - (-5)) = **870 lb**

(d) F = 665 sin (-5) + 870 cos (-5) = **809 lb**

21.13 A carbon steel bar with 7.64 in diameter has a tensile strength of 65,000 lb/in^2 and a shear strength of 45,000 lb/in^2. The diameter is reduced using a turning operation at a cutting speed of 400 ft/min. The feed is 0.011 in/rev and the depth of cut is 0.120 in. The rake angle on the tool in the direction of chip flow is 13°. The cutting conditions result in a chip ratio of 0.52. Using the orthogonal model as an approximation of turning, determine (a) the shear plane angle, (b) shear force, (c) cutting force and feed force, and (d) coefficient of friction between the tool and chip.

Solution: (a) $\phi = \tan^{-1}$(0.52 cos 13/(1 - 0.52 sin 13)) = $\tan^{-1}$(0.5738) = **29.8°**

(b) $A_s = t_o w/\sin \phi$ = (0.011)(0.12)/sin 29.8 = 0.00265 in^2.
$F_s = A_s S$ = 0.00587(40,000) = **119.4 lb**

(c) $\beta = 2(45) + \alpha - 2(\phi) = 90 + 10 - 2(29.8) = 43.3°$
$F_c = F_s \cos(\beta - \alpha)/\cos(\phi + \beta - \alpha)$
F_c = 264.1 cos (43.3 - 13)/cos (29.8 + 43.3 - 13) = **207 lb**
$F_t = F_s \sin(\beta - \alpha)/\cos(\phi + \beta - \alpha)$
F_t = 264.1 sin (43.3 - 13)/cos (29.8 + 43.3 - 13) = **121 lb**
(d) $\mu = \tan\beta$ = tan 43.3 = **0.942**

21.14 Low carbon steel having a tensile strength of 300 MPa and a shear strength of 220 MPa is cut in a turning operation with a cutting speed of 3.0 m/s. The feed is 0.20 mm/rev and the depth of cut is 3.0 mm. The rake angle of the tool is 5° in the direction of chip flow. The resulting chip ratio is 0.45. Using the orthogonal model as an approximation of turning, determine (a) the shear plane angle, (b) shear force, (c) cutting force and feed force.

Solution: (a) $\phi = \tan^{-1}$(0.45 cos 5/(1 - 0.45 sin 5)) = $\tan^{-1}$(0.4666) = **25.0°**

(b) $A_s = t_o w/\sin \phi$ = (0.2)(3.0)/sin 25.0 = 1.42 mm^2.
$F_s = A_s S$ = 1.42(220) = **312 N**

(c) $\beta = 2(45) + \alpha - 2(\phi) = 90 + 5 - 2(25.0) = 45.0°$
$F_c = F_s \cos(\beta - \alpha)/\cos(\phi + \beta - \alpha)$
F_c = 312 cos(45 - 5)/cos(25.0 + 45.0 - 5) = **566 N**
$F_t = F_s \sin(\beta - \alpha)/\cos(\phi + \beta - \alpha)$
F_t = 312 sin(45 - 5)/cos(25.0 + 45.0 - 5) = **474 N**

21.15 A turning operation is made with a rake angle of 10°, a feed of 0.010 in/rev and a depth of cut = 0.100 in. The shear strength of the work material is known to be 50,000 lb/in^2, and the chip thickness ratio is measured after the cut to be 0.40. Determine the cutting force and the feed force. Use the orthogonal cutting model as an approximation of the turning process.

Solution: $\phi = \tan^{-1}$(0.4 cos 10/(1 - 0.4 sin 10)) = $\tan^{-1}$(0.4233) = **22.9°**
A_s = (0.010)(0.10)/sin 22.9 = 0.00257 in^2
$F_s = A_s S$ = 0.00256(50,000) = **128 lb**
$\beta = 2(45) + \alpha - 2(\phi) = 90 + 10 - 2(22.9) = 54.1°$
F_c = 128 cos (54.1 - 10)/cos (22.9 + 54.1 - 10) = **236 lb**
F_t = 128 sin (54.1 - 10)/cos (22.9 + 54.1 - 10) = **229 lb**

21.16 Show how Eq. (21.3) is derived from the definition of chip ratio, Eq. (21.2), and Figure 21.5(b).

Solution: Begin with the definition of the chip ratio, Eq. (21.2): $r = t_o/t_c = \sin\phi/\cos(\phi - \alpha)$

Rearranging, $r \cos(\phi - \alpha) = \sin\phi$
Using the trigonometric identity $\cos(\phi - \alpha) = \cos\phi \cos\alpha + \sin\phi \sin\alpha$
$r(\cos\phi\cos\alpha + \sin\phi\sin\alpha) = \sin\phi$
Dividing both sides by $\sin\phi$, we obtain $r\cos\alpha/\tan\phi + r\sin\alpha = 1$
$r\cos\alpha/\tan\phi = 1 - r\sin\alpha$
Rearranging, $\tan\phi = r\cos\alpha/(1 - r\sin\alpha)$ Q.E.D.

21.17 Show how Eq. (21.4) is derived from Figure 21.6.

Solution: In the figure, $\gamma = AC/BD = (AD + DC)/BD = AD/BD + DC/BD$
$AD/BD = \cot\phi$ and $DC/BD = \tan(\phi - \alpha)$
Thus, $\gamma = \cot\phi + \tan(\phi - \alpha)$ Q.E.D.

21.18 Derive the force equations for F, N, F_s, and F_n (Eqs. (21.9) through (21.12) in the text) using the force diagram of Figure 21.11.

Solution: <u>Eq. (21.9):</u> In Figure 23.11, construct a line starting at the intersection of $\boldsymbol{F_t}$ and $\boldsymbol{F_c}$ that is perpendicular to the friction force $\boldsymbol{F}$. The constructed line is at an angle α with $\boldsymbol{F_c}$. The vector $\boldsymbol{F}$ is divided into two line segments, one of which = $\boldsymbol{F_c}\sin\alpha$ and the other = $\boldsymbol{F_t}\cos\alpha$.
Thus, $\boldsymbol{F} = \boldsymbol{F_c}\sin\alpha + \boldsymbol{F_t}\cos\alpha$. Q.E.D.

<u>Eq. (21.10):</u> In Figure 23.11, translate vector $\boldsymbol{N}$ vertically upward until it coincides with the previously constructed line, whose length = $\boldsymbol{F_c}\cos\alpha$. Next, translate vector $\boldsymbol{F_t}$ to the right and downward at an angle α until its base is at the arrowhead of $\boldsymbol{F}$. $\boldsymbol{F_t}$ now makes an angle α with $\boldsymbol{F}$. The arrowhead of $\boldsymbol{F_t}$ will now be at the base of the translated base of **N**. The distance along the previously constructed line between the $\boldsymbol{F_t}$ arrowhead (base of translated $\boldsymbol{N}$ vector) and $\boldsymbol{F}$ is $\boldsymbol{F_t}\sin\alpha$.
Hence, $\boldsymbol{N} = \boldsymbol{F_c}\cos\alpha - \boldsymbol{F_t}\sin\alpha$ Q.E.D.

<u>Eq. (21.11):</u> In Figure 23.11, extend vector $\boldsymbol{F_s}$ in the opposite direction of its arrowhead, and from the intersection of $\boldsymbol{F_t}$ and $\boldsymbol{F_c}$ construct a line that is perpendicular to vector $\boldsymbol{F_s}$. A right triangle now exists in which $\boldsymbol{F_c}$ is the hypotenuse and the two sides are (1) the extended $\boldsymbol{F_s}$ vector and (2) the constructed line that runs between F_s and the intersection of $\boldsymbol{F_c}$ and $\boldsymbol{F_t}$. The extended $\boldsymbol{F_s}$ vector is related to $\boldsymbol{F_c}$ as $\boldsymbol{F_c}\cos\phi$. The length difference between the extended $\boldsymbol{F_s}$ vector and the original $\boldsymbol{F_s}$ vector is $\boldsymbol{F_t}\sin\phi$.
Thus $\boldsymbol{F_s}$ (original) = $\boldsymbol{F_c}\cos\phi - \boldsymbol{F_t}\sin\phi$ Q.E.D.

<u>Eq. (21.12):</u> In Figure 23.11, construct a line from the intersection of $\boldsymbol{F_t}$ and $\boldsymbol{F_c}$ that is perpendicular to and intersects with vector $\boldsymbol{F_n}$. Vector $\boldsymbol{F_n}$ is now divided into two line segments, one of which = $\boldsymbol{F_t}\cos\phi$ and the other = $\boldsymbol{F_c}\sin\phi$.
Hence, $\boldsymbol{F_n} = \boldsymbol{F_c}\sin\phi + \boldsymbol{F_t}\cos\phi$ Q.E.D.

Power and Energy in Machining

21.18 In a turning operation on stainless steel with hardness = 200 HB, the cutting speed = 200 m/min, feed = 0.25 mm/rev, and depth of cut = 7.5 mm. How much power will the lathe draw in performing this operation if its mechanical efficiency = 90%. Use Table 21.2 to obtain the appropriate specific energy value.

Solution: From Table 21.2, $U = 2.8$ N-m/mm^3 = 2.8 J/mm^3
$R_{MR} = vfd = (200 \text{ m/min})(10^3 \text{ mm/m})(0.25 \text{ mm})(7.5 \text{ mm}) = 375{,}000 \text{ mm}^3\text{/min} = 6250 \text{ mm}^3\text{/s}$
$P_c = (6250 \text{ mm}^3\text{/s})(2.8 \text{ J/mm}^3) = 17{,}500 \text{ J/s} = 17{,}500 \text{ W} = 17.5 \text{ kW}$
Accounting for mechanical efficiency, $P_g = 17.5/0.90 =$ **19.44 kW**

21.19 In Problem 21.18, compute the lathe power requirements if feed = 0.50 mm/rev.

Solution: This is the same basic problem as the previous, except that a correction must be made for the "size effect." Using Figure 21.14, for f = 0.50 mm, correction factor = 0.85.
From Table 21.2, U = 2.8 J/mm^3. With the correction factor, U = 2.8(0.85) = 2.38 J/mm^3.
$R_{MR} = vfd$ = (200 m/min)(10^3 mm/m)(0.50 mm)(7.5 mm) = 750,000 mm^3/min = 12,500 mm^3/s
P_c = (12,500 mm^3/s)(2.38 J/mm^3) = 29,750 J/s = 29,750 W = 29.75 kW
Accounting for mechanical efficiency, P_g = 29.75/0.90 = **33.06 kW**

21.20 In a turning operation on aluminum, cutting speed = 900 ft/min, feed = 0.020 in/rev, and depth of cut = 0.250 in. What horsepower is required of the drive motor, if the lathe has a mechanical efficiency = 87%? Use Table 21.2 to obtain the appropriate unit horsepower value.

Solution: From Table 21.2, HP_u = 0.25 hp/(in^3/min) for aluminum. Since feed is greater than 0.010 in/rev in the table, a correction factor must be applied from Figure 21.14. For f = 0.020 in/rev = t_o, correction factor = 0.9.
$HP_c = HP_u$ x R_{MR}, $HP_g = HP_c/E$
$R_{MR} = vfd$ = 900 x 12(.020)(0.250) = 54 in^3/min
HP_c = 0.9(0.25)(54) = 12.2 hp
HP_g = 12.2/0.87 = **14.0 hp**

21.21 In a turning operation on plain carbon steel whose Brinell hardness = 275 HB, the cutting speed is set at 200 m/min and depth of cut = 6.0 mm. The lathe motor is rated at 25 kW, and its mechanical efficiency = 90%. Using the appropriate specific energy value from Table 21.2, determine the maximum feed that can be set for this operation. Use of a spreadsheet calculator is recommended for the iterative calculations required in this problem.

Solution: From Table 21.2, U = 2.8 N-m/mm^3 = 2.8 J/mm^3
$R_{MR} = vfd$ = (200 m/min)(10^3 mm/m)(6 mm)f = 1200(10^3)f mm^3/min = 20(10^3)f mm^3/s
Available power $P_c = P_g\, E$ = 25(10^3)(0.90) = 22.5 (10^3) = 22,500W = 22,500 N-m/s
Required power P_c = (2.8 N-m/mm^3)(20 x 10^3) f = 56,000 f (units are N-m/s)
Setting available power = required power, 22,500 = 56,000 f
f = 22,500/56,000 = 0.402 mm (this should be interpreted as mm/rev for a turning operation)
However, for this feed, correction factor in Figure 21.14 = 0.9. Thus U = 2.8(0.90) = 2.52 N-m/mm^3 and an iterative calculation procedure is required to match the unit power value with the feed, taking the correction factor into account.
Required P_c = (2.52)(20 x 10^3) f = 50,400 f
Again setting available power = required power, 22,500 = 50,400 f
f = 22,500/50,400 = 0.446 mm/rev
One more iteration using the correction factor yields a value around ***f* = 0.45 mm/rev**.

The author's spreadsheet calculations (using Excel) returned a value closer to ***f* = 0.46 mm/rev**. However, whether a spreadsheet is used or not, the difficulty that remains is reading the values of the feed and the correction factor in Figure 21.14.

21.22 A turning operation is to be performed on a 20 hp lathe that has an 87% efficiency rating. The roughing cut is made on alloy steel whose hardness is in the range 325 to 335 HB. The cutting speed is 375 ft/min, feed is 0.030 in/rev, and depth of cut is 0.150 in. Based on these values, can the job be performed on the 20 hp lathe? Use Table 21.2 to obtain the appropriate unit horsepower value.

Solution: From Table 21.2, HP_u = 1.3 hp/(in^3/min)
Since the uncut chip thickness (0.030 in) is different from the tabular value of 0.010, a correction factor must be applied. From Figure 21.14, the correction factor is 0.8. Therefore, the corrected HP_u = 0.8*1.3 = 1.04 hp/(in^3/min)
$R_{MR} = vfd$ = 375 ft/min(12 in/ft)(0.03 in)(0.150 in) = 20.25 in^3/min
HP_c = (20.25 in^3/min)(1.04 hp/(in^3/min)) = **21.06 hp** required.

At efficiency E = 87%, available horsepower = 0.87(20) = **17.4 hp**
Since required horsepower exceeds available horsepower, the job cannot be accomplished on the 20 hp lathe, at least not at the specified cutting speed of 375 ft/min.

21.23 Suppose the cutting speed in Problems 21.7 and 21.8 is 200 ft/min. From your answers to those problems, find (a) the horsepower consumed in the operation, (b) metal removal rate in in^3/min, (c) unit horsepower (hp-min/in^3), and (d) the specific energy (in-lb/in^3).

Solution: (a) From Problem 21.8, F_c = 155 lb. HP_c = 155(200)/33,000 = **0.94 hp**

(b) $R_{MR} = vfd$ = (200 x 12)(0.012)(0.100) = **2.88 in^3/min**

(c) HP_u = 0.94/2.88 = **0.326 hp/(in^3/min)**

(d) U = 155(200)/2.88 = **10,764 ft-lb/in^3 = 129,167 in-lb/in^3**

21.24 For Problem 21.12, the lathe has a mechanical efficiency = 0.83. Determine (a) the horsepower consumed by the turning operation; (b) horsepower that must be generated by the lathe; (c) unit horsepower and specific energy for the work material in this operation.

Solution: (a) From Problem 21.12, F_c = 207 lb.
$HP_c = F_c v$/33,000 = 207(400)/33,000 = **2.51 hp**

(b) $HP_g = HP_c$/E = 2.51/0.83 = **3.02 hp**

(c) R_{MR} = 12 vfd = (400 x 12)(0.011)(0.120) = **6.336 in^3/min**
$HP_u = HP_c/R_{MR}$ = 2.51/6.336 = **0.396 hp/(in^3/min)**
$U = F_c v/R_{MR}$ = 207(400 x 12)/6.336 = **157,000 in-lb/in^3**

21.25 In a turning operation on low carbon steel (175 BHN), cutting speed = 400 ft/min, feed = 0.010 in/rev, and depth of cut = 0.075 in. The lathe has a mechanical efficiency = 0.85. Based on the unit horsepower values in Table 21.2, determine (a) the horsepower consumed by the turning operation and (b) the horsepower that must be generated by the lathe.

Solution: (a) From Table 21.2, HP_u = 0.6 hp/(in^3/min) for low carbon steel.
$HP_c = HP_u$ x R_{MR}
$R_{MR} = vfd$ = 400 x 12(.010)(0.075) = 3.6 in^3/min
HP_c = 0.6(3.6) = **2.16 hp**

(b) HP_g = 2.16/0.85 = **2.54 hp**

21.26 Solve Problem 21.25 except that the feed = 0.0075 in/rev and the work material is stainless steel (Brinell Hardness = 240 HB).

Solution: (a) From Table 21.2, HP_u = 1.0 hp/(in^3/min) for stainless steel. Since feed is lower than 0.010 in/rev in the table, a correction factor must be applied from Figure 21.14. For f = 0.0075 in/rev = t_o, correction factor = 1.1.
$HP_c = HP_u$ x R_{MR}
R_{MR} = 400 x 12(0.0075)(0.12) = 4.32 in^3/min
HP_c = 1.1(1.0)(4.32) = **4.75 hp**

(b) HP_g = 5.01/0.83 = **5.73 hp**

21.27 A turning operation is carried out on aluminum (100 BHN). Cutting speed = 5.6 m/s, feed = 0.25 mm/rev, and depth of cut = 2.0 mm. The lathe has a mechanical efficiency = 0.85. Based on the specific energy values in Table 21.2, determine (a) the cutting power and (b) gross power in the turning operation, in Watts.

Solution: (a) From Table 21.2, U = 0.7 N-m/mm^3 for aluminum.
$R_{MR} = vfd$ = 5.6(10^3)(.25)(2.0) = 2.8(10^3) mm^3/s.

$P_c = U\,R_{MR} = 0.7(2.8)(10^3) = 1.96(10^3)$ N-m/s = **1960 W**

(b) Gross power P_g = 1960/0.85 = **2306 W**

21.28 Solve Problem 21.27 but with the following changes: cutting speed = 1.3 m/s, feed = 0.75 mm/rev, and depth = 4.0 mm. Note that although the power used in this operation is only about 10% greater than in the previous problem, the metal removal rate is about 40% greater.

Solution: (a) From Table 21.2, U = 0.7 N-m/mm^3 for aluminum. Since feed is greater than 0.25 mm/rev in the table, a correction factor must be applied from Figure 21.14. For f = 0.75 mm/rev = t_o, correction factor = 0.80.
$R_{MR} = vfd = 1.3(10^3)(.75)(4.0) = 3.9(10^3)$ mm^3/s.
$P_c = U\,R_{MR} = 0.8(0.7)(3.9)(10^3) = 2.184(10^3)$ N-m/s = **2184 W**

(b) Gross power P_g = 2184/0.85 = **2569 W**

21.29 A turning operation is performed on an engine lathe using a tool with zero rake angle in the direction of chip flow. The work material is an alloy steel with hardness = 325 Brinell hardness. The feed is 0.015 in/rev, depth of cut is 0.125 in and cutting speed is 300 ft/min. After the cut, the chip thickness ratio is measured to be 0.45. (a) Using the appropriate value of specific energy from Table 21.2, compute the horsepower at the drive motor, if the lathe has an efficiency = 85%. (b) Based on horsepower, compute your best estimate of the cutting force for this turning operation. Use the orthogonal cutting model as an approximation of the turning process.

Solution: (a) From Table 21.2, $U = P_u$ = 520,000 in-lb/in^3 for alloy steel of the specified hardness. Since feed is greater than 0.010 in/rev in the table, a correction factor must be applied from Figure 21.14. For f = 0.015 in/rev = t_o, correction factor = 0.95. Thus,
U = 520,000(0.95) = 494,000 in-lb/in^3 = 41,167 ft-lb/in^3.
R_{MR} = 300 x 12(.015)(0.125) = 6.75 in^3/min
$P_c = U\,R_{MR}$ = 41,167(6.75) = 277,875 ft-lb/min
HP_c = 277,875/33,000 = 8.42 hp
HP_g = 8.42/0.85 = **9.9 hp**

(b) $HP_c = vF_c/33{,}000$. Rearranging, $F_c = 33{,}000\,(HP_c/v)$ = 33,000(8.42/300) = **926 lb.**

Check: Use unit horsepower from Table 21.2 rather than specific energy. HP_u = 1.3 hp/(in^3/min). Applying the correction factor correction factor = 0.95, HP_u = 1.235 hp/(in^3/min).
R_{MR} = 300 x 12(.015)(0.125) = 6.75 in^3/min, same as before
HP_c = 1.235(6.75) = 8.34 hp
HP_g = 8.34/0.85 = **9.8 hp**

(b) F_c = 33,000 (8.3/300) = **913 lb.**

21.30 A lathe performs a turning operation on a workpiece of 6.0 in diameter. The shear strength of the work is 40,000 lb/in^2 and the tensile strength is 60,000 lb/in^2. The rake angle of the tool is 6°. The cutting speed = 700 ft/min, feed = 0.015 in/rev, and depth = 0.090 in. The chip thickness after the cut is 0.025 in. Determine (a) the horsepower required in the operation, (b) unit horsepower for this material under these conditions, and (c) unit horsepower as it would be listed in Table 21.2 for a t_o of 0.010 in. Use the orthogonal cutting model as an approximation of the turning process.

Solution: (a) Must find F_c and v to determine HP.
r = 0.015/0.025 = 0.6
$\phi = \tan^{-1}(0.6 \cos 6/(1 - 0.6 \sin 6)) = \tan^{-1}(0.6366) = 32.5°$
$\beta = 2(45) + \alpha - 2(\phi) = 90 + 6 - 2(32.5) = 31.0°$
$A_s = t_o w/\sin \phi = (0.015)(0.09)/\sin 32.5 = 0.00251$ in^2
$F_s = SA_s$ = 40,000(0.00251) = 101 lb.
$F_c = F_s \cos(\beta - \alpha)/\cos(\phi + \beta - \alpha)$

F_c = 101 cos(31 - 6)/cos(32.5 + 31.0 – 6) = 170 lb.
$HP_c = F_c v$/33,000 = 170(700)/33,000 = **3.61 hp.**

(b) R_{MR} = 700 x 12(0.0075)(0.075) = 11.3 in^3/min
$HP_u = HP_c / R_{MR}$ = 3.61/11.3 = **0.319 hp/(in^3/min)**

(c) Correction factor = 0.85 from Fig. 21.14 to account for the fact that f = 0.015 in/rev instead of 0.010 in/rev. Taking this correction factor into account, HP_u = 0.375/0.85 = **0.441 hp/(in^3/min)** as it would appear in Table 21.2 for a feed (t_o) = 0.010 in/rev.

21.31 In a turning operation on an aluminum alloy workpiece, the feed = 0.020 in/rev, and depth of cut = 0.250 in. The motor horsepower of the lathe is 20 hp and it has a mechanical efficiency = 92%. The unit horsepower value = 0.25 hp/(in^3/min) for this aluminum grade. What is the maximum cutting speed that can be used on this job?

Solution: From Table 21.3, HP_u = 0.25 hp/(in^3/min) for aluminum. Since feed is greater than 0.010 in/rev in the table, a correction factor must be applied from Figure 21.14. For f = 0.020 in/rev = t_o, correction factor = 0.9.
$HP_c = HP_u$ x R_{MR}, $HP_g = HP_c/E$
$R_{MR} = vfd = 12v(.020)(0.250) = 0.06\,v$ in^3/min
$HP_c = 0.9(0.25)(0.06\,v) = 0.0135\,v$ hp
$HP_g = 0.0135\,v/0.92 = 0.014674\,v$ = 20 hp
v = 20/0.014674 = 1363 ft/min

Cutting Temperature

21.32 Orthogonal cutting is performed on a metal whose mass specific heat = 1.0 J/g-C, density = 2.9 g/cm^3, and thermal diffusivity = 0.8 cm^2/s. The cutting speed is 4.5 m/s, uncut chip thickness is 0.25 mm, and width of cut is 2.2 mm. The cutting force is measured at 1170 N. Using Cook's equation, determine the cutting temperature if the ambient temperature = 22°C.

Solution: ρC = (2.9 g/cm^3)(1.0 J/g-°C) = 2.90 J/cm^3-°C = (2.90x10^{-3}) J/mm^3-°C
K = 0.8 cm^2/s = 80 mm^2/s
$U = F_c v/R_{MR}$ = 1170 N x 4.5 m/s/(4500 mm/s x 0.25 mm x 2.2 mm) = 2.127 N-m/mm^3
$T = 0.4U/(\rho C) \text{ x } (vt_o/K)^{0.333}$
T = 22 + (0.4 x 2.127 N-m/mm^3/(2.90x10^{-3}) J/mm^3-C) [4500 mm/s x 0.25 mm/80 mm^2/s]$^{0.333}$
T = 22 + (0.2934 x 10^3 C)(14.06)$^{.333}$ = 22 + 293.4(2.41) = 22° + 707° = **729°C**

21.33 Consider a turning operation performed on steel whose hardness = 225 HB at a speed = 3.0 m/s, feed = 0.25 mm, and depth = 4.0 mm. Using values of thermal properties found in the tables and definitions of Section 4.1 and the appropriate specific energy value from Table 21.2, compute an estimate of cutting temperature using the Cook equation. Assume ambient temperature = 20°C.

Solution: From Table 21.2, U = 2.2 N-m/mm^3 = 2.2 J/mm^3
From Table 4.1, ρ = 7.87 g/cm^3 = 7.87(10^{-3}) g/mm^3
From Table 4.1, C = 0.11 Cal/g-°C. From note “a” at the bottom of the table, 1 cal = 4.186 J.
Thus, C = 0.11(4.186) = 0.460 J/ g-°C
ρC = (7.87 g/cm^3)(0.46 J/g-°C) = 3.62(10^{-3}) J/mm^3-°C
From Table 4.2, thermal conductivity k = 0.046 J/s-mm-°C
From Eq. (4.3), thermal diffusivity $K = k/\rho C$
K = 0.046 J/s-mm-°C /[(7.87 x 10^{-3} g/mm^3)(0.46 J/g-°C)] = 12.7 mm^2/s
Using Cook’s equation, $t_o = f$ = 0.25 mm
$T = (0.4(2.2)/3.62(10^{-3}))[3(10^3)(0.25)/12.7]^{0.333} = 0.2428(10^3)(59.06)^{0.333}$
= 242.8(3.89) = 944.4 C°
Final temperature, taking ambient temperature in account T = 20 + 944 = **964°C**

21.34 An orthogonal cutting operation is performed on a certain metal whose volumetric specific heat = 110 in-lb/in^3-F, and thermal diffusivity = 0.140 in^2/sec. The cutting speed = 350 ft/min, chip thickness before the cut = 0.008 in, and width of cut = 0.100 in. The cutting force is measured at 200 lb. Using Cook's equation, determine the cutting temperature if the ambient temperature = 70°F.

Solution: v = 350 ft/min x 12 in/ft/60 sec/min = 70 in/sec.
$U = F_c v/vt_o w$ = 200(70)/(70 x 0.008 x 0.100) = 250,000 in-lb/in^3.
$T = 70 + (0.4U/\rho C)(vt_o/K)^{0.333}$ =
$T = 70 + (0.4 \text{ x } 250{,}000/110)[70 \text{ x } 0.008/0.14]^{0.333} = 70 + (909)(4)^{0.333} = 70 + 1436 =$ **1506°F**

21.35 It is desired to estimate the cutting temperature for a certain alloy steel whose hardness = 240 Brinell. Use the appropriate value of specific energy from Table 21.2 and compute the cutting temperature by means of the Cook equation for a turning operation in which the cutting speed is 500 ft/min, feed is 0.005 in/rev, and depth of cut is 0.070 in. The work material has a volumetric specific heat of 210 in lb/in^3-F and a thermal diffusivity of 0.16 in^2/sec. Assume ambient temperature = 88°F.

Solution: From Table 21.2, U for alloy steel (310 BHN) = 320,000 in-lb/in^3.
Since f = 0.005 in/rev, correction factor = 1.25.
Therefore U = 320,000(1.25) = 400,000 in-lb/in^3.
v = 500 ft/min x 12 in/ft/60 sec/min = 100 in/sec.
$T = T_a + (0.4U/\rho C)(vt_o/K)^{0.333} = 88 + (0.4 \text{ x } 400{,}000/210)(100 \text{ x } 0.005/0.16)^{0.333}$
$= 88 + (762)(3.125)^{0.333} = 88 + 1113 =$ **1201°F**

21.36 An orthogonal machining operation removes metal at 1.8 in^3/min. The cutting force in the process = 300 lb. The work material has a thermal diffusivity = 0.18 in^2/sec and a volumetric specific heat = 124 in-lb/in^3-F. If the feed $f = t_o$ = 0.010 in and width of cut = 0.100 in, use the Cook formula to compute the cutting temperature in the operation given that ambient temperature = 70°F.

Solution: $R_{MR} = vt_o w$, $v = R_{MR}/t_o w$ = 1.8/(0.01 x 0.100) = 1800 in/min = 30 in/sec
$U = F_c v/vt_o w$ = 300(30)/(30 x 0.010 x 0.100) = 300,000 in-lb/in^3.
$T = 70 + (0.4U/\rho C)(vt_o/K)^{0.333} = 70 + (0.4 \text{ x } 300{,}000/124)(30 \text{ x } 0.010/0.18)^{0.333}$
$= 70 + (968)(1.667)^{0.333} = 70 + 1147 =$ **1217°F**

21.37 A turning operation uses a cutting speed = 200 m/min, feed = 0.25 mm/rev, and depth of cut = 4.00 mm. The thermal diffusivity of the work material = 20 mm^2/s and the volumetric specific heat = 3.5 (10^{-3}) J/mm^3-C. If the temperature increase above ambient temperature (20°F) is measured by a tool-chip thermocouple to be 700°C, determine the specific energy for the work material in this operation.

Solution: Rearranging the Cook equation, $U = T(\rho C/0.4)(K/vt_o)^{0.333}$
$U = (700 - 20)(3.5 \text{ x } 10^{-3}/0.4)(20/\{(200/60)(10^3)(0.25)\})^{0.333}$
$U = 680(8.75 \text{ x } 10^{-3})(0.024)^{0.333} = 5.95(0.2888) =$ **1.72 N-m/mm³**

21.38 During a turning operation, a tool-chip thermocouple was used to measure cutting temperature. The following temperature data were collected during the cuts at three different cutting speeds (feed and depth were held constant): (1) v = 100 m/min, T = 505°C, (2) v = 130 m/min, T = 552°C, (3) v = 160 m/min, T = 592°C. Determine an equation for temperature as a function of cutting speed that is in the form of the Trigger equation, Eq. (21.23).

Solution: Trigger equation $T = Kv^m$
Choose points (1) and (3) and solve simultaneous equations using $T = Kv^m$ as the model.
(1) $505 = K(100)^m$ and (3) $592 = K(160)^m$
(1) $\ln 505 = \ln K + m \ln 100$ and (3) $\ln 592 = \ln K + m \ln 160$

Combining (1) and (3): ln 505 - m ln 100 = ln 592 - m ln 160
6.2246 – 4.6052 m = 6.3835 – 5.0752 m
0.47 m = 0.1589 **m = 0.338**
(1) $K = 505/100^{0.338} = 505/4.744 = 106.44$
(2) $K = 592/160^{0.338} = 592/5.561 = 106.45$ Use ***K* = 106.45**

Check equation with data point (2): $T = 106.45(130)^{0.338} = 551.87$°C (pretty close to the given value of 552°C).

22 MACHINING OPERATIONS AND MACHINE TOOLS

Review Questions

22.1 What are the differences between rotational parts and prismatic parts in machining?

Answer. Rotational parts are cylindrical or disk-shaped and are machined on a turning machine (e.g., a lathe); prismatic parts are block-shaped or flat and are generally produced on a milling machine, shaper, or planer.

22.2 Distinguish between generating and forming when machining workpart geometries.

Answer. Generating refers to the creation of work geometry due to the feed trajectory of the cutting tool; examples include straight turning, taper turning, and profile milling. Forming involves the creation of work geometry due to the shape of the cutting tool; common examples include form turning and drilling.

22.3 Give two examples of machining operations in which generating and forming are combined to create workpart geometry.

Answer. The two examples given in the text are thread cutting on a lathe and slot milling.

22.4 Describe the turning process.

Answer. Turning is a machining process in which a single-point tool removes material from the surface of a rotating cylindrical workpiece, the tool being fed in a direction parallel to the axis of work rotation.

22.5 What is the difference between threading and tapping?

Answer. A threading operation is performed on a turning machine and produces an external thread, while tapping is normally performed on a drilling machine and produces an internal thread.

22.6 How does a boring operation differ from a turning operation?

Answer. Boring produces an internal cylindrical shape from an existing hole, while turning produces an external cylindrical shape.

22.7 What is meant by the designation 12 x 36 inch lathe?

Answer. A 12 x 36 lathe has a 12 inch swing (maximum work diameter that can be accommodated) and a 36 inch distance between centers (indicating the maximum work length that can be held between centers).

22.8 Name the various ways in which a workpart can be held in a lathe.

Answer. Methods of holding the work in a lathe include: (1) between centers, (2) chuck, (3) collet, and (4) face plate.

22.9 What is the difference between a live center and a dead center, when these terms are used in the context of workholding in a lathe?

Answer. A center holds the work during rotation at the tailstock end of the lathe. A live center is mounted in bearings and rotates with the work, while a dead center does not rotate - the work rotates about it.

22.10 How does a turret lathe differ from an engine lathe?

Answer. A turret lathe has a toolholding turret in place of a tailstock; the tools in the turret can be brought to work to perform multiple cutting operations on the work without the need to change tools as in operating a conventional engine lathe.

22.11 What is a blind hole?

Answer. A blind hole does not exit the work; by comparison, a through hole exits the opposite side of the workpart.

22.12 What is the distinguishing feature of a radial drill press?

Answer. A radial drill has a long radial arm along which the drill head can be positioned to allow the drilling of large work parts. The radial arm can also be swiveled about the column to drill parts on either side of the worktable.

22.13 What is the difference between peripheral milling and face milling?

Answer. In peripheral milling, cutting is accomplished by the peripheral teeth of the milling cutter and the tool axis is parallel to the work surface; in face milling, cutting is accomplished by the flat face of the cutter whose axis is perpendicular to the work surface.

22.14 Describe profile milling.

Answer. Profile milling generally involves the milling of the outside periphery of a flat part.

22.15 What is pocket milling?

Answer. Pocket milling uses an end milling cutter to machine a shallow cavity (pocket) into a flat workpart.

22.16 Describe the difference between up milling and down milling?

Answer. In up milling, the cutter speed direction is opposite the feed direction; in down milling, the direction of cutter rotation is the same as the feed direction.

22.17 How does a universal milling machine differ from a conventional knee-and-column machine?

Answer. The universal milling machine has a worktable that can be rotated about a vertical axis to present the part at any specified angle to the cutter spindle.

22.18 What is a machining center?

Answer. A machining center is a CNC machine tool capable of performing multiple types of cutting operations involving rotating spindles (e.g., milling, drilling); the machine is typically equipped with automatic tool-changing, pallet shuttles to speed workpart changing, and automatic workpart positioning.

22.19 What is the difference between a machining center and a turning center?

Answer. A machining center is generally confined to rotating spindle operations (e.g., milling, drilling); while a turning center performs turning type operations, generally with single-point tools.

22.20 What can a mill-turn center do that a conventional turning center cannot do?

Answer. The mill-turn center has the capacity to position a rotational workpart at a specified angular location, permitting milling or drilling to be performed at a location on the periphery of the part.

22.21 How do shaping and planing differ?

Answer. In shaping, the work is stationary during the cut, and the speed motion is performed by the cutting tool; while in planing, the cutting tool is stationary, and the workpart is moved past the tool in the speed motion.

22.22 What is the difference between internal broaching and external broaching?

Answer. Internal broaching is accomplished on the inside surface (hole) of a workpart; while external broaching is performed on one of the outside surfaces of the part.

22.23 Identify the three basic forms of sawing operation?

Answer. The three forms of sawing are: (1) hacksawing, (2) bandsawing, and (3) circular sawing.

22.24 (**Video**) For what types of parts are VTLs (vertical turret lathes) used?

Answer: VTLs are used to turn large diameter round parts that are too large to be held in a horizontal lathe.

22.25 (**Video**) List the four axes for a vertical machining center (VMC) with a rotational axis on the table.

Answer: The four axes are the three linear axes: X, Y, and Z; and the rotational axis: B.

22.26 (**Video**) What is the purpose of a tombstone that is used with a horizontal machining center (HMC)?

Answer: The tombstone is a multi-sided work holding device (often rectangular) that rotates into position for machining to occur. Parts are clamped to each of the sides of the tombstone. The tombstone rotates the next part towards the spindle before the cycle starts.

22.27 (**Video**) List the three parts of a common twist drill.

Answer: The three parts of a common twist drill are the: 1) shank, 2) flutes, and 3) point.

22.28 (**Video**) What is a gang-drilling machine?

Answer: A gang drilling machine consist of two or more common drilling machines mounted on a common base or table. Each machine is setup to perform a different operation on a part. The operator can move down the line performing each operation in succession.

Multiple Choice Questions

There are 23 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

22.1 Which of the following are examples of generating the workpart geometry in machining, as opposed to forming the geometry (two best answers): (a) broaching, (b) contour turning, (c) drilling, (d) profile milling, and (e) thread cutting?

Answer. (b) and (d).

22.2 In a turning operation, the change in diameter of the workpart is equal to which one of the following: (a) 1 x depth of cut, (b) 2 x depth of cut, (c) 1 x feed, or (d) 2 x feed?

Answer. (b).

22.3 A lathe can be used to perform which of the following machining operations (three correct answers): (a) boring, (b) broaching, (c) drilling, (d) milling, (e) planing, and (f) turning?

Answer. (a), (c), and (f).

22.4 A facing operation is normally performed on which one of the following machine tools: (a) drill press, (b) lathe, (c) milling machine, (d) planer, or (e) shaper?

Answer. (b).

22.5 Knurling is performed on a lathe, but it is not a metal cutting operation: (a) true or (b) false?

Answer. (a). It is a metal forming operation.

22.6 Which one of the following cutting tools cannot be used on a turret lathe: (a) broach, (b) cutoff tool, (c) drill bit, (d) single-point turning tool, or (e) threading tool?

Answer. (a).

22.7 Which one of the following turning machines permits very long bar stock to be used: (a) chucking machine, (b) engine lathe, (c) screw machine, (d) speed lathe, or (e) turret lathe?

Answer. (c).

22.8 The twist drill is the most common type of drill bit: (a) true or (b) false?

Answer. (a).

22.9 A tap is a cutting tool used to create which one of the following geometries: (a) external threads, (b) flat planar surfaces, (c) holes used in beer kegs, (d) internal threads, or (e) square holes?

Answer. (d).

22.10 Reaming is used for which of the following functions (three correct answers): (a) accurately locate a hole position, (b) enlarge a drilled hole, (c) improve surface finish on a hole, (d) improve tolerance on hole diameter, and (e) provide an internal thread?

Answer. (b), (c), and (d).

22.11 End milling is most similar to which one of the following: (a) face milling, (b) peripheral milling, (c) plain milling, or (d) slab milling?

Answer. (a).

22.12 The basic milling machine is which one of the following: (a) bed type, (b) knee-and-column, (c) profiling mill, (d) ram mill, or (e) universal milling machine?

Answer. (b).

22.13 A planing operation is best described by which one of the following: (a) a single-point tool moves linearly past a stationary workpart, (b) a tool with multiple teeth moves linearly past a stationary workpart, (c) a workpart is fed linearly past a rotating cutting tool, or (d) a workpart moves linearly past a single-point tool?

Answer. (d).

22.14 A broaching operation is best described by which one of the following: (a) a rotating tool moves past a stationary workpart, (b) a tool with multiple teeth moves linearly past a stationary workpart, (c) a workpart is fed past a rotating cutting tool, or (d) a workpart moves linearly past a stationary single-point tool?

Answer. (b).

22.15 The three basic types of sawing, according to type of blade motion involved, are (a) abrasive cutoff, (b) bandsawing, (c) circular sawing, (d) contouring, (e) friction sawing, (f) hacksawing, and (g) slotting?

Answer. (b), (c), and (f).

22.16 Gear hobbing is a special form of which one of the following machining operations: (a) grinding, (b) milling, (c) planing, (d) shaping, or (e) turning?

Answer. (b).

Problems

Turning and Related Operations

22.1 A cylindrical workpart 200 mm in diameter and 700 mm long is to be turned in an engine lathe. Cutting speed = 2.30 m/s, feed = 0.32 mm/rev, and depth of cut = 1.80 mm. Determine (a) cutting time, and (b) metal removal rate.

Solution: (a) $N = v/(\pi D) = (2.30\text{ m/s})/0.200\pi = 3.66$ rev/s
$f_r = Nf = 6.366(.3) = 1.17$ mm/s
$T_m = L/f_r = 700/1.17 = 598$ s = **9.96 min**

Alternative calculation using Eq. (22.5), $T_m = 200(700)\pi/(2{,}300 \text{ x } 0.32) = 597.6$ sec = 9.96 min

(b) $R_{MR} = vfd = (2.30\text{ m/s})(10^3)(0.32\text{ mm})(1.80\text{ mm})$ = **1320 mm³/s**

22.2 In a production turning operation, the foreman has decreed that a single pass must be completed on the cylindrical workpiece in 5.0 min. The piece is 400 mm long and 150 mm in diameter. Using a feed = 0.30 mm/rev and a depth of cut = 4.0 mm, what cutting speed must be used to meet this machining time requirement?

Solution: Starting with Eq. (22.5): $T_m = \pi D_o L/vf$.
Rearranging to determine cutting speed: $v = \pi D_o L/fT_m$
$v = \pi(0.4)(0.15)/(0.30)(10^{-3})(5.0) = 0.1257(10^3)$ m/min = **125.7 m/min**

22.3 A facing operation is performed on an engine lathe. The diameter of the cylindrical part is 6 in and the length is 15 in. The spindle rotates at a speed of 180 rev/min. Depth of cut = 0.110 in, and feed = 0.008 in/rev. Assume the cutting tool moves from the outer diameter of the workpiece to exactly the center at a constant velocity. Determine (a) the velocity of the tool as it moves from the outer diameter towards the center and (b) the cutting time.

Solution: (a) $f_r = fN = (0.008\text{ in/rev})(180\text{ rev/min})$ = **1.44 in/min**
(b) L = distance from outside to center of part = $D/2$; $T_m = L/f_r = D/(2f_r) = 6/(2 \text{ x } 1.44)$ = **2.083 min**

22.4 A tapered surface is to be turned on an automatic lathe. The workpiece is 750 mm long with minimum and maximum diameters of 100 mm and 200 mm at opposite ends. The automatic controls on the lathe permit the surface speed to be maintained at a constant value of 200 m/min by adjusting the rotational speed as a function of workpiece diameter. Feed = 0.25 mm/rev and depth of cut = 3.0 mm. The rough geometry of the piece has already been formed, and this operation will be the final cut. Determine (a) the time required to turn the taper and (b) the rotational speeds at the beginning and end of the cut.

Solution: (a) $R_{MR} = vfd = (200\text{ m/min})(10^3\text{ mm/m})(0.25\text{ mm})(3.0\text{ mm}) = 150{,}000\text{ mm}^3\text{/min}$
Area of frustrum of cone $A = \pi(R_1 + R_2)\{h^2 + (R_1 - R_2)^2\}^{0.5}$
Given $R_1 = 100$ mm, $R_2 = 50$ mm, and $h = 750$ mm,
$A = \pi(100 + 50)\{750^2 + (100 - 50)^2\}^{0.5} = 150\pi(565{,}000)^{0.5} = 354{,}214\text{ mm}^2$
Given depth of cut $d = 3.0$ mm, volume cut $V = Ad = (354{,}214\text{ mm}^2)(3.0\text{ mm}) = 1{,}062{,}641\text{ mm}^3$
$T_m = V/R_{MR} = (1{,}062{,}641\text{ mm}^3)/(150{,}000\text{ mm}^3\text{/min})$ = **7.084 min**

(b) At beginning of cut ($D_1 = 100$ mm), $N = v/\pi D = 200{,}000/100\pi$ = **636.6 rev/min**
At end of cut ($D_2 = 200$ mm), $N = 200{,}000/200\pi$ = **318.3 rev/min**

22.5 In the taper turning job of Problem 22.4, suppose that the automatic lathe with surface speed control is not available and a conventional lathe must be used. Determine the rotational speed that would be required to complete the job in exactly the same time as your answer to part (a) of that problem.

Solution: At a constant rotational speed and feed, feed rate f_r is constant and Eqs. (22.3) and (22.4) can be used. Combining, $T_m = L/Nf$ and then rearranging to obtain rotational speed $N = L/fT_m$
Given L = 750 mm, f = 0.25 mm/rev, and T_m = 7.084 min from Problem 22.3,
N = 750/(0.25)(7.084) = **423.5 rev/min**

22.6 A cylindrical work bar with 4.5 in diameter and 52 in length is chucked in an engine lathe and supported at the opposite end using a live center. A 46.0 in portion of the length is to be turned to a diameter of 4.25 in one pass at a speed of 450 ft/min. The metal removal rate should be 6.75 in^3/min. Determine (a) the required depth of cut, (b) the required feed, and (c) the cutting time.

Solution: (a) depth d = (4.50 - 4.25)/2 = **0.125 in**
(b) $R_{MR} = vfd$; $f = R_{MR}/(12vd)$ = 6.75/(12 x 450 x 0.125) = 0.010 in
f = **0.010 in/rev**

(c) $N = v/\pi D$ = 450 x 12/4.5π = 382 rev/min
f_r = 382(0.010) = 3.82 in/min
T_m = 46/3.82 = **12.04 min**

22.7 A 4.00-in-diameter workpiece that is 25 in long is to be turned down to a diameter of 3.50 in, using two passes on an engine lathe using a cutting speed = 300 ft/min, feed = 0.015 in/rev, and depth of cut = 0.125 in. The bar will be held in a chuck and supported on the opposite end in a live center. With this workholding setup, one end must be turned to diameter; then the bar must be reversed to turn the other end. Using an overhead crane available at the lathe, the time required to load and unload the bar is 5.0 minutes, and the time to reverse the bar is 3.0 minutes. For each turning cut an allowance must be added to the cut length for approach and overtravel. The total allowance (approach plus overtravel) = 0.50 in. Determine the total cycle time to complete this turning operation.

Solution: First end: cut 15 in of 25 in length.
N = 300 x 12/4π = 286.4 rev/min, f_r = 286.4(0.015) = 4.297 in/min
T_m = (15 + 0.5)/4.297 = 3.61 min; this reduces diameter to 3.75 in
N = 300 x 12/3.75π = 305.5 rev/min, f_r = 305.5(0.015) = 4.583 in/min
T_m = 15.5/4.583 = 3.38 min to reduce the diameter to 3.50 in

Reverse bar, which takes 3.0 min and cut remaining 10 in of 25 in length.
N = 300 x 12/4π = 286.4 rev/min, f_r = 286.4(0.015) = 4.297 in/min
T_m = (10 + 0.5)/4.297 = 2.44 min; this reduces diameter to 3.75 in
N = 300 x 12/3.75π = 305.5 rev/min, f_r = 305.5(0.015) = 4.583 in/min
T_m = 10.5/4.583 = 2.29 min to reduce the diameter to 3.50 in

Loading and unloading bar takes 5.0 min.

Total cycle time = 5.0 + 3.61 + 3.38 + 3.0 + 2.44 + 2.29 = **19.72 min**

22.8 The end of a large tubular workpart is to be faced on a NC vertical boring mill. The part has an outside diameter of 38.0 in and an inside diameter of 24.0 in. If the facing operation is performed at a rotational speed of 40.0 rev/min, feed of 0.015 in/rev, and depth of cut of 0.180 in, determine (a) the cutting time to complete the facing operation and the cutting speeds and metal removal rates at the beginning and end of the cut.

Solution: (a) Distance traveled $L = (D_o - D_i)/2$ = (38 - 24)/2 = 7.0 in
f_r = (40 rev/min)(0.015 in/rev) = 0.60 in/min
T_m = 7.0/0.60 = **11.67 min**

(b) At D_o = 38 in, $N = v/\pi D$, $v = N\pi D$ = (40 rev/min)(π38/12) = **398 ft/min**
$R_{MR} = vfd$ = (398 x 12)(0.015)(0.18) = **12.89 in^3/min**

At D_i = 24 in, $N=v/\pi D$, $v = N\pi D$ = (40 rev/min)(π24/12) = **251 ft/min**
$R_{MR} = vfd$ = (251 x 12)(0.015)(0.18) = **8.14 in^3/min**

22.9 Solve Problem 22.8 except that the machine tool controls operate at a constant cutting speed by continuously adjusting rotational speed for the position of the tool relative to the axis of rotation. The rotational speed at the beginning of the cut = 40 rev/min, and is continuously increased thereafter to maintain a constant cutting speed.

Solution: (a) Total metal removed $V_{MR} = 0.25\pi d(D_o^2 - D_i^2) = 0.25\pi(0.180)(38.0^2 – 24.0^2)$ = 122.7 in^3
R_{MR} is constant throughout cutting if v is constant.
$N=v/\pi D$; $v = N\pi D$ = (40 rev/min)(π38/12) = **398 ft/min**
$R_{MR} = vfd$ = (398 x 12)(0.015)(0.18) = **12.89 in^3/min**
$T_m = V_{MR}/R_{MR}$ = 122.7/12.89 = **9.52 min**

Drilling

22.10 A drilling operation is to be performed with a 12.7 mm diameter twist drill in a steel workpart. The hole is a blind hole at a depth of 60 mm and the point angle is 118°. The cutting speed is 25 m/min and the feed is 0.30 mm/rev. Determine (a) the cutting time to complete the drilling operation, and (b) metal removal rate during the operation, after the drill bit reaches full diameter.

Solution: (a) $N = v/\pi D = 25(10^3) / (12.7\pi)$ = 626.6 rev/min
$f_r = Nf$ = 626.6(0.30) = 188 mm/min
$A = 0.5D \tan(90 – \theta/2) = 0.5(12.7)\tan(90 – 118/2)$ = 3.82 mm
$T_m = (d + A)/f_r$ = (60 + 3.82)/188 = 0.339 min

(b) $R_{MR} = 0.25\pi D^2 f_r = 0.25\pi(12.7)^2(188)$ = 23,800 mm^3/min

22.11 A two-spindle drill simultaneously drills a ½ in hole and a ¾ in hole through a workpiece that is 1.0 inch thick. Both drills are twist drills with point angles of 118°. Cutting speed for the material is 230 ft/min. The rotational speed of each spindle can be set individually. The feed rate for both holes must be set to the same value because the 2 spindles lower at the same rate. The feed rate is set so the total metal removal rate does not exceed 1.50 in^3/min. Determine (a) the maximum feed rate (in/min) that can be used, (b) the individual feeds (in/rev) that result for each hole, and (c) the time required to drill the holes.

Solution: (a) Total $R_{MR} = 1.50 = 0.25\pi D_1^2 f_r + 0.25\pi D_2^2 f_r = 0.25\pi(D_1^2 + D_2^2)f_r$
$1.50 = 0.25\pi(0.5^2 + 0.75^2)f_r = 0.638f_r$
f_r = 1.50/0.638 = **2.35 in/min**

(b) For 1/2 in hole, $N = v/\pi D = 230/(0.50\pi/12)$ = 1757
For 3/4 in hole, $N = v/\pi D = 230/(0.75\pi/12)$ = 1171
$f = f_r/N$. For 1/2 hole, f = 2.35/1757 = **0.0013 in/rev**
For 3/4 hole, f = 2.35/1171 = **0.0020 in/rev**

(c) Must use maximum Allowance for the 2 drills.
For 1/2 in hole, $A = 0.5D \tan(90 – \theta/2) = 0.5(0.50) \tan(90 – 118/2)$ = 0.150 in
For 3/4 in hole, $A = 0.5D \tan(90 – \theta/2) = 0.5(0.75) \tan(90 – 118/2)$ = 0.225 in
$T_m= (t + A)/f_r$ = (1.00 + 0.225)/2.35 = **0.522 min = 31.2 seconds**

22.12 A NC drill press is to perform a series of through-hole drilling operations on a 1.75 in thick aluminum plate that is a component in a heat exchanger. Each hole is 3/4 in diameter. There are 100 holes in all, arranged in a 10 by 10 matrix pattern, and the distance between adjacent hole centers (along the square) = 1.5 in. The cutting speed = 300 ft/min, the penetration feed (z-direction) = 0.015 in/rev, and the traverse rate between holes (x-y plane) = 15.0 in/min. Assume that x-y moves are made at a distance of 0.50 in above the work surface, and that this distance must be included in the penetration feed rate for each hole. Also, the rate at which the drill is retracted from each hole is twice the penetration feed rate. The drill has a point angle = 100°. Determine the time required from the beginning of the first hole to the completion of the last hole, assuming the most efficient drilling sequence will be used to accomplish the job.

Solution: Time to drill each hole:
N = 300 x 12/0.75π = 1527.7 rev/min
f_r = 1527.7(0.015) = 22.916 in/min
Distance per hole = 0.5 + A + 1.75
A = 0.5(0.75) tan(90 – 100/2) = 0.315 in
T_m = (0.5 + 0.315 + 1.75)/22.916 = 0.112 min

Time to retract drill from hole = 0.112/2 = 0.056 min

All moves between holes are at a distance = 1.5 in using a back and forth path between rows of holes. Time to move between holes = 1.5/15 = 0.1 min. With 100 holes, the number of moves between holes = 99.

Total cycle time to drill 100 holes = 100(0.112 + 0.056) + 99(0.1) = **26.7 min**

22.13 A gundrilling operation is used to drill a 9/64-in diameter hole to a certain depth. It takes 4.5 minutes to perform the drilling operation using high pressure fluid delivery of coolant to the drill point. The current spindle speed = 4000 rev/min, and feed = 0.0017 in/rev. In order to improve the surface finish in the hole, it has been decided to increase the speed by 20% and decrease the feed by 25%. How long will it take to perform the operation at the new cutting conditions?

Solution: $f_r = Nf$ = 4000 rev/min (0.0017 in/rev) = 6.8 in/min
Hole depth d = 4.5 min (6.8 in/min) = 30.6 in
New speed v = 4000(1 + 0.20) = 4800 rev/min
New feed f = 0.0017(1- 0.25) = 0.001275 in/min
New feed rate f_r = 4800(0.001275) = 6.12 in/min
New drilling time T_m = 30.6/6.12 in/min = **5.0 min**

Milling

22.14 A peripheral milling operation is performed on the top surface of a rectangular workpart which is 400 mm long by 60 mm wide. The milling cutter, which is 80 mm in diameter and has five teeth, overhangs the width of the part on both sides. Cutting speed = 70 m/min, chip load = 0.25 mm/tooth, and depth of cut = 5.0 mm. Determine (a) the actual machining time to make one pass across the surface and (b) the maximum material removal rate during the cut.

Solution: (a) $N = v/\pi D$ = 70,000 mm/80π = 279 rev/min
$f_r = Nn_tf$ = 279(5)(0.25) = 348 mm/min
$A = (d(D\text{-}d))^{0.5} = (5(80\text{-}5))^{0.5}$ = 19.4 mm
T_m = (400 + 19.4)/348 = **1.20 min**

(b) $R_{MR} = wdf_r$ = 60(5)(348) = **104,400 mm^3/min**

22.15 e A face milling operation is used to machine 6.0 mm from the top surface of a rectangular piece of aluminum 300 mm long by 125 mm wide in a single pass. The cutter follows a path that is centered over the workpiece. It has four teeth and is 150 mm in diameter. Cutting speed = 2.8 m/s, and chip load = 0.27 mm/tooth. Determine (a) the actual machining time to make the pass across the surface and (b) the maximum metal removal rate during cutting.

Solution: (a) $N = v/\pi D$ = (2800 mm/s)/150π = 5.94 rev/s
$f_r = Nn_tf$ = 5.94(4)(0.27) = 6.42 mm/s

$A = 0.5\left(D - \sqrt{D^2 - w^2}\right) = 0.5\left(150 - \sqrt{150^2 - 125^2}\right) = 0.5(150 – 82.9) = 33.5$ mm

$T_m = (L + A)/f_r = (300 + 33.5))/6.42 =$ **52 s = 0.87 min**

(b) $R_{MR} = wdf_r = 125(6)(6.42) =$ **4813 mm^3/s**

22.16 A slab milling operation is performed on the top surface of a steel rectangular workpiece 12.0 in long by 2.5 in wide. The helical milling cutter, which has a 3.0 in diameter and ten teeth, is set up to overhang the width of the part on both sides. Cutting speed is 125 ft/min, feed is 0.006 in/tooth, and depth of cut = 0.300 in. Determine (a) the actual machining time to make one pass across the surface and (b) the maximum metal removal rate during the cut. (c) If an additional approach distance of 0.5 in is provided at the beginning of the pass (before cutting begins), and an overtravel distance is provided at the end of the pass equal to the cutter radius plus 0.5 in, what is the duration of the feed motion.

Solution: (a) $N = v/\pi D = 125(12)/3\pi = 159.15$ rev/min
$f_r = Nn_tf = 159.15(10)(0.006) = 9.55$ in/min
$A = (d(D\text{-}d))^{0.5} = (0.30(3.0\text{-}0.30))^{0.5} = 0.90$ in
$T_m = (L + A)/f_r = (12.0 + 0.9)/9.55 =$ **1.35 min**

(b) $R_{MR} = wdf_r = 2.5(0.30)(9.55) =$ **7.16 in^3/min**

(c) The cutter travels 0.5 in before making contact with the work. It moves 0.90 in before reaching full depth of cut. It then feeds the length of the work (12.0 in). The overtravel consists of the cutter radius (1.5 in) plus an additional 0.5 in. Thus,
$T_f = (0.5 + 0.9 + 12.0 + 1.5 + 0.5)/9.55 =$ **1.56 min**

22.17 A face milling operation is performed on the top surface of a steel rectangular workpiece 12.0 in long by 2.5 in wide. The milling cutter follows a path that is centered over the workpiece. It has five teeth and a 3.0 in diameter. Cutting speed = 250 ft/min, feed = 0.006 in/tooth, and depth of cut = 0.150 in. Determine (a) the actual cutting time to make one pass across the surface and (b) the maximum metal removal rate during the cut. (c) If an additional approach distance of 0.5 in is provided at the beginning of the pass (before cutting begins), and an overtravel distance is provided at the end of the pass equal to the cutter radius plus 0.5 in, what is the duration of the feed motion.

Solution: (a) $N = v/\pi D = 250(12)/3\pi = 318.3$ rev/min
$f_r = 318.3(5)(0.006) = 9.55$ in/min

$A = 0.5\left(D - \sqrt{D^2 - w^2}\right) = 0.5\left(3 - \sqrt{3^2 - 2.5^2}\right) = 0.671$ in

$T_m = (12.0 + 0.671)/9.55 =$ **1.33 min**

(b) $R_{MR} = 2.5(0.150)(9.55) =$ **3.58 in^3/min**

(c) The cutter travels 0.5 in before making contact with the work. It moves 1.50 in before its center is aligned with the starting edge of the 12.0 in workpiece. It then feeds the length of the work (12.0 in). The overtravel consists of the cutter radius (1.5 in) plus an additional 0.5 in. Thus,
$T_f = (0.5 + 1.5 + 12.0 + 1.5 + 0.5)/9.55 =$ **1.68 min**

22.18 Solve Problem 22.17 except that the workpiece is 5.0 in wide and the cutter is offset to one side so that the swath cut by the cutter = 1.0 in wide. This is called partial face milling, Figure 22.20(b).

Solution: (a) $N = 250(12)/3\pi = 318.3$ rev/min
$f_r = 318.3(5)(0.006) = 9.55$ in/min
$A = (1(3\text{-}1))^{.5} = 1.414$ in
$T_m = (12.0 + 1.414)/9.55 =$ **1.405 min**

(b) $R_{MR} = 1.0(.150)(9.55) =$ **1.43 in^3/min**

(c) The cutter travels 0.5 in before making contact with the work. It moves 1.414 in before reaching full width of cut. It then feeds the length of the work (12.0 in). The overtravel consists of the cutter radius (1.5 in) plus an additional 0.5 in. Thus,
T_f = (0.5 + 1.414 + 12.0 + 1.5 + 0.5)/9.55 = **1.67 min**

22.19 A face milling operation removes 0.32 in depth of cut from the end of a cylinder that has a diameter of 3.90 in. The cutter has a 4-in diameter with 4 teeth, and its feed trajectory is centered over the circular face of the work. The cutting speed is 375 ft/min and the chip load is 0.006 in/tooth. Determine (a) the time to machine, (b) the average metal removal rate (considering the entire machining time), and (c) the maximum metal removal rate.

Solution: (a) $N = v/\pi D$ = 375(12)/4π = 358 rev/min
$f_r = Nn_tf$ = 358(4)(0.006) = 8.59 in/min
$T_m = L/f_r$ = 3.9/8.59 = **0.454 min**

(b) $R_{MRaverage}$ = total removed/total time = $0.25\pi D^2 d/T_m = 0.25\pi(3.9)^2(0.32)/0.454$ = **8.42 in^3/min**

(c) R_{MRmax} = point where the cutter just about covers the entire cylinder. In this case it would be the same as milling a rectangle so $R_{MR} = wdf_r$
$R_{MR} = wdf_r$ = 3.9(0.32)8.59 = **10.73 in^3/min**

22.20 The top surface of a rectangular workpart is machined using a peripheral milling operation. The workpart is 735 mm long by 50 mm wide by 95 mm thick. The milling cutter, which is 60 mm in diameter and has five teeth, overhangs the width of the part equally on both sides. Cutting speed = 80 m/min, chip load = 0.30 mm/tooth, and depth of cut = 7.5 mm. (a) Determine the time required to make one pass across the surface, given that the setup and machine settings provide an approach distance of 5 mm before actual cutting begins and an overtravel distance of 25 mm after actual cutting has finished. (b) What is the maximum material removal rate during the cut?

Solution: (a) $N = v/\pi D$ = 80,000 mm/60π = 424.4 rev/min
$f_r = Nn_tf$ = 424.4(5)(0.3) = 636.6 mm/min
$A = (d(D-d))^{0.5} = (7.5(60-7.5))^{0.5}$ = 19.84 mm
T_m = (735 + 5 + 19.84 + 25)/636.6 = **1.233 min**

(b) $R_{MR} = wdf_r$ = 60(7.5)(636.6) = **286,470 mm^3/min**

Machining and Turning Centers

22.21 A three-axis CNC machining center is tended by a worker who loads and unloads parts between machining cycles. The machining cycle takes 5.75 min, and the worker takes 2.80 min using a hoist to unload the part just completed and load and fixture the next part onto the machine worktable. A proposal has been made to install a two-position pallet shuttle at the machine so that the worker and the machine tool can perform their respective tasks simultaneously rather than sequentially. The pallet shuttle would transfer the parts between the machine worktable and the load/unload station in 15 sec. Determine (a) the current cycle time for the operation and (b) the cycle time if the proposal is implemented. What is the percentage increase in hourly production rate that would result from using the pallet shuttle?

Solution: (a) The current cycle time is the machine cycle time plus the load unload time.
T_c = 5.75 + 2.80 = **8.55 min**

(b) The cycle time under the proposal is T_c = Max{5.75, 2.80} + 0.25 = **6.00 min**

(c) The current hourly production rate R_p = 60/8.55 = 7.02 pc/hr
The production rate under the proposal R_p = 60/6.0 = 10 pc/hr
This is an increase of (10 – 7.02)/7.02 = 0.425 = **42.5%**

22.22 A part is produced using six conventional machine tools consisting of three milling machines and three drill presses. The machine cycle times on these machines are 4.7 min, 2.3 min, 0.8 min, 0.9 min, 3.4 min, and 0.5 min. The average load/unload time for each of these operations is 1.25 min. The corresponding setup times for the six machines are 1.55 hr, 2.82 hr, 57 min, 45 min, 3.15 hr, and 36 min, respectively. The total material handling time to carry one part between the machines is 20 min (consisting of five moves between six machines). A CNC machining center has been installed, and all six operations will be performed on it to produce the part. The setup time for the machining center for this job is 1.0 hr. In addition, the machine must be programmed for this part (called "part programming"), which takes 3.0 hr. The machine cycle time is the sum of the machine cycle times for the six machines. Load/unload time is 1.25 min. (a) What is the total time to produce one of these parts using the six conventional machines if the total consists of all setups, machine cycle times, load/unload times, and part transfer times between machines? (b) What is the total time to produce one of these parts using the CNC machining center if the total consists of the setup time, programming time, machine cycle time, and load/unload time, and what are the percent savings in total time compared to your answer in (a)? (c) If the same part is produced in a batch of 20 pieces, what is the total time to produce them under the same conditions as in (a) except that the total material handling time to carry the 20 parts in one unit load between the machines is 40 min? (d) If the part is produced in a batch of 20 pieces on the CNC machining center, what is the total time to produce them under the same conditions as in part (b), and what are the percent savings in total time compared to your answer in (c)? (e) In future orders of 20 pieces of the same part, the programming time will not be included in the total time because the part program has already been prepared and saved. In this case, how long does it take to produce the 20 parts using the machining center, and what are the percent savings in total time compared to your answer in (c)?

Solution: (a) $TT = \Sigma T_{su} + \Sigma T_m + \Sigma T_L + \Sigma T_{MH}$
$\Sigma T_{su} = 60(1.55 + 2.82 + 3.15) + 57 + 45 + 36 = 589.2$ min
$\Sigma T_m = 4.7 + 2.3 + 0.8 + 0.9 + 3.4 + 0.5 = 12.6$ min
$\Sigma T_L + \Sigma T_{MH} = 6(1.25) + 20 = 27.5$ min
$TT = 589.2 + 12.6 + 27.5 = 629.3$ min $= 10.49$ hr

(b) $TT = T_{pp} + T_{su} + \Sigma T_m + T_L$
$TT = 180 + 60 + 12.6 + 1.25 = 253.85$ min $= 4.23$ hr
% savings = (10.49 – 4.23)/10.49 = 6.26/10.49 = 0.597 = 59.7%

(c) $TT = \Sigma T_{su} + 20\Sigma T_m + 20\Sigma T_L + \Sigma T_{MH}$
$\Sigma T_{su} = 60(1.55 + 2.82 + 3.15) + 57 + 45 + 36 = 589.2$ min
$20\Sigma T_m = 20(4.7 + 2.3 + 0.8 + 0.9 + 3.4 + 0.5) = 20(12.6) = 252$ min
$20\Sigma T_L + \Sigma T_{MH} = 20(6)(1.25) + 40 = 150 + 40 = 190$ min
$TT = 589.2 + 252 + 190 = 1031.2$ min $= 17.19$ hr

(d) $TT = T_{pp} + T_{su} + 20\Sigma T_m + 20T_L$
$TT = 180 + 60 + 20(12.6) + 20(1.25) = 517$ min $= 8.62$ hr
% savings = (17.19 – 8.62)/17.19 = 8.57/17.19 = 0.499 = 49.9%

(e) $TT = T_{su} + 20\Sigma T_m + 20T_L$
$TT = 60 + 20(12.6) + 20(1.25) = 337$ min $= 5.62$ hr
% savings = (17.19 – 5.62)/17.19 = 11.57/17.19 = 0.673 = 67.3%

Other Operations

22.23 A shaper is used to reduce the thickness of a 50 mm part to 45 mm. The part is made of cast iron and has a tensile strength of 270 MPa and a Brinell hardness of 165 HB. The starting dimensions of the part are 750 mm x 450 mm x 50 mm. The cutting speed is 0.125 m/sec and the feed is 0.40

mm/pass. The shaper ram is hydraulically driven and has a return stroke time that is 50% of the cutting stroke time. An extra 150 mm must be added before and after the part for acceleration and deceleration to take place. Assuming the ram moves parallel to the long dimension of the part, how long will it take to machine?

Solution: Time per forward stroke = (150 + 750 + 150)/(0.125 x 1000) = 8.4 sec
Time per reverse stroke = 0.50(8.4) = 4.2 sec
Total time per pass = 8.4 + 4.2 = 12.6 sec = 0.21 min
Number of passes = 450/0.40 = 1125 passes
Total time T_m = 1125(0.21) = **236 min**

22.24 An open side planer is to be used to plane the top surface of a rectangular workpart, 20.0 in by 45.0 in. The cutting speed is 30 ft/min, the feed is 0.015 in/pass, and the depth of cut is 0.250 in. The length of the stroke across the work must be set up so that 10 in are allowed at both the beginning and end of the stroke for approach and overtravel. The return stroke, including an allowance for acceleration and deceleration, takes 60% of the time for the forward stroke. The workpart is made of carbon steel with a tensile strength of 50,000 lb/in^2 and a Brinell hardness of 110 HB. How long will it take to complete the job, assuming that the part is oriented in such a way as to minimize the time?

Solution: Orient work so that its length (L = 45 in) is in direction of stroke. This will minimize the number of passes required which will minimize time in this case. Time per forward stroke = (10 + 45 + 10)/(30 x 12) = 0.18 min
Time per reverse stroke = 0.60(.18) = 0.11 min
Total time per pass = 0.18 + 0.11 = 0.29 min
Number of passes = 20.0/0.015 = 1333 passes
Total time T_m = 1333(0.29) = **387 min**

Check: orient work so that its width (w = 20 in) is in direction of stroke.
Time per forward stroke = (10 + 20 + 10)/(30 x 12) = 0.11 min
Time per reverse stroke = 0.60(.11) = 0.067 min
Total time per pass = 0.11 + 0.067 = 0.177 min
Number of passes = 45.0/0.015 = 3000 passes
Total time = 3000(0.177) = **531 min**

22.25 High-speed machining (HSM) is being considered to produce the aluminum part in Problem 22.15. All cutting conditions remain the same except for the cutting speed and the type of insert used in the cutter. Assume the cutting speed will be at the limit given in Table 22.1. Determine (a) the new time to machine the part and (b) the new metal removal rate. (c) Is this part a good candidate for high-speed machining? Explain.

Solution: Assume the same indexable tool (face mill with appropriate inserts) will be used in the new operation. For aluminum, the HSM cutting speed will be 3,600 m/min

(a) $N = v/\pi D$ = (3600(10^3) mm/min)/(150π mm/rev) = 7639 rev/min
$f_r = Nn_tf$ = 7639(4)(0.27) = 8250.6 mm/min
$A = D/2$ = 150/2 = 75 mm
$T_m = (L+A)/f_r$ = (300 + 75)/8250.6 = **0.0454 min = 2.73 sec**

(b) $R_{MR} = wdf_r$ = 125(6)(8250.6) = **5.157 x 10^6 mm^3/min = 6,187,950 mm^3/sec**

(c) This is probably not a good candidate because the machining time is so small and it is a single, simple-geometry operation. The time to load and unload the part will be about as long as the machining time and the machine will be idle while that is happening. It would become a better choice if another part could be loaded and unloaded while the machining was taking place. Then the only delay would be bringing the new part into position. Generally, HSM is justified by at least one of the following conditions: (1) large volumes of metal removed from large parts, (2) multiple cutting operations requiring many different tools, and (3) complex shapes and hard materials (as in the die and mold industry).

23 CUTTING TOOL TECHNOLOGY

Review Questions

23.1 What are the two principal aspects of cutting-tool technology?

Answer. The two main aspects of cutting tool technology are (1) tool material and (2) tool geometry.

23.2 Name the three modes of tool failure in machining.

Answer. The three tool failure modes are (1) fracture failure, (2) temperature failure, and (3) gradual wear.

23.3 What are the two principal locations on a cutting tool where tool wear occurs?

Answer. Wear occurs on the top face of the cutting tool as crater wear and on the side or flank of the tool, called flank wear. Portions of flank wear are often identified separately as notch wear, corresponding to the surface of the work; and nose radius wear, corresponding to the tool point.

23.4 Identify the mechanisms by which cutting tools wear during machining.

Answer. The important tool wear mechanisms are (1) abrasion, (2) adhesion, (3) diffusion, and (4) plastic deformation of the cutting edge.

23.5 What is the physical interpretation of the parameter C in the Taylor tool life equation?

Answer. The parameter C is the cutting speed corresponding to a one-minute tool life. C is the speed-axis intercept on the log-log plot of the tool life data.

23.6 In addition to cutting speed, what other cutting variables are included in the expanded version of the Taylor tool life equation?

Answer. The expanded version of the Taylor equation can include any of the following: feed, depth of cut, and/or work material hardness.

23.7 What are some of the tool life criteria used in production machining operations?

Answer. As identified in the text, tool life criteria used in production include (1) complete failure of the tool, (2) visual observation of flank or crater wear, (3) fingernail test to feel flank wear, (4) sound of the tool, (5) chip disposal problems, (6) degradation of finish, (7) power increase, (8) workpiece count, and (9) length of cutting time for the tool.

23.8 Identify three desirable properties of a cutting-tool material.

Answer. Three desirable properties are (1) toughness to resist fracture failure, (2) hot hardness to resist temperature failure, and (3) wear resistance to prolong the life of the tool during gradual wear.

23.9 What are the principal alloying ingredients in high-speed steel?

Answer. Principal alloying ingredients in HSS are (1) either tungsten or a combination of tungsten and molybdenum, (2) chromium, (3) vanadium, and (4) carbon. Some grades of HSS also contain cobalt.

23.10 What is the difference in ingredients between steel cutting grades and nonsteel-cutting grades of cemented carbides?

Answer. In general, non-steel cutting grades contain only WC and Co. Steel cutting grades contain TiC and/or TaC in addition to WC-Co.

23.11 Identify some of the common compounds that form the thin coatings on the surface of coated carbide inserts.

Answer. The common coatings are: TiN, TiC, and Al_2O_3.

23.12 Name the seven elements of tool geometry for a single point cutting tool.

Answer. The seven elements of single-point tool geometry are (1) back rake angle, (2) side rake angle, (3) end relief angle, (4) side relief angle, (5) end cutting edge angle, (6) side cutting edge angle, and (7) nose radius.

23.13 Why are ceramic cutting tools generally designed with negative rake angles?

Answer. Ceramics possess low shear and tensile strength but good compressive strength. During cutting, this combination of properties is best exploited by giving the tool a negative rake angle to load the tool in compression.

23.14 Identify the alternative ways by which a cutting tool is held in place during machining.

Answer. There are three principal ways: (1) solid shank, in which the cutting edge is an integral part of the tool shank, an example being high speed steel tooling; (2) brazed inserts, used for some cemented carbides; and (3) mechanically clamped inserts, used for most hard tool materials including cemented carbides, coated carbides, cermets, ceramics, SPD, and CBN.

23.15 Name the two main categories of cutting fluid according to function.

Answer. The two functional categories of cutting fluids are: (1) coolants and (2) lubricants.

23.16 Name the four categories of cutting fluid according to chemistry.

Answer. The four categories of cutting fluids according to chemistry are (1) cutting oils, (2) emulsified oils, (3) chemical fluids, and (4) semi-chemical fluids.

23.17 What are the principal lubricating mechanisms by which cutting fluids work?

Answer. There are two lubricating mechanisms that are believed to be effective in metal cutting: (1) boundary lubrication, which involves the formation of a thin fluid film to help separate and protect the contacting surfaces; and (2) extreme pressure lubrication, in which a thin solid layer of a salt such as iron sulfide is formed on the tool surface to provide lubrication.

23.18 What are the methods by which cutting fluids are applied in a machining operation?

Answer. The most common method of application is flooding, in which a steady stream of fluid is direct at the operation. Other methods include mist application, fluid-hole delivery through the tool, and manual application (e.g., using a paint brush).

23.19 Why are cutting fluid filter systems becoming more common and what are their advantages?

Answer. Cutting fluid filter systems are becoming more common due to the environmental protection laws and the need to prolong the life of the fluid before disposal. Advantages of filter systems include longer fluid life, reduced disposal costs, better hygiene, lower machine tool maintenance, and longer cutting tool life.

23.20 Dry machining is being considered by machine shops because of certain problems inherent in the use of cutting fluids. What are those problems associated with the use of cutting fluids?

Answer. Cutting fluids become contaminated over time with a variety of contaminants, including tramp oil, garbage, small chips, molds, fungi, and bacteria. In addition to causing odors and health hazards, contaminated cutting fluids do not perform their lubricating function as well as when they are fresh and clean.

23.21 What are some of the new problems introduced by machining dry?

Answer. Problems with dry machining include (1) overheating the tool, (2) operating at lower cutting speeds and production rates to prolong tool life, and (3) absence of chip removal benefits that are provided by cutting fluids in grinding and milling.

23.22 (**Video**) List the two principal categories of cutting tools**.**

Answer: The two principal categories of cutting tools are (1) single-point cutting tools (used on lathes) and (2) multi point cutting tools (used on mills, drills, reamers, and taps).

23.23 (**Video**) According to the video clip, what is the objective in selection of cutting tools for a given operation?

Answer: The objective when choosing a cutting tool is to safely machine a workpiece in the shortest amount of time while meeting the part's quality requirement. Furthermore, the tooling should be the least costly and least complex to meet the production demands.

23.24 (**Video**) What are the factors a machinist should know in order to select the proper tooling? List at least five.

Answer: The factors a machinist must know in order to select the proper tooling are (1) workpiece starting and finished shape, (2) workpiece hardness, (3) workpiece tensile strength, (4) material abrasiveness, (5) whether the material breaks into short chips or long stringy chips, (6) workholding setup, and (6) power and speed capacity of the machine tool.

23.25 (**Video**) List five characteristics of a good tool material.

Answer: The characteristics of a good tool material are the following, as indicated in the video: (1) it is harder than the workpiece, (2) it retains hardness at high temperatures, (3) it resists wear and thermal shock, (4) it has impact resistant, and (5) it is chemically inert.

Multiple Choice Quiz

There are 19 correct answers in the following multiple-choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

23.1 Of the following cutting conditions, which one has the greatest effect on tool wear: (a) cutting speed, (b) depth of cut, or (c) feed?

Answer. (a).

23.2 As an alloying ingredient in high-speed steel, tungsten serves which of the following functions (two best answers): (a) forms hard carbides to resist abrasion, (b) improves strength and hardness, (c) increases corrosion resistance, (d) increases hot hardness, and (e) increases toughness?

Answer. (a) and (d).

23.3 Cast cobalt alloys typically contain which of the following main ingredients (three best answers): (a) aluminum, (b) cobalt, (c) chromium, (d) iron, (e) nickel, (f) steel, and (g) tungsten?

Answer. (b), (c), and (g).

23.4 Which of the following is not a common ingredient in cemented carbide cutting tools (two correct answers): (a) Al_2O_3, (b) Co, (c) CrC, (d) TiC, and (e) WC?

Answer. (a) and (c).

23.5 An increase in cobalt content has which of the following effects on WC-Co cemented carbides (two best answers): (a) decreases hardness, (b) decreases transverse rupture strength, (c) increases hardness, (d) increases toughness, and (e) increases wear resistance?

Answer. (a) and (d).

23.6 Steel-cutting grades of cemented carbide are typically characterized by which of the following ingredients (three correct answers): (a) Co, (b) Fe, (c) Mo, (d) Ni, (e) TiC, and (f) WC?

Answer. (a), (e), and (f).

23.7 If you had to select a cemented carbide for an application involving finish turning of steel, which C-grade would you select (one best answer): (a) C1, (b) C3, (c) C5, or (d) C7?

Answer. (d).

23.8 Which of the following processes are used to provide the thin coatings on the surface of coated carbide inserts (two best answers): (a) chemical vapor deposition, (b) electroplating, (c) physical vapor deposition, (d) pressing and sintering, and (e) spray painting?

Answer. (a) and (c).

23.9 Which one of the following materials has the highest hardness: (a) aluminum oxide, (b) cubic boron nitride, (c) high-speed steel, (d) titanium carbide, or (e) tungsten carbide?

Answer. (b).

23.10 Which of the following are the two main functions of a cutting fluid in machining (two best answers): (a) improve surface finish on the workpiece, (b) reduce forces and power, (c) reduce friction at the tool-chip interface, (d) remove heat from the process, and (e) wash away chips?

Answer. (c) and (d).

Problems

Tool Life and the Taylor Equation

23.1 Flank wear data were collected in a series of turning tests using a coated carbide tool on hardened alloy steel at a feed of 0.30 mm/rev and a depth of 4.0 mm. At a speed of 125 m/min, flank wear = 0.12 mm at 1 min, 0.27 mm at 5 min, 0.45 mm at 11 min, 0.58 mm at 15 min, 0.73 at 20 min, and 0.97 mm at 25 min. At a speed of 165 m/min, flank wear = 0.22 mm at 1 min, 0.47 mm at 5 min, 0.70 mm at 9 min, 0.80 mm at 11 min, and 0.99 mm at 13 min. The last value in each case is when final tool failure occurred. (a) On a single piece of linear graph paper, plot flank wear as a function of time for both speeds. Using 0.75 mm of flank wear as the criterion of tool failure, determine the tool lives for the two cutting speeds. (b) On a piece of natural log-log paper, plot your results determined in the previous part. From the plot, determine the values of n and C in the Taylor Tool Life Equation. (c) As a comparison, calculate the values of n and C in the Taylor equation solving simultaneous equations. Are the resulting n and C values the same?

Solution: (a) and (b) Student exercises. For part (a), at v_1 = 125 m/min, T_1 = 20.4 min using criterion FW = 0.75 mm, and at v_2 = 165 m/min, T_2 = 10.0 min using criterion FW = 0.75 mm. In part (b), values of C and n may vary due to variations in the plots. The values should be approximately the same as those obtained in part (c) below.

(c) Two equations: (1) $125(20.4)^n = C$, and (2) $165(10.0)^n = C$
(1) and (2) $125(20.4)^n = 165(10.0)^n$
$\ln 125 + n \ln 20.4 = \ln 165 + n \ln 10.0$
$4.8283 + 3.0155\, n = 5.1059 + 2.3026\, n$
$0.7129\, n = 0.2776$ $\qquad$ $\boldsymbol{n = 0.3894}$

(1) $C = 125(20.4)^{0.3894} = 404.46$
(2) $C = 165(10.0)^{0.3894} = 404.46$ **C = 404.46**

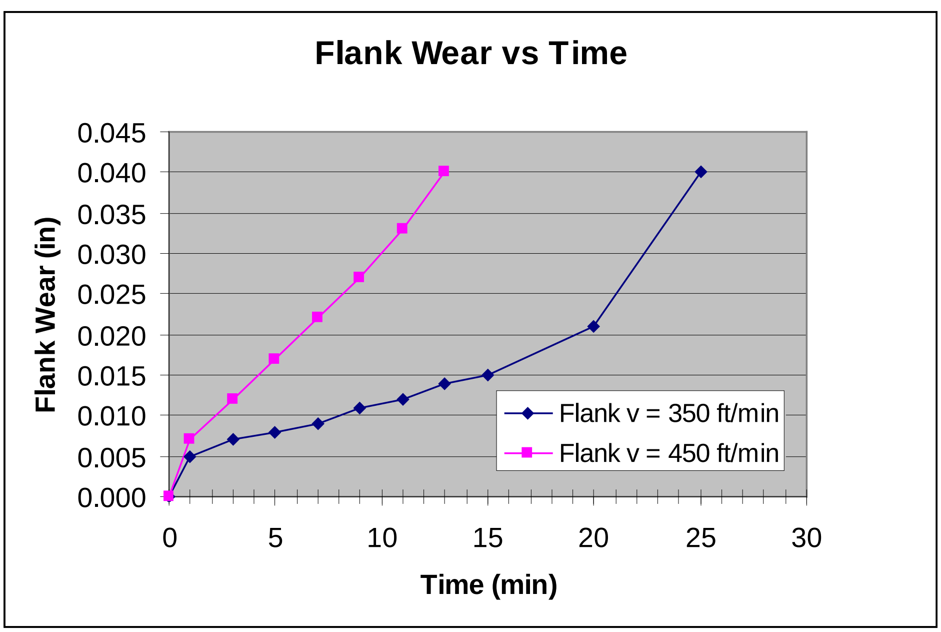
23.2 Solve Problem 23.1 except that the tool life criterion is 0.50 mm of flank land wear rather than 0.75 mm.

Solution: (a) and (b) Student exercises. For part (a), at v_1 = 125 m/min, T_1 = 13.0 min using criterion FW = 0.50 mm, and at v_2 = 165 m/min, T_2 = 5.6 min using criterion FW = 0.50 mm. In part (b), values of C and n may vary due to variations in the plots. The values should be approximately the same as those obtained in part (c) below.

(c) Two equations: (1) $125(13.0)^n = C$, and (2) $165(5.6)^n = C$
(1) and (2) $125(13.0)^n = 165(5.6)^n$
$\ln 125 + n \ln 13.0 = \ln 165 + n \ln 5.6$
$4.8283 + 2.5649\,n = 5.1059 + 1.7228\,n$
$0.8421\,n = 0.2776$ **n = 0.3296**
(1) $C = 125(13.0)^{0.3894} = 291.14$
(2) $C = 165(5.6)^{0.3894} = 291.15$ **C = 291.15**

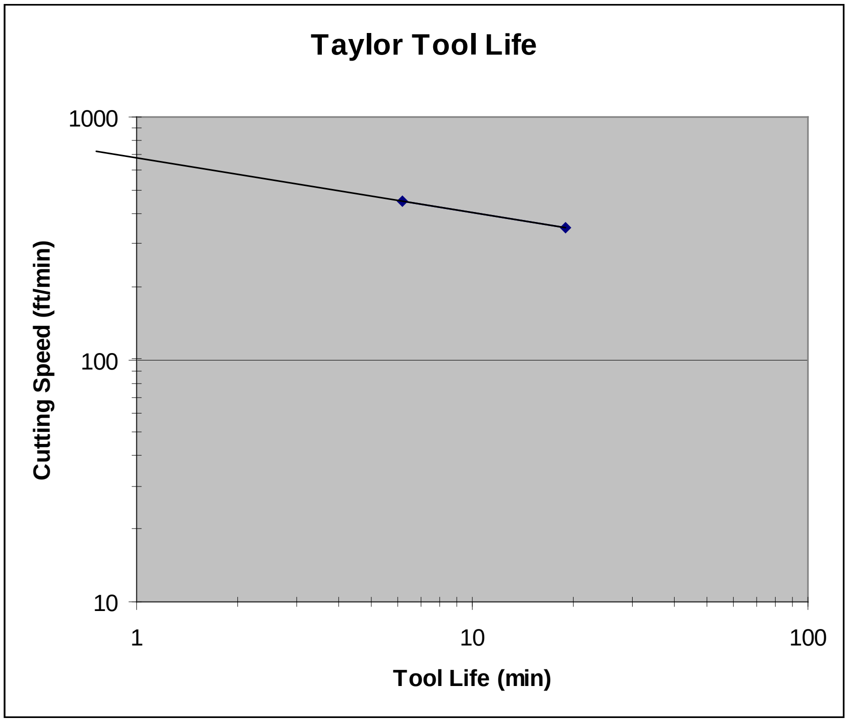
23.3 A series of turning tests were conducted using a cemented carbide tool, and flank wear data were collected. The feed was 0.010 in/rev and the depth was 0.125 in. At a speed of 350 ft/min, flank wear = 0.005 in at 1 min, 0.008 in at 5 min, 0.012 in at 11 min, 0.0.015 in at 15 min, 0.021 in at 20 min, and 0.040 in at 25 min. At a speed of 450 ft/min, flank wear = 0.007 in at 1 min, 0.017 in at 5 min, 0.027 in at 9 min, 0.033 in at 11 min, and 0.040 in at 13 min. The last value in each case is when final tool failure occurred. (a) On a single piece of linear graph paper, plot flank wear as a function of time. Using 0.020 in of flank wear as the criterion of tool failure, determine the tool lives for the two cutting speeds. (b) On a piece of natural log-log paper, plot your results determined in the previous part. From the plot, determine the values of n and C in the Taylor Tool Life Equation. (c) As a comparison, calculate the values of n and C in the Taylor equation solving simultaneous equations. Are the resulting n and C values the same?

Solution: (a)



Using the graph, at 350 ft/min the tool last about **6.2 min**; at 450 ft/min, it lasts **19.0 min**.

(b) The points are graphed in Excel and the line connecting the two points is extended to the axis.



C is read from the Y-intercept and is approximately 680 ft/min. The slope, *n*, can be determined by taking the ln of the *x* and *y* coordinates of any 2 points and determining ΔY/ΔX. It is positive because the Taylor tool life equation is derived assuming the slope is negative. Using the points (1,680) and (19,350) the slope is about 0.226.

(c) Depending on the values of tool life read from the flank wear graph, the values of n and C will vary. Two equations: (1) $350(19.0)^n = C$, and (2) $450(6.2)^n = C$
(1) and (2) $350(19.0)^n = 450(6.2)^n$
$\ln 350 + n \ln 19.0 = \ln 450 + n \ln 6.2$
$5.8579 + 2.9444\, n = 6.1092 + 1.8245\, n$
$1.1199\, n = 0.2513$ **n = 0.224**
(1) $C = 350(19.0)^{0.224} = 677$
(2) $C = 450(6.2)^{0.224} = 677$ **C = 677**

23.4 Solve problem 23.3 except the tool life wear criterion is 0.015 in of flank wear. What cutting speed should be used to get 20 minutes of tool life?

Solution: Reading the time of tool failure on the Flank Wear vs Time plot yields the following data points. Note the values of *n* and *C* will change based on the estimates for time of failure. $v_1 = 350$ ft/min, $T_1 = 15$ min and $v_2 = 450$ ft/min, $T_2 = 4.2$ min

Two equations: (1) $350(15.0)^n = C$, and (2) $450(4.2)^n = C$
(1) and (2) $350(15.0)^n = 450(4.2)^n$
$\ln 350 + n \ln 15.0 = \ln 450 + n \ln 4.2$
$5.8579 + 2.7081\, n = 6.1092 + 1.4351\, n$
$1.2730\, n = 0.2513$ **n = 0.197**
(1) $C = 350(15.0)^{0.197} = 597$
(2) $C = 450(4.2)^{0.197} = 597$ **C = 597**

To achieve 20 min of tool life: $v = C/T^n = 597/20^{0.197} = 597/1.8065 =$ **330 ft/min**

23.5 Tool life tests on a lathe have resulted in the following data: (1) at a cutting speed of 375 ft/min, the tool life was 5.5 min; (2) at a cutting speed of 275 ft/min, the tool life was 53 min. (a) Determine the parameters *n* and *C* in the Taylor tool life equation. (b) Based on the *n* and *C* values, what is the likely tool material used in this operation? (c) Using your equation, compute the tool life that corresponds to a cutting speed of 300 ft/min. (d) Compute the cutting speed that corresponds to a tool life $T = 10$ min.

Solution: (a) $VT^n = C$; Two equations: (1) $375(5.5)^n = C$ and (2) $275(53)^n = C$
$375(5.5)^n = 275(53)^n$
$375/275 = (53/5.5)^n$
$1.364 = (9.636)^n$
$\ln 1.364 = n \ln 9.636$
$0.3102 = 2.2655\, n$ **n = 0.137**
$C = 375(5.5)^{0.137} = 375(1.2629)$ **C = 474**
Check: $C = 275(53)^{0.137} = 275(1.7221) = 474$

(b) Comparing these values of *n* and *C* with those in Table 23.2, the likely tool material is high speed steel.

(c) At $v = 300$ ft/min, $T = (C/v)^{1/n} = (474/300)^{1/0.137} = (1.579)^{7.305}$ = **28.1 min**

(d) For $T = 10$ min, $v = C/T^n = 474/10^{0.137} = 474/1.371$ = **346 ft/min**

23.6 Tool life tests in turning yield the following data: (1) when cutting speed is 100 m/min, tool life is 10 min; (2) when cutting speed is 75 m/min, tool life is 30 min. (a) Determine the *n* and *C* values in the Taylor tool life equation. Based on your equation, compute (b) the tool life for a speed of 110 m/min, and (c) the speed corresponding to a tool life of 15 min.

Solution: (a) Two equations: (1) $120(7)^n = C$ and (2) $80(28)^n = C$.
$120(7)^n = 80(28)^n$
$\ln 120 + n \ln 7 = \ln 80 + n \ln 28$
$4.7875 + 1.9459\, n = 4.3820 + 3.3322\, n$
$4.7875 - 4.3820 = (3.3322 - 1.9459)\, n$
$0.4055 = 1.3863\, n$ **n = 0.2925**
$C = 120(7)^{0.2925} = 120(1.7668)$ **C = 212.0**
Check: $C = 80(28)^{0.2925} = 80(2.6503) = 212.0$

(b) $110\, T^{0.2925} = 212.0$
$T^{0.2925} = 212.0/110 = 1.927$
$T = 1.927^{1/0.2925} = 1.927^{3.419}$ = **9.42 min**

(c) $v\,(15)^{0.2925} = 212.0$
$v = 212.0/(15)^{0.2925} = 212.0/2.2080$ = **96.0 m/min**

23.7 Turning tests have resulted in 1-min tool life at a cutting speed = 4.0 m/s and a 20-min tool life at a speed = 2.0 m/s. (a) Find the *n* and *C* values in the Taylor tool life equation. (b) Project how long the tool would last at a speed of 1.0 m/s.

Solution: (a) For data (1) $T = 1.0$ min, then **C = 4.0 m/s = 240 m/min**
For data (2) $v = 2$ m/s = 120 m/min
$120(20)^n = 240$
$20^n = 240/120 = 2.0$
$n \ln 20 = \ln 2.0$
$2.9957\, n = 0.6931$ **n = 0.2314**

(b) At $v = 1.0$ m/s = 60 m/min
$60(T)^{0.2314} = 240$

$(T)^{0.2314} = 240/60 = 4.0$
$T = (4.0)^{1/0.2314} = (4)^{4.3215} =$ **400 min**

23.8 A 15.0-in-by-2.0-in-workpart is machined in a face milling operation using a 2.5 in diameter fly cutter with a single carbide insert. The machine is set for a feed of 0.010 in/tooth and a depth of 0.20 in. If a cutting speed of 400 ft/min is used, the tool lasts for 3 pieces. If a cutting speed of 200 ft/min is used, the tool lasts for 12 parts. Determine the Taylor tool life equation.

Solution: $N_1 = v/\pi D = 400(12)/2.5\pi = 611$ rev/min
$f_r = Nf n_t = 611(0.010)(1) = 6.11$ in/min
From Eq. (22.18) in the previous chapter, $A = 0.5(2.5 - (2.5^2 - 2.0^2)^{0.5}) = 0.5$ in
$T_m = (L+A)/f_r = (15 + 0.5))/6.11 = 2.537$ min
$T_1 = 3T_m = 3(2.537) = 7.61$ min when $v_1 = 400$ ft/min
$N_2 = 200(12)/2.5\pi = 306$ rev/min
$f_r = Nf n_t = 306(0.010)(1) = 3.06$ in/min
$T_m = (15 + 0.5))/3.06 = 5.065$ min
$T_2 = 12T_m = 12(5.065) = 60.78$ min when $v_2 = 200$ ft/min
$n = \ln(v_1/v_2)/\ln(T_2/T_1) = \ln(400/200)/\ln(60.78/7.61) =$ **0.3336**
$C = vT^n = 400(7.61)^{0.3336} =$ **787.2**

23.9 In a production turning operation, the workpart is 125 mm in diameter and 300 mm long. A feed of 0.225 mm/rev is used in the operation. If cutting speed = 3.0 m/s, the tool must be changed every 5 workparts; but if cutting speed = 2.0 m/s, the tool can be used to produce 25 pieces between tool changes. Determine the Taylor tool life equation for this job.

Solution: (1) $T_m = \pi(125 \text{ mm})(0.3 \text{ m})/(3.0 \text{ m/s})(0.225 \text{ mm}) = 174.53 \text{ s} = 2.909$ min
$T = 5(2.909) = 14.54$ min

(2) $T_m = \pi(125 \text{ mm})(0.3 \text{ m})/(2.0 \text{ m/s})(0.225 \text{ mm}) = 261.80\text{s} = 4.363$ min
$T = 25(4.363) = 109.08$ min

(1) $v = 3$ m/s = 180 m/min
(2) $v = 2$ m/s = 120 m/min
(1) $180(14.54)^n = C$
(2) $120(109.08)^n = C$
$180(14.54)^n = 120(109.08)^n$
$\ln 180 + n \ln(14.54) = \ln 120 + n \ln(109.08)$
$5.1929 + 2.677\, n = 4.7875 + 4.692\, n$
$5.1929 - 4.7875 = (4.692 - 2.677)\, n$
$0.4054 = 2.0151\, n$ **$n = 0.2012$**
$C = 180\,(14.54)^{0.2012}$ **$C = 308.43$**

23.10 For the tool life plot of Figure 23.5, show that the middle data point ($v = 130$ m/min, $T = 12$ min) is consistent with the Taylor equation determined in Example Problem 23.1.

Solution: Taylor equation calculated in Example 23.1 is: $vT^{0.223} = 229$. Consistency would be demonstrated by using the values from the middle data point ($T = 12$ min at $v = 130$ ft/min) in the equation and obtaining the same value of C as above ($C = 229$).
$130(12)^{0.223} = 130(1.7404) = 226.3$
This represents a difference of less than 1.2%, which is close enough and well within expected random variation in typical tool life data.

23.11 In the tool wear plots of Figure 23.4, complete failure of the cutting tool is indicated by the end of each wear curve. Using complete failure as the criterion of tool life instead of 0.50 mm flank wear, the resulting data are: (1) $v = 160$ m/min, $T = 5.75$ min; (2) $v = 130$ m/min, $T = 14.25$ min; and (3) v

= 100 m/min, T = 47 min. Determine the parameters n and C in the Taylor tool life equation for this data.

Solution: Let us use the two extreme data points to calculate the values of n and C, then check the resulting equation against the middle data point.
(1) $160(5.75)^n = C$ and (3) $100(47)^n = C$
$160(5.75)^n = 100(47)^n$
$\ln 160 + n \ln 5.75 = \ln 100 + n \ln 47$
$5.0752 + 1.7492\, n = 4.6052 + 3.8501\, n$
$0.4700 = 2.1009\, n$ **$n = 0.224$**
(1) $C = 160(5.75)^{0.224} = 236.7$
(3) $C = 100(47)^{0.224} = 236.9$ use average: **$C = 236.8$**

Check against data set (2): $130(14.25)^{0.224} = 235.7$. This represents a difference of less than 0.5%, which would be considered good agreement for experimental data. Better results on determining the Taylor equation would be obtained by using regression analysis on all three data sets to smooth the variations in the tool life data. Note that the n value is very close to the value obtained in Example 23.1 (n = 0.224 here vs. n = 0.223 in Example 23.1), and that the C value is higher here (C = 236.8 here vs. C = 229 in Example 23.1). The higher C value here reflects the higher wear level used to define tool life (complete failure of cutting edge here vs. a flank wear level of 0.50 mm in Example 23.1).

23.12 The Taylor equation for a certain set of test conditions is $vT^{.25} = 1000$, where the U.S. customary units are used: ft/min for v and min for T. Convert this equation to the equivalent Taylor equation in the International System of units (metric), where v is in m/sec and T is in seconds. Validate the metric equation using a tool life = 16 min. That is, compute the corresponding cutting speeds in ft/min and m/sec using the two equations.

Solution: $vT^{0.25} = 1000(T_{ref})^{0.25}$
C = 1000 ft/min for a 1.0 min tool life; ft/min converts to m/s as (1000 ft/min)(0.3048m/ft)(1 min/60 s) = 5.08 m/s
T_{ref} = 1 min = 60 s.
$(T_{ref})^{0.25} = (60)^{0.25} = 2.78316$
The converted value of C = 5.08(2.78316) = 14.14
The converted equation is: **$vT^{0.25} = 14.14$,** where v = m/s and T = s.

Check both equations at T = 16 min = 960 s.
USCU: $v = 1000/16^{0.25} = 1000/2 = 500$ ft/min
SI: $v = 14.14/960^{0.25} = 14.14/5.566 = 2.54$ m/s
Check: (500 ft/min)(0.3048m/ft)(1 min/60 s) = 2.54 m/s Q.E.D.

23.13 A series of turning tests are performed to determine the parameters n, m, and K in the expanded version of the Taylor equation, Eq. (23.4). The following data were obtained during the tests: (1) cutting speed = 1.9 m/s, feed = 0.22 mm/rev, tool life = 10 min; (2) cutting speed = 1.3 m/s, feed = 0.22 mm/rev, tool life = 47 min; and (3) cutting speed = 1.9 m/s, feed = 0.32 mm/rev, tool life = 8 min. (a) Determine n, m, and K. (b) Using your equation, compute the tool life when the cutting speed is 1.5 m/s and the feed is 0.28 mm/rev.

Solution: Three equations to be solved simultaneously:
(1) $(1.9 \text{ x } 60)(10)^n(0.22)^m = K$
(2) $(1.3 \text{ x } 60)(47)^n(0.22)^m = K$
(3) $(1.9 \text{ x } 60)(8)^n(0.32)^m = K$

(1) and (2): $\ln 114 + n \ln 10 + m \ln 0.22 = \ln 78 + n \ln 47 + m \ln 0.22$
$\ln 114 + n \ln 10 = \ln 78 + n \ln 47$

4.7362 + 2.3026 n = 4.3567 + 3.8501 n
0.3795 = 1.548 n **n = 0.245**

(1) and (3): ln 114 + 0.245 ln 10 + m ln 0.22 = ln 114 + 0.245 ln 8 + m ln 0.32
0.5646 + m (-1.5141) = 0.5099 + m (-1.1394)
-0.3747 m = -0.0547 **m = 0.146**

(1) $K = 114(10)^{0..245}(0.22)^{0.146}$ =114(1.7588)(0.8016) = **K = 160.7**

(b) v = 1.5 m/s, f = 0.28 mm/rev
$(1.5 \text{ x } 60)(T)^{0.245}(0.28)^{0.146} = 160.7$
$90(\text{T})^{0.245}(0.8304) = 160.7$
$(T)^{0.245} = 2.151$
$T = 2.151^{1/0.245}$ = **22.7 min**

23.14 Eq. (23.4) in the text relates tool life to speed and feed. In a series of turning tests conducted to determine the parameters n, m, and K, the following data were collected: (1) v = 400 ft/min, f = 0.010 in/rev, T = 10 min; (2) v = 300 ft/min, f = 0.010 in/rev, T = 35 min; and (3) v = 400 ft/min, f = 0.015 in/rev, T = 8 min. Determine n, m, and K. What is the physical interpretation of the constant K?

Solution: Three equations to be solved simultaneously:
(1) $400(10)^n(0.010)^m = K$
(2) $300(35)^n(0.010)^m = K$
(3) $400(8)^n(0.015)^m = K$

(1) and (2): ln 400 + n ln 10 + m ln 0.010 = ln 300 + n ln 35 + m ln 0.010
ln 400 + n ln 10 = ln 300 + n ln 35
5.9915 + 2.3026 n = 5.7038 + 3.5553 n
0.2877 = 1.2527 n **n = 0.2297**

(1) and (3): ln 400 + n ln 10 + m ln 0.010 = ln 400 + n ln 8 + m ln 0.015
n ln 10 + m ln 0.010 = n ln 8 + m ln 0.015
0.2297(2.3026) + m (-4.6052) = 0.2297(2.0794) + m (-4.1997)
0.2297(2.3026 - 2.0794) = m(-4.1997 + 4.6052)
0.05127 = 0.4055 m **m = 0.1264**

(1) $K = 400(10)^{0.2297}(0.010)^{0.1264}$ = 400(1.6971)(0.5587) = 379.3
(2) $K = 300(35)^{0.2297}(0.010)^{0.1264}$ = 300(2.2629)(0.5587) = 379.3
(3) $K = 400(8)^{0.2297}(0.015)^{0.1264}$ = 400(1.6123)(0.5881) = 379.3 **K = 379.3**

The constant K represents the cutting speed (ft/min) for a 1.0 minute tool life at a feed rate of 1.0 in/rev. This feed is of course an extrapolation and not a real possible feed value.

23.15 The n and C values in Table 23.2 are based on a feed rate of 0.25 mm/rev and a depth of cut = 2.5 mm. Determine how many cubic mm of steel would be removed for each of the following tool materials, if a 10-min tool life were required in each case: (a) plain carbon steel, (b) high speed steel, (c) cemented carbide, and (d) ceramic. Use of a spreadsheet calculator is recommended.

Solution: (a) Plain carbon steel: n = 0.10, C = 20 m/min
$v = 20/10^{0.1}$ = 20/1.259 = 15.886 m/min
$R_{MR} = 15.886(10^3)(0.25)(2.50) = 9.9288(10^3)\text{ m}^3\text{/min}$
For 10 min, metal removed = $10(9.9288)(10^3)$ = **$99.288(10^3)$ mm^3**

(b) HSS: n = 0.125, C = 70 m/min
$v = 70/10^{0.125}$ = 70/1.333 = 52.513 m/min
$R_{MR} = 52.513(10^3)(0.25)(2.50) = 32.821(10^3)\text{ mm}^3\text{/min}$

For 10 min, metal removed = $10(32.821(10^3))$ = $\mathbf{328.21(10^3)\ mm^3}$

(c) Cemented carbide: $n = 0.25$, $C = 500$ m/min
$v = 500/10^{0.25} = 500/1.778 = 281.215$ m/min
$R_{MR} = 281.215(10^3)(0.25)(2.50) = 175.759(10^3)$ mm^3/min
For 10 min, metal removed = $10(175.759(10^3))$ = $\mathbf{1{,}757.59(10^3))\ mm^3}$

(d) Ceramic: $n = 0.60$, $C = 3000$ m/min
$v = 3000/10^{0.6} = 3000/3.981 = 753.58$ m/min
$R_{MR} = 753.58\ (10^3)(0.25)(2.50) = 470.987(10^3)$ mm^3/min
For 10 min, metal removed = $10(470.987\ (10^3))$ = $\mathbf{4{,}709.87(10^3)\ mm^3}$

23.16 A drilling operation is performed in which 0.5 in diameter holes are drilled through cast iron plates that are 1.0 in thick. Sample holes have been drilled to determine the tool life at two cutting speeds. At 80 surface ft/min, the tool lasted for exactly 50 holes. At 120 surface ft/min, the tool lasted for exactly 5 holes. The feed of the drill was 0.003 in/rev. (Ignore effects of drill entrance and exit from the hole. Consider the depth of cut to be exactly 1.00 in, corresponding to the plate thickness.) Determine the values of n and C in the Taylor tool life equation for the above sample data, where cutting speed v is expressed in ft/min, and tool life T is expressed in min.

Solution: (1) $v = 80$ ft/min, $N = (80)/(0.5\pi/12) = 611$ rev/min
feed rate $f_r = (0.003)(611) = 1.833$ in/min
time per hole $T_m = 1.0$ in/(1.833 in/min) = 0.545 min
for 50 holes, $T = 50(0.545\text{ min}) = 27.25$ min
Formulating the data as $vT^n = C$, we have: $80(27.25)^n = C$

(2) $v = 120$ ft/min, $N = (120)/(.5\pi/12) = 917$ rev/min
feed rate $f_r = (0.003)(917) = 2.75$ in/min
time per hole $T_m = 1.0$ in/(2.75 in/min) = 0.364 min
for 5 holes, $T = 5(0.364\text{ min}) = 1.82$ min
Formulating the data as $vT^n = C$, we have: $120(1.82)^n = C$

Setting (1) = (2): $80(27.25)^n = 120(1.82)^n$
$\ln 80 + n \ln 27.25 = \ln 120 + n \ln 1.82$
$4.382 + 3.3051\,n = 4.7875 + 0.5978\,n$
$2.7073\,n = 0.4055$ $\qquad$ $\boldsymbol{n = 0.15}$
$C = 80(27.25)^{0.15} = 80(1.6417) = 131.34$
$C = 120(1.82)^{0.15} = 120(1.094) = 131.29$ $\qquad$ $\boldsymbol{C = 131.32}$

23.17 The outside diameter of a cylinder made of titanium alloy is to be turned. The starting diameter is 400 mm and the length is 1100 mm. The feed is 0.35 mm/rev and the depth of cut is 2.5 mm. The cut will be made with a cemented carbide cutting tool whose Taylor tool life parameters are: $n = 0.24$ and $C = 450$. Units for the Taylor equation are min for tool life and m/min for cutting speed. Compute the cutting speed that will allow the tool life to be just equal to the cutting time for this part.

Solution: In this problem we want $T_m = T$, where T_m = machining time per piece and T = tool life. Both of these times must be expressed in terms of cutting speed.
$T_m = \pi DL/fv$ and $T = (C/v)^{1/n}$
$T_m = \pi(400)(1100)(10^{-6})/0.35(10^{-3})v = 3949/v = 3949\ (v)^{-1}$
$T = (450/v)^{1/.24} = (450/v)^{4.1667} = 450^{4.1667}(v)^{-4.1667} = 1135(10^8)(v)^{-4.1667}$
Setting $T_m = T$: $3949\ v^{-1} = 1135(10^8)(v)^{-4.1667}$
$v^{3.1667} = 0.2874(10^8)$
$v = \{0.2874(10^8)\}^{1/3.1667} = \{0.2874(10^8)\}^{0.3158}$ = **226.6 m/min**

Check: $T_m = 3949\ (226.6)^{-1} = 17.4$ min

$T = (450/226.6)^{1/.24} = (450/226.6)^{4.1667} = 17.4$ min

23.18 The outside diameter of a roll for a steel rolling mill is to be turned. In the final pass, the starting diameter = 26.25 in and the length = 48.0 in. The cutting conditions will be: feed = 0.0125 in/rev, and depth of cut = 0.125 in. A cemented carbide cutting tool is to be used and the parameters of the Taylor tool life equation for this setup are: $n = 0.25$ and $C = 1300$. Units for the Taylor equation are min for tool life and ft/min for cutting speed. It is desirable to operate at a cutting speed so that the tool will not need to be changed during the cut. Determine the cutting speed that will make the tool life equal to the time required to complete the turning operation.

Solution: In this problem we want $T_m = T$, where T_m = machining time per piece and T = tool life. Both of these times must be expressed in terms of cutting speed.

$T_m = \pi DL/12fv$ and $T = (C/v)^{1/n}$

$T_m = \pi(26.25)(48.0)/12(0.0125)v = 26{,}389.38/v = 26{,}389.38(v)^{-1}$

$\mathrm{T} = (1300/v)^{1/.25} = (1300/v)^{4.0} = 1300^{4.0}(v)^{-4.0} = 2.8561(10^{12})(v)^{-4.0}$

Setting $T_m = \mathrm{T}$: $26{,}389.38(v)^{-1}= 2.8561(10^{12})(v)^{-4.0}$

$v^{3.0} = 1.08229(10^8)$

$v = \{1.08229(10^8)\}^{1/3} = \{1.08229(10^8)\}^{0.3333} =$ **476.56 ft/min**

Check: $T_m = 26{,}389.38\ (476.56)^{-1}= 55.375$ min

$T = (1300/476.56)^{1/.25} = (1300/476.56)^{4.0} = 55.375$ min

23.19 The workpart in a turning operation is 88 mm in diameter and 400 mm long. A feed of 0.25 mm/rev is used in the operation. If cutting speed = 3.5 m/s, the tool must be changed every 3 workparts; but if cutting speed = 2.5 m/s, the tool can be used to produce 20 pieces between tool changes. Determine the cutting speed that will allow the tool to be used for 50 parts between tool changes.

Solution: (1) $v = 3.5$ m/s = 210 m/min

$T_m = \pi(0.088\text{ m})(0.4\text{ m})/(210\text{ m/min})(0.00025\text{ m}) = 2.106$ min

$T = 3(2.106) = 6.32$ min

(2) $v = 2.5$ m/s = 150 m/min

$T_m = \pi(0.088\text{ m})(0.4\text{ m})/(150\text{ m/min})(0.00025\text{ mm}) = 2.949$ min

$T = 20(2.949) = 58.98$ min

(1) $210(6.32)^n = C$

(2) $150(58.98)^n = C$

$210(6.32)^n = 150(58.98)^n$

$\ln 210 + n \ln(6.32) = \ln 150 + n \ln(58.98)$

$5.347 + 1.844\, n = 5.011 + 4.077\, n$

$5.347 - 5.011 = (4.077 - 1.844)\, n$

$0.336 = 2.233\, n$ $\qquad$ $\boldsymbol{n = 0.150}$

$C = 210\ (6.32)^{0.150}$ $\qquad$ $C = 277.15$

Check: $150(58.98)^{0.150} = 277.03$) Close enough. use $C = 277.1$

Set $T = 50\ T_m$

$vT^{0.15} = 277.1$, $T^{0.15} = 277.1/v$, $T = (277.1/v)^{1/0.15} = (277.1/v)^{6.646} = 1.711415(10)^{16}/v^{6.646}$

$T_m = \pi(0.088)(0.4)/0.00025\ v = 442.34/v$

$1.711415(10)^{16}/v^{6.646} = 50(442.34/v) = 22116.8/v$

$1.711415(10)^{16}/v^{5.646} = 22116.8$

$\mathrm{v}^{5.646} = 1.711415(10)^{16}/22116.8= 7.738075(10)^{11} = 773{,}807{,}500{,}000$

$\mathrm{v} = (773{,}807{,}500{,}000)^{1/5.646} = (773{,}807{,}500{,}000)^{0.177122} =$ **127.57 m/min**

Check: $T_m = 442.34/127.57 = 3.468$ min, $50\ T_m = 173.4$ min

$T = (277.1/127.57)^{6.646} = (2.172)^{6.646} = 173.3$ min (Close enough!)

23.20 In a production turning operation, the steel workpart has a 4.5 in diameter and is 17.5 in long. A feed of 0.012 in/rev is used in the operation. If cutting speed = 400 ft/min, the tool must be changed every four workparts; but if cutting speed = 275 ft/min, the tool can be used to produce 15 pieces between tool changes. A new order for 25 pieces has been received but the dimensions of the workpart have been changed. The new diameter is 3.5 in, and the new length is 15.0 in. The work material and tooling remain the same, and the feed and depth are also unchanged, so the Taylor tool life equation determined for the previous workparts is valid for the new parts. Determine the cutting speed that will allow one cutting tool to be used for the new order.

Solution: (1) v = 400 ft/min
$T_m = \pi$(4.5 in)(17.5 in)/(400 x 12 in/min)(0.012 in) = 4.295 min
T = 4(4.295) = 17.18 min
(2) v = 275 ft/min
$T_m = \pi$(4.5 in)(17.5 in)/(275 x 12 in/min)(0.012 in) = 6.247 min
T = 15(6.247) = 93.71 min

(1) $400(17.18)^n = C$
(2) $275(93.71)^n = C$
$400(17.18)^n = 275(93.71)^n$
ln 400 + n ln(17.18) = ln 275 + n ln(93.71)
5.991 + 2.844 n = 5.617 + 4.540 n
5.991 - 5.617 = (4.540 - 2.844) n
0.374 = 1.696 n **n = 0.2205**
$C = 400\ (17.18)^{0.2205}$ C = 748.87 (ft/min)

Check: $275(93.71)^{0.2205}$ = 748.43, use **C = 748.65**

Set $T = 25\ T_m$
$vT^{0.2205} = 748.65$, $T^{0.2205} = 748.65/v$, $T = (748.65/v)^{1/0.2205} = (748.65/v)^{4.535}$
$T = 10.8184(10)^{12}/v^{4.535}$

For the new part dimensions, $T_m = \pi$(3.5 in)(15 in)/(12v in/min)(0.012 in) = 1145.37/v
$10.8184(10)^{12}/v^{4.535} = 25(1145.37/v) = 28634.25/v$
$10.8184(10)^{12}/v^{3.535} = 28634.25$
$v^{3.535} = 10.8184(10)^{12}/28634.25 = 377{,}813{,}096.3$
$v = (377{,}813{,}096.3)^{1/3.535} = (377{,}813{,}096.3)^{0.2829}$ = **267.025 ft/min**

Check: T_m = 1145.37/267.025 = 4.289 min, 25 T_m = 107.23 min
$T = (748.65/267.025)^{4.535} = (2.804)^{4.535}$ = 107.23 min

23.21 The outside diameter of a cylinder made of a steel alloy is to be turned. The starting diameter is 300 mm and the length is 625 mm. The feed is 0.35 mm/rev and the depth of cut is 2.5 mm. The cut will be made with a cemented carbide cutting tool whose Taylor tool life parameters are: n = 0.24 and C = 450. Units for the Taylor equation are min for tool life and m/min for cutting speed. Compute the cutting speed that will allow the tool life to be just equal to the cutting time for three of these parts.

Solution: In this problem we want $3T_m = T$, where T_m = machining time per piece and T = tool life. Both of these times must be expressed in terms of cutting speed.
$T_m = \pi DL/fv$ and $T = (C/v)^{1/n}$
$T_m = \pi(300)(625)(10^{-6})/0.35(10^{-3})v = 1683/v = 1683\ (v)^{-1}$
$3T_m = 3(1683\ (v)^{-1}) = 5049(v)^{-1}$
$T = (450/v)^{1/.24} = (450/v)^{4.1667} = 450^{4.1667}(v)^{-4.1667} = 1135(10^8)(v)^{-4.1667}$
Setting $3T_m = T$: $5049v^{-1} = 1135(10^8)(v)^{-4.1667}$
$v^{3.1667} = 0.2248(10^8)$
$v = \{0.2248(10^8)\}^{1/3.1667} = \{0.2248(10^8)\}^{0.3158}$ = **209.747 m/min**

Check: $3T_m = 5049\ (209.747)^{-1} = 24.07$ min
$T = (450/209.747)^{1/.24} = (450/209.747)^{4.1667} = 24.06$ min (close enough)

Tooling Applications

23.22 Specify the ANSI C-grade or grades (C1 through C8 in Table 23.5) of cemented carbide for each of the following situations: (a) turning the diameter of a high carbon steel shaft from 4.2 in to 3.5 in, (b) making a final face milling pass using a shallow depth of cut and feed on a titanium part, (c) boring out the cylinders of an alloy steel automobile engine block prior to honing, and (d) cutting the threads on the inlet and outlet of a large brass valve.

Solution: (a) High carbon steel limits choice to grades C5-C8. A large amount of material is being removed so it is a roughing cut. C5 or C6 could be used, depending on the finish required after the process is complete.

(b) Titanium limits the choice of grades to C1-C4. Small feed and depth of cut indicate a finish pass. Depending on the finish requirements, C3 or C4 would be selected.

(c) Alloy steel limits the choice of grades to C5-C8. Boring cylinders requires precision finishing. Choose either C7 or C8

(d) Brass limits the choice of grades to C1-C4. This is a finishing operation that could use C3 or C4.

23.23 A certain machine shop uses four cemented carbide grades in its operations. The chemical composition of these grades are as follows: Grade 1 contains 95% WC and 5% Co; Grade 2 contains 82% WC, 4% Co, and 14% TiC; Grade 3 contains 80% WC, 10% Co, and 10% TiC; and Grade 4 contains 89% WC and 11% Co. (a) Which grade should be used for finish turning of unhardened steel? (b) Which grade should be used for rough milling of aluminum? (c) Which grade should be used for finish turning of brass? (d) Which of the grades listed would be suitable for machining cast iron? For each case, explain your recommendation.

Solution: (a) Finish turning of unhardened steel. Specify a steel-cutting grade suitable for finishing. This is a grade with TiC and low cobalt. Choose grade 2.

(b) Rough milling of aluminum. Specify a non-steel roughing grade. This is a grade with no TiC and high cobalt. Choose grade 4.

(c) Finish turning of brass. Specify a non-steel finishing grade. This is a grade with no TiC and low cobalt. Choose grade 1.

(d) Machining cast iron. Cast iron is included with the non-steel grades. Specify grade 1 for finishing and grade 4 for roughing.

23.24 List the ISO R513-1975(E) group (letter and color in Table 23.6) and whether the number would be toward the lower or higher end of the ranges for each of the following situations: (a) milling the head gasket surface of an aluminum cylinder head of an automobile (cylinder head has a hole for each cylinder and must be very flat and smooth to mate up with the block), (b) rough turning a hardened steel shaft, (c) milling a fiber-reinforced polymer composite that requires a precise finish, and (d) milling the rough shape in a die made of steel before it is hardened.

Solution: (a) Aluminum would be the K (red) group. Milling the surface with large holes in it will create shock loading on the tool. This will require higher toughness. Because it is a finish cut, it will require higher hardness. A mid-range number will provide both. Move towards the low numbers for higher hardness if possible.

(b) Hardened steel shaft would indicate group P (blue). Rough cut would require higher toughness so choose a higher number

(c) Composite is a nonmetallic and would use group K (red). Precise machining would require a high hardness (lower number).

(d) Steel would indicate the P (blue) group. Rough milling would indicate a higher toughness and thus a high number.

23.25 A turning operation is performed on a steel shaft with diameter = 5.0 in and length = 32 in. A slot or keyway has been milled along its entire length. The turning operation reduces the shaft diameter. For each of the following tool materials, indicate whether it is a reasonable candidate to use in the operation: (a) plain carbon steel, (b) high-speed steel, (c) cemented carbide, (d) ceramic, and (e) sintered polycrystalline diamond. For each material that is not a good candidate, give the reason why it is not.

Solution: The lengthwise slot results in an interrupted cut, so toughness is important in the tool material.

(a) Plain carbon steel: not economical because of low cutting speeds.

(b) HSS: this is a reasonable candidate; it has good toughness for the interrupted cut.

(c) Cemented carbide: this is a reasonable candidate; it must be a steel cutting grade with high toughness (high cobalt content).

(d) Ceramic: this is not a good candidate because of its low toughness; it is likely to fracture during interrupted cutting.

(e) Sintered polycrystalline diamond: SPD is not suitable for cutting steel.

Cutting Fluids

23.26 In a milling operation with no coolant, a cutting speed of 500 ft/min is used. The current cutting conditions (dry) yield Taylor tool life equation parameters of $n = 0.25$ and $C = 1300$ (ft/min). When a coolant is used in the operation, the cutting speed can be increased by 20% and still maintain the same tool life. Assuming n does not change with the addition of coolant, what is the resulting change in the value of C?

Solution: Find the present tool life T
$vT^n = C$; $T = (C/v)^{(1/n)}$
$T = (1300/500)^{(1/.25)} = 2.60^{4.0} = 45.7$ min
After coolant, the new cutting speed would be 500(1+.20) = 600
If the tool life stays the same, $C = vT^n = 600(45.7)^{.25} = 1560$
% increase in C = (1560-1500)/1500 = **20%**

Note: When viewing the log-log plot of the Taylor tool life curve, it is a straight line. Since n, the slope, is not affected by the coolant, the coolant effectively raises the line on the graph. Raising the curve so that it increases the value of v by a certain percentage will increase C by the same percentage. This is true independent of the values of n and C.

23.27 In a turning operation using high-speed steel tooling, cutting speed = 110 m/min. The Taylor tool life equation has parameters $n = 0.140$ and $C = 150$ (m/min) when the operation is conducted dry. When a coolant is used in the operation, the value of C is increased by 15%. Determine the percent increase in tool life that results if the cutting speed is maintained at 110 m/min.

Solution: Dry: $110(T)^{0.14} = 150$
$T = (150/110)^{1/.14} = (1.364)^{7.143} = 9.18$ min
With coolant: $110(T)^{0.14} = 150(1 + 15\%) = 150(1.15) = 172.5$
$T = (172.5/110)^{1/.14} = (1.568)^{7.143} = 24.85$ min
Increase = (24.85 – 9.18)/9.18 = 1.71 = **171%**

23.28 A production turning operation on a steel workpiece normally operates at a cutting speed of 125 ft/min using high-speed steel tooling with no cutting fluid. The appropriate n and C values in the Taylor equation are given in Table 23.2 in the text. It has been found that the use of a coolant type cutting fluid will allow an increase of 25 ft/min in the speed without any effect on tool life. If it can be assumed that the effect of the cutting fluid is simply to increase the constant C by 25, what would be the increase in tool life if the original cutting speed of 125 ft/min were used in the operation?

Solution: From Table 23.2, $n = 0.125$ and $C = 200$ for dry cutting.
With cutting fluid, $C = 200 + 25 = 225$.
Dry: at $v = 125$ ft/min, $T = (200/125)^{1/.125} = (1.6)^8 = 42.95$ min
With cutting fluid: at $v = 125$ ft/min, $T = (225/125)^{1/.125} = (1.8)^8 = 110.2$ min
Increase = (110.2 - 42.95) = **67.25 min = 156.6%**

23.29 A high speed steel 6.0 mm twist drill is being used in a production drilling operation on mild steel. A cutting oil is applied by the operator by brushing the lubricant onto the drill point and flutes prior to each hole. The cutting conditions are: speed = 25 m/min, and feed = 0.10 mm/rev, and hole depth = 40 mm. The foreman says that the "speed and feed are right out of the handbook" for this work material. Nevertheless, he says, "the chips are clogging in the flutes, resulting in friction heat, and the drill bit is failing prematurely due to overheating." What's the problem? What do you recommend to solve it?

Solution: There are several problems here. First, the depth-to-diameter ratio is 1.75:0.25 = 7:1, which is greater than the 4:1 which is usually recommended. As a consequence the chips produced in the hole are having difficulty exiting, thus causing overheating of the drill. Second, the manual method of applying the cutting oil may not be particularly effective. Third, with overheating as a problem, the cutting oil may not be removing heat from the operation effectively.

Recommendation: The 7:1 depth-to-diameter ratio is a given, a requirement of the drilling operation, and we assume it cannot be changed. The twist drill might be operated in a peck-drilling mode to solve the chip clogging problem. Peck-drilling means drilling for a distance approximately equal to one drill diameter, then retract the drill, then drill some more, etc. A twist drill with a fluid hole could be used to more effectively deliver the cutting fluid to the drill point to help extract the chips. Finally, an emulsified oil might be tried in the operation, one with good lubricating qualities, as a substitute for the cutting oil. Since overheating is a problem, it makes sense to try a coolant.

24 ECONOMIC AND PRODUCT DESIGN CONSIDERATIONS IN MACHINING

Review Questions

24.1 Define machinability.

Answer. Machinability can be defined as the relative ease with which a material can be machined using an appropriate cutting tool under appropriate cutting conditions.

24.2 What are the criteria by which machinability is commonly assessed in a production machining operation?

Answer. The machinability criteria include (1) tool wear and tool life, (2) forces and power, (3) surface finish, and (4) ease of chip disposal.

24.3 Name some of the important mechanical and physical properties that affect the machinability of a work material.

Answer. The properties mentioned in the text include hardness, strength, and thermal diffusivity.

24.4 Why do costs tend to increase when better surface finish is required on a machined part?

Answer. Costs tend to increase when better surface finish is required because additional operations such as grinding, lapping, or similar finishing processes must be included in the manufacturing sequence.

24.5 What are the basic factors that affect surface finish in machining?

Answer. The factors that affect surface finish are (1) geometric factors such as type of operation, feed, and tool shape (nose radius in particular); (2) work material factors such as built-up edge effects, and tearing of the work surface when machining ductile materials, which factors are affected by cutting speed; and (3) vibration and machine tool factors such as setup and workpart rigidity, and backlash in the feed mechanism.

24.6 What are the parameters that have the greatest influence in determining the ideal surface roughness R_i in a turning operation?

Answer. The ideal surface roughness is determined by the following geometric parameters of the machining operation: (1) tool nose radius and (2) feed. In some cases, the end cutting edge and end cutting edge angle of the single-point tool affects the feed mark pattern on the work surface.

24.7 Name some of the steps that can be taken to reduce or eliminate vibrations in machining.

Answer. Steps to reduce vibration in machining include (1) increase stiffness or damping in the setup; (2) operate at speeds away from the natural frequency of the machine tool system; (3) reduce forces in machining by changing feed or depth and cutter design (e.g., reduced rake angle), and (4) change the cutter design to reduce forces.

24.8 What are the factors on which the selection of feed in a machining operation should be based?

Answer. The factors are (1) type of tooling (e.g., a cemented carbide tool should be used at a lower feed than a high-speed steel tool), (2) whether the operation is roughing or finishing (e.g., higher feeds are used in roughing operations), (3) cutting forces limitations that would require lower feeds, and (4) surface roughness requirements.

24.9 The unit cost in a machining operation is the sum of four cost terms. The first three terms are: (1) part load/unload cost, (2) cost of time the tool is actually cutting the work, and (3) cost of the time to change the tool. What is the fourth term?

Answer. The fourth term is the cost of the tool itself (purchasing the tool and grinding it, if applicable).

24.10 Which cutting speed is always lower for a given machining operation, cutting speed for minimum cost or cutting speed for maximum production rate? Why?

Answer. Cutting speed for minimum cost is always lower because of the fourth term in the unit cost equation, which deals with the actual cost of the cutting edge. This term tends to push the U-shaped function toward a lower value in the case of cutting speed for minimum cost.

Multiple Choice Quiz

There are 14 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

24.1 Which of the following criteria are generally recognized to indicate good machinability (four best answers): (a) ease of chip disposal, (b) high cutting temperatures, (c) high power requirements, (d) high value of R_a, (e) long tool life, (f) low cutting forces, and (g) zero shear plane angle?

Answer. (a), (d), (e), and (f).

24.2 Of the various methods for testing machinability, which one of the following is the most important: (a) cutting forces, (b) cutting temperature, (c) horsepower consumed in the operation, (d) surface roughness, (e) tool life, or (f) tool wear?

Answer. (e).

24.3 A machinability rating greater than 1.0 indicates that the work material is (a) easier to machine than the base metal or (b) more difficult to machine than the base metal, where the base metal has a rating = 1.0?

Answer. (a).

24.4 In general, which one of the following materials has the highest machinability: (a) aluminum, (b) cast iron, (c) copper, (d) low carbon steel, (e) stainless steel, (f) titanium alloys, or (g) unhardened tool steel?

Answer. (a).

24.5 Which one of the following operations is generally capable of the closest tolerances: (a) broaching, (b) drilling, (c) end milling, (d) planing, or (e) sawing?

Answer. (a).

24.6 When cutting a ductile work material, an increase in cutting speed will generally (a) degrade surface finish, which means a higher value of R_a or (b) improve surface finish, which means a lower value of R_a?

Answer. (b).

24.7 Which one of the following operations is generally capable of the best surface finishes (lowest value of R_a): (a) broaching, (b) drilling, (c) end milling, (d) planing, or (e) turning?

Answer. (a).

24.8 Which of the following time components in the average production machining cycle is affected by cutting speed (two correct answers): (a) part loading and unloading time, and (b) setup time for the machine tool, (c) time the tool is engaged in cutting, and (d) average tool change time per piece?

Answer. (c) and (d).

24.9 Which cutting speed is always lower for a given machining operation: (a) cutting speed for maximum production rate, or (b) cutting speed for minimum cost?

Answer. (b).

24.10 A high tooling cost and/or tool change time will tend to (a) decrease, (b) have no effect on, or (c) increase the cutting speed for minimum cost?

Answer. (a).

Problems

Machinability

24.1 A machinability rating is to be determined for a new work material using the cutting speed for a 60-min tool life as the basis of comparison. For the base material (B1112 steel), test data resulted in Taylor equation parameter values of $n = 0.29$ and $C = 500$, where speed is in m/min and tool life is min. For the new material, the parameter values were $n = 0.21$ and $C = 400$. These results were obtained using cemented carbide tooling. (a) Compute a machinability rating for the new material. (b) Suppose the machinability criterion were the cutting speed for a 10-min tool life rather than the present criterion. Compute the machinability rating for this case. (c) What do the results of the two calculations show about the difficulties in machinability measurement?

Solution: (a) Base material: $v_{60} = 500/60^{0.29} = 152.5$ m/min
New material: $v_{60} = 400/60^{0.21} = 169.3$ m/min
$MR = 169.3/152.5 =$ **1.11 = 111%**

(b) Base material: $v_{10} = 500/10^{0.29} = 256.4$ m/min
New material: $v_{10} = 400/10^{0.21} = 246.6$ m/min
$MR = 246.6/256.4 =$ **0.96 = 96%**

(c) Different test conditions often result in different machinability results.

24.2 A small company uses a band saw to cut through 2-inch metal bar stock. A material supplier is pushing a new material that is supposed to be more machinable while providing similar mechanical properties. The company does not have access to sophisticated measuring devices, but they do have a stopwatch. They have acquired a sample of the new material and cut both the present material and the new material with the same band saw settings. In the process, they measured how long it took to cut through each material. To cut through the present material, it took an average of 2 minutes, 20 seconds. To cut through the new material, it took an average of 2 minutes, 6 seconds. (a) Develop a machinability rating system based on time to cut through the 2.0-inch bar stock, using the present material as the base material. (b) Using your rating system, determine the machinability rating for the new material.

Solution: (a) Since a material with a shorter cutting time is better, it should have a higher machinability rating. To achieve this the cutting time of the base material needs to be in the numerator and the time of the tested material needs to be in the denominator. Therefore, if the test material has a shorter cutting time, the rating will be greater than 100%. The appropriate *MR* equation is the following: $MR = T_m$(base material)/T_m(test material) x 100%

(b) Convert times to minutes
For the base material, $T_m = 2 + 20/60 = 2.333$ min

For the test material, $T_m = 2 + 6/60 = 2.1$ min
$MR = 2.333/2.1 =$ **1.11 = 111 %**

24.3 A machinability rating is to be determined for a new work material. For the base material (B1112), test data resulted in a Taylor equation with parameters $n = 0.29$ and $C = 490$. For the new material, the Taylor parameters were $n = 0.23$ and $C = 430$. Units in both cases are: speed in m/min and tool life in min. These results were obtained using cemented carbide tooling. (a) Compute a machinability rating for the new material using cutting speed for a 30-min tool life as the basis of comparison. (b) If the machinability criterion were tool life for a cutting speed of 150 m/min, what is the machinability rating for the new material?

Solution: (a) Base material: $v_{30} = 490/30^{.29} = 182.7$ m/min
New material: $v_{30} = 430/30^{.23} = 196.7$ m/min
$MR = 196.7/182.7 =$ **1.08 = 108%**

(b) Base material: $T_{150} = (490/150)^{1/.29} = (3.27)^{3.448} = 59.3$ min
New material: $v_{10} = (430/150)^{1/.23} = (2.87)^{4.348} = 97.4$ min
$MR = 97.4/59.3 =$ **1.64 = 164%**

24.4 Tool life turning tests have been conducted on B1112 steel with high-speed steel tooling, and the resulting parameters of the Taylor equation are: $n = 0.13$ and $C = 225$. B1112 is the base metal and has a machinability rating = 1.00 (100%). During the tests, feed = 0.010 in/rev, and depth of cut = 0.100 in. Based on this information, and machinability data given in Table 24.1, determine the cutting speed you would recommend for the following work materials, if the tool life desired in operation is 30 min (the same feed and depth of cut are to be used): (a) C1008 low carbon steel with 150 Brinell hardness, (b) 4130 alloy steel with 190 Brinell hardness, and (c) B1113 steel with 170 Brinell hardness.

Solution: First determine v_{30} for the base material: $v_{30} = 225/30^{.13} = 225/1.556 = 144.6$ ft/min

(a) From Table 24.1, MR for C1008 = 0.50. Recommended $v_{30} = 0.50(144.6) =$ **72 ft/min**

(b) From Table 24.1, MR for 4130 = 0.65. Recommended $v_{30} = 0.65(144.6) =$ **94 ft/min**

(c) From Table 24.1, MR for B1113 = 1.35. Recommended $v_{30} = 1.35(144.6) =$ **195 ft/min**

Surface Roughness

24.5 In a turning operation on cast iron, the nose radius on the tool = 1.5 mm, feed = 0.22 mm/rev, and speed = 1.8 m/s. Compute an estimate of the surface roughness for this cut.

Solution: $R_i = f^2/32NR = (0.22)^2/(32 \times 1.5) = 0.00101$ mm. = 1.01 μm.
From Fig. 24.2, $r_{ai} = 1.25$
$R_a = 1.01 \times 1.25 =$ **1.26 μm.**

24.6 A turning operation uses a 2/64 in nose radius cutting tool on a free machining steel with a feed rate = 0.010 in/rev and a cutting speed = 300 ft/min. Determine the surface roughness for this cut.

Solution: $R_i = f^2/32NR = (0.010)^2/(32 \times 2/64) = 0.0001$ in = 100 μin
From Fig. 24.2, $r_{ai} = 1.02$
$R_a = 1.02 \times 100 =$ **102 μin**

24.7 A single-point HSS tool with a 3/64 in nose radius is used in a shaping operation on a ductile steel workpart. The cutting speed is 120 ft/min. The feed is 0.014 in/pass and depth of cut is 0.135 in. Determine the surface roughness for this operation.

Solution: $R_i = f^2/32NR = (0.014)^2/(32 \times 3/64) = 0.000131$ in = 131 μin
From Fig. 24.2, $r_{ai} = 1.8$
$R_a = 1.8 \times 131 =$ **235 μin**

24.8 A part to be turned in an engine lathe must have a surface finish of 1.6 μm. The part is made of a free-machining aluminum alloy. Cutting speed = 150 m/min, and depth of cut = 4.0 mm. The nose radius on the tool = 0.75 mm. Determine the feed that will achieve the specified surface finish.

Solution: For free-machining aluminum at 150 m/min, from Figure 24.2 ratio r_{ai} = 1.0 in Eq. (24.3), so $R_a = R_i$
$R_a = R_i = f^2/32NR$
Rearranging, $f^2 = R_i(32NR) = 1.6(10^{-6})(32)(0.75)(10^{-3}) = 38.4(10^{-9}) = 3.84(10^{-8})$ m^2
$f = (3.84(10^{-8})\text{ m}^2)^{0.5} = 1.96(10^{-4})$ m = **0.196 mm** (mm is interpreted mm/rev)

24.9 Solve previous Problem 24.8 except that the part is made of cast iron instead of aluminum and the cutting speed is reduced to 100 m/min.

Solution: For cast iron at 150 m/min, extrapolating Figure 24.2 ratio r_{ai} = 1.2 in Eq. (24.3), so $R_a = 1.2\ R_i = 1.2f^2/32NR$
Rearranging, $f^2 = R_i(32NR)/1.2 = 1.6(10^{-6})(32)(0.75)(10^{-3})/1.2 = 31.96(10^{-9}) = 3.196(10^{-8})$ m^2
$f = 3.196(10^{-8})\text{ m}^2)^{0.5} = 1.79(10^{-4})$ m = **0.179 mm** (mm is interpreted mm/rev)

24.10 A part to be turned in an engine lathe must have a surface finish of 1.5 μm. The part is made of a aluminum. The cutting speed is 1.5 m/s and the depth is 3.0 mm. The nose radius on the tool = 1.0 mm. Determine the feed that will achieve the specified surface finish.

Solution: For aluminum, a ductile material at 90 m/min, from Figure 24.2 ratio r_{ai} = 1.25.
Therefore, the theoretical requirement is $R_i = R_a / r_{ai}$ = 1.5 / 1.25 = 1.2 μm
$R_i = f^2/32NR$; $f = (32\ (NR)\ R_i\ )^{0.5} = (32(10^{-3})(1.2x10^{-6}))^{0.5} = 3.84x10^{-8}$ m^2
$f = (3.84(10^{-8})\text{ m}^2)^{0.5} = 1.96(10^{-4})$ m = **0.196 mm** (here, mm is interpreted mm/rev)

24.11 The surface finish specification in a turning job is 0.8 μm. The work material is cast iron. Cutting speed = 75 m/min, feed = 0.3 mm/rev, and depth of cut = 4.0 mm. The nose radius of the cutting tool must be selected. Determine the minimum nose radius that will obtain the specified finish in this operation.

Solution: For cast iron at 75 m/min, from Figure 24.2 ratio r_{ai} = 1.35 in Eq. (24.3), so $R_a = 1.35R_i = 1.35f^2/32NR$
Rearranging, $NR = 1.35f^2/(32R_a)$
$NR = 1.35(0.3\text{ x }10^{-3})^2/(32)(0.8)(10^{-6}) = 0.00475$ m = **4.75 mm**

24.12 A face milling operation is to be performed on a cast iron part to finish the surface to 36 μ-in. The cutter uses four inserts and its diameter is 3.0 in. The cutter rotates at 475 rev/min. To obtain the best possible finish, a type of carbide insert with 4/64 in nose radius is to be used. Determine the required feed rate (in/min) that will achieve the 36 μ-in finish.

Solution: $v = \pi DN = \pi(3/12)(475) = 373$ ft/min
For cast iron at 373 ft/min, from Figure 24.2 ratio r_{ai} = 1.26, so $R_a = 1.26\ R_i$
$R_i = R_a/1.26 = 36/1.26 = 28.6$ μin
$R_i = f^2/32\ NR$
Rearranging, $f^2 = 32R_a(NR) = 32(28.6\text{ x }10^{-6})(4/64) = 57.1\text{ x }10^{-6}$ in^2
$f = (57.1\text{ x }10^{-6})^{.5} = 7.56\text{ x }10^{-3} = 0.00756$ in/tooth.
$f_r = Nn_tf = 475(4)(0.00756) =$ **14.4 in/min**

24.13 A face milling operation is not yielding the required surface finish on the work. The cutter is a four-tooth insert type face milling cutter. The machine shop foreman thinks the problem is that the work material is too ductile for the job, but this property tests well within the ductility range for the material specified by the designer. Without knowing any more about the job, what changes in (a) cutting conditions and (b) tooling would you suggest to improve the surface finish?

Solution: (a) Changes in cutting conditions: (1) decrease chip load f, (2) increase cutting speed v, (3) use cutting fluid.

(b) Changes in tooling: (1) increase nose radius NR, (2) increase rake angle, and (3) increase relief angle. Items (2) and (3) will have a marginal effect.

24.14 A turning operation is to be performed on C1010 steel, which is a ductile grade. It is desired to achieve a surface finish of 64 μ-in, while at the same time maximizing the metal removal rate. It has been decided that the speed should be in the range 200 ft/min to 400 ft/min, and that the depth of cut will be 0.080 in. The tool nose radius = 3/64 in. Determine the speed and feed combination that meets these criteria.

Solution: Increasing feed will increase both R_{MR} and R_a. Increasing speed will increase R_{MR} and reduce R_a. Therefore, it stands to reason that we should operate at the highest possible v.

Try v = 400 ft/min. From Fig. 25.45, r_{ai} = 1.15.
$R_a = 1.15\ R_i$
$R_i = R_a/1.15 = 64/1.15 = 55.6\ \mu$in
$R_i = f^2/32NR$
$f^2 = 32R_a(NR) = 32(55.6 \text{ x } 10^{-6})(3/64) = 83.4 \text{ x } 10^{-6}$ in^2
$f = (83.4 \text{ x } 10^{-6})^{.5} = 0.0091$ in/rev
$R_{MR} = 3.51$ in^3/min

Compare at v = 300 ft/min. From Fig. 25.45, r_{ai} = 1.26.
$R_a = 1.26\ R_i$
$R_i = R_a/1.26 = 64/1.26 = 50.8\ \mu$in
$R_i = f^2/32NR$
$f^2 = 32R_a(NR) = 32(50.8)(10^{-6})(3/64) = 76.2(10^{-6})$in^2
$f = (76.2 \text{ x } 10^{-6})^{.5} = 0.0087$ in/rev
$R_{MR} = 2.51$ in^3/min

Optimum cutting conditions are: ***v* = 400 ft/min** and ***f* = 0.0091 in/rev**, which maximizes R_{MR} = **3.51 in^3/min**

Machining Economics

24.15 A high-speed steel tool is used to turn a steel workpart that is 300 mm long and 80 mm in diameter. The parameters in the Taylor equation are: n = 0.13 and C = 75 (m/min) for a feed of 0.4 mm/rev. The operator and machine tool rate = $30.00/hr, and the tooling cost per cutting edge = $4.00. It takes 2.0 min to load and unload the workpart and 3.50 min to change tools. Determine (a) cutting speed for maximum production rate, (b) tool life in min of cutting, and (c) cycle time and cost per unit of product.
Solution: (a) C_o = $30/hr = $0.50/min
$v_{max} = 75/[(1/0.13 - 1)(3.5)]^{.13} = 75/[6.692 \text{ x } 3.5]^{.27} =$ **49.8 m/min**

(b) $T_{max} = (75/49.8)^{1/.13} = (1.506)^{7.692} =$ **23.42 min**

(c) $T_m = \pi DL/fv = \pi(80)(300)/(.4 \text{ x } 49.8 \text{ x } 10^3) = 3.787$ min
$n_p = 23.42/3.787 = 6.184$ pc/tool life Use $n_p = 6$ pc/tool life
$T_c = T_h + T_m + T_t/n_p = 2.0 + 3.787 + 3.5/6 =$ **6.37 min/pc.**
$C_c = 0.50(6.37) + 4.00/6 =$ **$3.85/pc**

24.16 Solve Problem 24.15 except that in part (a), determine cutting speed for minimum cost.

Solution: (a) C_o = $30/hr = $0.50/min
$v_{min} = 75[0.50/((1/0.13 - 1)(.50 \text{ x } 3.5 + 4.00))]^{.13} = 75[.50/(6.692 \text{ x } 5.75)]^{.13} =$ **42.6 m/min**

(b) $T_{min} = (75/42.6)^{1/.13} = (1.76)^{7.692} =$ **76.96 min**

(c) $T_m = \pi DL/fv = \pi(80)(300)/(.4 \text{ x } 42.6 \text{ x } 10^3) = 4.42$ min/pc.
$n_p = 76.96/4.42 = 17.41$ pc/tool life Use $n_p = 17$ pc/tool life
$T_c = T_h + T_m + T_t/n_p = 2.0 + 4.42 + 3.5/17 =$ **6.63 min/pc.**
$C_c = 0.50(6.63) + 4.0/17 =$ **\$3.55/pc**

24.17 A cemented carbide tool is used to turn a part with a length of 14.0 in and diameter = 4.0 in. The parameters in the Taylor equation are: $n = 0.25$ and $C = 1000$ (ft/min). The rate for the operator and machine tool = \$45.00/hr, and the tooling cost per cutting edge = \$2.50. It takes 2.5 min to load and unload the workpart and 1.50 min to change tools. The feed = 0.015 in/rev. Determine (a) cutting speed for maximum production rate, (b) tool life in min of cutting, and (c) cycle time and cost per unit of product.

Solution: (a) $v_{max} = C/((1/n\text{-}1)T_t)^n = 1000/[(1/0.25 - 1)(1.5)]^{.25}$
$= 1000/[(4.0\text{-}1) \text{ x } 1.5]^{.25} =$ **687 ft/min**

(b) $T_{max} = (1000/687)^{1/.25} = (1.456)^{4.0} =$ **4.5 min** or $(1/n - 1)\ T_t = (4\text{-}1)1.5 =$ **4.5 min**

(c) $T_m = \pi DL/fv = \pi(4)(14)/(.015 \text{ x } 687 \text{ x } 12) = 1.42$ min
$n_p = 4.5/1.42 = 3.17$ pc/tool Use $n_p = 3$ pc/tool life
$T_c = T_h + T_m + T_t/n_p = 2.5 + 1.42 + 1.5/3 =$ **4.42 min/pc**.
$C_o =$ \$45/hr = \$0.75/min
$C_c = C_o\,(T_h + T_m + T_t/n_p) + C_t/n_p = 0.75(4.42\ ) + 2.5/3 =$ **\$4.15/pc**

24.18 Solve Problem 24.17 except that in part (a), determine cutting speed for minimum cost.

Solution: (a) $C_o =$ \$45/hr = \$0.75/min
$v_{min} = C[(n/(1\text{-}n))(C_o/(C_oT_t + C_t))]^n = 1000[(0.25/(1\text{-}0.25))(0.75/(0.75(1.5) + 2.5))]^{0.25} =$
$1000[.3333*0.75/(1.125+2.5)]^{.25} = 1000[\ .333*0.75/3.625]^{0.25} = 1000\ [\ 0.06897]^{0.25} =$ **512 ft/min**

(b) $T_{min} = (1000/512)^{1/.25} = (1.953)^{4.0} =$ **14.55 min**

(c) $T_m = \pi DL/fv = \pi(4)(14)/(0.015 \text{ x } 512 \text{ x } 12) = 1.91$ min
$n_p = 14.55/1.91 = 7.62$ pc/tool Use $n_p = 7$ pc/tool life
$T_c = T_h + T_m + T_t/n_p = 2.5 + 1.91 + 1.5/7 =$ **4.62 min/pc.**
$C_c = C_o\,(T_h + T_m + T_t/n_p) + C_t/n_p = 0.75(4.62) + 2.5/7 =$ **\$3.83/pc**

24.19 Compare disposable and regrindable tooling. The same grade of cemented carbide tooling is available in two forms for turning operations in a certain machine shop: disposable inserts and brazed inserts. The parameters in the Taylor equation for this grade are: $n = 0.25$ and $C = 300$ (m/min) under the cutting conditions considered here. For the disposable inserts, price of each insert = \$6.00, there are four cutting edges per insert, and the tool change time = 1.0 min (this is an average of the time to index the insert and the time to replace it when all edges have been used). For the brazed insert, the price of the tool = \$30.00 and it is estimated that it can be used a total of 15 times before it must be scrapped. The tool change time for the regrindable tooling = 3.0 min. The standard time to grind or regrind the cutting edge is 5.0 min, and the grinder is paid at a rate = \$20.00/hr. Machine time on the lathe costs \$24.00/hr. The workpart to be used in the comparison is 375 mm long and 62.5 mm in diameter, and it takes 2.0 min to load and unload the work. The feed = 0.30 mm/rev. For the two tooling cases, compare (a) cutting speeds for minimum cost, (b) tool lives, (c) cycle time and cost per unit of production. Which tool would you recommend?

Solution: <u>Disposable inserts</u>: (a) $C_o =$ \$24/hr = \$0.40/min, $C_t =$ \$6/4 = \$1.50/edge
$v_{min} = 300[0.40/((1/0.25 - 1)(0.40 \text{ x } 1.0 + 1.50))]^{.25} = 300[0.40/(3 \text{ x } 1.9)]^{.25} =$ **154.4 m/min**

(b) $T_{min} = (1/0.25 - 1)(0.4 + 1.5)/0.4 = 3(1.9/0.4) =$ **14.25 min**

(c) $T_m = \pi(62.5)(375)/(0.30)(10^{-3})(154.4) = 1.59$ min/pc
$n_p = 14.25/1.59 = 8.96$ pc/tool life Use $n_p = 8$ pc/tool

T_c = 2.0 + 1.59 + 1.0/8 = **3.72 min/pc.**
C_c = 0.40(3.72) + 1.50/8 = **$1.674/pc**

Regrindable tooling: (a) C_o = $24/hr = $0.40/min, C_t = $30/15 + 5($20/60) = $3.67/edge
$v_{min} = 300[0.40/((1/0.25 - 1)(0.40 \text{ x } 3.0 + 3.67))]^{.25} = 300[0.40/(3 \text{ x } 4.87)]^{.25}$ = **122.0 m/min**

(b) T_{min} = (1/0.25 - 1)(0.4 x 3 + 3.67)/0.4 = 3(4.87/0.4) = **36.5 min**

(c) $T_m = \pi(62.5)(375)/(0.30)(10^{-3})(122)$ = 2.01 min/pc
n_p = 36.5/2.01 = 18.16 pc/tool life   Use n_p = 18 pc/tool
T_c = 2.0 + 2.01 + 3.0/18 = **4.18 min/pc**
C_c = 0.40(4.18) + 3.67/18 = **$1.876/pc**

Disposable inserts are recommended. Cycle time and cost per piece are less.

24.20 Solve Problem 24.19 except that in part (a), determine the cutting speeds for maximum production rate.

Solution: Disposable inserts: (a) C_o = $24/hr = $0.40/min, C_t = $6/4 = $1.50/edge
$v_{max} = 300[1.0/((1/0.25 - 1)(1.0)]^{.25} = 300[1.0/(3 \text{ x } 1.0)]^{.25}$ = **228.0 m/min**

(b) T_{max} = (1/0.25 - 1)(1.0) = 3(1.0) = **3.0 min**

(c) $T_m = \pi(62.5)(375)/(0.30)(10^{-3})(228)$ = 1.08 min/pc
n_p = 3.0/1.08 = 2.78 pc/tool life   Use n_p = 2 pc/tool
T_c = 2.0 + 1.08 + 1.0/2 = **3.58 min/pc.**
C_c = 0.40(3.58) + 1.50/2 = **$2.182/pc**

Regrindable tooling: (a) C_o = $24/hr = $0.40/min, C_t = $30/15 + 5($20/60) = $3.67/edge
$v_{max} = 300[1.0/((1/0.25 - 1)(3.0))]^{.25} = 300[1.0/(3 \text{ x } 3.0)]^{.25}$ = **173.2 m/min**

(b) T_{max} = (1/0.25 - 1)(3) = 3(3.0) = **9.0 min**

(c) $T_m = \pi(62.5)(375)/(0.30)(10^{-3})(173.2)$ = 1.42 min/pc
n_p = 9.0/1.42 = 6.34 pc/tool life   Use n_p = 6 pc/tool
T_c = 2.0 + 1.42 + 3.0/6 = **3.92 min/pc.**
C_c = 0.40(3.92) + 3.67/6 = **$2.180/pc**

Disposable inserts are recommended. Cycle time and cost per piece are less. Comparing the results in this problem with those of the previous problem, note that with the maximum production rate objective in the current problem, cycle times are less, but that unit costs are less in the previous problem where the objective is minimum cost per piece.

24.21 Three tool materials are to be compared for the same finish turning operation on a batch of 150 steel parts: high-speed steel, cemented carbide, and ceramic. For the high-speed steel tool, the Taylor equation parameters are: n = 0.130 and C = 80 (m/min). The price of the HSS tool is $20.00 and it is estimated that it can be ground and reground 15 times at a cost of $2.00 per grind. Tool change time is 3 min. Both carbide and ceramic tools are in insert form and can be held in the same mechanical toolholder. The Taylor equation parameters for the cemented carbide are: n = 0.30 and C = 650 (m/min); and for the ceramic: n = 0.6 and C = 3,500 (m/min). The cost per insert for the carbide is $8.00 and for the ceramic is $10.00. There are 6 cutting edges per insert in both cases. Tool change time is 1.0 min for both tools. The time to change a part is 2.5 min. The feed is 0.30 mm/rev, and depth of cut is 3.5 mm. The cost of machine time is $40/hr. The part is 73.0 mm in diameter and 250 mm in length. Setup time for the batch is 2.0 hr. For the three tooling cases, compare: (a) cutting speeds for minimum cost, (b) tool lives, (c) cycle time, (d) cost per production unit, (e) total time to complete the batch and production rate. (f) What is the proportion of time spent actually cutting metal for each tooling? Use of a spreadsheet calculator is recommended.

Solution: HSS tooling: (a) C_t = \$20/15 + 2.00 = \$3.33/edge. C_o = \$40/hr = \$0.667/min
$v_{min} = 80[0.667/((1/.13 - 1)(0.667 \text{ x } 3.0 + 3.33))]^{.130}$ = **47.7 m/min**

(b) T_{min} = (1/.13 - 1)(0.667 x 3 + 3.33)/0.667 = 6.69(5.33/.667) = **53.4 min**

(c) $T_m = \pi(73)(250(10^{-6}))/(0.30(10^{-3})47.7)$ = 4.01min/pc
n_p = 53.4/4.01 = 13.3 pc/tool life Use n_p = 13 pc/tool life
T_c = 2.5 + 4.01 + 3.0/13 = **6.74 min/pc.**

(d) C_c = 0.667(6.74) + 3.33/13 = **\$4.75/pc**

(e) Time to complete batch = 2.5(60) + 150(6.74) = **1161 min = 19.35 hr.**
Production rate R_p = 100 pc/13.8 hr = **7.75 pc/hr.**

(f) Proportion of time spent cutting = 100(4.81)/828 = **0.518 = 51.8%**

Cemented carbide tooling: (a) C_t = \$8/6 = \$1.33/edge. C_o = \$40/hr = \$0.667/min
$v_{min} = 650[0.667/((1/.30 - 1)(0.667 \text{ x } 1.0 + 1.333))]^{.30}$ = **363 m/min**

(b) T_{min} = (1/.30 - 1)(0.667 x 1 + 1.333)/0.667 = 2.333(2.0/0.667) = **7 min**

(c) $T_m = \pi(73)(250(10^{-6}))/(0.30(10^{-3})363)$ = 0.53 min/pc
n_p = 7/0.53 = 13.2 pc/tool life Use n_p = 13 pc/tool life
T_c = 2.5 + 0.53 + 1.0/13 = **3.11 min/pc.**

(d) C_c = 0.667(3.11) + 1.333/13 = **\$2.18/pc**

(e) Time to complete batch = 2.5(60) + 150(3.11) = **616.5 min = 10.28 hr.**

Production rate R_p = 150 pc/10.28 hr = **14.59 pc/hr.**

(f) Proportion of time spent cutting = 150(0.53)/616.5 = **0.129 = 12.9%**

Ceramic tooling**:** (a) C_t = \$10/6 = \$1.67/edge. C_o = \$40/hr = \$0.667/min
$v_{min} = 3{,}500[0.667/((1/.6 - 1)(0.667 \text{ x } 1.0 + 1.67))]^{.6}$ = **2105 m/min**

(b) T_{min} = (1/0.6 - 1)(0.667 x 1 + 1.67)/0.667 = 0.667(2.33/0.667) = **2.33 min**

(c) $T_m = \pi(73)(250(10^{-6}))/(0.30(10^{-3})2105)$ = 0.091 min/pc

n_p = 2.33/0.091 = 25.6 pc/tool life Use n_p = 25 pc/tool life
T_c = 2.5 + 0.091 + 1.0/25 = **2.63 min/pc.**

(d) C_c = 0.667(2.63) + 1.67/25 = **\$1.82/pc**

(e) Time to complete batch = 2.5(60) + 150(2.63) = **544 min = 9.08 hr.**
Production rate R_p = 150 pc/9.08 hr = **16.52 pc/hr.**

(f) Proportion of time spent cutting = 150(0.091)/544 = **0.025 = 2.5%**

Comment: One might conclude that such a low proportion of time spent cutting would argue against the use of the calculated cutting speed for ceramic tooling. However, note that ceramic tooling provides a significant advantage in terms of unit cost, batch time, and production rate compared to HSS tooling and even carbide tooling. The very small cutting time T_m and resulting low proportion of time spent cutting for ceramic tooling focuses attention on the nonproductive work elements in the batch time, specifically, setup time and workpart handling time; and puts pressure on management to seek ways to reduce these nonproductive elements.

24.22 Solve Problem 24.21 except that in parts (a) and (b), determine the cutting speeds and tool lives for maximum production rate. Use of a spreadsheet calculator is recommended.

Solution: HSS tooling: (a) C_t = \$20/15 + 2.00 = \$3.33/edge. C_o = \$40/hr = \$0.667/min

v_{max} = 80/[(1/.13 - 1)(3.0)]$^{.130}$ = 80/[6.69 x 3)]$^{.130}$ = **54 m/min**

(b) T_{max} = (1/0.13 - 1)(3) = 6.69(3) = **20.0 min**

(c) T_m = π(73)(250(10^{-6}))/(0.30(10^{-3})54) = 3.53 min/pc
n_p = 20.0/3.53 = 5.66 pc/tool life   Use n_p = 5 pc/tool life
T_c = 2.5 + 3.53 + 3.0/5 = **6.63 min/pc.**

(d) C_c = 0.667(6.63) + 3.33/5 = **$5.09/pc**

(e) Time to complete batch = 2.5(60) + 150(6.63) = **1144.5 min = 19.08 hr.**
Production rate R_p = 150 pc/19.08 hr = **7.86 pc/hr.**

(f) Proportion of time spent cutting = 150(3.53)/1144.5 = **0.463 = 46.3%**

<u>Cemented carbide tooling</u>: (a) C_t = $8/6 = $1.33/edge. C_o = $40/hr = $0.667/min
v_{max} = 650/[(1/.30 - 1)(1.0)]$^{.30}$ = 650/[(2.33 x 1.0)]$^{.30}$ = **504 m/min**

(b) T_{max} = (1/0.30 - 1)(1.0) = 2.33(1.0) = **2.33 min**

(c) T_m = π(73)(250(10^{-6}))/(0.30(10^{-3})504) = 0.38 min/pc
n_p = 2.33/0.38 = 6.13 pc/tool life   Use n_p = 6 pc/tool life
T_c = 2.5 + 0.38 + 1.0/6 = **3.05 min/pc.**

(d) C_c = 0.667(3.05) + 1.33/6 = **$2.25/pc**

(e) Time to complete batch = 2.5(60) + 150(3.05) = **607 min = 10.12 hr.**

Production rate R_p = 150 pc/10.12 hr = **14.82 pc/hr.**

(f) Proportion of time spent cutting = 150(0.38)/607 = **0.094 = 9.4%**

<u>Ceramic tooling</u>**:** (a) C_t = $10/6 = $1.67/edge. C_o = $40/hr = $0.667/min
v_{max} = 3,500/[(1/.6 - 1)(1.0)]$^{.6}$ = 3,500/[.667 x 1.0]$^{.6}$ = **4464 m/min**

(b) T_{max} = (1/0.6 - 1)(1) = 0.667(1) = **.667 min**

(c) T_m = π(73)(250(10^{-6}))/(0.30(10^{-3})4464) = 0.043 min/pc

n_p = 0.667/0.043 = 15.58 pc/tool life   Use n_p = 15 pc/tool life
T_c = 2.5 + 0.043 + 1.0/15 = **2.61 min/pc.**

(d) C_c = 0.667(2.61) + 1.67/15 = **$1.85/pc**

(e) Time to complete batch = 2.5(60) + 150(2.61) = **541 min = 9.02 hr.**
Production rate R_p = 150 pc/9.02 hr = **16.63 pc/hr.**

(f) Proportion of time spent cutting = 150(0.043)/541 = **0.012 = 1.2%**

Comment: One might conclude that such a low proportion of time spent cutting would argue against the use of the calculated cutting speed for ceramic tooling. However, note that ceramic tooling provides a significant advantage in terms of unit cost, batch time, and production rate compared to HSS tooling and even carbide tooling. The very small cutting time T_m and resulting low proportion of time spent cutting for ceramic tooling focuses attention on the nonproductive work elements in the batch time, specifically, setup time and workpart handling time; and puts pressure on management to seek ways to reduce these nonproductive elements.

24.23 A vertical boring mill is used to bore the inside diameter of a large batch of tube-shaped parts. The diameter = 28.0 in and the length of the bore = 14.0 in. Current cutting conditions are: speed = 200 ft/min, feed = 0.015 in/rev, and depth = 0.125 in. The parameters of the Taylor equation for the cutting tool in the operation are: n = 0.23 and C = 850 (ft/min). Tool change time = 3.0 min, and tooling cost = $3.50 per cutting edge. The time required to load and unload the parts = 12.0 min, and the cost of machine time on this boring mill = \$42.00/hr. Management has decreed that the production rate must be increased by 25%. Is that possible? Assume that feed must remain unchanged in order to achieve the required surface finish. What is the current production rate and the maximum possible production rate for this job?

Solution: At the current operating speed v = 200 ft/min:
$T = (850/200)^{1/.23} = 540$ min
$T_m = \pi(28)(14)/(200 \times 12 \times 0.015) = 34.2$ min/pc
$n_p = 540/34.2 = 15$ pc/tool life
$T_c = 12 + 34.2 + 3/15 = 46.4$ min
$R_c = 60/46.4 =$ **1.293 pc/hr**

Find v_{max} to compare with current operating speed.
$v_{max} = 850/[(1/.23 - 1)(3.0)]^{.23} = 850/[(3.348 \times 3.0)]^{.23} = 500$ ft/min
$T_{max} = (1/.23 - 1)(3.0) = 3.348(3.0) = 10.0$ min
$T_m = \pi(28)(14)/(500 \times 12 \times 0.015) = 13.7$ min/pc
$n_p = 10/13.7 = 0.73$ pc/tool life
$T_c = 12 + 13.7 + 3/.73 = 29.8$ min
$R_c = 60/29.8 =$ **2.01 pc/hr**
This is a 56% increase in production rate relative to the 200 ft/min cutting speed.

24.24 An NC lathe cuts two passes across a cylindrical workpiece under automatic cycle. The operator loads and unloads the machine. The starting diameter of the work is 3.00 in and its length = 10 in. The work cycle consists of the following steps (with element times given in parentheses where applicable): 1 - Operator loads part into machine, starts cycle (1.00 min); 2 - NC lathe positions tool for first pass (0.10 min); 3 - NC lathe turns first pass (time depends on cutting speed); 4 - NC lathe repositions tool for second pass (0.4 min); 5 - NC lathe turns second pass (time depends on cutting speed); and 6 - Operator unloads part and places in tote pan (1.00 min). In addition, the cutting tool must be periodically changed. This tool change time takes 1.00 min. The feed rate = 0.007 in/rev and the depth of cut for each pass = 0.100 in. The cost of the operator and machine = \$39/hr and the tool cost = \$2.00/cutting edge. The applicable Taylor tool life equation has parameters: n = 0.26 and C = 900 (ft/min). Determine (a) the cutting speed for minimum cost per piece, (b) the average time required to complete one production cycle, (c) cost of the production cycle. (d) If the setup time for this job is 3.0 hours and the batch size = 300 parts, how long will it take to complete the batch?

Solution: (a) C_o = \$39/hr = \$0.65/min
$v_{min} = 900[.65/((1/.26 - 1)(.65 \times 1.0 + 2.00))]^{.26} = 900[.65/(2.846 \times 2.65)]^{.26} =$ **476 ft/min**

(b) $T_{min} = (1/.26 - 1)(.65 \times 1 + 2.0)/.65 = 2.846(2.65/.65) =$ **11.6 min**
$T_m = \pi(3)(10)/(476 \times 12 \times 0.007) = 2.36$ min/pc. Assume both passes have equal T_m.
$n_p = 11.6/2.36 = 4.9$ passes/tool life
Since there are two passes/workpiece, $n_p = 2.45$ pc/tool life
$T_c = 2.5 + 2 \times 2.36 + 1.0/2.45 =$ **7.63 min/pc.**

(c) $C_c = 0.65(2.5 + 2 \times 2.36) + (0.65 \times 1 + 2.00)/2.45 =$ **\$5.77/pc**

(d) Time to complete batch $T_b = 3.0(60) + 300(7.63) =$ **2469 min = 41.15 hr.**

24.25 As indicated in Section 23.4, the effect of a cutting fluid is to increase the value of C in the Taylor tool life equation. In a certain machining situation using HSS tooling, the C value is increased from C = 200 to C = 225 due to the use of the cutting fluid. The n value is the same with or without fluid at n = 0.125. Cutting speed used in the operation is v = 125 ft/min. Feed = 0.010 in/rev and depth = 0.100 in. The effect of the cutting fluid can be to either increase cutting speed (at the same tool life) or increase tool life (at the same cutting speed). (a) What is the cutting speed that would result from using the cutting fluid if tool life remains the same as with no fluid? (b) What is the tool life that would result if the cutting speed remained at 125 ft/min? (c) Economically, which effect is better, given that tooling cost = \$2.00 per cutting edge, tool change time = 2.5 min, and operator and machine rate = \$30/hr? Justify you answer with calculations, using cost per cubic in of metal machined as the criterion of comparison. Ignore effects of workpart handling time.

Solution: Cutting dry, the Taylor tool life equation parameters are n = 0.125 and C = 200.
At v = 125 ft/min, tool life $T = (200/125)^{1/.125} = (1.6)^8 = 43$ min
With a cutting fluid, the Taylor tool life equation parameters are n = 0.125 and C = 225.
The corresponding cutting speed for a 43 min tool life $v = 225/43^{0.125}$ = **140.6 ft/min**

(b) Cutting at v = 125 ft/min with a cutting fluid gives a tool life $T = (225/125)^{8.0}$ = **110 min**

(c) Which is better, (1) cutting at a speed of 140.6 ft/min to give a 43 min tool life, or (2) cutting at 125 ft/min to give a 110 min tool life. Use 1.0 in^3 of metal cut as the basis of comparison, with cost and time parameters as follows: C_t = \$2.00/cutting edge, T_t = 2.5 min, and C_o = \$30/hr = \$0.50/min

(1) At v =140.6 ft/min, $T_m = 1.0\ in^3/R_{MR}$ = 1.0/(140.6 x 12 x 0.010 x 0.100) = 0.5927 min
For T = 43 min, volume cut per tool life = 43/0.5927 = 72.5 in^3 between tool changes.
Ignoring work handling time, cost/in^3 = 0.50(.5927) + (0.50 x 2.5 + 2.00)/72.5 = **\$0.341/in^3.**

(2) At 125 ft/min, $T_m = 1.0\ in^3/R_{MR}$ = 1.0/(125 x 12 x 0.010 x 0.100) = 0.6667 min
For T = 110 min, volume cut per tool life = 110/0.6667 = 164.9 in^3 between tool changes.
Ignoring work handling time, cost/in^3 = 0.50(.6667) + (0.50 x 2.5 + 2.00)/164.9 = **\$0.353/in^3.**

Conclusion: it is better to take the benefit of a cutting fluid in the form of increased cutting speed.

24.26 In a turning operation on ductile steel, it is desired to obtain an actual surface roughness of 63 μ-in with a 2/64 in nose radius tool. The ideal roughness is given by Eq. (24.1) and an adjustment will have to be made using Figure 24.2 to convert the 63 μ-in actual roughness to an ideal roughness, taking into account the material and cutting speed. Disposable inserts are used at a cost of \$1.75 per cutting edge (each insert costs \$7.00 and there are four edges per insert). Average time to change each insert = 1.0 min. The workpiece length = 30.0 in and its diameter = 3.5 in. The machine and operator's rate = \$39.00 per hour including applicable overheads. The Taylor tool life equation for this tool and work combination is given by: $vT^{0.23} f^{0.55} = 40.75$, where T = tool life, min; v = cutting speed, ft/min; and f = feed, in/rev. Solve for (a) the feed in in/rev that will achieve the desired actual finish, (b) cutting speed for minimum cost per piece at the feed determined in (a). ***Hint***: To solve (a) and (b) requires an iterative computational procedure. Use of a spreadsheet calculator is recommended for this iterative procedure.

Solution: Cost and time parameters: C_o = \$39/hr = \$0.65/min, C_t = \$1.75/cutting edge, T_t = 1.0 min

<u>Iteration 1</u>: assume $R_i = R_a = 63\ \mu\text{-in} = 63 \times 10^{-6}$ in
Rearranging Eq. (24.1), $f^2 = 32NR(R_i) = 32(2/64)(63 \times 10^{-6})\ in^2 = 63(10^{-6})\ in^2$
$f = (63 \times 10^{-6})^{0.5} = 0.00794$ in (interpreted as in/rev for turning)
$C = vT^{0.23} = 40.75/f^{0.55} = 40.75/0.00794^{0.55} = 582.5$
$v_{min} = 582.5\{(0.23/(1\text{-}0.23))(0.65/(0.65 \times 1.0 + 1.75)\}^{0.23} = 582.5\{0.0809\}^{0.23} = 326.8$ ft/min

<u>Iteration 2</u>: At v = 326.8 ft/min, the ratio from Figure 24.2 r_{ai} = 1.24.
Thus, $R_i = R_a/1.24 = 63/1.24 = 52.5\ \mu\text{-in} = 50.8(10^{-6})$ in
$f^2 = 32NR(R_i) = 32(2/64)(50.8 \times 10^{-6})\ in^2 = 50.8(10^{-6})\ in^2$
$f = (50.8 \times 10^{-6})^{0.5} = 0.00713$ in
$C = vT^{0.23} = 40.75/f^{0.55} = 40.75/0.00713^{0.55} = 617.9$
$v_{min} = 617.9\{(0.23/(1\text{-}0.23))(0.65/(0.65 \times 1.0 + 1.75)\}^{0.23} = 617.9\{0.0809\}^{0.23} = 346.5$ ft/min

<u>Iteration 3</u>: At v = 346.5 ft/min, the ratio from Figure 24.2 r_{ai} = 1.21.
Thus, $R_i = R_a/1.2 = 63/1.21 = 52.1\ \mu\text{-in} = 52.1(10^{-6})$ in

$f^2 = 32NR(R_i) = 32(2/64)(52.1 \text{ x } 10^{-6}) \text{ in}^2 = 52.1(10^{-6}) \text{ in}^2$
$f = (52.1 \text{ x } 10^{-6})^{0.5} = 0.00722$ in
$C = vT^{0.23} = 40.75/f^{0.55} = 40.75/0.00722^{0.55} = 613.9$
$v_{min} = 613.9\{(0.23/(1\text{-}0.23))(0.65/(0.65 \text{ x } 0.5 + 1.75)\}^{0.23} = 613.9\{0.0809\}^{0.23} = 344.3$ ft/min

Select ***v* = 344.3 ft/min** and ***f* = 0.0072 in/rev**.

The author's spreadsheet calculator (Excel) returned values of ***v* = 344.3 ft/min** and ***f* = 0.00722 in/rev** after three iterations. The challenge in these calculations is reading the ratio values from Figure 24.2 with sufficient precision.

24.27 Solve Problem 24.26 only using maximum production rate as the objective rather than minimum piece cost. Use of a spreadsheet calculator is recommended.

Solution: The author's spreadsheet calculator (Excel) returned values of ***v* = 451.8 ft/min** and ***f* = 0.0076 in/rev** after two iterations. The challenge in these calculations is reading the ratio values from Figure 24.2 with sufficient precision.

24.28 Verify that the derivative of Eq. (24.6) results in Eq. (24.7).

Solution: Starting with Eq. (24.6): $T_c = T_h + \pi DL/fv + T_t(\pi DLv^{1/n-1})/fC^{1/n}$
$T_c = T_h + (\pi DL/f)v^{-1} + (T_t\pi DL/fC^{1/n})v^{1/n-1}$
$dT_c/dv = 0 - (\pi DL/f)v^{-2} + (1/n - 1)(T_t\pi DL/fC^{1/n})v^{1/n-2} = 0$
$(\pi DL/f)v^{-2} = (1/n - 1)(T_t\pi DL/fC^{1/n})v^{1/n-2} = 0$
$(\pi DL/f) = (1/n - 1)(T_t\, \pi DL/fC^{1/n})v^{1/n}$
$1 = (1/n - 1)(T_t/C^{1/n})v^{1/n}$
$v^{1/n} = C^{1/n}/[(1/n\text{-}1)T_t]$

$v_{max} = C/[(1/n\text{-}1)T_t]^n$ Q.E.D

24.29 Verify that the derivative of Eq. (24.12) results in Eq. (24.13).

Solution: Starting with Eq. (24.12): $T_c = T_h + \pi DL/fv + (C_oT_t + C_t)(\pi DLv^{1/n-1})/fC^{1/n}$
$T_c = T_h + (\pi DL/f)v^{-1} + (C_oT_t + C_t)(\pi DL/fC^{1/n})v^{1/n-1}$
$dT_c/dv = 0 - (\pi DL/f)v^{-2} + (1/n - 1)(C_oT_t + C_t)(\pi DL/fC^{1/n})v^{1/n-2} = 0$
$(\pi DL/f)v^{-2} = (1/n - 1)(C_oT_t + C_t)(\pi DL/fC^{1/n})v^{1/n-2} = 0$
$(\pi DL/f) = (1/n - 1)(C_oT_t + C_t)\pi DL/fC^{1/n})v^{1/n}$
$1 = (1/n - 1)((C_oT_t + C_t)/C^{1/n})v^{1/n}$
$v^{1/n} = C^{1/n}/[(1/n\text{-}1)(C_oT_t + C_t)]$

$v_{max} = C/[(1/n\text{-}1)(C_oT_t + C_t)]^n$ Q.E.D

25 GRINDING AND OTHER ABRASIVE PROCESSES

Review Questions

25.1 Why are abrasive processes technologically and commercially important?

Answer. Important reasons include (1) applications on all types of materials, (2) very fine finishes, and (3) close tolerances.

25.2 What are the five principal parameters of a grinding wheel?

Answer. The parameters are (1) abrasive material, (2) grit size, (3) bonding material, (4) wheel structure, which refers to the relative spacing of grains, and (5) wheel grade, which refers to the bond strength of the wheel in retaining abrasive grains.

25.3 What are some of the principal abrasive materials used in grinding wheels?

Answer. The principal abrasive grit materials include (1) aluminum oxide, (2) silicon carbide, (3) cubic boron nitride, and (4) diamond.

25.4 Name some of the principal bonding materials used in grinding wheels.

Answer. The bonding materials in grinding wheels are (1) vitrified bond - clay and ceramics, (2) silicate, (3) rubber, (4) resinoid, (5) shellac, and (6) metallic.

25.5 What is wheel structure?

Answer. Wheel structure indicates the relative spacing of the abrasive grains in the wheel. An open structure is one in which the grains are far apart, and a dense structure indicates that the grains are close together.

25.6 What is wheel grade?

Answer. Wheel grade refers to the wheel's ability to retain abrasive grains during cutting. It indicates the bond strength of the bonding material used to shape the wheel. A soft grade indicates that the grains are released easily from the bonding material. A hard wheel is one which retains the abrasive grains.

25.7 Why are specific energy values so much higher in grinding than in traditional machining processes such as milling?

Answer. Reasons for higher specific energy in grinding include: (1) size effect - smaller chip size means higher specific energy; (2) extremely negative rake angles on the abrasive particles in a grinding wheel; and (3) not all of the grains in the wheel surface are engaged in cutting; some are plowing or deforming the surface while others are simply rubbing and creating friction at the surface of the work.

25.8 Grinding creates high temperatures. How is temperature harmful in grinding?

Answer. High temperatures in grinding create surface burns and cracks. High temperatures can also soften the surfaces of workparts that have been heat treated for high hardness.

25.9 What are the three mechanisms of grinding wheel wear?

Answer. The mechanisms are (1) grain fracture, in which a portion of the grain breaks off during cutting; (2) attritious wear, in which the grains become dull during cutting; and (3) bond fracture, in which the grains are pulled out of the bonding material.

25.10 What is dressing, in reference to grinding wheels?

Answer. Dressing is a procedure applied to worn grinding wheels to break off dull grits and expose fresh grits, and to remove chips of work material that have become clogged in the wheel. It uses a rotating disk or abrasive stick held against the wheel while it rotates.

25.11 What is truing, in reference to grinding wheels?

Answer. Truing is similar to dressing, but it also restores the ideal cylindrical shape to the wheel. It uses a diamond-pointed tool fed slowly and precisely across the wheel while it rotates.

25.12 What abrasive material would one select for grinding a cemented carbide cutting tool?

Answer. Choose a diamond wheel.

25.13 What are the functions of a grinding fluid?

Answer. Functions of a grinding fluid include (1) reducing friction, (2) removing heat, (3) washing away chips, and (4) reducing workpiece temperature.

25.14 What is centerless grinding?

Answer. Centerless grinding is a grinding operation in which cylindrical workparts (e.g., rods) are fed between two rotating wheels: (1) a high speed grinding wheel and (2) a low speed regulating wheel which is tilted at a slight angle to control the feed-through rate.

25.15 How does creep feed grinding differ from conventional grinding?

Answer. In creep feed grinding, the depth of cut is very high - several thousand times higher than conventional grinding - and the feed rates are lower by about the same proportion.

25.16 How does abrasive belt grinding differ from a conventional surface grinding operation?

Answer. Instead of a grinding wheel, abrasive belt grinding uses abrasive particles bonded to a flexible cloth belt loop which is moved around a pulley system to obtain the speed motion. Parts are pressed against the belt to accomplish grinding.

25.17 Name some of the abrasive operations available to achieve very good surface finishes.

Answer. High finish abrasive processes include honing, lapping, superfinishing, buffing, and polishing.

25.18 (**Video**) Describe a wheel ring test**.**

Answer: A wheel ring test is performed by suspending the wheel and lightly striking it with a solid, non-metal object, similar to striking a bell. The wheel should ring a clear long tone. If it has cracks, it will not ring properly.

25.19 (**Video**) List two purposes of dressing a grinding wheel.

Answer: Two purposes of dressing a grinding wheel are (1) to renew the wheel surface by fracturing abrasive particles and (2) to remove tiny pieces of embedded workpiece material.

25.20 (**Video**) What is the purpose of using a coolant in the grinding process?

Answer: According to the video, the purpose of using coolant in the grinding process are threefold: (1) to reduce grinding power required, (2) to maintain work quality, and (3) to stabilize part dimensions over long production runs.

Multiple Choice Quiz

There are 16 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and

each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

25.1 Which one of the following conventional machining processes is closest to grinding: (a) drilling, (b) milling, (c) shaping, or (d) turning?

Answer. (b).

25.2 Of the following abrasive materials, which one has the highest hardness: (a) aluminum oxide, (b) cubic boron nitride, or (c) silicon carbide?

Answer. (b).

25.3 Smaller grain size in a grinding wheel tends to (a) degrade surface finish, (b) have no effect on surface finish, or (c) improve surface finish?

Answer. (c).

25.4 Which of the following would tend to give higher material removal rates: (a) larger grain size, or (b) smaller grain size?

Answer. (a).

25.5 Which of the following will improve surface finish in grinding (three best answers): (a) denser wheel structure, (b) higher wheel speed, (c) higher workspeeds, (d) larger infeed, (e) lower infeed, (f) lower wheel speed, (g) lower workspeed, and (h) more open wheel structure?

Answer. (a), (b), and (g).

25.6 Which one of the following abrasive materials is most appropriate for grinding steel and cast iron: (a) aluminum oxide, (b) cubic boron nitride, (c) diamond, or (d) silicon carbide?

Answer. (a).

25.7 Which one of the following abrasive materials is most appropriate for grinding hardened tool steel: (a) aluminum oxide, (b) cubic boron nitride, (c) diamond, or (d) silicon carbide?

Answer. (b).

25.8 Which one of the following abrasive materials is most appropriate for grinding nonferrous metals: (a) aluminum oxide, (b) cubic boron nitride, (c) diamond, or (d) silicon carbide?

Answer. (d).

25.9 Which of the following will help to reduce the incidence of heat damage to the work surface in grinding (four correct answers): (a) frequent dressing or truing of the wheel, (b) higher infeeds, (c) higher wheel speeds, (d) higher workspeeds, (e) lower infeeds, (f) lower wheel speeds, and (g) lower workspeeds?

Answer. (a), (d), (e), and (g).

25.10 Which one of the following abrasive processes achieves the best surface finish: (a) centerless grinding, (b) honing, (c) lapping, or (d) superfinishing?

Answer. (d).

25.11 The term deep grinding refers to which one of the following: (a) alternative name for any creep feed grinding operation, (b) external cylindrical creep feed grinding, (c) grinding operation performed at the bottom of a hole, (d) surface grinding that uses a large crossfeed, or (e) surface grinding that uses a large infeed?

Answer. (b).

Problems

25.1 In a surface grinding operation wheel diameter = 150 mm and infeed = 0.07 mm. Wheel speed = 1450 m/min, workspeed = 0.25 m/s, and crossfeed = 5 mm. The number of active grits per area of wheel surface = 0.75 grits/mm^2. Determine (a) average length per chip, (b) metal removal rate, and (c) number of chips formed per unit time for the portion of the operation when the wheel is engaged in the work.

Solution: (a) $l_c = (Dd)^{0.5} = (150 \text{ x } 0.07)^{0.5} =$ **3.24 mm**

(b) $R_{MR} = v_w wd$ = (0.25 m/s)(10^3 mm/m)(5.0 mm)(0.07 mm) = 87.5 mm^3/s = **5250 mm^3/min**

(c) $n_c = vwC$ = (1450 m/min)(10^3 mm/m)(5.0 mm)(0.75 grits/mm^2) = **5,437,500 chips/min**

25.2 The following conditions and settings are used in a certain surface grinding operation: wheel diameter = 6.0 in, infeed = 0.003 in, wheel speed = 4750 ft/min, workspeed = 50 ft/min, and crossfeed = 0.20 in. The number of active grits per square inch of wheel surface = 500. Determine (a) average length per chip, (b) metal removal rate, and (c) number of chips formed per unit time for the portion of the operation when the wheel is engaged in the work.

Solution: (a) $l_c = (Dd)^{0.5} = (6.0 \text{ x } 0.003)^{0.5} = (0.018)^{0.5} =$ **0.1342 in**

(b) $R_{MR} = v_w wd$ = (50 x 12)(0.20)(0.003) = **0.36 in^3/min**

(c) $n_c = vwC$ = (4750 x 12)(0.2)(500) = **5,700,000 chips/min**

25.3 An internal cylindrical grinding operation is used to finish an internal bore from an initial diameter of 250.00 mm to a final diameter of 252.5 mm. The bore is 125 mm long. A grinding wheel with an initial diameter of 150.00 mm and a width of 20.00 mm is used. After the operation, the diameter of the grinding wheel has been reduced to 149.75 mm. Determine the grinding ratio in this operation.

Solution: GR = (volume of work material removed)/(volume of wheel removed)
Volume of work material removed = (π/4)(125)(252.5^2 – 250.0^2) = 123,332 mm^3
Volume of wheel removed = (π/4)(20)(150^2 – 149.75^2) = 1177 mm^3
GR = 123,332/1177 = **104.8**

25.4 In a surface grinding operation performed on hardened plain carbon steel, the grinding wheel has a diameter = 200 mm and width = 25 mm. The wheel rotates at 2400 rev/min, with a depth of cut (infeed) = 0.05 mm/pass and a crossfeed = 3.50 mm. The reciprocating speed of the work is 6 m/min, and the operation is performed dry. Determine (a) length of contact between the wheel and the work and (b) volume rate of metal removed. (c) If there are 64 active grits/cm^2 of wheel surface, estimate the number of chips formed per unit time. (d) What is the average volume per chip? (e) If the tangential cutting force on the work = 25 N, compute the specific energy in this operation?

Solution: (a) $l_c = (Dd)^{0.5} = (200 \text{ x } 0.05)^{0.5} =$ **3.16 mm**

(b) $R_{MR} = v_w wd$ = (6 m/min)(10^3 mm/m)(3.5 mm)(0.05 mm) = **1050 mm^3/min**

(c) $n_c = vwC$
$v = N\pi D$ = (2400 rev/min)(200π mm/rev) = 1,507,964 mm/min
n_c = (1,507,964 mm/min)(3.5 mm)(64 grits/cm^2)(10^{-2} cm^2/mm^2)
= **3,377,840 grits/min (= chips/min)**

(d) 3,377,840 grits/min = 3,377,840 chips/min
Average volume per chip = (1050 mm^3/min)/(3,377,840 chips/min) = **0.00031 mm^3/chip**

(e) $U = F_c v/R_{MR}$
v = 1,507,964 mm/min = 1,508 m/min
U = 25(1508)/1050 = **35.9 N-m/mm^3**

25.5 An 8-in diameter grinding wheel, 1.0 in wide, is used in a surface grinding job performed on a flat piece of heat-treated 4340 steel. The wheel rotates to achieve a surface speed of 5000 ft/min, with a depth of cut (infeed) = 0.002 in per pass and a crossfeed = 0.15 in. The reciprocating speed of the work is 20 ft/min, and the operation is performed dry. (a) What is the length of contact between the wheel and the work? (b) What is the volume rate of metal removed? (c) If there are 300 active grits/in^2 of wheel surface, estimate the number of chips formed per unit time. (d) What is the average volume per chip? (e) If the tangential cutting force on the workpiece = 7.3 lbs, what is the specific energy calculated for this job?

Solution: (a) $l_c = (Dd)^{0.5} = (8 \text{ x } 0.002)^{0.5} = (0.016)^{0.5} =$ **0.1265 in**

(b) $R_{MR} = v_w wd = (20 \text{ x } 12)(0.15)(0.002) =$ **0.072 in^3/min**

(c) $n_c = vwC = (5000 \text{ x } 12)(0.15)(300) =$ **2,700,000 chips/min**

(d) Avg volume/chip = (0.072 in^3/min)/(2,700,000 chips/min) = 0.000000026 in^3 = **26 x 10^{-9} in^3**

(e) $U = F_c v/R_{MR} = 7.3(5000 \text{ x } 12)/0.072 =$ **6,083,333 in-lb/in^3 = 15.4 hp/(in^3/min)**

25.6 A surface grinding operation is being performed on a 6150 steel workpart (annealed, approximately 200 BHN). The designation on the grinding wheel is C-24-D-5-V. The wheel diameter = 7.0 in and its width = 1.00 in. Rotational speed = 3000 rev/min. The depth (infeed) = 0.002 in per pass, and the crossfeed = 0.5 in. Workspeed = 20 ft/min. This operation has been a source of trouble right from the beginning. The surface finish is not as good as the 16 μ-in specified on the part print, and there are signs of metallurgical damage on the surface. In addition, the wheel seems to become clogged almost as soon as the operation begins. In short, nearly everything that can go wrong with the job has gone wrong. (a) Determine the rate of metal removal when the wheel is engaged in the work. (b) If the number of active grits per square inch = 200, determine the average chip length and the number of chips formed per time. (c) What changes would you recommend in the grinding wheel to help solve the problems encountered? Explain why you made each recommendation.

Solution: (a) $R_{MR} = v_w wd = (20 \text{ x } 12)(0.5)(0.002) =$ **0.24 in^3/min**

(b) $l_c = (Dd)^{0.5} = (7.0 \text{ x } .002)^{0.5} = 0.1183$ in
$v = \pi DN = \pi(7.0/12)(3000) = 5498$ ft/min = 65,973 in/min
$n_c = vwC = 65{,}973(0.5)(200) =$ **6,597,300 grits/min**

(c) Changes in wheel to help solve problems cited: (1) use Al_2O_3 oxide abrasive rather than silicon carbide; (2) use smaller grain size than 24; (3) use shellac bond rather than vitrified bond; and (4) use more open structure than number 5 to reduce wheel clogging.

25.7 The grinding wheel in a centerless grinding operation has a diameter = 200 mm, and the regulating wheel diameter = 125 mm. The grinding wheel rotates at 3000 rev/min and the regulating wheel rotates at 200 rev/min. The inclination angle of the regulating wheel = 2.5°. Determine the throughfeed rate of cylindrical workparts that are 25.0 mm in diameter and 175 mm long.

Solution: From Eq. (25.11), $f_r = \pi D_r N_r \sin I$
$f_r = \pi(125)(200) \sin 2.5° = 25{,}000\pi(0.04362) = 3426$ mm/min
Parts through-feed rate = (3426 mm/min)/(175 mm/pc) = **19.58 pc/min**

25.8 A centerless grinding operation uses a regulating wheel that is 150 mm in diameter and rotates at 500 rev/min. At what inclination angle should the regulating wheel be set, if it is desired to feed a workpiece with length = 3.5 m and diameter = 18 mm through the operation in exactly 30 sec?

Solution: From Eq. (25.11), $f_r = \pi D_r N_r \sin I$
f_r = 3.5 m per 30 sec = 0.11667 m/s = 7.0 m/min
$f_r = \pi(150 \text{ x } 10^{-3})(500 \text{ rev/min}) \sin I = 235.62 \sin I$ (units are m/min)
7.0 m/min = 235.62 sin I m/min

sin I = 7.0/235.62 = 0.0297 **I = 1.70°**

25.9 In a certain centerless grinding operation, the grinding wheel diameter = 8.5 in, and the regulating wheel diameter = 5.0 in. The grinding wheel rotates at 3500 rev/min and the regulating wheel rotates at 150 rev/min. The inclination angle of the regulating wheel = 3°. Determine the throughfeed rate of cylindrical workparts that have the following dimensions: diameter = 1.25 in and length = 8.0 in.

Solution: From Eq. (25.11), $f_r = \pi D_r N_r \sin I = \pi(5.0)(150) \sin 3° = 123.33$ in/min
Parts feed at (8.0 in/part)/(123.33 in/min) = 0.0649 min/part = 3.9 sec/part
Throughfeed rate = 1/0.0649 = **15.4 parts per min**

25.10 It is desired to compare the cycle times required to grind a particular workpiece using traditional surface grinding and using creep feed grinding. The workpiece is 200 mm long, 30 mm wide, and 75 mm thick. To make a fair comparison, the grinding wheel in both cases is 250 mm in diameter, 35 mm in width, and rotates at 1500 rev/min. It is desired to remove 25 mm of material from the surface. When traditional grinding is used, the infeed is set at 0.025 mm, and the wheel traverses twice (forward and back) across the work surface during each pass before resetting the infeed. There is no crossfeed since the wheel width is greater than the work width. Each pass is made at a workspeed of 12 m/min, but the wheel overshoots the part on both sides. With acceleration and deceleration, the wheel is engaged in the work for 50% of the time on each pass. When creep feed grinding is used, the depth is increased by 1000 and the forward feed is decreased by 1000. How long will it take to complete the grinding operation (a) with traditional grinding and (b) with creep feed grinding?

Solution: (a) Conventional surface grinding:
Time of engagement/pass = 200 x 10^{-3} m/(12 m/min) = 0.01667 min = 1 s
Forward and backward stroke = 2(1 s)/50% = 4 s
Number of passes to remove 25 mm = 25/0.025 = 1000 passes
Time to complete 1000 passes = 1000(4) = 4000 s = **66.67 min**

(b) Creep feed grinding:
Total length of feed = 200 mm + approach = 200 + $(d(D-d))^{0.5}$
Given D = 250 mm and d = 25 mm, Total feed length = 200 + $(25(250-25))^{0.5}$ = 275 mm
f_r = (12 x 10^3 mm/min)/1000 = 12 mm/min
Time to feed = 275/12 = **22.917 min**

Note: Creep feed grinding requires about 1/3 the time of conventional surface grinding for the situation defined here.

25.11 In a certain grinding operation, the grade of the grinding wheel should be "M" (medium), but the only available wheel is grade "T" (hard). It is desired to make the wheel appear softer by making changes in cutting conditions. What changes would you recommend?

Solution: A hard wheel means that the grains are not readily pulled from the wheel bond. The wheel can be made to appear softer by increasing the force on the individual grits as given by Eq. (25.8). According to this equation, the force on the abrasive grains will be increased by increasing work speed v_w, decreasing wheel speed v, and increasing infeed d.

25.12 An aluminum alloy is to be ground in an external cylindrical grinding operation to obtain a good surface finish. Specify the appropriate grinding wheel parameters and the grinding conditions for this job.

Solution: Grinding wheel specification:
Abrasive type: silicon carbide
Grain size: small - high grit size number

Bond material: shellac bond
Wheel structure: dense
Wheel grade: medium to hard
Wheel specification: **C-150-E-5-B**

Grinding conditions:
Wheel speed: high speed, around 1800 m/min (6000 ft/min)
Work speed: low, around 10 m/min (30 ft/min)
Infeed (depth of cut): low, around 0.012 mm (0.0005 in)
Crossfeed: low, around 1/6 of wheel width.

25.13 A high-speed steel broach (hardened) is to be resharpened to achieve a good finish. Specify the appropriate parameters of the grinding wheel for this job.

Solution: Grinding wheel specification:
Abrasive type: cubic boron nitride
Grain size: small - high grit size number
Bond material: vitrified bond
Wheel grade: soft to medium
Wheel specification: XX**-B-150-P-XY-V-**XZ-1/8, where XX, XY, and XZ are manufacturer's symbols.

25.14 Based on equations in the text, derive an equation to compute the average volume per chip formed in the grinding process.

Solution: From Eq. (25.3), $R_{MR} = v_w wd$ (in^3/min)
From Eq. (25.6), $n_c = vwC$ (chips/min)
Volume per chip = $R_{MR}/n_c = v_w wd/vwC = \boldsymbol{v_w d/vC}$

26 NONTRADITIONAL MACHINING AND THERMAL CUTTING PROCESSES

Review Questions

26.1 Why are the nontraditional material removal processes important?

Answer. Reasons for importance of are nontraditional material removal processes (1) the need to shape new metal alloys and non-metals that are difficult to machine by conventional processes; (2) the requirement of unusual and complex workpart geometries; and (3) the need to avoid surface damage which is often associated with conventional machining.

26.2 There are four categories of nontraditional machining processes, based on principal energy form. Name the four categories.

Answer. The four categories are (1) mechanical, but not including conventional machining; (2) electrical; (3) thermal; and (4) chemical.

26.3 How does the ultrasonic machining process work?

Answer. In ultrasonic machining, abrasives contained in a slurry are driven at high velocity against the work by a tool vibrating at low amplitude and high frequency. The tool oscillates in a direction perpendicular to the work surface, and is fed slowly into the work, so that the shape of the tool is formed in the part. The abrasives, impinging against the work surface, perform the chip removal.

26.4 Describe the water jet cutting process.

Answer. Water jet cutting uses a high-pressure, high-velocity stream of water directed at the work surface to cut the work.

26.5 What is the difference between water jet cutting, abrasive water jet cutting, and abrasive jet cutting?

Answer. WJC cuts with a narrow, high velocity water stream; AWJC adds abrasive grits to the water stream; and AJM cuts with abrasive particles that have been added to a high velocity air stream.

26.6 Name the three main types of electrochemical machining.

Answer. The three types are electrochemical machining, deburring, and grinding.

26.7 Identify the two significant disadvantages of electrochemical machining.

Answer. Disadvantages of ECM include (1) cost of electrical power to operate the process, and (2) cost of disposal of electrolyte sludge.

26.8 How does increasing discharge current affect metal removal rate and surface finish in electric discharge machining?

Answer. As discharge current increases, metal removal rate increases and surface finish is degraded.

26.9 What is meant by the term overcut in electric discharge machining?

Answer. Overcut refers to the gap between the electrode (tool) in EDM on each side of the tool and the machined hole, cavity, or kerf (in wire EDM).

26.10 Identify two major disadvantages of plasma arc cutting.

Answer. Two disadvantages of PAC are (1) rough surface on cut edge and (2) metallurgical damage to cut surface.

26.11 What are some of the fuels used in oxyfuel cutting?

Answer. Principal fuels are acetylene, MAPP (methylacetylene-propadiene), propylene, propane, and natural gas.

26.12 Name the four principal steps in chemical machining.

Answer. The four steps are (1) cleaning, (2) masking, (3) etching, and (4) demasking.

26.13 What are the three methods of performing the masking step in chemical machining?

Answer. The three masking methods are (1) cut and peel, (2) screen resist, and (3) photographic resist.

26.14 What is a photoresist in chemical machining?

Answer. A photoresist is a masking material that is sensitive to light. When exposed, it chemically transforms and can be removed from the surface of the work, leaving the desired surface unprotected by the maskant.

26.15 (**Video**) What are the three layers of a part's surface after undergoing EDM**.**

Answer: The three layers are the following: (1) Spheres attached to the surface made of part material and electrode material that have spattered the surface. This layer is easily removed. (2) Recast or white layer where EDM has altered the workpiece metallurgical structure. It can be reduced by specifying the proper settings and removed by polishing. (3) Heat affected zone or annealed layer. It has only been heated, not melted.

26.16 (**Video**) What are two other names for ram type EDMs?

Answer: A ram type EDM machines is also called a die sinker and a vertical EDM machine.

26.17 (**Video**) Name the four subsystems in a RAM EDM process.

Answer: The four subsystems in a RAM EDM process are (1) power supply, (2) dielectric system, (3) electrode, and (4) servo system.

26.18 (**Video**) Name the four subsystems in a wire EDM process.

Answer: The four subsystems in a wire EDM process are (1) power supply, (2) dielectric system, (3) wire feeding system, and (4) positioning system.

Multiple Choice Quiz

There are 17 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

26.1 Which of the following processes use mechanical energy as the principal energy source (three correct answers): (a) electrochemical grinding, (b) laser beam machining, (c) conventional milling, (d) ultrasonic machining, (e) water jet cutting, and (f) wire EDM?

Answer. (c), (d), and (e).

26.2 Ultrasonic machining can be used to machine both metallic and nonmetallic materials: (a) true or (b) false?

Answer. (a).

26.3 Applications of electron beam machining are limited to metallic work materials due to the need for the work to be electrically conductive: (a) true or (b) false?

Answer. (b).

26.4 Which one of the following is closest to the temperatures used in plasma arc cutting: (a) 2750°C (5000°F), (b) 5500°C (10,000°F), (c) 8300°C (15,000°F), (d) 11,000°C (20,000°F), or (e) 16,500°C (30,000°F)?

Answer. (d).

26.5 Chemical milling is used in which of the following applications (two best answers): (a) drilling holes with high depth-to-diameter ratio, (b) making intricate patterns in thin sheet metal, (c) removing material to make shallow pockets in metal, (d) removing metal from aircraft wing panels, and (e) cutting of plastic sheets?

Answer. (c) and (d).

26.6 Etch factor is equal to which of the following in chemical machining (more than one): (a) anisotropy, (b) CIt, (c) d/u, and (d) u/d; where C = specific removal rate, d = depth of cut, I = current, t = time, and u = undercut?

Answer. (a) and (c).

26.7 Of the following processes, which one is noted for the highest material removal rates: (a) electric discharge machining, (b) electrochemical machining, (c) laser beam machining, (d) oxyfuel cutting, (e) plasma arc cutting, (f) ultrasonic machining, or (g) water jet cutting?

Answer. (e).

26.8 Which one of the following processes would be appropriate to drill a hole with a square cross section, 0.25 inch on a side and 1-inch deep in a steel workpiece: (a) abrasive jet machining, (b) chemical milling, (c) EDM, (d) laser beam machining, (e) oxyfuel cutting, (f) water jet cutting, or (g) wire EDM?

Answer. (c).

26.9 Which of the following processes would be appropriate for cutting a narrow slot, less than 0.015 inch wide, in a 3/8-in-thick sheet of fiber-reinforced plastic (two best answers): (a) abrasive jet machining, (b) chemical milling, (c) EDM, (d) laser beam machining, (e) oxyfuel cutting, (f) water jet cutting, and (g) wire EDM?

Answer. (d) and (f).

26.10 Which one of the following processes would be appropriate for cutting a hole of 0.003 inch diameter through a plate of aluminum that is 1/16 in thick: (a) abrasive jet machining, (b) chemical milling, (c) EDM, (d) laser beam machining, (e) oxyfuel cutting, (f) water jet cutting, and (g) wire EDM?

Answer. (d).

26.11 Which of the following processes could be used to cut a large piece of 1/2-inch plate steel into two sections (two best answers): (a) abrasive jet machining, (b) chemical milling, (c) EDM, (d) laser beam machining, (e) oxyfuel cutting, (f) water jet cutting, and (g) wire EDM?

Answer. (e) and (g).

Problems

Application Problems

26.1 For the following application, identify one or more nontraditional machining processes that might be used, and present arguments to support your selection. Assume that either the part geometry or the work material (or both) preclude the use of conventional machining. The application is a matrix of 0.1 mm (0.004 in) diameter holes in a plate of 3.2 mm (0.125 in) thick hardened tool steel. The matrix is rectangular, 75 by 125 mm (3.0 by 5.0 in) with the separation between holes in each direction = 1.6 mm (0.0625 in).

Solution: Application: matrix of holes in 0.125 inch thick hardened steel, hole diameter = 0.004 in, separation between holes = 0.0625 in. Possible processes: **EBM** and **LBM** can make holes of this size with depth-to-diameter ratios as large as 0.125/0.004 = 31.25.

26.2 For the following application, identify one or more nontraditional machining processes that might be used, and present arguments to support your selection. Assume that either the part geometry or the work material (or both) preclude the use of conventional machining. The application is an engraved aluminum printing plate to be used in an offset printing press to make 275 by 350 mm (11 by 14 in) posters of Lincoln's Gettysburg address.

Solution: Application: engraved aluminum printing press plate for 11 in by 14 in posters. Possible process: photochemical engraving; making a negative of the speech and transferring this to either a silk screen or directly to the photoresist would seem to be the most straightforward methods.

26.3 For the following application, identify one or more nontraditional machining processes that might be used, and present arguments to support your selection. Assume that either the part geometry or the work material (or both) preclude the use of conventional machining. The application is a through-hole in the shape of the letter L in a 12.5 mm (0.5 in) thick plate of glass. The size of the "L" is 25 by 15 mm (1.0 by 0.6 in) and the width of the hole is 3 mm (1/8 in).

Solution: Application: through-hole in the shape of the letter "L" drilled through 0.5-in thick plate glass. Possible process: USM works on glass and other brittle non-metallic materials. This is probably the best process.

26.4 For the following application, identify one or more nontraditional machining processes that might be used, and present arguments to support your selection. Assume that either the part geometry or the work material (or both) preclude the use of conventional machining. The application is a blind-hole in the shape of the letter G in a 50 mm (2.0 in) cube of steel. The overall size of the "G" is 25 by 19 mm (1.0 by 0.75 in), the depth of the hole is 3.8 mm (0.15 in), and its width is 3 mm (1/8 in).

Solution: Application: the letter "G" drilled to a depth of 0.15 in in block of steel. Possible processes: **ECM** and **EDM** would be useful for pocketing operations such as this.

26.5 Much of the work at the Cut-Anything Company involves cutting and forming of flat sheets of fiber-glass for the pleasure boat industry. Manual methods based on portable saws are currently used to perform the cutting operation, but production is slow and scrap rates are high. The foreman says the company should invest in a plasma arc cutting machine, but the plant manager thinks it would be too expensive. What do you think? Justify your answer by indicating the characteristics of the process that make PAC attractive or unattractive in this application.

Solution: In plasma arc cutting, the workpart must be an electrically conductive material. Fiber glass is not electrically conductive. PAC is therefore not an appropriate process for this application.

26.6 A furniture company that makes upholstered chairs and sofas must cut large quantities of fabrics. Many of these fabrics are strong and wear-resistant, which properties make them difficult to cut.

What nontraditional process(es) would you recommend to the company for this application? Justify your answer by indicating the characteristics of the process that make it attractive.

Solution: Water jet cutting would be an ideal process for this application. WJC cuts through fabrics quickly and cleanly, and the process could be readily automated.

Electrochemical Machining

26.7 The frontal working area of the electrode in an ECM operation is 2000 mm^2. The applied current = 1800 amps and the voltage = 12 volts. The material being cut is nickel (valence = 2), whose specific removal rate is given in Table 26.1. (a) If the process is 90% efficient, determine the rate of metal removal in mm^3/min. (b) If the resistivity of the electrolyte = 140 ohm-mm, determine the working gap.

Solution: (a) From Table 26.1, $C = 3.42 \times 10^{-2}$ mm^3/A-s
From Eq. (26.6) $R_{MR} = f_r A = (CI/A)A = CI = (3.42 \times 10^{-2}\ mm^3/A\text{-}s)(1800\ A)$
$= 6156 \times 10^{-2}\ mm^3/s = 61.56\ mm^3/s = 3693.6\ mm^3/min$
At 90% efficiency $R_{MR} = 0.9(3693.6\ mm^3/min) =$ **3324.2 mm^3/min**

(b) Given resistivity r = 140 ohm-mm, $I = EA/gr$ in Eq. (26.2). Rearranging, $g = EA/Ir$
$g = (12\ V)(2000\ mm^2)/(1800\ A)(140\ ohm\text{-}mm) =$ **0.095 mm**

26.8 In an electrochemical machining operation, the frontal working area of the electrode is 2.5 in^2. The applied current = 1500 amps, and the voltage = 12 volts. The material being cut is pure aluminum, whose specific removal rate is given in Table 26.1. (a) If the ECM process is 90 percent efficient, determine the rate of metal removal in in^3/hr. (b) If the resistivity of the electrolyte = 6.2 ohm-in, determine the working gap.

Solution: (a) From Table 26.1, $C = 0.000126$ in^3/A-min
$R_{MR} = f_r A = (CI/A)(A) = CI$
$R_{MR} = CI = 0.000126(1500) = 0.189\ in^3/min$ at 100% efficiency.
At 90% efficiency $R_{MR} = 0.189(0.90) = 0.1701\ in^3/min =$ **10.206 in^3/hr.**

(b) $I = EA/gr$; Rearranging, $g = EA/Ir = 12(2.5)/(1500 \times 6.2) =$ **0.0032 in**

26.9 A square hole is to be cut using ECM through a plate of pure copper (valence = 1) that is 20 mm thick. The hole is 25 mm on each side, but the electrode used to cut the hole is slightly less that 25 mm on its sides to allow for overcut, and its shape includes a hole in its center to permit the flow of electrolyte and to reduce the area of the cut. This tool design results in a frontal area of 200 mm^2. The applied current = 1000 amps. Using an efficiency of 95%, determine how long it will take to cut the hole.

Solution: From Table 26.1, $C = 7.35 \times 10^{-2}$ mm^3/A-s
From Eq. (26.6) $f_r = CI/A = (7.35 \times 10^{-2}\ mm^3/A\text{-}s)(1000\ A)/(200\ mm^2) = 0.3675\ mm/s$
At 95% efficiency, $f_r = 0.95(0.3675\ mm/s) = 0.349\ mm/s$
Time to machine = (20 mm)/(0.349 mm/s) = **57.3 s**

26.10 A 3.5 in diameter through hole is to be cut in a block of pure iron (Valence = 2) by electrochemical machining. The block is 2.0 in thick. To speed the cutting process, the electrode tool will have a center hole of 3.0 in which will produce a center core that can be removed after the tool breaks through. The outside diameter of the electrode is undersized to allow for overcut. The overcut is expected to be 0.005 in on a side. If the efficiency of the ECM operation is 90%, what current will be required to complete the cutting operation in 20 minutes?

Solution: Electrode frontal gap area $A = 0.25\pi(3.5^2 - 3.0^2) = 2.553\ in^2$
From Table 26.1, $C = 0.000135$ in^3/A-min
$f_r = CI/A = 0.000135\ I/2.553 = 0.0000529\ I$ in/min at 100% efficiency.

At 90% efficiency $f_r = 0.9(0.0000529\ I) = 0.0000476\ I$ in/min
To cut through a 2.0 inch thickness in 20 minutes requires a feed rate $f_r = 2.0/20 = 0.1$ in/min
$f_r = 0.1 = 0.0000476$ I
$I = 0.1/0.0000476 =$ **2101 A.**

Electric Discharge Machining

26.11 An electric discharge machining operation is being performed on two work materials: tungsten and tin. Determine the amount of metal removed in the operation after one hour at a discharge current of 20 amps for each of these metals. Use metric units and express the answers in mm^3/hr. From Table 4.1, the melting temperatures of tungsten and tin are 3410°C and 232°C, respectively.

Solution: For tungsten, using Eq. (26.7), $R_{MR} = KI/T_m^{1.23} = 664(20)/(3410^{1.23}) = 13{,}280/22{,}146$ $= 0.5997$ mm^3/s = **2159 mm^3/hr**

For tin, $R_{MR} = KI/T_m^{1.23} = 664(20)/(232^{1.23}) = 13{,}280/812 = 16.355$ mm^3/s = **58,878 mm^3/hr**

26.12 An electric discharge machining operation is being performed on two work materials: tungsten and zinc. Determine the amount of metal removed in the operation after one hour at a discharge amperage = 20 amps for each of these metals. Use U.S. Customary units and express the answer in in^3/hr. From Table 4.1, the melting temperatures of tungsten and zinc are 6170°F and 420°F, respectively.

Solution: For tungsten, using Eq. (26.7), $R_{MR} = KI/T_m^{1.23} = 5.08(20)/(6170^{1.23}) = 101.6/45{,}925$ $= 0.00221$ in^3/s = **0.1327 in^3/hr**

For Zinc, $R_{MR} = KI/T_m^{1.23} = 5.08(20)/(420^{1.23}) = 101.6/1685 = 0.0603$ in^3/s = **3.62 in^3/hr**

26.13 Suppose the hole in Problem 26.10 were to be cut using EDM rather than ECM. Using a discharge current = 20 amps (which would be typical for EDM), how long would it take to cut the hole? From Table 4.1, the melting temperature of iron is 2802°F.

Solution: Using Eq. (26.7), $R_{MR} = 5.08\ I/T_m^{1.23} = 5.08(20)/2802^{1.23} = 101.6/17{,}393$
$= 0.00584$ in^3/min
Cross-sectional area of tool from previous problem $A = 2.553$ in^2
$f_r = R_{MR}/A = 0.00584/2.553 = 0.002293$ in/min
Time to machine the 2.0 inch thickness $T_m = 2.0/0.002293 =$ **874.3 min = 14.57 hr.**

26.14 A metal removal rate of 0.01 in^3/min is achieved in a certain EDM operation on a pure iron workpart. What metal removal rate would be achieved on nickel in this EDM operation, if the same discharge current were used? The melting temperatures of iron and nickel are 2802°F and 2651°F, respectively.

Solution: For iron, $R_{MR} = 5.08\ I/2802^{1.23} = 5.08\ I/17{,}393 = 0.000292\ I$ in^3/min
Given that $R_{MR} = 0.01$ in^3/min
$0.000292\ I = 0.01$
$I = 0.01/0.000292 = 34.24$ A.
For = nickel, $R_{MR} = 5.08(34.24)/2651^{1.23} = 173.93/16{,}248 =$ **0.0107 in^3/min**

26.15 In a wire EDM operation performed on 7-mm-thick C1080 steel using a tungsten wire electrode whose diameter = 0.125 mm, past experience suggests that the overcut will be 0.02 mm, so that the kerf width will be 0.165 mm. Using a discharge current = 10 amps, what is the allowable feed rate that can be used in the operation? Estimate the melting temperature of 0.80% carbon steel from the phase diagram of Figure 6.4.

Solution: From Figure 6.4, $T_m = 1500$°C for 1080 steel
Using Eq. (26.7), $R_{MR} = 664(10)/(1500^{1.23}) = 6640/8065 = 0.8233$ mm^3/s
Frontal area of kerf $A = 0.165(7.0) = 1.155$ mm^2

f_r = 49.4/1.155 = **42.79 mm/min**

26.16 A wire EDM operation is to be performed on a slab of ¾-in-thick aluminum using a brass wire electrode whose diameter = 0.005 in. It is anticipated that the overcut will be 0.001 in, so that the kerf width will be 0.007 in. Using a discharge current = 7 amps, what is the expected allowable feed rate that can be used in the operation? The melting temperature of aluminum is 1220°F.

Solution: Using Eq. (26.7), $R_{MR} = 5.08(7)/1220^{1.23} = 35.56/6255 = 0.005685$ in^3/min
Frontal area of kerf A = 0.75(0.007) = 0.00525 in^2
f_r = 0.005685/0.00525 = **1.083 in/min**

26.17 A wire EDM operation is used to cut out punch-and-die components from 25-mm-thick tool steel plates. However, in preliminary cuts, the surface finish on the cut edge is poor. What changes in discharge current and frequency of discharges should be made to improve the finish?

Solution: As indicated in Figure 26.8(a), surface finish in EDM could be improved by reducing discharge current and increasing frequency of discharges.

Chemical Machining

26.18 Chemical milling is used in an aircraft plant to create pockets in wing sections made of an aluminum alloy. The starting thickness of one workpart of interest is 20 mm. A series of rectangular-shaped pockets 12 mm deep are to be etched with dimensions 200 mm by 400 mm. The corners of each rectangle are radiused to 15 mm. The part is an aluminum alloy and the etchant is NaOH. The penetration rate for this combination is 0.024 mm/min and the etch factor is 1.75. Determine (a) metal removal rate in mm^3/min, (b) time required to etch to the specified depth, and (c) required dimensions of the opening in the cut and peel maskant to achieve the desired pocket size on the part.

Solution: (a) Neglecting the fact that the initial area would be less than the given dimensions of 200 mm by 400 mm, and that the material removal rate (R_{MR}) would therefore increase during the cut as the area increased, area A = 200 x 400 – (30 x 30 - $\pi(15)^2$) = 80,000 – 193 = 79,807 mm^2
R_{MR} = (0.024 mm/min)(79,807 mm^2) = **1915.4 mm^3/min**

(b) Time to machine (etch) T_m = 12/0.024 = **500 min = 8.33 hr**.

(c) Given F_e = 1.75, undercut $u = d/F_e$ = 12/1.75 = 6.86 mm
Maskant opening length = $L - 2u$ = 400 – 2(6.86) = **386.28 mm**
Maskant opening width = $W - 2u$ = 200 – 2(6.86) = **186.28 mm**
Radius on corners = $R - u$ = 15 – 6.86 = **8.14 mm**

26.19 In a chemical milling operation on a flat mild steel plate, it is desired to cut an ellipse-shaped pocket to a depth of 0.4 in. The semiaxes of the ellipse are a = 9.0 in and b = 6.0 in. A solution of hydrochloric and nitric acids will be used as the etchant. Determine (a) metal removal rate in in^3/hr, (b) time required to etch to depth, and (c) required dimensions of the opening in the cut and peel maskant required to achieve the desired pocket size on the part.

Solution: (a) Neglecting the fact that the initial area would be less than the given dimensions of 9 in by 6 in, and that the material removal rate (R_{MR}) would therefore increase during the cut as the area increased, area of an ellipse $A = \pi ab = \pi(9.0)(6.0) = 54\pi$ = 169.65 in^2
R_{MR} = (0.001 in/min)(169.65 in^2) = 0.16965 in^3/min = **10.18 in^3/hr**

(b) Time to machine (etch) T_m = 0.4/0.001 = **400 min = 6.67 hr**.

(c) Given F_e = 2.0, undercut $u = d/F_e$ = 0.4/2.0 = 0.2 mm
This must be doubled to determine the effect on a and b.
Maskant opening $a' = a - u$ = 9.0 – 2(0.2) = **8.6 in**
Maskant opening $b' = b - u$ = 6.0 – 2(0.2) = **5.6 in**

26.20 In a certain chemical blanking operation, a sulfuric acid etchant is used to remove material from a sheet of magnesium alloy. The sheet is 0.25 mm thick. The screen resist method of masking was used to permit high production rates to be achieved. As it turns out, the process is producing a large proportion of scrap. Specified tolerances of ±0.025 mm are not being achieved. The foreman in the CHM department complains that there must be something wrong with the sulfuric acid. "Perhaps the concentration is incorrect," he suggests. Analyze the problem and recommend a solution.

Solution: The problem in this chemical blanking operation is that the screen resist method of masking cannot achieve the tolerances specified. The photoresist method should have been used, and the process should be changed over to adopt this method.

26.21 In a chemical blanking operation, stock thickness of the aluminum sheet is 0.015 in. The pattern to be cut out of the sheet is a hole pattern, consisting of a matrix of 0.100 in diameter holes. If photochemical machining is used to cut these holes, and contact printing is used to make the resist (maskant) pattern, determine the diameter of the holes that should be used in the pattern.

Solution: From Table 26.2, $F_e = 1.75$.
In chemical blanking, etching will occur on both sides of the part. Therefore, the effective hole depth on each side = one-half of the stock thickness = 0.015/2 = 0.0075 in.
Undercut u = 0.0075/1.75 = 0.0043 in
Diameter of opening = 0.100 - 2(0.0043) = **0.0914 in**

27 HEAT TREATMENT OF METALS

Review Questions

27.1 Why are metals heat treated?

Answer. Metals are heat-treated to effect metallurgical changes that beneficially alter properties.

27.2 Identify the important reasons why metals are annealed.

Answer. The purposes of annealing include (1) to control properties, (2) to reduce brittleness and improve toughness, (3) to recrystallize cold-worked metals, and (4) to relieve stresses from prior metalworking.

27.3 What is the most important heat treatment for hardening steels?

Answer. The most important heat treatment for steels is martensite formation by heating steel into the austenite region and quenching.

27.4 What is the mechanism by which carbon strengthens steel during heat treatment?

Answer. When steel containing carbon is heat-treated, martensite is formed which is a hard and brittle non-equilibrium phase of steel. The extreme hardness of martensite results from the lattice strain created by carbon atoms trapped in the body-centered tetragonal structure, thus providing a barrier to slip.

27.5 What information is conveyed by the TTT curve?

Answer. The time-temperature-transformation (TTT) curve indicates what phases in the iron-carbon phase diagram will be produced under various conditions of cooling.

27.6 What function is served by tempering?

Answer. Tempering involves heating and soaking of martensite for about one hour at a temperature below the austenitizing region, followed by slow cooling to reduce brittleness, relieve stresses, and increase toughness and ductility.

27.7 Define hardenability.

Answer. Hardenability is the relative capacity of a steel to be hardened by transformation to martensite.

27.8 Name some of the elements that have the greatest effect on the hardenability of steel.

Answer. Important hardenability elements are chromium, manganese, molybdenum, and nickel.

27.9 Indicate how the hardenability alloying elements in steel affect the TTT curve.

Answer. The hardenability alloying elements operate by pushing the nose of the TTT curve to the right, thereby permitting slower cooling rates for conversion of austenite to martensite.

27.10 Define precipitation hardening.

Answer. Precipitation hardening is a heat treatment in which very fine particles (precipitates) are formed so that dislocation movement is blocked and the metal is thus strengthened and hardened.

27.11 How does carburizing work?

Answer. Carburizing adds carbon to the surface of low-C steel, thereby transforming the surface into high-C steel for greater hardening potential.

27.12 Identify the selective surface-hardening methods.

Answer. The selective surface-hardening methods include flame hardening, induction hardening, high-frequency (HF) resistance heating, electron beam (EB) heating, and laser beam (LB) heating.

27.13 (**Video**) List three properties of ferrite at room temperature**.**

Answer: At room temperature, ferrite is body centered cubic structure, relatively soft, magnetic, and has almost 0% carbon content.

27.14 (**Video**) How does austenite differ from ferrite?

Answer: Austenite exists at higher temperatures than ferrite. At low carbon levels, steel contains mostly ferrite. As the temperature increases, more of structure converts to austenite. Austenite is a face-centered cubic structure, whereas ferrite is a body centered cubic structure.

Multiple Choice Quiz

There are 12 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

27.1 Which of the following are the usual objectives of heat treatment (three best answers): (a) increase hardness, (b) increase melting temperature, (c) increase recrystallization temperature, (d) reduce brittleness, (e) reduce density, and (f) relieve stresses?

Answer. (a), (d), and (f).

27.2 Of the following quenching media, which one produces the most rapid cooling rate: (a) air, (b) brine, (c) oil, or (d) pure water?

Answer. (b).

27.3 On which one of the following metals is the treatment called austenitizing be performed: (a) aluminum alloys, (b) brass, (c) copper alloys, or (d) steel?

Answer. (d).

27.4 The treatment in which the brittleness of martensite is reduced is called which one of the following: (a) aging, (b) annealing, (c) austenitizing, (d) normalizing, (e) quenching, or (f) tempering?

Answer. (f).

27.5 The Jominy end-quench test is designed to indicate which one of the following: (a) cooling rate, (b) ductility, (c) hardenability, (d) hardness, or (e) strength?

Answer. (c). The reader might be tempted to select (d) because the Jominy test plots hardness as a function of distance from the quenched surface of the test specimen. However, the reason for measuring hardness in the Jominy test is to indicate hardenability.

27.6 In precipitation hardening, the hardening and strengthening of the metal occurs in which one of the following steps: (a) aging, (b) quenching, or (c) solution treatment?

Answer. (a).

27.7 Which one of the following surface-hardening treatments is the most common: (a) boronizing, (b) carbonitriding, (c) carburizing, (d) chromizing, or (e) nitriding?

Answer. (c).

27.8 Which of the following are selective surface-hardening methods (three correct answers): (a) austenitizing, (b) electron beam heating, (c) fluidized bed furnaces, (d) induction heating, (e) laser beam heating, and (f) vacuum furnaces?

Answer. (b), (d), and (e).

28 SURFACE PROCESSING OPERATIONS

Review Questions

28.1 What are some of the important reasons why manufactured parts must be cleaned?

Answer. The reasons include (1) to prepare the surface for subsequent industrial processing, (2) to improve hygiene conditions, (3) to remove contaminants which might chemically react with the surface; and (4) to enhance product appearance and performance.

28.2 Mechanical surface treatments are often performed for reasons other than or in addition to cleaning. What are the reasons?

Answer. Reasons for mechanical surface treatments include deburring, improving smoothness, adding luster, and enhancing surface properties.

28.3 What are the basic types of contaminants that must be cleaned from metallic surfaces in manufacturing?

Answer. Basic contaminant types mentioned in the text are (1) oil and grease, (2) solid particles, such as metal chips, abrasive grits, shop dirt, and dust, (3) buffing and polishing compounds, and (4) oxide films, rust, and scale.

28.4 Name some of the important chemical cleaning methods.

Answer. The chemical cleaning methods can be categorized as follows (1) alkaline cleaning, (2) emulsion cleaning, (3) solvent cleaning, (4) acid cleaning and pickling, and (5) ultrasonic cleaning.

28.5 In addition to surface cleaning, what is the main function performed by shot peening?

Answer. Shot peening is primarily used to improve the fatigue strength of metals by introducing cold working the metallic surface.

28.6 What is meant by the term mass finishing?

Answer. In mass finishing, parts are mechanically cleaned and deburred in bulk, usually in a barrel by the mixing action of an abrasive media.

28.7 What is the difference between diffusion and ion implantation?

Answer. Diffusion is a process in which atoms or molecules move across a boundary between two contacting materials. Ion implantation produces a similar result, but the process involves penetration of high-velocity ions into the surface of a substrate material.

28.8 What is calorizing?

Answer. Calorizing is the diffusion of aluminum into carbon steel, alloy steels, and the alloys of nickel and cobalt. The process is also known as aluminizing.

28.9 Why are metals coated?

Answer. Reasons for coating metals include (1) to provide corrosion protection, (2) to enhance appearance, (3) to provide a specific color, (4) to increase electrical conductivity, (5) to increase electrical resistance, (6) prepare surface for subsequent processing, and (7) to rebuild worn or eroded surfaces.

28.10 Identify the most common types of coating processes.

Answer. The common coating processes are (1) plating, (2) chemical conversion coatings, such as anodizing, (3) vapor deposition processes such as PVD and CVD, (4) organic coating, such as painting, (5) porcelain enameling, and (6) thermal and mechanical coating processes.

28.11 What are the two basic mechanisms of corrosion protection?

Answer. The mechanisms are (1) barrier protection, in which the coating simply covers the substrate to protect it, and (2) sacrificial protection, in which the coating metal corrodes sacrificially to protect the substrate.

28.12 What is the most commonly plated substrate metal?

Answer. The most commonly plated substrate metal is steel.

28.13 One of the mandrel types in electroforming is a solid mandrel. How is the part removed from a solid mandrel?

Answer. A solid mandrel has certain geometric features, such as a taper, that permit the part to be removed. Parts are also sometimes removed by taking advantage of a difference in coefficient of thermal expansion.

28.14 How does electroless plating differ from electrochemical plating?

Answer. Electroless plating uses only chemical reactions to form the plating; electroplating uses electrolysis.

28.15 What is a conversion coating?

Answer. A conversion coating is a thin coating produced by chemical reaction of the metallic surface. The most common conversion coatings are phosphates, chromates, and oxides.

28.16 How does anodizing differ from other conversion coatings?

Answer. Anodizing uses electrochemical processing methods to convert the metallic surface. The best example is aluminum anodizing.

28.17 What is physical vapor deposition?

Answer. Physical vapor deposition (PVD) refers to a family of processes in which a material is converted to its vapor phase in a vacuum chamber and condensed onto a substrate surface as a very thin film.

28.18 What is the difference between physical vapor deposition (PVD) and chemical vapor deposition (CVD)?

Answer. In PVD, the coating vapors are synthesized by heating the coating material and allowing it to condense as a thin film on the surface of the workpart. In CVD a coating is formed on a heated substrate by the chemical reaction or dissociation of vapors and/or gases; the reaction product nucleates and grows on the substrate surface.

28.19 What are some of the applications of PVD?

Answer. PVC applications include: decorative coatings on trophies and automotive trim, antireflection coatings on optical lenses, deposition of metal in electronic connections, and coatings on cutting tool coatings.

28.20 Name the commonly used coating materials deposited by PVD onto cutting tools?

Answer. The common coating materials deposited by PVD onto cutting tools are titanium nitride (TiN), titanium carbide (TiC), and aluminum oxide (Al_2O_3). TiN is probably the most common.

28.21 What are some of the advantages of chemical vapor deposition?

Answer. Advantages of CVD include (1) capability to deposit refractory materials at temperatures below their melting or sintering temperatures, (2) grain size control, (3) process is performed at atmospheric pressure, and (4) good bonding to substrate surface.

28.22 What are the two most common titanium compounds that are coated onto cutting tools by chemical vapor deposition?

Answer. TiC and TiN.

28.23 Identify the four major types of ingredients in organic coatings.

Answer. The major ingredients are (1) binder, which are polymers, (2) dyes or pigments, which provide color, (3) solvents, and (4) additives such as surfactants and plasticizers.

28.24 What is meant by the term transfer efficiency in organic coating technology?

Answer. Transfer efficiency indicates how much of the organic coating liquid reaches the target surface.

28.25 Describe the principal methods by which organic coatings are applied to a surface.

Answer. The main methods include brushing and rolling, spraying, immersion (dip coating), and flow coating.

28.26 The terms drying and curing have different meanings; indicate the distinction.

Answer. Drying means evaporation of solvents in the organic coating liquid. Curing involves a chemical change in the organic resin (polymerization and/or cross-linking) which hardens the coating.

28.27 In porcelain enameling, what is frit?

Answer. Frit is glassy porcelain prepared as fine particles (powders) by crushing and milling.

Multiple Choice Quiz

There are 20 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

28.1 Which of the following are reasons why workparts must be cleaned in industry (four best answers): (a) to avoid air pollution, (b) to avoid water pollution, (c) to enhance appearance, (d) to enhance mechanical properties of the surface, (e) to improve hygiene conditions for workers, (f) to improve surface finish, (g) to prepare the surface for subsequent processing, and (h) to remove contaminants that might chemically attack the surface?

Answer. (c), (e), (g), and (h).

28.2 Which of the following chemicals are associated with alkaline cleaning (two correct answers): (a) borax, (b) hydrochloric acid, (c) propane, (d) sodium hydroxide, (e) sulfuric acid, and (f) trichlorethylene?

Answer. (a) and (d).

28.3 In sand blasting, which one of the following blast media is used: (a) Al_2O_3, (b) crushed nut shells, (c) nylon beads, (d) SiC, or (e) SiO_2?

Answer. (e).

28.4 Which of the following processes generally produces a deeper penetration of atoms in the impregnated surface: (a) diffusion or (b) ion implantation?

Answer. (a).

28.5 Calorizing is the same as which one of the following surface processes: (a) aluminizing, (b) doping, (c) hot sand blasting, or (d) siliconizing?

Answer. (a).

28.9 Which one of the following plate metals produces the hardest surface on a metallic substrate: (a) cadmium, (b) chromium, (c) copper, (d) nickel, or (e) tin?

Answer. (b).

28.10 Which one of the following plating metals is associated with the term galvanizing: (a) iron, (b) lead, (c) steel, (d) tin, or (e) zinc?

Answer. (e).

28.11 Which of the following processes involves electrochemical reactions (two correct answers): (a) anodizing, (b) chromate coatings, (c) electroless plating, (d) electroplating, and (e) phosphate coatings?

Answer. (a) and (d).

28.12 With which one of the following metals is anodizing most commonly associated (one answer): (a) aluminum, (b) magnesium, (c) steel, (d) titanium, or (e) zinc?

Answer. (a).

28.13 Sputtering is a form of which one of the following: (a) chemical vapor deposition, (b) defect in arc welding, (c) diffusion, (d) ion implantation, or (e) physical vapor deposition?

Answer. (e).

28.14 Which one of the following gases is the most commonly used in sputtering and ion plating: (a) argon, (b) chlorine, (c) neon, (d) nitrogen, or (e) oxygen?

Answer. (a).

28.15 The principal methods of applying powder coatings are which of the following (two best answers): (a) brushing, (b) electrostatic spraying, (c) fluidized bed, (d) immersion, and (e) roller coating?

Answer. (b) and (c).

28.16 Porcelain enamel is applied to a surface in which one of the following forms: (a) liquid emulsion, (b) liquid solution, (c) molten liquid, or (d) powders?

Answer. (d).

28.17 Hard facing utilizes which one of the following basic processes: (a) arc welding, (b) brazing, (c) dip coating, (d) electroplating, or (e) mechanical deformation to work harden the surface?

Answer. (a).

Problems

Electroplating

28.1 What volume (cm^3) and weight (g) of zinc will be deposited onto a cathodic workpart if 10 amps of current are applied for one hour?

Solution: From Table 29.1, $C = 4.75 \times 10^{-2}$ mm^3/A-s, cathode efficiency E = 95%.
Volume $V = ECIt = 0.95(4.75 \times 10^{-2}\ mm^3\text{/A-s})(10\ A)(1\ hr)(3600\ s/hr) = \mathbf{1624.5\ mm^3}$
$\mathbf{= 1.6245\ cm^3}$

Density of zinc from Table 4.1 $\rho = 7.15$ g/cm^3. Weight $W = 1.6245(7.15) =$ **11.615 g**

28.2 A sheet metal steel part with surface area = 100 cm^2 is to be zinc plated. What average plating thickness will result if 15 amps are applied for 12 minutes in a chloride electrolyte solution?

Solution: From Table 29.1, $C = 4.75 \times 10^{-2}$ mm^3/A-s, cathode efficiency $E = 95\%$.
Volume $V = ECIt = 0.95(4.75 \times 10^{-2}$ mm^3/A-s)(15 A)(12 min)(60 s/min) = 487.35 mm^3
Area $A = 100$ cm^2 = 10,000 mm^2
Plating thickness $d = 487.35$ mm^3/10,000 mm^2 = **0.049 mm**

28.3 A sheet metal steel part with surface area = 15.0 in^2 is to be chrome plated. What average plating thickness will result if 15 amps are applied for 10 minutes in a chromic acid-sulfate bath?

Solution: From Table 29.1, $C = 0.92 \times 10^{-4}$ in^3/A-min, cathode efficiency $E = 15\%$.
Volume $V = ECIt = 0.15(0.92 \times 10^{-4})(15)(10) = 0.00207$ in^3.
Plating thickness $d = 0.00207/15 =$ **0.000138 in.**

28.4 Twenty-five jewelry pieces, each with a surface area = 0.5 in^2 are to be gold plated in a batch plating operation. (a) What average plating thickness will result if 8 amps are applied for 10 min in a cyanide bath? (b) What is the value of the gold that will be plated onto each piece if one ounce of gold is valued at $900? The density of gold = 0.698 lb/in^3.

Solution: (a) From Table 29.1, $C = 3.87 \times 10^{-4}$ in^3/A-min, cathode efficiency $E = 80\%$.
Volume $V = ECIt = 0.80(3.87 \times 10^{-4})(8)(10) = 0.02477$ in^3.
With $Q = 25$ pieces and average area per piece = 0.5 in^2, total area $A = 25(0.5) = 12.5$ in^2
Plating thickness $d = 0.02477/12.5 =$ **0.00198 in**.

(b) Given density for gold $\rho = 0.698$ lb/in^3
Weight of plated gold = (0.698 lb/in^3)(0.02477 in^3) = 0.01729 lb = 0.277 oz.
At $300/oz, the total value of plated gold = $900(0.277) = $249.30
The value per piece is $249.30/25 = **$9.97**

28.5 A part made of sheet steel is to be nickel plated. The part is a rectangular flat plate that is 0.075 cm thick and whose face dimensions are 14 cm by 19 cm. The plating operation is carried out in an acid sulfate electrolyte, using a current = 20 amps for a duration = 30 min. Determine the average thickness of the plated metal resulting from this operation.

Solution: From Table 29.1, $C = 3.42 \times 10^{-2}$ mm^3/A-s, cathode efficiency $E = 95\%$.
Volume $V = ECIt = 0.95(3.42 \times 10^{-2}$ mm^3/A-s)(20 A)(30 min)(60 s/min) = 1169.6 mm^3
Area $A = 2(19 \times 14) + 0.075 \times 2(19 + 14) = 536.95$ cm^2 = 53,695 mm^2
Plating thickness $d = 1169.6/53{,}695 =$ **0.022 mm**

28.6 A steel sheet metal part has total surface area = 36 in^2. How long will it take to deposit a copper plating (assume valence = +1) of thickness = 0.001 in onto the surface if 15 amps of current are applied?

Solution: From Table 29.1, $C = 2.69 \times 10^{-4}$ in^3/A-min, cathode efficiency $E = 98\%$.
Required volume of plate metal = 36(0.001) = 0.036 in^3
Plated volume $V = ECIt = 0.98(2.69 \times 10^{-4}$ in^3/A-min)(15 A) $t = 0.003954\, t$ in^3
$0.003954\, t = 0.036$ $\qquad t = 0.036/0.003954 =$ **9.1 min.**

28.7 Increasing current is applied to a workpart surface in an electroplating process according to the relation $I = 12.0 + 0.2t$, where I = current, amps; and t = time, min. The plating metal is chromium, and the part is submersed in the plating solution for a duration of 20 min. What volume of coating will be applied in the process?

Solution: From Table 29.1, $C = 0.92 \times 10^{-4}$ in^3/A-min, cathode efficiency $E = 15\%$.
Plated volume $V = EC\int I dt = EC\int(12 + 0.2t)dt = EC(12t + 0.1t^2)$ over the range 0 to 20 min.

$V = 0.15(0.92 \times 10^{-4})(12 \times 20 + 0.1(20)^2) =$ **0.00386 in^3**

28.8 A batch of 100 parts is to be nickel plated in a barrel plating operation. The parts are identical, each with a surface area $A = 7.8$ in^2. The plating process applies a current $I = 120$ amps, and the batch takes 40 minutes to complete. Determine the average plating thickness on the parts.

Solution: From Table 29.1, $C = 1.25 \times 10^{-4}$ in^3/A-min, cathode efficiency $E = 95\%$.
Volume $V = ECIt = 0.95(1.25 \times 10^{-4})(120)(40) = 0.57$ in^3.
Area $A = 100(7.8) = 780$ in^2 Plating thickness $d = 0.57/780 =$ **0.00073 in.**

28.9 A batch of 40 identical parts is to be chrome plated using racks. Each part has a surface are = 22.7 cm^2. If it is desired to plate an average thickness = 0.010 mm on the surface of each part, how long should the plating operation be allowed to run at a current = 80 amps?

Solution: From Table 29.1, $C = 2.5 \times 10^{-2}$ mm^3/A-s, cathode efficiency $E = 15\%$.
Volume $V = ECIt = 0.15(2.5 \times 10^{-2}$ mm^3/A-s)(80 A)$t = 0.3t$ mm^3
With $Q = 40$ pieces and average area per piece = 22.7 mm^2,
total area $A = 40(22.7) = 908$ cm^2 = 90,800 mm^2
Plating thickness $d = V/A = (0.3\ t$ mm$^3)/(90{,}800$ mm$^2) = 0.03304(10^{-4})\ t$ mm
Given that $d = 0.010$ mm, $0.03304(10^{-4})$ t = 0.010
Thus, $t = 0.010/0.03304(10^{-4}) = 0.3027 \times 10^4 =$ **3027 s = 50.44 min**.

29 FUNDAMENTALS OF WELDING

Review Questions

29.1 What are the advantages and disadvantages of welding compared to other types of assembly operations?

Answer. Advantages: (1) it provides a permanent joint, (2) joint strength is typically as high as the strength of base metals, (3) it is most economical in terms of material usage, and (4) it is versatile in terms of where it can be accomplished. Disadvantages: (1) it is usually performed manually, so labor cost is high and the skilled labor to perform it is sometimes scarce, (2) welding is inherently dangerous, (3) a welded joint is difficult to disassemble, and (4) quality defects are sometimes difficult to detect.

29.2 What were the two discoveries of Sir Humphrey Davy that led to the development of modern welding technology?

Answer. The two discoveries of Sir Humphrey Davy were (1) the electric arc and (2) acetylene gas.

29.3 What is meant by the term faying surface?

Answer. The faying surfaces are the contacting surfaces in a welded joint.

29.4 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.

29.5 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.

29.6 What is an autogenous weld?

Answer. An autogenous weld is a fusion weld made without the addition of filler metal.

29.7 Discuss the reasons why most welding operations are inherently dangerous.

Answer. Most welding operations are carried out at high temperatures that can cause serious burns on skin and flesh. In gas welding, the fuels are a fire hazard. In arc welding and resistance welding, the high electrical energy can cause shocks that are fatal to the worker. In arc welding, the electric arc emits intense ultraviolet radiation that can cause blinding. Other hazards include sparks, smoke, fumes, and weld spatter.

29.8 What is the difference between machine welding and automatic welding?

Answer. An automatic welding operation uses a weld cycle controller that regulates the arc movement and workpiece positioning; whereas in machine welding, a human worker must continuously control the arc and the relative movement of the welding head and the workpart.

29.9 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 28.3 in the text.

29.10 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 29.4 in text for sketch.

29.11 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 29.5 in text for sketch.

29.12 Why is a surfacing weld different from the other weld types?

Answer. Because it does not join to distinct parts, but instead adds only filler metal to a surface.

29.13 Why is it desirable to use energy sources for welding that have high heat densities?

Answer. Because the heat is concentrated in a small region for greatest efficiency and minimum metallurgical damage.

29.14 What is the unit melting energy in welding, and what are the factors on which it depends?

Answer. The unit melting energy is the amount of heat energy required to melt one cubic inch or one cubic mm of metal. The factors on which it depends are (1) specific heat, (2) melting point, and (3) heat of fusion of the metal.

29.15 Define and distinguish the two terms heat transfer factor and melting factor in welding.

Answer. Heat transfer factor is the ratio of the actual heat received at the work surface divided by the total heat generated by the source. Melting factor is the ratio of heat required for melting divided by the heat received at the work surface.

29.16 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.

Multiple Choice Quiz

There are 14 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

29.1 Welding can only be performed on metals that have the same melting point; otherwise, the metal with the lower melting temperature always melts while the other metal remains solid: (a) true, (b) false?

Answer. (b). Welding can be accomplished between certain combinations of dissimilar metals using solid state welding processes.

29.2 A fillet weld can be used to join which of the following joint types (three correct answers): (a) butt, (b) corner, (c) edge, (d) lap, and (e) tee?

Answer. (b), (d), and (e).

29.3 A fillet weld has a cross-sectional shape that is approximately which one of the following: (a) rectangular, (b) round, (c) square, or (d) triangular?

Answer. (d).

29.4 Groove welds are most closely associated with which one of the following joint types: (a) butt, (b) corner, (c) edge, (d) lap, or (e) tee?

Answer. (a).

29.5 A flange weld is most closely associated with which one of the following joint types: (a) butt, (b) corner, (c) edge, (d) lap, or (e) tee?

Answer. (c).

29.6 For metallurgical reasons, it is desirable to melt the weld metal with minimum energy input. Which one of the following heat sources is most consistent with this objective: (a) high power, (b) high power density, (c) low power, or (d) low power density?

Answer. (b).

29.7 The amount of heat required to melt a given volume of metal depends strongly on which of the following properties (three best answers): (a) coefficient of thermal expansion, (b) heat of fusion, (c) melting temperature, (d) modulus of elasticity, (e) specific heat, (f) thermal conductivity, and (g) thermal diffusivity?

Answer. (b), (c), and (e).

29.8 The heat transfer factor in welding is correctly defined by which one of the following descriptions: (a) the proportion of the heat received at the work surface that is used for melting, (b) the proportion of the total heat generated at the source that is received at the work surface, (c) the proportion of the total heat generated at the source that is used for melting, or (d) the proportion of the total heat generated at the source that is used for welding?

Answer. (b).

29.9 The melting factor in welding is correctly defined by which one of the following descriptions: (a) the proportion of the heat received at the work surface that is used for melting, (b) the proportion of the total heat generated at the source that is received at the work surface, (c) the proportion of the total heat generated at the source that is used for melting, or (d) the proportion of the total heat generated at the source that is used for welding?

Answer. (a).

29.10 Weld failures always occur in the fusion zone of the weld joint, since this is the part of the joint that has been melted: (a) true, (b) false?

Answer. (b). Failures also occur in the heat-affected zone because metallurgical damage often occurs in this region.

Problems

Power Density

29.1 A heat source can transfer 3500 J/sec to a metal part surface. The heated area is circular, and the heat intensity decreases as the radius increases, as follows: 70% of the heat is concentrated in a circular area that is 3.75 mm in diameter. Is the resulting power density enough to melt metal?

Solution: Area $A = \pi(3.75)^2/4 = 11.045$ mm^2
Power $P = 0.70(3500) = 2450$ J/s = 2450 W.
Power density $PD = 2450$ W/11.0447^2 = **222 W/mm^2.** This power density is most probably sufficient for melting the metal.

29.2 In a laser beam welding process, what is the quantity of heat per unit time (J/sec) that is transferred to the material if the heat is concentrated in circle with a diameter of 0.2 mm? Assume the power density provided in Table 29.1.

Solution: PD from Table 29.1 is 9000 W/mm^2 for laser beam welding
$P = PD \text{ x } A = 9000\ \pi(0.2)^2/4 =$ **283 W = 283 J/sec**

29.3 A welding heat source is capable of transferring 150 Btu/min to the surface of a metal part. The heated area is approximately circular, and the heat intensity decreases with increasing radius as follows: 50% of the power is transferred within a circle of diameter = 0.1 inch and 75% is transferred within a concentric circle of diameter = 0.25 in. What are the power densities in (a) the 0.1-inch diameter inner circle and (b) the 0.25-inch diameter ring that lies around the inner circle? (c) Are these power densities sufficient for melting metal?

Solution: (a) Area $A = \pi(0.1)^2/4 = 0.00785$ in^2
150 Btu/min = 2.5 Btu/sec.
Power $P = 0.50(2.5) = 1.25$ Btu/sec
Power density PD = (1.25 Btu/sec)/0.00785 in^2 = **159 Btu/sec-in^2**

(b) $A = \pi(0.25^2 - 0.1^2)/4 = 0.0412$ in^2
Power $P = (0.75 - 0.50)(2.5) = 0.625$ Btu/sec
Power density PD = (0.625 Btu/sec)/0.0412 in^2 = **15.16 Btu/sec-in^2**

(c) Power densities are sufficient certainly in the inner circle and probably in the outer ring for welding.

Unit Melting Energy

29.4 Compute the unit energy for melting for the following metals: (a) aluminum and (b) plain low carbon steel.

Solution: (a) From Table 29.2, T_m for aluminum = 930 K (1680 R)
Eq. (29.2) for SI units: $U_m = 3.33(10^{-6})T_m^2$ $U_m = 3.33 \times 10^{-6} (930)^2$ = **2.88 J/mm^3**
Eq. (29.2) for USCS units: $U_m = 1.467(10^{-5})T_m^2$ $U_m = 1.467 \times 10^{-5} (1680)^2$ = **41.4 Btu/in^3**

(b) From Table 29.2, T_m for plain low carbon steel = 1760 K (3160 R)
Eq. (29.2) for SI units: $U_m = 3.33(10^{-6})T_m^2$ $U_m = 3.33 \times 10^{-6} (1760)^2$ = **10.32 J/mm^3**
Eq. (29.2) for USCS units: $U_m = 1.467(10^{-5})T_m^2$ $U_m = 1.467 \times 10^{-5} (3160)^2$ = **146.5 Btu/in^3**

29.5 Compute the unit energy for melting for the following metals: (a) copper and (b) titanium.

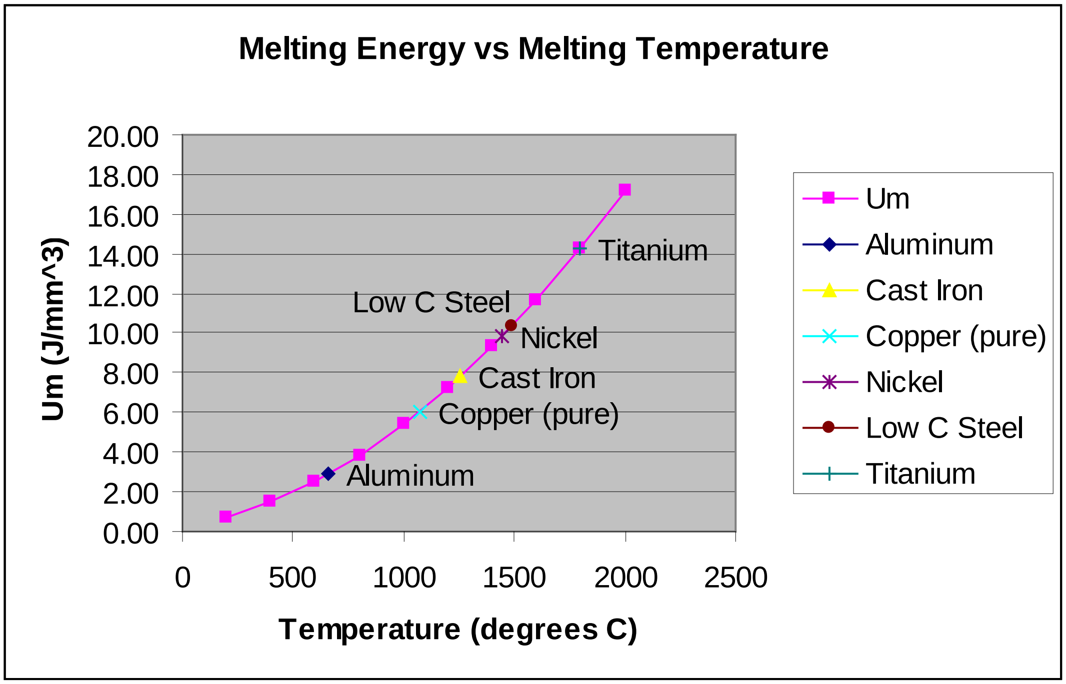
Solution: (a) From Table 29.2, T_m for copper = 1350 K (2440 R)
Eq. (29.2) for SI units: $U_m = 3.33(10^{-6})T_m^2$ $U_m = 3.33 \times 10^{-6} (1350)^2$ = **6.07 J/mm^3**
Eq. (29.2) for USCS units: $U_m = 1.467(10^{-5})T_m^2$ $U_m = 1.467 \times 10^{-5} (2440)^2$ = **87.3 Btu/in^3**

(b) From Table 29.2, T_m for titanium = 2070 K (3730 R)
Eq. (29.2) for SI units: $U_m = 3.33(10^{-6})T_m^2$ $U_m = 3.33 \times 10^{-6} (2070)^2$ = **14.27 J/mm^3**
Eq. (29.2) for USCS units: $U_m = 1.467(10^{-5})T_m^2$ $U_m = 1.467 \times 10^{-5} (3730)^2$ = **204.1 Btu/in^3**

29.6 Make the calculations and plot on linearly scaled axes the relationship for unit melting energy as a function of temperature. Use temperatures as follows to construct the plot: 200°C, 400°C, 600°C, 800°C, 1000°C, 1200°C, 1400°C, 1600°C, 1800°C, and 2000°C. On the plot, mark the positions of some of the welding metals in Table 29.2. Use of a spreadsheet program is recommended for the calculations.

Solution: Eq. (29.2) for SI units: $U_m = 3.33 \times 10^{-6}\ \mathrm{T_m}^2$. The plot is based on the following calculated values.
For T_m = **200°C** = (200 + 273) = 473°K: $U_m = 3.33 \times 10^{-6} (473)^2$ = **0.75 J/mm^3**
For T_m = **400°C** = (400 + 273) = 673°K: $U_m = 3.33 \times 10^{-6} (673)^2$ = **1.51 J/mm^3**
For T_m = **600°C** = (600 + 273) = 873°K: $U_m = 3.33 \times 10^{-6} (873)^2$ = **2.54 J/mm^3**
For T_m = **800°C** = (800 + 273) = 1073°K: $U_m = 3.33 \times 10^{-6} (1073)^2$ = **3.83 J/mm^3**
For T_m = **1000°C** = (1000 + 273) = 1273°K: $U_m = 3.33 \times 10^{-6} (1273)^2$ = **5.40 J/mm^3**
For T_m = **1200°C** = (1200 + 273) = 1473°K: $U_m = 3.33 \times 10^{-6} (1473)^2$ = **7.23 J/mm^3**
For T_m = **1400°C** = (1400 + 273) = 1673°K: $U_m = 3.33 \times 10^{-6} (1673)^2$ = **9.32 J/mm^3**

For T_m = **1600°C** = (1600 + 273) = 1873°K: $U_m = 3.33 \times 10^{-6} (1873)^2$ = **11.68 J/mm³**
For T_m = **1800°C** = (1800 + 273) = 2073°K: $U_m = 3.33 \times 10^{-6} (2073)^2$ = **14.31 J/mm³**
For T_m = **2000°C** = (2000 + 273) = 2273°K: $U_m = 3.33 \times 10^{-6} (2273)^2$ = **17.20 J/mm³**



29.7 Make the calculations and plot on linearly scaled axes the relationship for unit melting energy as a function of temperature. Use temperatures as follows to construct the plot: 500°F, 1000°F, 1500°F, 2000°F, 2500°F, 3000°F, and 3500°F. On the plot, mark the positions of some of the welding metals in Table 29.2. Use of a spreadsheet program is recommended for the calculations.

Solution: Eq. (29.2) for USCS units: $U_m = 1.467(10^{-5})T_m^2$. The plot is based on the following calculated values. The plot is left as a student exercise.
For T_m = **500°F** = (500 + 460) = 960°R: $U_m = 1.467 \times 10^{-5} (960)^2$ = **13.5 Btu/in³**
For T_m = **1000°F** = (1000 + 460) = 1460°R: $U_m = 1.467 \times 10^{-5} (1460)^2$ = **31.3 Btu/in³**
For T_m = **1500°F** = (1500 + 460) = 1960°R: $U_m = 1.467 \times 10^{-5} (1960)^2$ = **56.4 Btu/in³**
For T_m = **2000°F** = (2000 + 460) = 2460°R: $U_m = 1.467 \times 10^{-5} (2460)^2$ = **88.8 Btu/in³**
For T_m = **2500°F** = (2500 + 460) = 2960°R: $U_m = 1.467 \times 10^{-5} (2960)^2$ = **128.5 Btu/in³**
For T_m = **3000°F** = (3000 + 460) = 3460°R: $U_m = 1.467 \times 10^{-5} (3460)^2$ = **175.6 Btu/in³**
For T_m = **3500°F** = (3500 + 460) = 3960°R: $U_m = 1.467 \times 10^{-5} (3960)^2$ = **230.0 Btu/in³**

29.8 A fillet weld has a cross-sectional area of 25.0 mm² and is 300 mm long. (a) What quantity of heat (in joules) is required to accomplish the weld, if the metal to be welded is low carbon steel? (b) How much heat must be generated at the welding source, if the heat transfer factor is 0.75 and the melting factor = 0.63?

Solution: (a) Eq. (29.2) for SI units: $U_m = 3.33 \times 10^{-6} T_m^2$
From Table 29.2, T_m for low carbon steel = 1760° K
$U_m = 3.33 \times 10^{-6} (1760)^2 = 10.32$ J/mm³
Volume of metal melted $V = 25(300) = 7500$ mm³
$H_w = 10.32(7500)$ = **77,360 J** at weld

(b) Given $f_1 = 0.75$ and $f_2 = 0.63$, $H = 77,360/(0.75 \times 0.63)$ = **163,700 J** at source.

29.9 A U-groove weld is used to butt weld 2 pieces of 7.0-mm-thick titanium plate. The U-groove is prepared using a milling cutter so the radius of the groove is 3.0 mm. During welding, the penetration of the weld causes an additional 1.5 mm of material to be melted. The final cross-sectional area of the weld can be approximated by a semicircle with a radius of 4.5 mm. The length of the weld is 200 mm. The melting factor of the setup is 0.57 and the heat transfer factor is 0.86. (a) What is the quantity of heat (in Joules) required to melt the volume of metal in this weld (filler metal plus base metal)? Assume the resulting top surface of the weld bead is flush with the top surface of the plates. (b) What is the required heat generated at the welding source?

Solution: (a) From Table 29.2, T_m for titanium is 2070°K
$U_m = 3.33 \times 10^{-6} (2070)^2 = 14.29$ J/mm^3
$A_w = \pi r^2/2 = \pi(4.5)^2/2 = 31.8$ mm^2
$V = A_w L = 31.8(200) = 6360$ mm^3
$H_w = U_m V = 14.29(6360) =$ **90,770 J**

(b) $H = H_w/(f_1 f_2) = 90{,}770/(0.86 \times 0.57) =$ **185,200 J**

29.10 A groove weld has a cross-sectional area = 0.045 in^2 and is 10 inches long. (a) What quantity of heat (in Btu) is required to accomplish the weld, if the metal to be welded is medium carbon steel? (b) How much heat must be generated at the welding source, if the heat transfer factor = 0.9 and the melting factor = 0.7?

Solution: (a) Eq. (29.2) for USCS units: $U_m = 1.467 \times 10^{-5}\, T_m^2$
From Table 29.2, T_m for medium carbon steel = 3060 R
$U_m = 1.467 \times 10^{-5} (3060)^2 = 137.4$ Btu/in^3
Volume of metal melted $V = 0.045(10) = 0.45$ in^3
$H_w = 137.4(0.45) =$ **61.8 Btu** at weld

(b) Given $f_1 = 0.9$ and $f_2 = 0.7$. $H = 61.8/(0.9 \times 0.7) =$ **98.1 Btu** at source.

29.11 Solve the previous problem, except that the metal to be welded is aluminum, and the corresponding melting factor is half the value for steel.

Solution: (a) Eq. (29.2) for USCS units: $U_m = 1.467 \times 10^{-5}\, T_m^2$
From Table 29.2, T_m for aluminum = 1680 R
$U_m = 1.467 \times 10^{-5} (1680)^2 = 41.4$ Btu/in^3
Volume of metal melted $V = 0.045(10) = 0.45$ in^3
$H_w = 41.4(0.45) =$ **18.6 Btu** at weld

(b) Given $f_1 = 0.9$ and $f_2 = 0.35$. $H = 18.6/(0.9 \times 0.35) =$ **59.1 Btu** at source.

29.12 In a controlled experiment, it takes 3700 J to melt the amount of metal that is in a weld bead with a cross-sectional area of 6.0 mm^2 that is 150.0 mm long. (a) Using Table 29.2, what is the most likely metal? (b) If the heat transfer factor is 0.85 and the melting factor is 0.55 for a welding process, how much heat must be generated at the welding source to accomplish the weld?

Solution: $V = A_w L = 6.0(150) = 900$ mm^3
$U_m = H_w/V = 3700 / 900 = 4.111$ J/mm^3
$T_m = (U_m/k)^{0.5} = (4.111/3.33\text{x}10^{-6})^{0.5} = 1111°$ K
From Table 29.2, the metal with the closest melting point to 1111° is **Bronze (1120° K)**

(b) $H = H_w/f_1 f_2 = 3700/ (0.85 \times 0.55) =$ **7,914 Joules**

29.13 Compute the unit melting energy for (a) aluminum and (b) steel as the sum of: (1) the heat required to raise the temperature of the metal from room temperature to its melting point, which is the volumetric specific heat multiplied by the temperature rise; and (2) the heat of fusion, so that this value can be compared to the unit melting energy calculated by Eq. (29.2). Use either the SI units or

U.S. Customary units. Find the values of the properties needed in these calculations either in this text or in other references. Are the values close enough to validate Eq. (29.2)?

Solution: (a) Aluminum properties (from standard sources): heat of fusion H_f = 395,390 J/kg = 170 Btu/lb, melting temperature T_m = 660°C = 1220°F, density ρ = 2700 kg/m^3= 0.096 lb/in^3, specific heat C = 900 J/kg-°C = 0.215 Btu/lb-°F.
$U_m = \rho C(T_m - T_{ambient}) + \rho H_f$
U_m = (2.7x10^{-6} kg/mm^3)(900 J/kg-C))(660 - 21) + (2.7x10^{-6} kg/mm^3)(395390 J/kg) = **2.62 J/mm^3**
This compares with Eq. (29.2): U_m = 3.33 x 10^{-6} (660 + 273)^2 = **2.90 J/mm^3**, which is about a 10% difference. These values for aluminum show good agreement.
In USCS, $U_m = \rho C(T_m - 70) + \rho H_f$ = 0.096(0.215)(1220 - 70) + 0.096(170) = **40.1 Btu/in^3**
This compares with Eq. (29.2): U_m = 1.467 x 10^{-5} (1220 + 460)^2 = **41.4 Btu/in^3**, which is about a 3% difference.

(b) Steel properties (from standard sources): heat of fusion H_f = 272,123 J/kg = 117 Btu/lb, melting temperature T_m = 1480°C = 2700°F, density ρ = 7900 kg/m^3= 0.284 lb/in^3, specific heat C = 460 J/kg-°C = 0.11 Btu/lb-°F.
$U_m = \rho C(T_m - T_{ambient}) + \rho H_f$
U_m = (7.9x10^{-6} kg/mm^3)(460 J/kg-C))(1480 - 21) + (7.9x10^{-6} kg/mm^3)(272123 J/kg) = **7.45 J/mm^3**
This compares with Eq. (29.2): U_m = 3.33 x 10^{-6} (1480 + 273)^2 = **10.23 J/mm^3**, which is about a 37% difference.
In USCS, $U_m = \rho C(T_m - 70) + \rho H_f$ = 0.284(0.11)(2700 - 70) + 0.284(117) = **115.4 Btu/in^3**
This compares with Eq. (29.2): U_m = 1.467 x 10^{-5} (2700 + 460)^2 = **146.5 Btu/in^3**, which is about a 27% difference.

Comment: These values show a greater difference than for aluminum. This is at least partially accounted for by the fact that the specific heat of steel increases significantly with temperature, which would increase the calculated values based on $U_m = \rho C(T_m - T_{ambient}) + \rho H_f$.

Energy Balance in Welding

29.14 The welding power generated in a particular arc-welding operation = 3000 W. This is transferred to the work surface with a heat transfer factor = 0.9. The metal to be welded is copper whose melting point is given in Table 29.2. Assume that the melting factor = 0.25. A continuous fillet weld is to be made with a cross-sectional area = 15.0 mm^2. Determine the travel speed at which the welding operation can be accomplished.

Solution: From Table 29.2, T_m = 1350°K for copper.
U_m = 3.33 x 10^{-6}(1350)^2 = 6.07 J/mm^3
$v = f_1 f_2 R_H/U_m A_w$ = 0.9(0.25)(3000)/(6.07 x 15) = **7.4 mm/s.**

29.15 Solve the previous problem except that the metal to be welded is high carbon steel, the cross-sectional area of the weld = 25.0 mm^2, and the melting factor = 0.6.

Solution: From Table 29.2, T_m = 1650°K for high carbon steel.
U_m = 3.33 x 10^{-6}(1650)^2 = 9.07 J/mm^3
$v = f_1 f_2 R_H /U_m A_w$ = 0.9(0.6)(3000)/(9.07 x 25) = **7.15 mm/s.**

29.16 A welding operation on an aluminum alloy makes a groove weld. The cross-sectional area of the weld is 30.0 mm^2. The welding velocity is 4.0 mm/sec. The heat transfer factor is 0.92 and the melting factor is 0.48. The melting temperature of the aluminum alloy is 650°C. Determine the rate of heat generation required at the welding source to accomplish this weld.

Solution: U_m = 3.33 x 10^{-6}(650 + 273)^2 = 2.84 J/mm^3
$f_1 f_2 R_H = U_m A_w v$
$R_H = U_m A_w v/f_1 f_2$ = 2.84(30)(4)/(0.92 x 0.48) = **771 J/s = 771 W.**

29.17 The power source in a particular welding operation generates 125 Btu/min, which is transferred to the work surface with heat transfer factor = 0.8. The melting point for the metal to be welded = 1800°F and its melting factor = 0.5. A continuous fillet weld is to be made with a cross-sectional area = 0.04 in^2. Determine the travel speed at which the welding operation can be accomplished.

Solution: $U_m = 1.467 \times 10^{-5}\,(1800 + 460)^2 = 74.9$ Btu/in^3
$v = f_1 f_2 R_H / U_m A_w = 0.8(0.5)(125)/(74.9 \times 0.04) =$ **16.7 in/min**

29.18 In a certain welding operation to make a fillet weld, the cross-sectional area = 0.025 in^2 and the travel speed = 15 in/min. If the heat transfer factor = 0.95 and melting factor = 0.5, and the melting point = 2000°F for the metal to be welded, determine the rate of heat generation required at the heat source to accomplish this weld.

Solution: $U_m = 1.467 \times 10^{-5}\,(2000 + 460)^2 = 88.8$ Btu/in^3
$v = 15 = f_1 f_2 R_H/U_m A_w = 0.95(0.5)R_H/(88.8 \times 0.025) = 0.214\,R_H$
$R_H = 15/0.214 =$ **70.1 Btu/min**

29.19 A fillet weld is used to join 2 medium carbon steel plates each having a thickness of 5.0 mm. The plates are joined at a 90° angle using an inside fillet corner joint. The velocity of the welding head is 6 mm/sec. Assume the cross section of the weld bead approximates a right isosceles triangle with a leg length of 4.5 mm, the heat transfer factor is 0.80, and the melting factor is 0.58. Determine the rate of heat generation required at the welding source to accomplish the weld.

Solution: $A_w = bh/2 = 4.5(4.5)/2 = 10.125$ mm^2
From Table 29.2, $T_m = 1700$°K
$U_m = 3.33 \times 10^{-6}\,(1700)^2 = 9.62$ J/mm^3
$R_H = U_m A_w v/(f_1 f_2) = 9.62(10.125)(5.0) / (0.8 \times 0.58) =$ **1260 J/sec = 1260 W.**

29.20 A spot weld was made using an arc-welding process. In a spot-welding operation, two 1/16-in-thick aluminum plates were joined. The melted metal formed a nugget that had a diameter of ¼ in. The operation required the power to be on for 4 sec. Assume the final nugget had the same thickness as the two aluminum plates (1/8 in thick), the heat transfer factor was 0.80 and the melting factor was 0.50. Determine the rate of heat generation that was required at the source to accomplish this weld.

Solution: From Table 29.2, $T_m = 1680$°R for aluminum.
$U_m = 1.467 \times 10^{-5}\,(1680)^2 = 41.4$ Btu/in^3
$V = \pi D^2/4\,(2t) = \pi\,(0.25^2/4)(2)(1/16) = 0.0061$ in^3
$H_w = U_m V = 41.4(0.0061) = 0.254$ Btu
$H = H_w/(f_1 f_2) = 0.254/(0.80 \times 0.5) = 0.635$ Btu
$R_H = H/T = 0.635/4 =$ **0.159 Btu/sec = 9.53 Btu/min**

29.21 A surfacing weld is to be applied to a rectangular low carbon steel plate that is 200 mm by 350 mm. The filler metal to be added is a harder (alloy) grade of steel, whose melting point is assumed to be the same. A thickness of 2.0 mm will be added to the plate, but with penetration into the base metal, the total thickness melted during welding = 6.0 mm, on average. The surface will be applied by making a series of parallel, overlapped welding beads running lengthwise on the plate. The operation will be carried out automatically with the beads laid down in one long continuous operation at a travel speed = 7.0 mm/s, using welding passes separated by 5 mm. Assume the welding bead is rectangular in cross section: 5 mm by 6 mm. Ignore the minor complications of the turnarounds at the ends of the plate. Assuming the heat transfer factor = 0.8 and the melting factor = 0.6, determine (a) the rate of heat that must be generated at the welding source, and (b) how long will it take to complete the surfacing operation.

Solution: (a) From Table 29.2, $T_m = 1760$°K for low carbon steel.
$U_m = 3.33 \times 10^{-6}(1760)^2 = 10.32$ J/mm^3
$R_H = U_m A_w v/f_1 f_2 = 10.32(6 \times 5)(7)/(0.8 \times 0.6) =$ **4515 J/s**

(b) Total length of cut = 350(200/5) = 14,000 mm
Time to travel at v = 7 mm/s = 14,000/7 = **2000 s = 33.33 min**

29.22 An axle-bearing surface made of high carbon steel has worn beyond its useful life. When it was new, the diameter was 4.00 in. In order to restore it, the diameter was turned to 3.90 in to provide a uniform surface. Next the axle was built up so that it was oversized by the deposition of a surface weld bead, which was deposited in a spiral pattern using a single pass on a lathe. After the weld buildup, the axle was turned again to achieve the original diameter of 4.00 in. The weld metal deposited was a similar composition to the steel in the axle. The length of the bearing surface was 7.0 in. During the welding operation, the welding apparatus was attached to the tool holder, which was fed toward the head of the lathe as the axle rotated. The axle rotated at a speed of 4.0 rev/min. The weld bead height was 3/32 in above the original surface. In addition, the weld bead penetrated 1/16 in into the surface of the axle. The width of the weld bead was 0.25 in, thus the feed on the lathe was set to 0.25 in/rev. Assuming the heat transfer factor was 0.80 and the melting factor was 0.65, determine (a) the relative velocity between the workpiece and the welding head, (b) the rate of heat generated at the welding source, and (c) how long it took to complete the welding portion of this operation.

Solution: (a) $v = N\pi D$ = 4.0π(3.90) = **49.01 in/min = 0.8168 in/sec**

(b) From Table 29.2, T_m = 2960°R for high carbon steel.
$U_m = 1.467 \times 10^{-5}(2960)^2 = 128.5$ Btu/in^3
$R_H = U_m A_w v / f_1 f_2 = 128.5\ (0.25(3/32+1/16))\ 49.01\ /\ (0.8 \times 0.65)$
= 128.5(0.0391)(49.01)/0.52 = **473 Btu/min**

(c) $T_{weld} = L/(fN)$ = 7.0/(0.25 x 4) = **7.0 min**

30 WELDING PROCESSES

Review Questions

30.1 Name the principal groups of processes included in fusion welding.

Answer. The principal groups of processes included in fusion welding are (1) arc welding, (2) resistance welding, (3) oxyfuel welding, and (4) other. The "other" category includes EBW, LBW, thermit welding, and others.

30.2 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.

30.3 Define what an electrical arc is.

Answer. An electrical arc is a discharge across a gap in a circuit. In arc welding, the arc is sustained by a thermally ionized column of gas through which the current can flow.

30.4 What do the terms arc-on time and arc time mean?

Answer. The two terms mean the same thing: the proportion of the total time in a shift that the arc is actually on, indicating that welding is occurring.

30.5 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.

30.6 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.

30.7 Why is the heat transfer factor in arc-welding processes that utilize consumable electrodes greater than in those that use nonconsumable electrodes?

Answer. Because molten metal from the electrode is transferred across the arc and contributes to the heating of the molten weld pool in arc-welding processes that utilize consumable electrodes.

30.8 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.

30.9 Why is the shielded metal arc-welding (SMAW) process difficult to automate?

Answer. Because the stick electrodes used in SMAW must be changed frequently, which would be difficult to do automatically. It is much easier to automate the feeding of continuous filler wire, such as in GMAW, FCAW, SAW, or GTAW.

30.10 Describe submerged arc welding (SAW).

Answer. SAW is an arc-welding process that uses a continuous, consumable bare wire electrode, and arc shielding is provided by a cover of granular flux.

30.11 Why are the temperatures much higher in plasma arc welding than in other AW processes?

Answer. Because the arc is restricted in diameter, thus concentrating the energy into a smaller area, resulting in much higher power densities.

30.12 Define resistance welding.

Answer. RW consists of a group of fusion welding processes that utilize a combination of heat and pressure to accomplish coalescence of the two faying surfaces. Most prominent in the group is resistance spot welding.

30.13 What are the desirable properties of a metal that would provide good weldability for resistance welding?

Answer. High resistivity, low electrical and thermal conductivity, and low melting point.

30.14 Describe the sequence of steps in the cycle of a resistance spot-welding operation.

Answer. The steps are (1) insert parts between electrodes, (2) squeeze parts between the electrodes, (3) weld, in which the current is switched on for a brief duration (0.1 to 0.4 sec), (4) hold, during which the weld nugget solidifies, and (5) open electrodes and remove parts.

30.15 What is resistance-projection welding?

Answer. RPW is a resistance welding process in which coalescence occurs at one or more relatively small points on the parts; the contact points are designed into the geometry of the parts as embossments or projections.

30.16 Describe cross-wire welding.

Answer. Cross-wire welding is a form of resistance projection welding used to fabricate welded wire products such as shopping carts and stove grills.

30.17 Why is the oxyacetylene welding process favored over the other oxyfuel welding processes?

Answer. Because acetylene and oxygen burn hotter than other oxyfuels.

30.18 Define pressure gas welding.

Answer. PGW is a fusion welding process in which coalescence is obtained over the entire contact surfaces of the two parts by heating them with an appropriate fuel mixture and then applying pressure to bond the surfaces.

30.19 Electron-beam welding has a significant disadvantage in high-production applications. What is that disadvantage?

Answer. EBW is usually carried out in a vacuum for a high quality weld. The time to draw the vacuum adds significantly to the production cycle time.

30.20 Laser-beam welding and electron-beam welding are often compared because they both produce very high power densities. LBW has certain advantages over EBW. What are they?

Answer. Advantages of LBW over EBW are (1) no vacuum chamber is required in LBM, (2) no x-rays are emitted in LBM; and (3) the laser beam can be focused and directed with conventional optical mirrors and lenses.

30.21 There are several modern-day variations of forge welding, the original welding process. Name them.

Answer. Variations of forge welding are (1) cold welding, (2) roll welding, (3) and hot pressure welding.

30.22 There are two basic types of friction welding (FRW). Describe and distinguish the two types.

Answer. The two types of FRW are (1) continuous-drive friction welding and (2) inertia friction welding. In continuous-drive friction welding, one part is rotated at a constant speed and forced into contact against a stationary part with a certain force so that friction heat is generated at the interface; when the right temperature is reached, the rotating part is stopped abruptly and the two parts are forced together at forging pressures. In inertia friction welding, the rotating part is connected to a flywheel which is brought up to proper speed; then the flywheel is disengaged from the drive motor and the parts are forced together, so that the kinetic energy of the flywheel is converted to friction heat for the weld.

30.23 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.

30.24 What is a sonotrode in ultrasonic welding?

Answer. It is the actuator which is attached to one of the two parts to be welded with USW and which provides the oscillatory motion that results in coalescence of the two surfaces. It is analogous to an electrode in resistance welding.

30.25 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) Welding conditions (speed, amount of filler metal used, etc.) can be selected to reduce warping. (5) The base parts can be preheated to reduce the level of thermal stresses experienced by the parts. (6) 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. (7) Proper design of the weldment itself can reduce the degree of warping.

30.26 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.

30.27 What are the three basic categories of inspection and testing techniques used for weldments? Name some typical inspections and/or tests in each category.

Answer. The three categories are: (1) visual inspection, which includes dimensional checks and inspection for warping, cracks, and other visible defects; (2) nondestructive evaluation, which includes dye-penetrant, magnetic particle, ultrasonic, and radiographic tests; and (3) destructive tests, which includes conventional mechanical and metallurgical tests adapted to weld joints.

30.28 What are the factors that affect weldability?

Answer. Factors affect weldability include (1) welding process, (2) metal properties such as melting point, thermal conductivity, coefficient of thermal expansion, (3) whether the base metals are similar or dissimilar - dissimilar base metals are generally more difficult to weld, (4) surface condition - surfaces should be clean and free of oxides, moisture, etc., and (5) filler metal and its composition relative to the base metals.

30.29 What are some of the design guidelines for weldments that are fabricated by arc welding?

Answer. The guidelines for weldments by arc welding include (1) Good fit-up of parts to be welded is important to maintain dimensional control and minimize distortion. Machining is sometimes required to achieve satisfactory fit-up. (2) The design of the assembly must provide access room to allow the welding gun to reach the welding area. (3) Whenever possible, design of the assembly should allow flat welding to be performed, as opposed to horizontal, vertical, or overhead arc welding positions.

31.29 (**Video**) According to the video, what are four possible functions of the electrodes in resistance spot welding?

Answer: The four possible functions of the electrodes in resistance spot welding are (1) to conduct welding current to the work/fix the current density in the weld zone, (2) to transmit a force to the workpieces, (3) to dissipate some heat from the weld zone, and (4) to maintain relative alignment and position of the workpieces.

Multiple Choice Quiz

There are 23 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

30.1 The feature that distinguishes fusion welding from solid-state welding is that melting of the faying surfaces occurs during fusion welding but not in solid-state welding: (a) true or (b) false?

Answer. (a).

30.2 Which of the following processes are classified as fusion welding (three correct answers): (a) electrogas welding, (b) electron-beam welding, (c) explosion welding, (d) forge welding, (e) laser-beam welding, and (f) ultrasonic welding?

Answer. (a), (b), and (e).

30.3 Which of the following processes are classified as fusion welding (two correct answers): (a) diffusion welding, (b) friction welding, (c) pressure gas welding, (d) resistance welding, and (e) roll welding?

Answer. (c) and (d).

30.4 Which of the following processes are classified as solid-state welding (three correct answers): (a) diffusion welding, (b) friction stir welding, (c) resistance spot welding, (d) roll welding, (e) thermit welding, and (f) upset welding?

Answer. (a), (b), and (d).

30.5 An electric arc is a discharge of current across a gap in an electrical circuit. The arc is sustained in arc welding processes by the transfer of molten metal across the gap between the electrode and the work: (a) true or (b) false?

Answer. (b). The arc is sustained, not by the transfer of molten metal, but by the presence of a thermally ionized column of gas through which the current flows.

30.6 Which one of the following arc welding processes uses a nonconsumable electrode: (a) FCAW, (b) GMAW, (c) GTAW, or (d) SMAW?

Answer. (c).

30.7 MIG welding is a term sometimes applied when referring to which one of the following processes: (a) FCAW, (b) GMAW, (c) GTAW, or (d) SMAW?

Answer. (b).

30.8 "Stick" welding is a term sometimes applied when referring to which one of the following processes: (a) FCAW, (b) GMAW, (c) GTAW, or (d) SMAW?

Answer. (d).

30.9 Which one of the following AW processes uses an electrode consisting of continuous consumable tubing containing flux and other ingredients in its core: (a) FCAW, (b) GMAW, (c) GTAW, or (d) SMAW?

Answer. (a).

30.10 Which one of the following arc-welding processes produces the highest temperatures: (a) CAW, (b) PAW, (c) SAW, or (a) TIG welding?

Answer. (b).

30.11 Resistance-welding processes make use of the heat generated by electrical resistance to achieve fusion of the two parts to be joined; no pressure is used in these processes, and no filler metal is added: (a) true or (b) false?

Answer. (b). Pressure is applied in RW processes and is key to the success of these processes.

30.12 Metals that are easiest to weld in resistance welding are ones that have low resistivities since low resistivity assists in the flow of electrical current: (a) true or (b) false?

Answer. (b). Metals with low resistivities, such as aluminum and copper, are difficult to weld in RW. Higher resistance is required in the conversion of electrical power to heat energy; hence, metals with high resistivity are generally preferable.

30.13 Oxyacetylene welding is the most widely used oxyfuel welding process because acetylene mixed with an equal volume of oxygen burns hotter than any other commercially available fuel: (a) true or (b) false?

Answer. (a).

30.14 The term "laser" stands for "light actuated system for effective reflection": (a) true or (b) false?

Answer. (b). Laser stands for "light amplification by stimulated emission of radiation."

30.15 Which of the following solid-state welding processes applies heat from an external source (two best answers): (a) diffusion welding, (b) forge welding, (c) friction welding, and (d) ultrasonic welding?

Answer. (a) and (b).

30.16 The term weldability takes into account not only the ease with which a welding operation can be performed, but also the quality of the resulting weld: (a) true or (b) false?

Answer. (a).

30.17 Copper is a relatively easy metal to weld because its thermal conductivity is high: (a) true or (b) false?

Answer. (b). True that copper has a high thermal conductivity, one of the highest of any metal, but this is one of the main reasons why copper is generally difficult to weld. The heat readily flows into the body of the parts that are to be welded, rather than remaining at the localized region where the joint is to be made.

Problems

Arc Welding

30.1 A SMAW operation is accomplished in a work cell using a fitter and a welder. The fitter takes 5.5 min to place the unwelded components into the welding fixture at the beginning of the work cycle, and 2.5 min to unload the completed weldment at the end of the cycle. The total length of the several weld seams to be made is 2000 mm, and the travel speed used by the welder averages 400 mm/min. Every 750 mm of weld length, the welding stick must be changed, which takes 0.8 min. While the fitter is working, the welder is idle (resting); and while the welder is working, the fitter is idle. (a) Determine the average arc time in this welding cycle. (b) How much improvement in arc time would result if the welder used FCAW (manually operated), given that the spool of flux-cored weld wire must be changed every five weldments, and it takes the welder 5.0 min to accomplish the change? (c) What are the production rates for these two cases (weldments completed per hour)?

Solution: (a) SMAW cycle time T_c = 5.5 + 2000/400 + (2000/750)(0.8) + 2.5
= 5.5 + 5.0 + 2.133 + 2.5 = 15.133 min
Arc time = 5.0/15.133 = **33.0%**

(b) FCAW cycle time T_c = 5.5 + 2000/400 + (1/5)(5.0) + 2.5
= 5.5 + 5.0 + 1.0 + 2.5 = 14.0 min
Arc time = 5.0/14.0 = **35.7%**

(c) SMAW R_p = 60/15.133 = **3.96 pc/hr**
FCAW R_p = 60/14.0 = **4.29 pc/hr**.

30.2 In the previous problem, suppose an industrial robot cell were installed to replace the welder. The cell consists of the robot (using GMAW instead of SMAW or FCAW), two welding fixtures, and the fitter who loads and unloads the parts. With two fixtures, fitter and robot work simultaneously, the robot welding at one fixture while the fitter unloads and loads at the other. At the end of each work cycle, they switch places. The electrode wire spool must be changed every five workparts, which task requires 5.0 minutes and is accomplished by the fitter. Determine (a) arc time and (b) production rate for this work cell.

Solution: (a) Fitter: T_c = 5.5 + 2.5 + (1/5)(5.0) = 9.0 min
Robot: T_c = 2000/400 = 5.0 min
Limiting cycle is the fitter: arc time = 5.0/9.0 = **55.5%**

(b) R_p = 60/9.0 = **6.67 pc/hr.**

30.3 A shielded metal arc-welding operation is performed on steel at a voltage = 30 volts and a current = 225 amps. The heat transfer factor = 0.85 and melting factor = 0.75. The unit melting energy for steel = 10.2 J/mm^3. Determine (a) the rate of heat generation at the weld and (b) the volume rate of metal welded.

Solution: (a) $R_{HW} = f_1 f_2 EI$ = (0.85)(0.75)(30)(225) = **4303.1 W**

(b) R_{WV} = (4303.1 W)/(10.2 J/mm^3) = **421.9 mm^3/sec.**

30.4 A GTAW operation is performed on low carbon steel, whose unit melting energy is 10.3 J/mm^3. The welding voltage is 22 volts and the current is 135 amps. The heat transfer factor is 0.7 and the melting factor is 0.65. If filler metal wire of 3.5 mm diameter is added to the operation, the final weld bead is composed of 60% volume of filler and 40% volume base metal. If the travel speed in the operation is 5 mm/sec, determine (a) cross-sectional area of the weld bead, and (b) the feed rate (mm/sec) at which the filler wire must be supplied.

Solution: (a) $R_{HW} = f_1 f_2 EI = U_m A_w v$
$A_w = f_1 f_2 EI/(U_m v)$ = 0.7(0.65)(22)(135)/(10.3x5.0) = **26.24 mm^2**

(b) Volume of weld = $A_w v$ = 26.24(5.0) = 131.2 mm^3/s
Filler wire $A = \pi D^2/4 = \pi(3.5)^2/4$ = 9.62 mm^2
At 60% filler metal, feed rate of filler wire = 131.2(0.60)/9.62 = **8.18 mm/s**

30.5 A flux-cored arc-welding operation is performed to butt weld two austenitic stainless steel plates together. The welding voltage is 21 volts and the current is 185 amps. The cross-sectional area of the weld seam = 75 mm^2 and the melting factor of the stainless steel is assumed to be 0.60. Using tabular data and equations given in this and the preceding chapter, determine the likely value for travel speed v in the operation.

Solution: From Table 30.1, f_1 = 0.9 for FCAW.
From Table 29.2, T_m = 1670°K for austenitic stainless steel.
$U_m = 3.33 \text{ x } 10^{-6} (1670)^2$ = 9.29 J/mm^3
$f_1 f_2 EI = U_m A_w v$
$v = f_1 f_2 EI/U_m A_w$ = 0.9(0.6)(21)(185)/(9.29 x 75) = **3.01 mm/s**

30.6 A flux-cored arc-welding process is used to join two low alloy steel plates at a 90° angle using an outside fillet weld. The steel plates are ½ in thick. The weld bead consists of 55% metal from the electrode and the remaining 45% from the steel plates. The melting factor of the steel is 0.65 and the heat transfer factor is 0.90. The welding current is 75 amps and the voltage is 16 volts. The velocity of the welding head is 40 in/min. The diameter of the electrode is 0.10 in. There is a core of flux running through the center of the electrode that has a diameter of 0.05 in and contains flux (compounds that do not become part of the weld bead). (a) What is the cross-sectional area of the weld bead? (b) How fast must the electrode be fed into the workpiece?

Solution: (a) T_m from Table 29.2 is 3060°R
$U_m = KT_m^2 = 1.467\text{x}10^{-5}(3060^2)$ = 137.4 Btu/in^3
$R_{HW} = f_1 f_2 EI = U_m A_w v$, rearranging, $A_w = f_1 f_2 EI/U_m v$
$f_1 f_2 EI$ = 0.90(0.65)(16)(75) = 702 J/sec
$U_m v$ = (137.4 Btu/in^3)(40 in/min) = 5496 Btu/in^2-min
Conversions: 1 Btu = 1055 J and 1 min = 60 sec
$U_m v$ = 5496 Btu/in^2-min(1055 J/Btu)(min/60 sec) = 96,638 J/in^2-sec
A_w = (702 J/sec) / (96,638 J/in^2-sec) = **0.00726 in^2**

(b) Volume of weld = $A_w v$ = 0.00726(40) = 0.2906 in^3/min
Electrode $A = \pi D^2/4 = \pi(0.10)^2/4 = 78.5\text{x}10^{-4}$ in^2
Flux $A = \pi D^2/4 = \pi(0.05)^2/4 = 19.6\text{x}10^{-4}$ in^2
Metal in electrode $A = 78.5\text{x}10^{-4} - 19.6\text{x}10^{-4}$ in^2 = $58.9\text{x}10^{-4}$ in^2 = 0.00589 in^2
At 55% electrode metal,
feed rate of electrode = 0.2906 in^3/min (0.55) / 0.00589 = **27.13 in/min (0.452 in/sec)**

30.7 A gas metal arc-welding test is performed to determine the value of melting factor f_2 for a certain metal and operation. The welding voltage = 25 volts, current = 125 amps, and heat transfer factor is assumed to be = 0.90, a typical value for GMAW. The rate at which the filler metal is added to the weld is 0.50 in^3 per minute, and measurements indicate that the final weld bead consists of 57% filler metal and 43% base metal. The unit melting energy for the metal is known to be 75 Btu/in^3. (a) Find the melting factor. (b) What is the travel speed if the cross-sectional area of the weld bead = 0.05 in^2?

Solution: (a) $f_1 f_2 EI = U_m A_w v$
$A_w v$ = welding volume rate = R_{WV} = (0.50 in^3/min)/0.57 = 0.877 in^3/min = 0.01462 in^3/sec.
Therefore, $f_1 f_2 EI = U_m(R_{WV})$
1 Btu/sec = 1055 J/s = 1055 W, so 75 Btu/sec = 79,125 W
$f_2 = U_m(R_{WV})/f_1 EI$ = 79,125(0.01462)/(0.9 x 25 x 125) = **0.41**

(b) Given that $A_w = 0.05$ in^2, $v = (R_{WV})/A_w = 0.877/0.05 =$ **17.54 in/min**

30.8 A continuous weld is to be made around the circumference of a round steel tube of diameter = 6.0 ft, using a submerged arc welding operation under automatic control at a voltage of 25 volts and current of 300 amps. The tube is slowly rotated under a stationary welding head. The heat transfer factor for SAW is = 0.95 and the assumed melting factor = 0.7. The cross-sectional area of the weld bead is 0.12 in^2. If the unit melting energy for the steel = 150 Btu/in^3, determine (a) the rotational speed of the tube and (b) the time required to complete the weld.

Solution: (a) $f_1 f_2 EI = U_m A_w v$
$v = f_1 f_2 EI/U_m A_w$
1 Btu/sec = 1055 J/s = 1055 W, so 150 Btu/sec = 158,250 W
$v = 0.95(0.7)(25)(300)/(158{,}250 \text{ x } 0.120) = 0.263$ in/sec = 15.76 in/min
Circumference $C = \pi D = 12 \text{ x } 6\pi = 226.2$ in/rev.
Rotational speed N = (15.76 in/min)/(226.2 in/rev) = **0.06967 rev/min**

(b) Time to weld around circumference = C/v = (226.2 in/rev)/(15.76 in/min) = **14.35 min**

Resistance Welding

30.9 An RSW operation is used to make a series of spot welds between two pieces of aluminum, each 2.0 mm thick. The unit melting energy for aluminum = 2.90 J/mm^3. Welding current = 6,000 amps, and time duration = 0.15 sec. Assume that the resistance = 75 micro-ohms. The resulting weld nugget measures 5.0 mm in diameter by 2.5 mm thick. How much of the total energy generated is used to form the weld nugget?

Solution: $H = I^2Rt = (6000)^2(75 \text{ x } 10^{-6})(0.15) = 405$ W-sec = 405 J
Weld nugget volume $V = \pi D^2 d/4 = \pi(5)^2(2.5)/4 = 49.1$ mm^3
Heat required for melting = $U_m V$ = (2.9 J/mm^3)(49.1 mm^3) = 142.4 J
Proportion of heat for welding =142.4/405 = **0.351 = 35.1%**

30.10 An RSW operation is used to join two pieces of sheet steel having a unit melting energy of 130 Btu/in^3. The sheet steel has a thickness of 1/8 in. The weld duration will be set at 0.25 sec with a current of 11,000 amp. Based on the electrode diameter, the weld nugget will have a diameter of 0.30 in. Experience has shown that 40% of the supplied heat melts the nugget and the rest is dissipated by the metal. If the electrical resistance between the surfaces is 130 micro-ohms, what is the thickness of the weld nugget assuming it has a uniform thickness?

Solution: $H = I^2Rt = 11{,}000^2(0.000130)(0.25) = 3{,}930$ J = 3,930/1055 = 3.727 Btu
$V = H_w/U_m = (0.4)(3.727/130) = 0.0115$ in^3
$V = (d)\pi D^2/4$; $d = V/(\pi D^2/4) = 0.0115/(0.25\pi(0.30^2)) =$ **0.162 in**

30.11 The unit melting energy for a certain sheet metal is 9.5 J/mm^3. The thickness of each of the two sheets to be spot welded is 3.5 mm. To achieve required strength, it is desired to form a weld nugget that is 5.5 mm in diameter and 5.0 mm thick. The weld duration will be set at 0.3 sec. If it is assumed that the electrical resistance between the surfaces is 140 micro-ohms, and that only one-third of the electrical energy generated will be used to form the weld nugget (the rest being dissipated), determine the minimum current level required in this operation.

Solution: $H_m = U_m V$
$V = \pi D^2 d/4 = \pi(5.5)^2(5.0)/4 = 118.8$ mm^3
$H_w = 9.5(118.8) = 1129$ J
Required heat for the RSW operation $H = 1129/(1/3) = 3386$ J
$H = I^2Rt = I^2(140 \text{ x } 10^{-6})(0.3) = 42 \text{ x } 10^{-6} I^2 = 3386$ J
$I^2 = 3386/(42 \text{ x } 10^{-6}) = 80.6 \text{ x } 10^6$ A^2
$I = 8.98 \text{ x } 10^3 =$ **8,980 A**

30.12 A resistance spot-welding operation is performed on two pieces of 0.040 in thick sheet steel (low carbon). The unit melting energy for steel = 150 Btu/in^3. Process parameters are: current = 9500 A and time duration = 0.17 sec. This results in a weld nugget of diameter = 0.19 in and thickness = 0.060 in. Assume the resistance = 100 micro-ohms. Determine (a) the average power density in the interface area defined by the weld nugget, and (b) the proportion of energy generated that went into formation of the weld nugget.

Solution: (a) $PD = I^2R/A$
$A = \pi D^2/4 = \pi(0.19)^2/4 = 0.02835$ in^2
$I^2R = (9500)^2\ (100 \times 10^{-6}) = 9025$ W
1 Btu/sec = 1055 W, so 9025 W = 8.554 Btu/sec
PD = 8.554/0.02835 = **302 Btu/sec-in^2**

(b) $H = I^2Rt = (9500)^2\ (100 \times 10^{-6})(0.17) = 1534$ W-sec = 1.454 Btu
Weld nugget volume $V = \pi D^2 d/4 = \pi(0.19)^2(0.060)/4 = 0.0017$ in^3
Heat required for melting = $U_m V$ = (150 Btu/in^3)(0.0017) = 0.255 Btu
Proportion of heat for welding = 0.255/1.454 = **0.175 = 17.5%**

30.13 A resistance seam-welding operation is performed on two pieces of 2.5-mm-thick austenitic stainless steel to fabricate a container. The weld current in the operation is 10,000 amps, the weld duration = 0.3 sec, and the resistance at the interface is 75 micro-ohms. Continuous motion welding is used, with 200-mm-diameter electrode wheels. The individual weld nuggets formed in this RSEW operation have diameter = 6 mm and thickness = 3 mm (assume the weld nuggets are disc-shaped). These weld nuggets must be contiguous to form a sealed seam. The power unit driving the process requires an off-time between spot welds of 1.0 s. Given these conditions, determine (a) the unit melting energy of stainless steel using the methods of the previous chapter, (b) the proportion of energy generated that goes into the formation of each weld nugget, and (c) the rotational speed of the electrode wheels.

Solution: (a) From Table 29.2, T_m = 1670°K for austenitic stainless steel.
$U_m = 3.33 \times 10^{-6}\ (1670)^2$ = **9.29 J/mm^3.**

(b) $H_w = U_m V$
$V = \pi D^2 d/4 = \pi(6.0)^2(3.0)/4 = 84.82$ mm^3
H_w = (9.29 J/mm^3)(84.82 mm^3) = 788 J
$H = I^2Rt = (10{,}000)^2(75 \times 10^{-6})(0.3) = 2225$ J
Proportion of heat for welding =788/2225= **0.354 = 35.4%**

(c) Total cycle time per weld T_c = 0.3 + 1.0 = 1.3 sec.
Distance moved per spot weld in order to have contiguous spot welds for the seam = D = 0.6 mm.
Therefore, surface speed of electrode wheel v = 6.00 mm/1.3 sec = 4.61 mm/s = 276.9 mm/min.
$N = v/\pi D$ = (276.9 mm/min)/(200π mm/rev) = **0.441 rev/min**

30.14 Suppose in the previous problem that a roll spot-welding operation is performed instead of seam welding. The interface resistance increases to 100 micro-ohms, and the center-to-center separation between weld nuggets is 25 mm. Given the conditions from the previous problem, with the changes noted here, determine (a) the proportion of energy generated that goes into the formation of each weld nugget, and (b) the rotational speed of the electrode wheels. (c) At this higher rotational speed, how much does the wheel move during the current on-time, and might this have the effect of elongating the weld nugget (making it elliptical rather than round)?

Solution: (a) $U_m = 3.33 \times 10^{-6}\ (1670)^2 = 9.29$ J/mm^3 from previous problem.
H_w = (9.29 J/mm^3)(84.82 mm^3) = 788 J from previous problem.
$H = I^2Rt = (10{,}000)^2(100 \times 10^{-6})(0.3) = 3000$ J
Proportion of heat for welding =788/3000 = **0.263 = 26.3%**

(b) Total cycle time per spot weld T_c = 1.3 sec as in previous problem.
Distance moved per spot weld = 25 mm as given.
Surface speed of electrode wheel v = 25 mm/1.3 sec = 19.23 mm/s = 1153.8 mm/min
$N = v/\pi D$ = (1153.8 mm/min)/(200π in/rev) = **1.836 rev/min**

(c) Power-on time during cycle = 0.3 sec.
Movement of wheel during 0.3 sec = (0.3 sec)(19.23 mm/s) = **5.77 mm**. This movement is likely to make the weld spot elliptical in shape.

30.15 Resistance projection welding is used to simultaneously weld two thin, steel plates together at four locations. One of the pieces of steel plate is preformed with projections that have a diameter of 0.25 in and a height of 0.20 in. The duration of current flow during the weld is 0.30 sec and all four projections are welded simultaneously. The plate steel has a unit melting energy of 140 Btu/in^3 and a resistance between plates of 90.0 micro-ohms. Experience has shown that 55% of the heat is dissipated by the metal and 45% melts the weld nugget. Assume the volume of the nuggets will be twice the volume of the projections because metal from both plates is melted. How much current is required for the process?

Solution: Volume single projection = $d\pi D^2/4$ = 0.00982 in^3
Volume of one nugget V = 2*0.00982 = 0.01964 in^3
Volume of 4 nuggets = 4(0.01964) = 0.07854 in^3
$H_m = U_m V$ = 140(0.07854) = 11.00 Btu
Total H required = H_w/(% used to melt plate) = 11.00/0.45 = 24.43 Btu
Total H in Joules = 24.43(1055) = 25,780 J
$I^2 = H/(Rt)$ = 25,780/(90x10^{-6}*0.3) = 9.55x10^8 amp^2
I = (9.55x10^8)$^{0.5}$ = **30,900 amp**

30.16 An experimental power source for spot welding is designed to deliver current as a ramp function of time: I = 100,000 t, where I = amp and t = sec. At the end of the power-on time, the current is stopped abruptly. The sheet metal being spot welded is low carbon steel whose unit melting energy = 10 J/mm^3. The resistance R = 85 micro-ohms. The desired weld nugget diameter = 4 mm and thickness = 2 mm (assume a disc-shaped nugget). It is assumed that 1/4 of the energy generated from the power source will be used to form the weld nugget. Determine the power-on time the current must be applied in order to perform this spot-welding operation.

Solution: $H_w = U_m V$
$V = \pi D^2 d/4 = \pi(4)^2(2)/4$ = 25.14 mm^3
H_w = (10 J/mm^3)(25.14 mm^3) = 251.4 J
H = 251.4/0.25 = 1005.6 J
Power $P = \int I^2 R\,dt = \int (100{,}000t)^2 R\,dt = 100{,}000R \int t^2\,dt = (10^5)^2(85 \times 10^{-6})t^3/3$ evaluated between 0 and t.
$H = 850{,}000t^3/3 = 31481.5\,t^3$ = 1005.6
t^3 = 1005.6/31481.5 = 0.031943
t = (0.031943)$^{1/3}$ = **0.317 s.**

Oxyfuel Welding

30.17 Suppose in Example 30.3 in the text that the fuel used in the welding operation is MAPP instead of acetylene, and the proportion of heat concentrated in the 9 mm circle is 60% instead of 75 %. Compute (a) rate of heat liberated during combustion, (b) rate of heat transferred to the work surface, and (c) average power density in the circular area.

Solution: (a) Rate of heat generated by the torch R_H = (0.3 m^3/hr)(91.7 x 10^6 J/m^3)
= 27.5 x 10^6 J/hr = **7642 J/s**

(b) Rate of heat received at work surface = $f_1 R_H$ = 0.25(7642) = **1910 J/s**

(c) Area of circle in which 60% of heat is concentrated $A = \pi D^2/4 = \pi(9.0)^2/4 = 63.6$ mm^2
Power density $PD = 0.60(1910)/63.6 =$ **18.0 W/mm^2**

30.18 An oxyacetylene torch supplies 8.5 ft^3 of acetylene per hour and an equal volume rate of oxygen for an OAW operation on 1/4 in steel. Heat generated by combustion is transferred to the work surface with a heat transfer factor of 0.3. If 80% of the heat from the flame is concentrated in a circular area on the work surface whose diameter = 0.40 in, find: (a) rate of heat liberated during combustion, (b) rate of heat transferred to the work surface, and (c) average power density in the circular area.

Solution: (a) Rate of heat generated by the torch R_H = (8.5 ft^3/hr)(1470 Btu/ft^3)
= **12,500 Btu/hr = 3.47 Btu/sec**

(b) Rate of heat received at work surface = f_1R_H = 0.30(3.47 Btu/sec) = **1.04 Btu/sec**

(c) Area of circle in which 80% of heat is concentrated $A = \pi D^2/4 = \pi(0.4)^2/4 = 0.1257$ in^2
Power density PD = 0.80(1.04 Btu/sec)/(0.1257 in^2) = **6.63 Btu/sec-in^2**

Electron Beam Welding

30.19 The voltage in an EBW operation is 45 kV. The beam current is 60 milliamp. The electron beam is focused on a circular area that is 0.25 mm in diameter. The heat transfer factor is 0.87. Calculate the average power density in the area in watt/mm^2.

Solution: Power density $PD = f_1EI/A$
Power $P = f_1EI = 0.87(45 \text{ x } 10^3)(60 \text{ x } 10^{-3}) = 2349$ W
Area $A = \pi D^2/4 = \pi(0.25)^2/4 = 0.0491$ mm^3
PD = 2349/0.0491 = **47,853 W/mm^2**

30.20 An electron-beam welding operation is to be accomplished to butt weld two sheet-metal parts that are 3.0 mm thick. The unit melting energy = 5.0 J/mm^3. The weld joint is to be 0.35 mm wide, so that the cross section of the fused metal is 0.35 mm by 3.0 mm. If accelerating voltage = 25 kV, beam current = 30 milliamp, heat transfer factor $f_1 = 0.85$, and melting factor $f_2 = 0.75$, determine the travel speed at which this weld can be made along the seam.

Solution: Available heat for welding $R_{HW} = f_1f_2EI = U_mA_wv$
Travel velocity $v = f_1f_2EI/U_mA_w$
Cross sectional area of weld seam A_w = (0.35)(3.0) = 1.05 mm^2
$v = 0.85(0.75)(25 \text{ x } 10^3)(30 \text{ x } 10^{-3})/(5.0 \text{ x } 1.05) =$ **91.05 mm/s**

30.21 An electron-beam welding operation will join two pieces of steel plate together. The plates are 1.00 in thick. The unit melting energy is 125 Btu/in^3. The diameter of the work area focus of the beam is 0.060 in, hence the width of the weld will be 0.060 in. The accelerating voltage is 30 kV and the beam current is 35 milliamp. The heat transfer factor is 0.70 and the melting factor is 0.55. If the beam moves at a speed of 50 in/min, will the beam penetrate the full thickness of the plates?

Solution: Assume the melted portion of the weld bead has a rectangular cross-section with a width of 0.060 in and a depth, d. Therefore A_w = 0.060d or $d = A_w/0.060$
$A_w = f_1f_2EI/U_mv$ = (0.70)(0.55)(30000)(0.035)/(125(50)) = 0.065 in^2
$d = A_w/D$ = (0.065)/(0.060) = **1.08 in**
The electron beam should penetrate the full thickness of the material.

30.22 An electron-beam welding operation uses the following process parameters: accelerating voltage = 25 kV, beam current = 100 milliamp, and the circular area on which the beam is focused has a diameter = 0.020 in. If the heat transfer factor = 90%, determine the average power density in the area in Btu/sec in^2.

Solution: Power density $PD = f_1EI/A$
Area in which beam is focused $A = \pi D^2/4 = \pi(0.020)^2/4 = 0.000314$ in^3

Power $P = 0.90(25 \times 10^3)(100 \times 10^{-3})/1055 = 2.133$ Btu/sec

$PD = 2.133/0.000314 =$ **6792 Btu/sec-in^2**

31 BRAZING, SOLDERING, AND ADHESIVE BONDING

Review Questions

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

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

31.2 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.

31.3 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.

31.4 Under what circumstances would brazing or soldering be preferred over welding?

Answer. Brazing or soldering might be preferred over welding if (1) the base metals have poor weldability, (2) the components cannot tolerate the higher heat and temperatures of welding, (3) production rates need to be faster and less expensive than welding, (4) joint areas are inaccessible for welding but brazing or soldering is possible, and (5) the high strength of a welded joint is not a requirement.

31.5 What are the two joint types most commonly used in brazing?

Answer. The two joint types most commonly used in brazing are butt and lap joints.

31.6 Certain changes in joint configuration are usually made to improve the strength of brazed joints. What are some of these changes?

Answer. In butt joints, the butting surface areas are increased in various ways such as scarfing or stepping the edges. In brazed or soldered lap joints, the overlap area is made as large as possible. Several of the adaptations are illustrated in the figures of this chapter.

31.7 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.

31.8 What are the desirable characteristics of a brazing flux?

Answer. The desirable characteristics of a brazing flux are (1) low melting temperature, (2) low viscosity when melted, (3) promotes wetting of metal surfaces, and (4) protects the joint until solidification occurs.

31.9 What is dip brazing?

Answer. The parts to be brazed are dipped into a molten salt or molten metal bath which supplies the heating for the operation.

31.10 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.

31.11 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.

31.12 What are the two most common alloying metals used in solders?

Answer. Tin and lead.

31.13 What are the functions served by the bit of a soldering iron in hand soldering?

Answer. The functions include (1) provide heat to the parts, (2) melt the solder, (3) convey solder to the joint, and (4) withdraw excess solder from the joint.

31.14 What is wave soldering?

Answer. Wave soldering involves the flow of molten solder onto the underside of a printed circuit board to provide soldered connections between the component leads that project through holes in the boards and the copper circuit lands on the board.

31.15 List the advantages often attributed to soldering as an industrial joining process?

Answer. Advantages of soldering include (1) lower heat energy required than brazing or welding, (2) various heating methods available, (3) good electrical and thermal conductivity of the joint, (4) capable of making air-tight and liquid-tight joints, and (5) ease of repair and rework.

31.16 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.

31.17 What is meant by the term structural adhesive?

Answer. A structural adhesive is capable of forming a strong permanent joint between strong, rigid components.

31.18 An adhesive must cure in order to bond. What is meant by the term curing?

Answer. Curing is the chemical reaction in which the adhesive transforms from liquid to solid and in the process forms the surface attachment between the two adherends.

31.19 What are some of the methods used to cure adhesives?

Answer. The curing methods include (1) chemical reaction between two components of the adhesive (e.g., epoxies), (2) heating of the adhesive, (3) use of ultraviolet light, and (4) application of pressure.

31.20 Name the three basic categories of commercial adhesives.

Answer. The categories are (1) natural adhesives (e.g., starch, collagen); (2) inorganic adhesives (e.g., sodium silicate); and (3) synthetic adhesives (e.g., thermoplastic and thermosetting polymers such as epoxies and acrylics).

31.21 What is an important precondition for the success of an adhesive bonding operation?

Answer. The surfaces of the adherends must be very clean. Special surface preparation is often required immediately prior to application of the adhesive in order to insure cleanliness.

31.22 What are some of the methods used to apply adhesives in industrial production operations?

Answer. Methods include (1) manual brushing, (2) use of manual rollers, (3) silk screening, (4) use of flow guns, (5) spraying, (6) automatic dispensers, and (7) roll coating.

31.23 Identify some of the advantages of adhesive bonding compared to alternative joining methods.

Answer. Advantages of adhesive bonding: (1) applicable to a wide variety of materials - similar or dissimilar, (2) fragile parts can be joined, (3) bonding occurs over entire surface area of joint, (4) certain adhesives are flexible after curing, thus permitting them to tolerate strains encountered in service, (5) low curing temperatures, (6) some adhesives are suited to sealing as well as bonding, and (7) simplified joint design.

31.24 What are some of the limitations of adhesive bonding?

Answer. Limitations of adhesive bonding: (1) adhesively bonded joints are generally not as strong as other joining techniques, (2) the adhesive must be compatible with the adherend materials, (3) service temperatures are limited, (4) surfaces to be bonded must be very clean, (5) curing times can limit production rates, (6) inspection of the bond is difficult.

Multiple Choice Quiz

There are 20 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

31.1 In brazing, the base metals melt at temperatures above 840°F (450°C) while in soldering they melt at 840°F (450°C) or below: (a) true or (b) false?

Answer. (b). Neither brazing or soldering involve melting of the base metals.

31.2 The strength of a brazed joint is typically (a) equal to, (b) stronger than, or (c) weaker than the filler metal out of which it is made?

Answer. (b).

31.3 Scarfing in the brazing of a butt joint involves the wrapping of a sheath around the two parts to be joined to contain the molten filler metal during the heating process: (a) true or (b) false?

Answer. (b). Scarfing involves a preparation of the two edges to increase surface area for brazing.

31.4 Best clearances between surfaces in brazing are which one of the following: (a) 0.0025-0.025 mm (0.0001-0.001 in.), (b) 0.025-0.250 mm (0.001-0.010 in.), (c) 0.250-2.50 mm (0.010-0.100 in.), or (d) 2.5-5.0 mm (0.10-0.20 in.)?

Answer. (b).

31.5 Which of the following is an advantage of brazing (three best answers): (a) annealing of the base parts is a by-product of the process, (b) dissimilar metals can be joined, (c) less heat and energy required than fusion welding, (d) metallurgical improvements in the base metals, (e) multiple joints can be brazed simultaneously, (f) parts can be readily disassembled, and (g) stronger joint than welding?

Answer. (b), (c), and (e).

31.6 Which of the following soldering methods are not used for brazing (two correct answers): (a) dip soldering, (b) infrared soldering, (c) soldering iron, (d) torch soldering, and (e) wave soldering?

Answer. (c) and (e).

31.7 Which one of the following is not a function of a flux in brazing or soldering: (a) chemically etch the surfaces to increase roughness for better adhesion of the filler metal, (b) promote wetting of the surfaces, (c) protect the faying surfaces during the process, or (d) remove or inhibit formation of oxide films?

Answer. (a).

31.8 Which of the following metals are used in solder alloys (four correct answers): (a) aluminum, (b) antimony, (c) gold, (d) iron, (e) lead, (f) nickel, (g) silver, (h) tin, and (i) titanium?

Answer. (b), (e), (g), and (h).

31.9 A soldering gun is capable of injecting molten solder metal into the joint area: (a) true, or (b) false?

Answer. (b). The trigger on a soldering gun is used to switch on the electric resistance heating elements.

31.10 In adhesive bonding, which one of the following is the term used for the parts that are joined: (a) adherend, (b) adherent, (c) adhesive, (d) adhibit, or (e) ad infinitum?

Answer. (a).

31.11 Weldbonding is an adhesive joining method in which heat is used to melt the adhesive: (a) true or (b) false?

Answer. (b). Weld-bonding is a combination of adhesive bonding and spot welding.

31.12 Adhesively bonded joints are strongest under which type of stresses (two best answers): (a) cleavage, (b) peeling, (c) shear, and (d) tension?

Answer. (c) and (d).

31.13 Roughening of the faying surfaces tends to (a) have no effect on, (b) increase, or (c) reduce the strength of an adhesively bonded joint because it increases the effective area of the joint and promotes mechanical interlocking?

Answer. (a).

32 MECHANICAL ASSEMBLY

Review Questions

32.1 How does mechanical assembly differ from the other methods of assembly discussed in previous chapters (e.g., welding, brazing, etc.)?

Answer. Mechanical assembly uses a mechanical fastening method for joining two (or more) parts, whereas welding, brazing, soldering, and adhesive bonding use heat and/or pressure, sometimes combined with a filler material to permanently join parts. Also, many of the mechanical fastening methods allow for disassembly - not possible with welding and brazing.

32.2 What are some of the reasons why assemblies must be sometimes disassembled?

Answer. For maintenance and repair service, to replace worn-out components, and to make adjustments.

32.3 What is the technical difference between a screw and a bolt?

Answer. Both are externally threaded fasteners. A screw is generally assembled into a blind threaded hole, whereas a bolt is assembled using a nut.

32.4 What is a stud (in the context of threaded fasteners)?

Answer. A stud is an externally threaded fastener that does not have the usual head possessed by a bolt.

32.5 What is torque-turn tightening?

Answer. Torque-turn tightening involves the tightening of the threaded fastener to a certain low torque level, and then advancing the fastener by a specified additional amount of turn (e.g., a quarter turn).

32.6 Define proof strength as the term applies in threaded fasteners.

Answer. Proof strength can be defined as the maximum tensile stress that an externally threaded fastener can sustain without permanent deformation.

32.7 What are the three ways in which a threaded fastener can fail during tightening?

Answer. (1) Stripping of the bolt or screw threads, (2) stripping of the internal fastener threads, and (3) excessive tensile load on the cross-sectional area of the bolt or screw.

32.8 What is a rivet?

Answer. A rivet is an unthreaded headed pin used to join two parts by inserting the pin through holes in the parts and deforming the unheaded portion over the opposite side.

32.9 What is the difference between a shrink fit and expansion fit in assembly?

Answer. In a shrink fit, the outside part is expanded by heating to fit over the mating component. Then cooling causes an interference fit with the component. In an expansion fit, the internal part is cooled so that it can be readily inserted into the mating component. Then, upon warming to room temperature, it expands to cause an interference fit with its mating part.

32.10 What are the advantages of snap fitting?

Answer. Advantages of snap fitting include (1) the method is fast, (2) no tooling is required, and (3) the parts can be designed with self-aligning features for ease of mating.

32.11 What is the difference between industrial stitching and stapling?

Answer. In stitching the U-shaped fasteners are formed during the assembly process. In stapling, the fasteners are preformed.

32.12 What are integral fasteners?

Answer. Integral fasteners make use of a forming operation on one of the parts to be joined to interlock the components and create a mechanically fastened joint.

32.13 Identify some of the general principles and guidelines for design for assembly.

Answer. Some of the general principles and guidelines in design for assembly include the following: (1) Use the fewest number of parts possible to reduce assembly required. (2) Reduce the number of threaded fasteners; instead use snap fits, retaining rings, integral fasteners, and similar fastening mechanisms that can be accomplished more rapidly. Use threaded fasteners only where justified, e.g., where disassembly or adjustment is required. (3) Standardize fasteners in order to reduce the number of sizes and styles in the product. (4) Design parts to be symmetrical and minimize asymmetric features. (5) Avoid parts that tangle.

32.14 Identify some of the general principles and guidelines that apply specifically to automated assembly.

Answer. Some of the principles and guidelines that apply specifically to automated assembly include the following: (1) Use modularity in product design. Each module to be produced on a single assembly system should have a maximum of 12 or 13 parts and should be designed around a base part to which other components are added. (2) Reduce the need for multiple components to be handled at once. (3) Limit the required directions of access. The ideal is for all components to be added vertically from above. (4) Use only high quality components. Poor quality components cause jams in feeding and assembly mechanisms. (5) Use snap fit assembly to eliminate the need for threaded fasteners.

Multiple Choice Quiz

There are 16 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

32.1 Which of the following are reasons why mechanical assembly is often preferred over other forming processes (two best answers): (a) ease of assembly, (b) ease of disassembly, (c) economies of scale, (d) involves melting of the base parts, (e) no heat affected zone in the base parts, and (f) specialization of labor?

Answer. (a) and (b). Answer (e) might also be given, but it is not mentioned in the text.

32.2 Most externally threaded fasteners are produced by which one of the following processes: (a) cutting the threads, (b) milling the threads, (c) tapping, (d) thread rolling, or (e) turning the threads?

Answer. (d).

32.3 Which of the following methods and tools are used for applying the required torque to achieve a desired preload of a threaded fastener (three best answers): (a) arbor press, (b) preload method, (c) sense of feel by a human operator, (d) snap fit, (e) stall-motor wrenches, (f) torque wrench, and (g) use of lockwashers?

Answer. (c), (e), and (f).

32.4 Which of the following are the common ways in which threaded fasteners fail during tightening (two best answers): (a) excessive compressive stresses on the head of the fastener due to force applied by the tightening tool, (b) excessive compressive stresses on the shank of the fastener, (c) excessive shear stresses on the shank of the fastener, (d) excessive tensile stresses on the head of the fastener due to force applied by the tightening tool, (e) excessive tensile stresses on the shank of the fastener, and (f) stripping of the internal or external threads?

Answer. (e) and (f).

32.5 The difference between a shrink fit and an expansion fit is that in a shrink fit the internal part is cooled to a sufficiently low temperature to reduce its size for assembly, whereas in an expansion fit, the external part is heated sufficiently to increase its size for assembly: (a) true or (b) false?

Answer. (b). In a shrink fit the external part is heated and then cooled to shrink it onto the internal part. In an expansion fit, the internal part is cooled to contract it for assembly; it then expands to form the interference fit.

32.6 Advantages of snap fit assembly include which of the following (three best answers): (a) components can be designed with features to facilitate part mating, (b) ease of disassembly, (c) no heat affected zone, (d) no special tools are required, (e) parts can be assembled quickly, and (f) stronger joint than with most other assembly methods?

Answer. (a), (d), and (e).

32.7 The difference between industrial stitching and stapling is that the U-shaped fasteners are formed during the stitching process while in stapling the fasteners are preformed: (a) true or (b) false?

Answer. (a).

32.8 From the standpoint of assembly cost, it is more desirable to use many small threaded fasteners rather than few large ones in order to distribute the stresses more uniformly: (a) true or (b) false?

Answer. (b). From the standpoint of assembly cost, it is more desirable to use few large threaded fasteners rather than many small ones because the large fasteners are easier to handle and since there are fewer of them, they require less assembly time.

32.9 Which of the following are considered good product design rules for automated assembly (two best answers): (a) design the assembly with the fewest number of components possible, (b) design the product using bolts and nuts to allow for disassembly, (c) design with many different fastener types to maximize design flexibility, (d) design parts with asymmetric features to mate with other parts having corresponding (but reverse) features, and (e) limit the required directions of access when adding components to a base part?

Answer. (a) and (e). All of the other answers go against design-for-assembly principles.

Problems

Threaded Fasteners

32.1 A 5-mm-diameter bolt is to be tightened to produce a preload = 250 N. If the torque coefficient = 0.23, determine the torque that should be applied.

Solution: $T = C_tDF = 0.23(5.0)(250) =$ **287.5 N-mm = 0.2875 N-m**

32.2 A 3/8-24 UNF nut and bolt (3/8 in nominal diameter, 24 threads/in) are inserted through a hole in two stacked steel plates. They are tightened so the plates are clamped together with a force of 1000 lb. The torque coefficient is 0.20. (a) What is the torque required to tighten them? (b) What is the resulting stress in the bolt?

Solution (a) $T = C_tDF = 0.20(3/8)(1000) =$ **75 in-lb**

(b) $A_s = 0.25\pi(D - 0.9743/n)^2 = 0.25\pi(3/8 - 0.9743/24)^2 = 0.0878$ in^2
$\sigma = F/A_s = 1000/0.0878 =$ **11,386 lb/in^2**

32.3 An alloy steel Metric 10x1.5 screw (10 mm diameter, pitch p = 1.5 mm) is to be turned into a threaded hole and tightened to one/half of its proof strength. According to Table 32.2, the proof strength = 830 MPa. Determine the maximum torque that should be used if the torque coefficient = 0.18.

Solution: $A_s = 0.25\pi(10 - 0.9382 \text{ x } 1.5)^2 = 57.99$ mm^2
σ = 0.5 of 830 MPa = 415 MPa = 415 N/mm^2
$F = \sigma A_s = 415(57.99) = 24{,}066$ N
$T = C_tDF = 0.18(10)(24{,}066) =$ **43,319 N-mm = 43.32 N-m**

32.4 A Metric 16x2 bolt (16 mm diameter, 2 mm pitch) is subjected to a torque of 15 N-m during tightening. If the torque coefficient is 0.24, determine the tensile stress on the bolt.

Solution: T = 15 N-m = 15,000 N-mm
$F = T/ C_tD = 15{,}000/(0.24 \text{ x } 16) = 3906$ N
$A_s = 0.25\pi(16 - 0.9382 \text{ x } 2)^2 = 156.7$ mm^2
$\sigma = 3906/156.7 =$ **24.9 N/mm^2 = 24.9 MPa**

32.5 A 1/2-13 screw is to be preloaded to a tension force = 1000 lb. Torque coefficient = 0.22. Determine the torque that should be used to tighten the bolt.

Solution: $T = C_tDF = 0.22(0.50)(1000) =$ **110 in-lb**

32.6 Threaded metric fasteners are available in several systems, two of which are coarse and fine (Table 32.1). Finer threads are not cut as deep and as a result have a larger tensile stress area for the same nominal diameter. (a) Determine the maximum preload that can be safely achieved for coarse pitch and fine pitch threads for a 12 mm bolt. (b) Determine the percent increase in preload of fine threads compared to course threads. Coarse pitch = 1.75 mm and fine pitch = 1.25 mm. Assume the proof strength for both bolts is 600 MPa.

Solution: (a) For standard thread,
$A_s = 0.25\pi(D - 0.9382p)^2 = 0.25\pi(12 - 0.9382 \text{ x } 1.75)^2 = 84.3$ mm^2
$F = A_s\sigma = 84.3(600) =$ **50,560 N**
For fine thread,
$A_s = 0.25\pi(D - 0.9382p)^2 = 0.25\pi(12 - 0.9382 \text{ x } 1.25)^2 = 92.1$ mm^2
$F = A_s\sigma = 92.1(600) =$ **55,243 N**

(b) Percent increase = (55,243 – 50,560)/50,560 = 0.0926 = **9.26 % increase**

32.7 A torque wrench is used on a 3/4-10 UNC bolt in an automobile final assembly plant. A torque of 70 ft-lb is generated by the wrench. If the torque coefficient = 0.17, determine the tensile stress in the bolt.

Solution: T = 70 ft-lb = 840 in-lb
$F = T/C_tD = 840/(0.17 \text{ x } 0.75) = 6588$ lb.
$A_s = 0.25\pi(0.75 - 0.9743/10)^2 = 0.334$ in^2
$\sigma = 6588/0.334 =$ **19,697 lb/in^2**

32.8 The designer has specified that a 3/8-16 UNC low-carbon bolt (3/8 in nominal diameter, 16 threads/in) in a certain application should be stressed to its proof stress of 33,000 lb/in^2 (see Table 32.2). Determine the maximum torque that should be used if C = 0.25.

Solution: $A_s = 0.25\pi(0.375 - 0.9743/16)^2 = 0.0775$ in^2

$F = \sigma A_s = 33{,}000(0.0775) = 2557.5$ lb
$T = C_t DF = 0.25(0.375)(2557.5) =$ **240 in-lb**

32.9 A 300-mm-long wrench is used to tighten a Metric 20x2.5 bolt. The proof strength of the bolt for the particular alloy is 380 MPa. The torque coefficient is 0.21. Determine the maximum force that can be applied to the end of the wrench so that the bolt does not permanently deform.

Solution: $A_s = 0.25\pi(D - 0.9382p)^2 = 0.25\pi(20 - 0.9382{*}2.50)^2 = 244.8\ \text{mm}^2$
Preload force, $F = A_s\sigma = 244.8(380) = 93{,}022$ N
$T = C_t DF = 0.21(20)(93{,}022) = 390{,}690$ N-mm
$T = F_{wrench}L_{wrench}$; $F_{wrench} = T/L_{wrench} = 390{,}690/300 =$ **1302 N**

32.10 A 1-8 UNC low carbon steel bolt (diameter = 1.0 in, 8 threads/in) is currently planned for a certain application. It is to be preloaded to 75% of its proof strength, which is 33,000 lb/in^2 (Table 32.2). However, this bolt is too large for the size of the components involved, and a higher strength but smaller bolt would be preferable. Determine (a) the smallest nominal size of an alloy steel bolt (proof strength = 120,000 lb/in^2) that could be used to achieve the same preload from the following standard UNC sizes used by the company: 1/4-20, 5/16-18, 3/8-16, 1/2-13, 5/8-11, or 3/4-10; and (b) compare the torque required to obtain the preload for the original 1-in bolt and the alloy steel bolt selected in part (a) if the torque coefficient in both cases = 0.20.

Solution: (a) $A_s = 0.25\pi(1.0 - 0.9743/8)^2 = 0.6057\ \text{in}^2$
$F = \sigma A_s = 0.75(33{,}000)(0.6057) = 14{,}992$ lb.
For the alloy bolt, $\sigma = 120{,}000$ lb/in^2.
$A_s = F/\sigma = 14992/(0.75 \times 120{,}000) = 0.1665\ \text{in}^2$
$A_s = 0.1665\ \text{in}^2 = 0.25\pi(D - 0.9743/n)^2$
$(D - 0.9743/n)^2 = 0.1665\ \text{in}^2/0.25\pi = 0.212\ \text{in}^2$
$(D - 0.9743/n) = 0.4605$ in
Possible bolt sizes are: (1) 1/4-20, (2) 5/16-18, (3) 3/8-16, (4) 1/2-13, (5) 5/8-11, (6) 3/4-10
Try (1): $(D - 0.9743/n) = (0.25 - 0.9743/20) = 0.2013$ in. Obviously, none of the D values below 0.4605 will be sufficient.
Try (4): $(D - 0.9743/n) = (0.500 - 0.9743/13) = 0.425\ \text{in} < 0.4605$ in. Cannot use ½-13 bolt
Try (5): $(D - 0.9743/n) = (0.625 - 0.9743/11) = 0.5364\ \text{in} > 0.4605$ in. **Use 5/8-11 bolt**

(b) For the original 1-8 bolt, $T = C_t DF = 0.2(1.0)(14{,}992) =$ **2,998 in-lb.**
For the 5/8-11 bolt, $T = C_t DF = 0.2(0.625)(14{,}992) =$ **1,874 in-lb**.

Interference Fits

32.11 A dowel pin made of steel (elastic modulus = 209,000 MPa) is to be press fitted into a steel collar. The pin has a nominal diameter of 16.0 mm, and the collar has an outside diameter of 27.0 mm. (a) Compute the radial pressure and the maximum effective stress if the interference between the shaft OD and the collar ID is 0.03 mm. (b) Determine the effect of increasing the outside diameter of the collar to 39.0 mm on the radial pressure and the maximum effective stress.

Solution: (a) $p_f = Ei(D_c^2 - D_p^2)/D_pD_c^2 = 209{,}000(0.03)(27^2 - 16^2)/(16 \times 27^2) =$ **254 MPa**
Max $\sigma_e = 2p_fD_c^2/(D_c^2 - D_p^2) = 2(254.3)(27^2)/(27^2 - 16^2) =$ **784 MPa**

(b) When $D_c = 39$ mm, $p_f = 209{,}000(0.03)(39^2 - 16^2)/(16 \times 39^2) =$ **326 MPa**
Max $\sigma_e = 2(325.9)(39^2)/(39^2 - 16^2) =$ **784 MPa**

32.12 A pin made of alloy steel is press-fitted into a hole machined in the base of a large machine. The hole has a diameter of 2.497 in. The pin has a diameter of 2.500 in. The base of the machine is 4 ft x 8 ft. The base and pin have a modulus of elasticity of 30 x 10^6 lb/in^2, a yield strength of 85,000 lb/in^2, and a tensile strength of 120,000 lb/in^2. Determine (a) the radial pressure between the pin and the base and (b) the maximum effective stress in the interface.

Solution: (a) i = 2.500 – 2.497 = 0.003 in
$p_f = Ei/D_p = 30\text{x}10^6 (0.003)/2.5 =$ **36,000 lb/in²**

(b) Max $\sigma_e = 2p_f = 2(36{,}000) =$ **72,000 lb/in²**

32.13 A gear made of aluminum (modulus of elasticity = 69,000 MPa) is press fitted onto an aluminum shaft. The gear has a diameter of 55 mm at the base of its teeth. The nominal internal diameter of the gear = 30 mm and the interference = 0.10 mm. Compute: (a) the radial pressure between the shaft and the gear, and (b) the maximum effective stress in the gear at its inside diameter.

Solution: (a) $p_f = Ei(D_c^2 - D_p^2)/D_pD_c^2 = 69{,}000(0.10)(55^2 - 30^2)/(30 \text{ x } 55^2) =$ **161.5 MPa**

(b) Max $\sigma_e = 2p_fD_c^2/(D_c^2 - D_p^2) = 2(161.5)(55^2)/ (55^2 - 30^2) =$ **460 MPa**

32.14 A steel collar is press fitted onto a steel shaft. The modulus of elasticity of steel is 30 x 10^6 lb/in^2. The collar has an internal diameter of 2.498 in and the shaft has an outside diameter = 2.500 in. The outside diameter of the collar is 4.000 in. Determine the radial (interference) pressure on the assembly, and (b) the maximum effective stress in the collar at its inside diameter.

Solution: (a) i = 2.500 – 2.498 = 0.002 in
$p_f = Ei(D_c^2 - D_p^2)/D_pD_c^2 = 30 \text{ x } 10^6(0.002)(4.000^2 - 2.500^2)/(2.500 \text{ x } 4.000^2) =$ **14,625 lb/in²**

(b) Max $\sigma_e = 2p_fD_c^2/(D_c^2 - D_p^2) = 2(14{,}625)(4.000^2)/ (4.000^2 – 2.500^2) =$ **48,000 lb/in²**

32.15 The yield strength of a certain metal = 50,000 lb/in^2 and its modulus of elasticity = 22 x 10^6 lb/in^2. It is to be used for the outer ring of a press-fit assembly with a mating shaft made of the same metal. The nominal inside diameter of the ring is 1.000 in and its outside diameter = 2.500 in. Using a safety factor = 2.0, determine the maximum interference that should be used with this assembly.

Solution: Max $\sigma_e \leq Y/SF$, use Max $\sigma_e = Y/SF$ = 50,000/2.0 = 25,000 lb/in^2 Eq. (32.9)
Max $\sigma_e = 2p_fD_c^2/(D_c^2 - D_p^2)$ = 25,000 lb/in^2 Eq. (32.6)
Rearranging, $p_f = \sigma_e(D_c^2 - D_p^2)/2D_c^2 = 25{,}000(2.5^2 - 1.0^2)/(2 \text{ x } 2.5^2)$ = 10,500 lb/in^2
$p_f = Ei(D_c^2 - D_p^2)/D_pD_c^2$ Eq. (32.5)
Rearranging, $i = p_f D_pD_c^2/E(D_c^2 - D_p^2)$
$i = 10{,}500(1.0)(2.5^2)/(22 \text{ x } 10^6 (2.5^2 - 1.0^2)) =$ **0.00057 in**

32.16 A shaft made of aluminum is 40.0 mm in diameter at room temperature (21°C). Its coefficient of thermal expansion = 24.8 x 10^{-6} mm/mm per °C. If it must be reduced in size by 0.20 mm in order to be expansion fitted into a hole, determine the temperature to which the shaft must be cooled.

Solution: $(D_2 - D_1) = -0.20 = 24.8 \text{ x } 10^{-6}(40)(T_2 - 21)$
$T_2 - 21 = -0.20/(24.8 \text{ x } 10^{-6} \text{ x } 40) = -201.6$
$T_2 = -201.6 + 21 =$ **-180.6°C**

32.17 A steel ring has an inside diameter = 30 mm and an outside diameter = 50 mm at room temperature (21°C). If the coefficient of thermal expansion of steel = 12.1 x 10^{-6} mm/mm per °C, determine the inside diameter of the ring when heated to 500°C.

Solution: $D_2 - D_1 = D_2 - 30 = 12.1 \text{ x } 10^{-6}(30)(500 - 21)$
$D_2 = 30 + 0.174 =$ **30.174 mm.**

32.18 A steel collar is to be heated from room temperature (70°F) to 700°F. Its inside diameter = 1.000 in, and its outside diameter = 1.625 in. If the coefficient of thermal expansion of the steel is = 6.7 x 10^{-6} in/in per °F, determine the increase in the inside diameter of the collar.

Solution: $(D_2 - D_1) = \alpha D_1(T_2 - T_1) = 6.7 \text{ x } 10^{-6}(1.0)(700 - 70) = 4221 \text{ x } 10^{-6} =$ **0.0042 in**

32.19 A bearing for the output shaft of a 200 hp motor is to be heated to expand it enough to press on the shaft. At 70°F the bearing has an inside diameter of 4.000 in and an outside diameter of 7.000 in.

The shaft has an outside diameter of 4.004 in. The modulus of elasticity for the shaft and bearing is 30×10^6 lb/in^2 and the coefficient of thermal expansion is 6.7×10^{-6} in/in per °F. (a) At what temperature will the bearing have 0.005 of clearance to fit over the shaft? (b) After it is assembled and cooled, what is the radial pressure between the bearing and shaft? (c) Determine the maximum effective stress in the bearing.

Solution: (a) interference i = 0.004 in, additional required clearance = 0.005 in
Total expansion = 0.004+0.005 = 0.009 in = $(D_2 - D_1)$
$T_2 = (D_2 - D_1)/\alpha D_1 + T_1 = 0.009/(6.7\text{x}10^{-6} \text{ x } 4.000) + 70 = 336 + 70 = \mathbf{406°F}$

(b) $p_f = Ei\ (D_c^2 - D_p^2)/D_pD_c^2 = 30\text{x}10^6(0.004)(7^2 - 4^2)/(4 \text{ x } 7^2) =$ **20,204 lb/in^2**

(c) Max $\sigma_e = 2p_fD_c^2/(D_c^2 - D_p^2) = 2(20{,}204)(7^2)/(7^2 - 4^2) =$ **60,000 lb/in^2**

32.20 A steel collar whose outside diameter = 3.000 in at room temperature is to be shrink fitted onto a steel shaft by heating it to an elevated temperature while the shaft remains at room temperature. The shaft diameter = 1.500 in. For ease of assembly when the collar is heated to an elevated temperature of 1000°F, the clearance between the shaft and the collar is to be 0.007 in. Determine (a) the initial inside diameter of the collar at room temperature so that this clearance is satisfied, (b) the radial pressure and (c) maximum effective stress on the resulting interference fit at room temperature (70°F). For steel, the elastic modulus = 30,000,000 lb/in^2 and coefficient of thermal expansion = 6.7 x 10^{-6} in/in per °F.

Solution: (a) If the clearance = 0.007 in, then the inside diameter of the collar must be
$D_2 = D_p + 0.007 = 1.500 + 0.007$.
$1.507 - D_1 = 6.7 \text{ x } 10^{-6}\ D_1(1000 - 70)$
$1.507 - D_1 = 0.00623\ D_1$
$1.507 = D_1 + 0.00623\ D_1 = 1.00623\ \mathrm{D}_1$
$D_1 = 1.507/1.00623 =$ **1.4977 in**

(b) Interference i = 1.500 - 1.4977 = 0.00233 in
$p_f = 30 \text{ x } 10^6\ (0.00233)(3.0^2 - 1.5^2)/(1.5 \text{ x } 3.0^2) =$ **34,950 lb/in^2**

(c) Max $\sigma_e = 2(34{,}950)(3.0^2)/\ (3.0^2 - 1.5^2) =$ **93,200 lb/in^2**

32.21 A pin is to be inserted into a collar using an expansion fit. Properties of the pin and collar metal are: coefficient of thermal expansion is 12.3 x 10^{-6} m/m/°C, yield strength is 400 MPa, and modulus of elasticity is 209 GPa. At room temperature (20°C), the outer and inner diameters of the collar = 95.00 mm and 60.00 mm, respectively, and the pin has a diameter = 60.03 mm. The pin is to be reduced in size for assembly into the collar by cooling to a sufficiently low temperature that there is a clearance of 0.06 mm. (a) What is the temperature to which the pin must be cooled for assembly? (b) What is the radial pressure at room temperature after assembly? (c) What is the safety factor in the resulting assembly?

Solution: (a) $D_2 - D_1 = \alpha D_1(T_2 - T_1) =$
$T_2 = (D_2\text{-}D_1)/(\alpha D_1) + T_1 = ((60.00\text{-}0.06) - 60.03)/(12.3\text{x}10^{-6}*60.03) + 20 =$ **-101.9°C**

(b) $p_f = Ei(D_c^2 - D_p^2)/D_pD_c^2$
$p_f = 209\text{x}10^9(0.03)(95^2 - 60^2)/(60(95^2) = 0.0628(10^9)$ N/m^2 = **62.8 MPa**

(c) Max $\sigma_e = 2p_fD_c^2/(D_c^2 - D_p^2) = 2(62.8)(95^2)/(95^2 - 60^2) = 209$ MPa
If Y = 400 MPa and Max $\sigma_e = Y/SF$, then $SF = Y/(\text{ Max } \sigma_e) = 400/209 =$ **1.91**

33 RAPID PROTOTYPING

Review Questions

33.1 What is rapid prototyping? Provide a definition of the term.

Answer. Rapid prototyping consists of a family of fabrication processes developed to make engineering prototypes in minimum possible lead times based on a computer-aided design (CAD) model of the item.

33.2 What are the three types of starting materials in rapid prototyping?

Answer. The three types of starting materials in RP are (1) liquid, (2) solid, and (3) powders.

33.3 Besides the starting material, what other feature distinguishes the rapid prototyping technologies?

Answer. The part-build process also distinguishes the different RP technologies. Some techniques use lasers to solidify the starting liquid, while others bond the solid layers of sheet, and still others bond the powders together.

33.4 What is the common approach used in all of the material addition technologies to prepare the control instructions for the RP system?

Answer. The text describes the common approach as a three step process: (1) Geometric modeling, which consists of modeling the component on a CAD system to define its enclosed volume; (2) tessellation of the geometric model, in which the CAD model is converted into a format that approximates its surfaces by facets (triangles or polygons); and (3) slicing of the model into layers that approximate the solid geometry.

33.5 Of all of the current rapid prototyping technologies, which one is the most widely used?

Answer. Stereolithography.

33.6 Describe the RP technology called solid ground curing.

Answer. Solid ground curing works by curing a photosensitive polymer layer by layer to create a solid model based on CAD geometric data. Instead of using a scanning laser beam to accomplish the curing of a given layer, the entire layer is exposed to an ultraviolet light source through a mask that is positioned above the surface of the liquid polymer.

33.7 Describe the RP technology called laminated-object manufacturing.

Answer. Laminated object manufacturing produces a solid physical model by stacking layers of sheet stock that are each cut to an outline corresponding to the cross-sectional shape of a CAD model that has been sliced into layers. The layers are bonded one on top of the previous prior to cutting. After cutting, the excess material in the layer remains in place to support the part during building. Starting material in LOM can be virtually any material in sheet stock form, such as paper, plastic, cellulose, metals, or fiber-reinforced materials. Stock thickness is 0.05 to 0.50 mm (0.002 to 0.020 in).

33.8 What is the starting material in fused-deposition modeling?

Answer. The starting material is a long filament of wax or polymer.

Multiple Choice Quiz

There are 11 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and

each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

33.1 Machining is never used for rapid prototyping because it takes too long: (a) true or (b) false?

Answer. (b). Desktop milling is the principal material removal technology used for rapid prototyping.

33.2 Which of the following rapid prototyping processes starts with a photosensitive liquid polymer to fabricate a component (two correct answers): (a) ballistic particle manufacturing, (b) fused-deposition modeling, (c) selective laser sintering, (d) solid ground curing, and (e) stereolithography?

Answer. (d) and (e).

33.3 Of all of the current material addition rapid prototyping technologies, which one is the most widely used: (a) ballistic particle manufacturing, (b) fused deposition modeling, (c) selective laser sintering, (d) solid ground curing, and (e) stereolithography?

Answer. (e).

33.4 Which one of the following RP technologies uses solid sheet stock as the starting material: (a) ballistic particle manufacturing, (b) fused-deposition modeling, (c) laminated-object manufacturing, (d) solid ground curing, or (e) stereolithography?

Answer. (c).

33.5 Which of the following RP technologies uses powders as the starting material (two correct answers): (a) ballistic particle manufacturing, (b) fused-deposition modeling, (c) selective laser sintering, (d) solid ground curing, and (e) three-dimensional printing?

Answer. (c) and (e).

33.6 Rapid prototyping technologies are never used to make production parts: (a) true or (b) false?

Answer. (b). Examples include small batch sizes of plastic parts that could not be economically injection molded, parts with intricate internal geometries, and one-of-a-kind parts such as bone replacements.

33.7 Which of the following are problems with the current material addition rapid prototyping technologies (three best answers): (a) inability of the designer to design the part, (b) inability to convert a solid part into layers, (c) limited material variety, (d) part accuracy, (e) part shrinkage, and (f) poor machinability of the starting material?

Answer. (c), (d), and (e).

Problems

33.1 A prototype of a tube with a square cross section is to be fabricated using stereolithography. The outside dimension of the square = 100 mm and the inside dimension = 90 mm (wall thickness = 5 mm except at corners). The height of the tube (*z*-direction) = 80 mm. Layer thickness = 0.10 mm. The diameter of the laser beam ("spot size") = 0.25 mm, and the beam is moved across the surface of the photopolymer at a velocity of 500 mm/s. Compute an estimate for the time required to build the part, if 10 s are lost each layer to lower the height of the platform that holds the part. Neglect the time for postcuring.

Solution: Layer area A_i same for all layers.
$A_i = 100^2 – 90^2 = 1900\text{ mm}^2$
Time to complete one layer T_i same for all layers.
$T_i = (1900\text{ mm}^2)/(0.25\text{ mm})(500\text{ mm/s}) + 10\text{ s} = 15.2 + 10 = 25.2\text{ s}$
Number of layers $n_l = (80\text{ mm})/(0.10\text{ mm/layer}) = 800$ layers

T_c = 800(25.2) = **20,160 s = 336.0 min = 5.6 hr**

33.2 Solve Problem 33.1 except that the layer thickness = 0.40 mm.

Solution: Layer area A_i same for all layers. $A_i = 100^2 - 90^2 = 1900$ mm^2
Time to complete one layer T_i same for all layers.
T_i = (1900 mm^2)/(0.25 mm)(500 mm/s)+ 10 s = 15.2 + 10 = 25.2 s
Number of layers n_l = (80 mm)/(0.40 mm/layer) = 200 layers
T_c = 200(25.2) = **5,040 s = 84.0 min = 1.4 hr**

33.3 The part in Problem 33.1 is to be fabricated using fused deposition modeling instead of stereolithography. Layer thickness is to be 0.20 mm and the width of the extrudate deposited on the surface of the part = 1.25 mm. The extruder workhead moves in the *x-y* plane at a speed of 150 mm/s. A delay of 10 s is experienced between each layer to reposition the workhead. Compute an estimate for the time required to build the part.

Solution: Use same basic approach as in stereolithography.
Layer area A_i same for all layers. $A_i = 100^2 - 90^2 = 1900$ mm^2
Time to complete one layer T_i same for all layers.
T_i = (1900 mm^2)/(1.25 mm)(150 mm/s)+ 10 s = 10.133 + 10 = 20.133 s
Number of layers n_l = (80 mm)/(0.20 mm/layer) = 400 layers
T_c = 400(20.133) = **8053.33 s = 134.22 min = 2.24 hr**

33.4 Solve Problem 33.3, except using the following additional information. It is known that the diameter of the filament fed into the extruder workhead is 1.25 mm, and the filament is fed into the workhead from its spool at a rate of 30.6 mm of length per second while the workhead is depositing material. Between layers, the feed rate from the spool is zero.

Solution: Cross-sectional area of filament = $\pi D^2/4 = 0.25\pi(1.25)^2$ = 1.227 mm^2
Volumetric rate of filament deposition = (1.227 mm^2)(30.6 mm/s) = 37.55 mm^3/s
Part volume = part cross sectional area x height = Ah
$A = 100^2 - 90^2 = 1900$ mm^2 and h = 80 mm. Part volume V = 1900(80) = 152,000 mm^3
T_c = (152,000 mm^3)/(37.55 mm^3/s) + (400 layers)(10 s delay/layer) = 4047.94 + 4000
= **8047.9 s = 134.13 min = 2.24 hr**
This is very close to previous calculated value - within round-off error.

33.5 A cone-shaped part is to be fabricated using stereolithography. The radius of the cone at its base = 35 mm and its height = 40 mm. The layer thickness = 0.20 mm. The diameter of the laser beam = 0.22 mm, and the beam is moved across the surface of the photopolymer at a velocity of 500 mm/s. Compute an estimate for the time required to build the part, if 10 s are lost each layer to lower the height of the platform that holds the part. Neglect post-curing time.

Solution: Volume of cone $V = \pi R^2h/3 = \pi(35)^2(40)/3$ = 51,313 mm^3
Layer thickness t = 0.20 mm
Number of layers n_i = 40 mm/(0.20 mm/layer) = 200 layers
Average volume per layer V_i= (51,313 mm^3)/200 = 256.56 mm^3
Since thickness t = 0.20 mm, average area/layer = (256.56 mm^3)/(0.20 mm) = 1282.8 mm^2
Average time per layer T_i = 1282.8/(0.22 x 500) = 11.66 + 10 = 21.66 s
Cycle time T_c = 200(21.66 s) = **4332.4 s = 72.2 min = 1.20 hr.**

33.6 The cone-shaped part in Problem 33.5 is to be built using laminated-object manufacturing. Layer thickness = 0.20 mm. The laser beam can cut the sheet stock at a velocity of 500 mm/s. Compute an estimate for the time required to build the part, if 10 s are lost each layer to lower the height of the platform that holds the part and advance the sheet stock in preparation for the next layer. Ignore cutting of the cross-hatched areas outside of the part since the cone should readily drop out of the stack owing to its geometry.

Solution: For LOM, we need the circumference of each layer, which is the outline to be cut by the laser beam. For a cone, the total surface area (not including the base) = $\pi R(R^2 + h^2)^{0.5}$
$A = \pi(35)(35^2 + 40)^{0.5} = 5844.2$ mm^2
Average surface area per layer = (5844.2 mm^2)/(200 layers) = 29.22 mm^2/layer
Since layer thickness t = 0.20 mm, circumference C = (29.22 mm^2)/(0.20 mm) = 146.1 mm
Average time to cut a layer T_i = (146.1 mm)/(500 mm/s) + 10 s = 0.292 + 10 = 10.292 s
Number of layers n_l = 40/0.20 = 200 layers
T_c = 200(10.292) = **2058.4 s = 34.3 min = 0.57 hr.**

33.7 Stereolithography is to be used to build the part in Figure 33.1 in the text. Dimensions of the part are: height = 125 mm, outside diameter = 75 mm, inside diameter = 65 mm, handle diameter = 12 mm, handle distance from cup = 70 mm measured from center (axis) of cup to center of handle. The handle bars connecting the cup and handle at the top and bottom of the part have a rectangular cross section and are 10 mm thick and 12 mm wide. The thickness at the base of the cup is 10 mm. The laser beam diameter = 0.25 mm, and the beam can be moved across the surface of the photopolymer at = 500 mm/s. Layer thickness = 0.20 mm. Compute an estimate of the time required to build the part, if 10 s are lost each layer to lower the height of the platform that holds the part. Neglect post-curing time.

Solution: The part can be sliced into cross sections that have one of three basic shapes: (1) base, which is 10 mm thick and includes the handle and handle bar; (2) cup ring and handle; and (3) top of cup, which is 10 mm thick and consists of the cup ring, handle, and handle bar. Let us compute the areas of the three shapes.
Area (1): $A_1 = \pi(75)^2/4 + \pi(12)^2/4$ + (approximately)$(12 \text{ x } 32.5 - 0.5\pi(12)^2/4)$
A_1 = 4417.9 + 113.1 + (390.0 – 56.5) = 4864.5 mm^2
Area (2): $A_2 = \pi(75^2 - 65^2)/4 + \pi(12)^2/4$ = 1099.6 + 113.1 = 1212.7 mm^2
Area (3): $A_3 = \pi(75^2 - 65^2)/4 + \pi(12)^2/4$ + (approximately)$(12 \text{ x } 32.5 - 0.5\pi(12)^2/4)$
A_3 = 1099.6 +113.1 + (390.0 – 56.5) = 1546.2 mm^2

Number of layers for each area:
(1) n_{l1} = (10 mm)/(0.2 mm/layer) = 50 layers
(2) n_{l2} = (125 – 10 – 10)/(0.2) = 525 layers
(3) n_{l3} = (10 mm)/(0.2 mm/layer) = 50 layers

Time to complete one layers for each of the three shapes:
(1) T_{i1} = (4864.5 mm^2)/(0.25 x 500) + 10 = 38.92 + 10 = 48.92 s
(2) T_{i2} = (1212.7 mm^2)/(0.25 x 500) + 10 = 9.70 + 10 = 19.70 s
(3) T_{i3} = (1546.2 mm^2)/(0.25 x 500) + 10 = 12.37 + 10 = 22.37 s

Total time for all layers T_c = 50(48.92) + 525(19.70) + 50(22.37)
T_c = **13,907 s + 231.78 min = 3.86 hr**

34.8 A prototype of a part is to be fabricated using stereolithography. The part is shaped like a right triangle whose base = 36 mm, height = 48 mm, and thickness = 25 mm. In application, the part will stand on its base, which is 36 mm by 25 mm. In the stereolithography process, the layer thickness = 0.20 mm. The diameter of the laser beam ("spot size") = 0.15 mm, and the beam is moved across the surface of the photopolymer at a velocity of 400 mm/s. Compute the minimum possible time required to build the part, if 8 sec are lost each layer to lower the height of the platform that holds the part. Neglect the time for postcuring.

Solution: The part should be oriented on its side in the stereolithography process; thus, layer area A_i is the same for all layers.
A_i = 0.5(36 x 48) = 864 mm^2
Time to complete one layer T_i same for all layers.
T_i = (864 mm^2)/(0.15 mm)(400 mm/s)+ 8 s = 14.4 + 8 = 22.4 s

Number of layers n_l = (25 mm)/(0.20 mm/layer) = 125 layers
T_c = 125(22.4) = **2800 s = 46.67 min = 0.7778 hr**

34 PROCESSING OF INTEGRATED CIRCUITS

Review Questions

34.1 What is an integrated circuit?

Answer. An integrated circuit is a collection of electronic devices (e.g., transistors, diodes, resistors) that have been fabricated and electrically intraconnected onto the surface of a small flat chip of semiconductor material.

34.2 Name some of the important semiconductor materials.

Answer. Important semiconductor materials include silicon (most important), germanium, and gallium arsenide.

34.3 Describe the planar process.

Answer. The planar process refers to the fabrication of an IC chip by a sequence of layering processes - adding, altering, and removing layers to create the devices and their intraconnections on the IC chip.

34.4 What are the three major stages in the production of silicon-based integrated circuits?

Answer. The three stages are (1) silicon processing, to produce very pure silicon and shape it into wafers; (2) IC fabrication, in which layers are added, altered, and removed in selected regions to form electronic devices on the face of the wafer; and (3) IC packaging, in which the wafers are tested, cut into chips, and the chips are encapsulated in a package.

34.5 What is a clean room and explain the classification system by which clean rooms are rated?

Answer. A clean room is a room or rooms where the air is purified to reduce airborne particles. The classification system indicates the quantity of particles of size 0.5 microns or greater per cubic foot of air. For example, a class 100 clean room contains 100 or fewer particles of size 0.5 microns per cubic foot.

34.6 What are some of the significant sources of contaminants in IC processing?

Answer. Sources of contaminants include humans (bacteria, cigarette smoke, viruses, and hair), and processing equipment (wear particles, oil, and dirt).

34.7 What is the name of the process most commonly used to grow single crystal ingots of silicon for semiconductor processing?

Answer. It is the Czochralski process.

34.8 What are the alternatives to photolithography in IC processing?

Answer. Alternatives to photolithography are extreme ultraviolet lithography (although technically this is still a photolithography technique), electron lithography, X-ray lithography, and ion lithography.

34.9 What is a photoresist?

Answer. A photoresist is a polymer that is sensitive to light radiation in a certain wavelength range; the sensitivity causes either an increase or a decrease in solubility of the polymer to certain chemicals.

34.10 Why is ultraviolet light favored over visible light in photolithography?

Answer. Because it has a shorter wavelength, the transferred images are sharper.

34.11 Name the three exposure techniques in photolithography.

Answer. The three exposure techniques are (1) contact printing, (2) proximity printing, and (3) projection printing.

34.12 What layer material is produced by thermal oxidation in IC fabrication?

Answer. Thermal oxidation produces SiO_2 on the surface of the silicon wafer.

34.13 Define epitaxial deposition.

Answer. Epitaxial deposition involves growth of a crystalline structure on the surface of a substrate that is an extension of the substrate's structure.

34.14 What are some of the important design functions of IC packaging?

Answer. Design functions of IC packaging include (1) provide electrical connections to external circuits, (2) encase chip for protection, and (3) heat dissipation.

34.15 What is Rent's rule?

Answer. Rent's rule indicates the number of input/output terminals n_{io} required for an integrated circuit of a given number of internal circuits n_c; the Rent's rule equation is: $n_{io} = C\, n_c^{\,m}$, where C and m are constants for a certain circuit type.

34.16 Name the two categories of component mounting to a printed circuit board.

Answer. The two types are (1) through-hole mounting and (2) surface mount technology.

34.17 What is a DIP?

Answer. DIP stands for dual in-line package, an IC package with two rows of terminals on each side of a rectangular body containing the IC chip.

34.18 What is the difference between postmolding and premolding in plastic IC chip packaging?

Answer. Postmolding refers to the use of transfer molding of epoxy around the chip and leadframe to form the package; a premolded package is one in which an enclosure is molded beforehand, and the chip and leadframe are then attached to it, adding a solid lid to complete the package.

Multiple Choice Quiz

There are 16 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

34.1 How many electronic devices would be contained in an IC chip in order for it to be classified in the VLSI category: (a) 1000, (b) 10,000, (c) 1 million, or (d) 100 million?

Answer. (c).

34.2 An alternative name for chip in semiconductor processing is which one of the following (one best answer): (a) component, (b) device, (c) die, (d) package, or (e) wafer?

Answer. (c).

34.3 Which one of the following is the source of silicon for semiconductor processing: (a) pure Si in nature, (b) SiC, (c) Si_3N_4, or (d) SiO_2?

Answer. (d).

34.4 Which one of the following is the most common form of radiation used in photolithography: (a) electronic beam radiation, (b) incandescent light, (c) infrared light, (d) ultraviolet light, or (e) X-ray?

Answer. (d).

34.5 After exposure to light, a positive resist becomes (a) less soluble or (b) more soluble to the chemical developing fluid?

Answer. (b).

34.6 Which of the following processes are used to add layers of various materials in IC fabrication (three best answers): (a) chemical vapor deposition, (b) diffusion, (c) ion implantation, (d) physical vapor deposition, (e) plasma etching, (f) thermal oxidation, and (g) wet etching?

Answer. (a), (d), and (f).

34.7 Which of the following are doping processes in IC fabrication (two best answers): (a) chemical vapor deposition, (b) diffusion, (c) ion implantation, (d) physical vapor deposition, (e) plasma etching, (f) thermal oxidation, and (g) wet etching?

Answer. (b) and (c).

34.8 Which one of the following is the most common metal for intraconnection of devices in a silicon integrated circuit: (a) aluminum, (b) copper, (c) gold, (d) nickel, (e) silicon, or (f) silver?

Answer. (a).

34.9 Which etching process produces the more anisotropic etch in IC fabrication: (a) plasma etching or (b) wet chemical etching?

Answer. (a).

34.10 Which of the following are the two principal packaging materials used in IC packaging: (a) aluminum, (b) aluminum oxide, (c) copper, (d) epoxies, and (e) silicon dioxide?

Answer. (b) and (d).

34.11 Which of the following metals are commonly used for wire bonding of chip pads to the lead frame (two best answers): (a) aluminum, (b) copper, (c) gold, (d) nickel, (e) silicon, and (f) silver?

Answer. (a) and (c).

Problems

Silicon Processing and IC Fabrication

34.1 A single crystal boule of silicon is grown by the Czochralski process to an average diameter of 320 mm with length = 1500 mm. The seed and tang ends are removed, which reduces the length to 1150 mm. The diameter is ground to 300 mm. A 90-mm-wide flat is ground on the surface which extends from one end to the other. The ingot is then sliced into wafers of thickness = 0.50 mm, using an abrasive saw blade whose thickness = 0.33 mm. Assuming that the seed and tang portions cut off the ends of the starting boule were conical in shape, determine (a) the original volume of the boule, mm^3; (b) how many wafers are cut from it, assuming the entire 1150 mm length can be sliced; and (c) the volumetric proportion of silicon in the starting boule that is wasted during processing.

Solution: (a) Total volume $V = V_1$ (tang) + V_2 (cylinder) + V_3 (seed)
$V_1 = V_3$ = (cone in which h = 0.5(1500-1150) = 175, D = 320, R = 160) = $\pi R^2 h/3$
$= 0.333\pi(160)^2(175) = 4{,}691{,}445$ mm^3.
$V_2 = \pi R^2 L = \pi(160)^2(1150) = 92{,}488{,}488$ mm^3
Total V = 2(4,691,445) + 92,488,488 = **101,871,378 mm^3**

(b) Number of wafers = 1150/(0.50 + 0.33) = 1385.5 → **1385 wafers**

(c) Area of one wafer $A_w = A_c - A_s$, where A_c = area of the circle of radius R = 150 mm, and A_s = the area of the segment A_s created by the flat ground on the cylindrical surface.
$A_c = \pi R^2 = \pi(150)^2 = 70685.8$ mm^2
The area of a segment of the circle created by the 170 mm chord $A_s = \pi R^2\theta/360 - 0.5R^2 \sin \theta$, where θ is the angle formed by two radii of the circle and the chord. $0.5\theta = \sin^{-1}(90/150) = 17.46°$.
$\theta = 34.92°$.
$A_s = \pi(150)^2(34.92)/360 - 0.5(150)^2 \sin 34.92 = 6855.6 – 6439.1 = 416.5$ mm^2
$A_w = A_c - A_s = 70685.8 - 416.5 = 70269.3$ mm^2
Volume of one wafer $V_w = A_w t = 70269.3(0.5) = 35134.7$ mm^3
Volume of 1385 wafers = 1385(35134.7) = 48,661,518 mm^3
Volume wasted = 101,871,378 - 48,661,518 = 53,209,860 mm^3
Proportion wasted = 53,209,860 / 101,871,378 = **52.23%.**

34.2 A silicon boule is grown by the Czochralski process to a diameter of 5.25 in and a length of 5 ft. The seed and tang ends are cut off, reducing the effective length to 48.00 in. Assume that the seed and tang portions are conical in shape. The diameter is ground to 4.921 in (125 mm). A primary flat of width 1.625 in is ground on the surface the entire length of the ingot. The ingot is then sliced into wafers 0.025 in thick, using an abrasive saw blade whose thickness = 0.0128 in. Determine (a) the original volume of the boule, in^3; (b) how many wafers are cut from it, assuming the entire 4 ft length can be sliced, and (c) what is the volumetric proportion of silicon in the starting boule that is wasted during processing?

Solution: (a) Volume $V = V_1$ (tang) + V_2 (cylinder) + V_3 (seed)
$V_1 = V_3$ = (cone in which h = 0.5(60-48) = 6.0, D = 5.25) = $\pi R^2 h/3 = 0.333\pi(5.25/2)^2(6.0)$
= 43.295 in^3.
$V_2 = \pi D^2 L/4 = \pi(5.25)^2(48)/4 = 1039.082$ in^3
V = 2(43.295) + 1039.082 = **1125.672 in^3**

(b) Number of wafers = 48.0/(0.025 + 0.0128) = 48/(0.0378) = 1269.8 → **1269 wafers**

(c) Area of one wafer $A_w = A_c - A_s$, where A_c = area of the circle of radius R = 4.921/2 = 2.4605 in, and A_s = the area of the segment A_s created by the flat ground on the cylindrical surface.
$A_c = \pi R^2 = \pi(2.4605)^2 = 19.0194$ in^2
The area of a segment of the circle created by the 1.625 in chord $A_s = \pi R^2\theta/360 - 0.5R^2 \sin \theta$, where θ is the angle formed by two radii of the circle and the chord. $0.5\theta = \sin^{-1}(1.625/4.921) = 19.28°$.
$\theta = 38.56°$.
$A_s = \pi(2.4605)^2(38.56)/360 - 0.5(2.4605)^2 \sin 38.56 = 2.0372 - 1.8869 = 0.1503$ in^2
$A_w = A_c - A_s = 19.0194 - 0.1503 = 18.8691$ in^2
Volume of one wafer $V_w = A_w t = 18.8691(0.025) = 0.4717$ in^3
Volume of 1269 wafers = 1269(0.4717) = 598.621 in^3
Volume wasted = 1125.672 - 598.621 = 527.051 in^3
Proportion wasted = 527.051/1125.672 = **46.82%.**

34.3 The processable area on a 156-mm-diameter wafer is a 150-mm-diameter circle. How many square IC chips can be processed within this area, if each chip is 7.5 mm on a side? Assume the cut lines (streets) between chips are of negligible width.

Solution: $n_c = 0.34(150/7.5)^{2.25} = 0.34(20)^{2.25} = 287.6$. Estimate n_c = **287 chips**.

34.4 Solve Problem 34.3, only use a wafer size of 257 mm whose processable area has a diameter = 250 mm. What is the percent increase in (a) wafer diameter, (b) processable wafer area, and (c) number of chips, compared to the values in the previous problem?

Solution: (a) Increase in wafer diameter = (250 – 150)/150 = 0.667 = **66.7% increase**

(b) Processable area $A = \pi D^2/4$
For the 150 mm diameter, $A = \pi(159)^2/4 = 17{,}671$ mm^2
For the 250 mm diameter, $A = \pi(250)^2/4 = 49{,}087$ mm^2
Increase in processable wafer area = (49,087 – 17,671)/17,671 = 1.78 = **178% increase**

(c) $n_c = 0.34(250/7.5)^{2.25} = 0.34(33.33)^{2.25} = 907$
Increase in number of chips = (907 – 287)/287 =2.16 = **216% increase**

Note: These results indicate the advantages of increasing wafer size. For a 67% increase in processable area, we get a 216% increase in number of chips.

34.5 A 6.0-in wafer has a processable area with a 5.85-in diameter. How many square IC chips can be fabricated within this area, if each chip is 0.50 in on a side? Assume the cut lines (streets) between chips are of negligible width.

Solution: $n_c = 0.34(5.85/0.5)^{2.25} = 0.34(11.7)^{2.25} = 86.1$. Use n_c = **86** chips.

34.6 Solve Problem 34.5, only use a wafer size of 12.0 in whose processable area has a diameter = 11.75 in. What is the percent increase in (a) processable area on the wafer and (b) number of chips on the wafer compared to the 200% increase in wafer diameter?

Solution: (a) Processable area $A = \pi D^2/4$
For the 4-in wafer with a processable area = 5.85 in, $A = \pi(5.85)^2/4 = 26.88$ in^2
For the 12-in wafer with a processable area = 11.75 in, $A = \pi(11.75)^2/4 = 108.43$ in^2
Increase in processable area = (108.43 – 26.88)/26.88 = 3.03 = **303% increase**

(b) For the 6-in wafer, n_c = 86 from previous problem.
For the 12-in wafer, $n_c = 0.34(11.75/0.5)^{2.25} = 0.34(23.5)^{2.25} = 413.4$ Use n_c = 413 chips.
Increase in number of chips = (413 – 86)/86 = 3.81 = **381% increase**

Note: The wafer diameter increases by 100%, the wafer area increases by 303%, and the number of chips increases by 381%. This is a principal motivation for using larger wafer diameters.

34.7 A 250 mm diameter silicon wafer has a processable area that is circular with a diameter = 225 mm. The IC chips that will be fabricated on the wafer surface are square with 20 mm on a side. However, the processable area on each chip is only 18 mm by 18 mm. The density of circuits within each chip's processable area is 465 circuits per mm^2. (a) How many IC chips can be placed onto the wafer? (b) Using Rent's Rule with C = 3.8 and m = 0.43, how many input/output terminals (pins) will be needed for each chip package?

Solution: (a) $n_c = 0.34(D_w/L_c)^{2.25} = 0.34(225/20)^{2.25} = 0.34(11.25)^{2.25} = 78.8$ round to 78

(b) Each chip surface area = 18 x 18 = 324 mm^2
Number of circuits per chip = 324(465) = 150,660 circuits
Rent's Rule $n_{io} = 3.8\ n_c^{0.43} = 3.8(150{,}660)^{0.43} = 3.8(168.476) = 640.2$ round to 640 pins

34.8 A 12-inch diameter silicon wafer has a processable area that is circular with a diameter = 11.4 in. The IC chips that will be fabricated on the wafer surface are square with 0.75 in on a side, including an allowance for subsequent chip separation. However, the processable area on each chip is only 0.60 in by 0.60 in. The density of circuits within each chip's processable area is 100,000 circuits per square inch. (a) How many IC chips can be placed onto the wafer? (b) Using Rent's Rule with C = 3.8 and m = 0.43, how many input/output terminals (pins) will be needed for each chip package?

Solution: (a) $n_c = 0.34(D_w/L_c)^{2.25} = 0.34(11.4/0.75)^{2.25} = 0.34(15.2)^{2.25} = 155.1$ round to 155

(b) Each chip surface area = 0.60 x 0.60 = 0.36 in^2

Number of circuits per chip = 100,000(0.36) = 36,000 circuits
Rent's Rule $n_{io} = 3.8\ n_c^{0.43} = 3.8(36{,}000)^{0.43} = 3.8(91.035) = 345.9$ round to 345 pins

34.9 A silicon boule has been processed through grinding to provide a cylinder whose diameter = 285 mm and whose length = 900 mm. Next, it will be sliced into wafers 0.7 mm thick using a cut-off saw with a kerf = 0.5 mm. The wafers thus produced will be used to fabricate as many IC chips as possible for the personal computer market. Each IC has a market value to the company of \$98. Each chip is square with 15 mm on a side. The processable area of each wafer is defined by a diameter = 270 mm. Estimate the value of all of the IC chips that could be produced, assuming an overall yield of 80% good product.

Solution: First determine the number of wafers that can be obtained from the cylinder. Each wafer takes 0.7 + 0.5 mm = 1.2 mm of the cylinder's length. Thus, the number of wafers is given by:
$n_w = 900/1.2 = 750$ wafers
Next determine the number of chips per wafer: $n_c = 0.34(270/15)^{2.25} = 0.34(18)^{2.25} = 227$ IC chips.
The total number of chips on 750 wafers, accounting for the yield of 80% is given by the following:
Total number of chips = 750(227)(0.80) = 136,200 good chips.
At \$98/chip, the total value = 136,200(\$98) = **\$13,347,600**.

34.10 The surface of a silicon wafer is thermally oxidized, resulting in a SiO_2 film that is 100 nm thick. If the starting thickness of the wafer was exactly 0.400 mm, what is the final wafer thickness after thermal oxidation?

Solution: A 100 nm film requires a layer of silicon = 0.44*d*
Final thickness $t_f = 0.400 - 0.44(100 \text{ x } 10^{-6}) + 100 \text{ x } 10^{-6} = 0.400 + 0.56(.0001) =$ **0.400056 mm**

34.11 It is desired to etch out a region of a silicon dioxide film on the surface of a silicon wafer. The SiO_2 film is 100 nm thick. The width of the etched-out area is specified to be 650 nm. (a) If the degree of anisotropy for the etchant in the process is known to be 1.25, what should be the size of the opening in the mask through which the etchant will operate? (b) If plasma etching is used instead of wet etching, and the degree of anisotropy for plasma etching is infinity, what should be the size of the mask opening?

Solution: (a) Anisotropy degree $A = d/u = 1.25$, $u = d/1.25 = 100/1.25 = 80$ nm
Mask opening size = 650.0 - 2(80) = **490 nm**

(b) $A = d/u = \infty$. $u = d/\infty = 0$ μm.
Mask opening size = 650.0 - 2(0) = **650.0 μm**

IC Packaging

34.12 An integrated circuit used in a microprocessor will contain 1000 logic gates. Use Rent's rule with C = 3.8 and m = 0.6 to determine the approximate number of input/output pins required in the package.

Solution: Rents rule: $n_{io} = Cn_c^m = 3.8(1000)^{0.6} = 63.1 \rightarrow$ **63 input/output pins**

34.13 A dual-in-line package has a total of 48 leads. Use Rent's rule with C = 4.5 and m = 0.5 to determine the approximate number of logic gates that could be fabricated in the IC chip for this package.

Solution: $48 = 4.5(n_c)^{0.5}$
$n_c^{0.5} = 48/4.5 = 10.667$
$n_c = (10.667)^2 = 113.8 \rightarrow$ **113 logic gates**

34.14 It is desired to determine the effect of package style on the number of circuits (logic gates) that can be fabricated onto an IC chip to which the package is assembled. Using Rent's rule with C = 4.5 and m = 0.5, compute the estimated number of devices (logic gates) that could be placed on the chip in the following cases: (a) a DIP with 16 I/O pins on a side - a total of 32 pins; (b) a square chip carrier with 16 pins on a side - a total of 64 I/O pins; and (c) a pin grid array with 16 by 16 pins - a total of 256 pins.

Solution: (a) Using Rent's rule: $n_{io} = 4.5(n_c)^{0.5}$, find n_c if $n_{io} = 32$
$n_c^{0.5} = 32/4.5 = 7.11$
$n_c = 50.6 \rightarrow$ **50 logic gates**

(b) Using Rent's rule: $n_{io} = 4.5(n_c)^{0.5}$, find n_c if $n_{io} = 64$
$n_c^{0.5} = 64/4.5 = 14.22$
$n_c = 202.3 \rightarrow$ **202 logic gates**

(c) Using Rent's rule: $n_{io} = 4.5(n_c)^{0.5}$, find n_c if $n_{io} = 256$.
$n_c^{0.5} = 256/4.5 = 56.89$
$n_c = 3236.3 \rightarrow$ **3236 logic gates**

34.15 An integrated circuit used in a memory module contains 2^{24} memory circuits. Sixteen of these integrated circuits are packaged onto a board to provide a 256 Mbyte memory module. Use Rent's rule, Eq. (34.11), with $C = 6.0$ and $m = 0.12$ to determine the approximate number of input/output pins required in each of the integrated circuits.

Solution: Rent's rule: $n_{io} = Cn_c^{m} = 6.0(2^{24})^{0.12} =$
$n_{io} = 6.0(16{,}777{,}216)^{0.12} = 44.2 \rightarrow$ **44** input/output pins

34.16 In the equation for Rent's rule with $C = 4.5$ and $m = 0.5$, determine the value of n_{io} and n_c at which the number of logic gates equals the number of I/O terminals in the package.

Solution: We have two equations and two unknowns: (1) $n_{io} = 4.5n_c^{0.5}$ and (2) $n_{io} = n_c$.
Using n_{io} in place of n_c in Eq. (1), $n_{io} = 4.5n_{io}^{0.5}$
$\ln n_{io} = \ln 4.5 + 0.5 \ln n_{io}$
$\ln n_{io} - 0.5 \ln n_{io} = 0.5 \ln n_{io} = \ln 4.5 = 1.50408$
$\ln n_{io} = 3.00816$
$n_{io} = n_c =$ **20.25.** The closest possible values are $n_{io} = n_c = 20$ or 21.

34.17 A static memory device will have a two-dimensional array with 64 by 64 cells. Determine the number of input/output pins required using Rent's rule with $C = 6.0$ and $m = 0.12$.

Solution: (a) Rent's rule: $n_{io} = 6.0\, n_c^{0.12} = 6.0(64 \times 64)^{0.12} = 6.0(4096)^{0.12} = 16.3 \rightarrow$ **17 pins**

34.18 To produce a 10 megabit memory chip, how many I/O pins are predicted by Rent's rule ($C = 6.0$ and $m = 0.12$)?

Solution: Rent's rule: $n_{io} = 6.0\, n_c^{0.12} = 6.0\,(10{,}000{,}000)^{0.12} = 41.5 \rightarrow$ **41 pins**

34.19 The first IBM personal computer was based on the Intel 8088 CPU, which was released in 1979. The 8088 had 29,000 transistors and 40 I/O pins. The final version of the Pentium III (1 GHz) was released in 2000. It contained 28,000,000 transistors and had 370 I/O pins. (a) Determine the Rent's rule coefficient values m and C assuming that a transistor can be considered a circuit. (b) Use the value of m and C to predict the number of I/O pins required for the first Pentium 4 assuming that it is manufactured with 42,000,000 transistors. (c) The first Pentium 4, released in 2001, used 423 I/O pins. Comment on the accuracy of your prediction.

Solution: (a) $n_{io} = Cn_c^{m}$; $40/29{,}000^m = C$ and $370/28{,}000{,}000^m = C$
$40/29{,}000^m = 370/28{,}000{,}000^m$
$40/370 = (29\text{x}10^3)^m/(28\text{x}10^6)^m$
$0.108108 = (29\text{x}10^3/28\text{x}10^6)^m$
$\ln (0.108108) = m \ln (0.001036)$
$m = -2.2246/(-6.8727) = 0.3237$
$C = 40/29{,}000^{0.3237} = 40/27.8277 = 1.437$

$\boldsymbol{n_{io} = 1.437\, n_c^{0.3237}}$

(b) $n_{io} = 1.437\,(42\text{x}10^6)^{0.3237} = 421.8 =$ **422 I/O pins**

(c) The actual and predicted values are almost too close to believe. Note that an updated Pentium 4 (2.2 GHz) released 6 months later increased to 55,000,000 transistors and remained at 423 I/O pins, so it does not fit as well for these coefficients of *m* and *C*. In very large integrated circuits that must remain backward compatible, the I/O pins are often frozen until the next generation. However, designers will add transistors to increase the functionality and speed of the processors. Therefore, there are discontinuities in the I/O pin count as new generations are released.

34.20 Suppose it is desired to produce a memory device that will be contained in a dual-in-line package with 32 I/O leads. How many memory cells can be contained in the device, as estimated by (a) Rent's rule with $C = 6.0$ and $m = 0.12$?

Solution: Rent's rule: $n_{io} = 6.0\, n_c^{0.12}$
$n_c^{0.12} = n_{io}/6.0 = 32/6 = 5.333$
$n_c = (5.333)^{1/.12} = (5.333)^{8.333} =$ **1,143,728 memory cells**

34.21 A 12-inch diameter silicon wafer has a processable area that is circular with a diameter = 11.4 in. The IC chips that will be fabricated on the wafer surface are square with 0.75 in on a side, including an allowance for subsequent chip separation. However, the processable area on each chip is only 0.60 in by 0.60 in. The density of circuits within each chip's processable area is 100,000 circuits per square inch. (a) How many IC chips can be placed onto the wafer? (b) Using Rent's Rule with $C = 3.8$ and $m = 0.43$, how many input/output terminals (pins) will be needed for each chip package?

Solution: (a) $n_c = 0.34(D_w/L_c)^{2.25} = 0.34(11.4/0.75)^{2.25} = 0.34(15.2)^{2.25} = 155.1$ round to **155** chips

(b) Each chip surface area = 0.60 x 0.60 = 0.36 in^2
Number of circuits per chip = 100,000(0.36) = 36,000 circuits
Rent's Rule $n_{io} = 3.8\, n_c^{0.43} = 3.8(36{,}000)^{0.43} = 3.8(91.035) = 345.9$ round to **346** pins

34.22 A 250 mm diameter silicon wafer has a processable area that is circular with a diameter = 225 mm. The IC chips that will be fabricated on the wafer surface are square with 20 mm on a side. However, the processable area on each chip is only 18 mm by 18 mm. The density of circuits within each chip's processable area is 465 circuits per mm^2. (a) How many IC chips can be placed onto the wafer? (b) Using Rent's Rule with $C = 4.5$ and $m = 0.35$, how many input/output terminals (pins) will be needed for each chip package?

Solution: (a) $n_c = 0.34(D_w/L_c)^{2.25} = 0.34(225/20)^{2.25} = 0.34(11.25)^{2.25} = 78.8$ round to **78**

(b) Each chip surface area = 18 x 18 = 324 mm^2
Number of circuits per chip = 324(465) = 150,660 circuits
Rent's Rule $n_{io} = 4.5\, n_c^{0.35} = 4.5(150{,}660)^{0.35} = 4.5(64.91) = 292.1$ round to **292 pins**

Yields in IC Processing

34.23 Given that crystal yield = 55%, crystal-to-slice yield = 60%, wafer yield = 75%, multiprobe yield = 65%, and final test yield = 95%, if a starting boule weighs 125 kg, what is the final weight of silicon that is represented by the non-defective chips after final test?

Solution: Overall yield $Y = Y_c\, Y_s\, Y_w\, Y_m\, Y_t = (0.55)(0.60)(0.75)(0.65)(0.95) = 0.1528$
$W_f = YW_i = 0.1528(125) =$ **19.1 kg**

34.24 On a particular production line in a wafer fabrication facility, the crystal yield is 60%, the crystal-to-slice yield is 60%, wafer yield is 90%, multiprobe is 70%, and final test yield is 80%. (a) What is the overall yield for the production line? (b) If wafer yield and multiprobe yield are combined into the same reporting category, what overall yield for the two operations would be expected?

Solution: (a) Overall $Y = Y_c\, Y_s\, Y_w\, Y_m\, Y_t$ = (0.60)(0.60)(0.90)(0.70)(0.80) = 0.1814 = **18.14%**

(b) $Y_w\, Y_m$ = (0.90)(0.70) = 0.63 = **63%**

34.25 A silicon wafer with a diameter of 200 mm is processed over a circular area whose diameter = 190 mm. The chips to be fabricated are square with 10 mm on a side. The density of point defects in the surface area is 0.0047 defects/cm^2. Determine an estimate of the number of good chips using the Bose-Einstein yield computation.

Solution: $n_c = 0.34(190/10)^{2.25} = 0.34(19)^{2.25} = 256$ chips
Processable wafer area $A = \pi(190)^2/4 = 28{,}353$ mm^2 = 283.53 cm^2
$Y_m = 1/(1 + AD) = 1/(1 + 283.53 \text{ x } 0.0047) = 1/2.333 = 0.4287$
Number of good chips = 0.4287(256) = 109.7 → **110 good chips**

34.26 A 12-in wafer is processed over a circular area of diameter = 11.75 in. The density of point defects in the surface area is 0.018 defects/in^2. The chips to be fabricated are square with an area of 0.16 in^2 each. Determine an estimate of the number of good chips using the Bose-Einstein yield computation.

Solution: Square chips with an area = 0.16 in^2 must have each side $L_c = (0.16)^{0.5} = 0.40$ in.
$n_c = 0.34(11.75/0.4)^{2.25} = 0.34(29.375)^{2.25} = 683$ chips
Processable wafer area $A = \pi(11.75)^2/4 = 108.43$ in^2
$Y_m = 1/(1 + AD) = 1/(1 + 108.43 \text{ x } 0.018) = 1/2.952 = 0.3388$
Number of good chips = 0.3388(683) = 231.4 → **231 good chips**

34.27 The yield of good chips in multiprobe for a certain batch of wafers is 83%. The wafers have a diameter of 150 mm with a processable area that is 140 mm in diameter. If the defects are all assumed to be point defects, determine the density of point defects using the Bose-Einstein method of estimating yield.

Solution: $Y_m = 1/(1 + AD)$
Processable area $A = \pi(140)^2/4 = 15{,}394$ mm^2 = 153.94 cm^2
$0.83 = 1/(1 + 153.94D)$
$0.83(1 + 153.94D) = 0.83 + 127.77\,D = 1$
$127.77\,D = 1 - 0.83 = 0.17$
$D = 0.17/127.77$ = **0.00133 defects/cm^2**

34.28 A silicon wafer has a processable area of 35.0 in^2. The yield of good chips on this wafer is Y_m = 75%. If the defects are all assumed to be point defects, determine the density of point defects using the Bose-Einstein method of estimating yield.

Solution: $Y_m = 1/(1 + AD)$
Processable area A = 35 in^2
$0.75 = 1/(1 + 35\,D)$
$0.75(1 + 35\,D) = 0.75 + 26.25\,D = 1$
$26.25\,D = 1 - 0.75 = 0.25$
$D = 0.25/26.25$ = **0.0095 defects/in^2**

35 ELECTRONICS ASSEMBLY AND PACKAGING

Review Questions

35.1 What are the functions of a well-designed electronics package?

Answer. The principal functions are (1) power distribution and signal interconnection, (2) structural support, (3) environmental protection, (4) heat dissipation, (5) minimum delays in signal transmission.

35.2 Identify the levels of packaging hierarchy in electronics.

Answer. The levels are (0) chip intraconnections, (1) IC chip to IC package, (2) IC component to PCB, (3) PCB to rack or chassis, and (4) wiring and cabling inside a cabinet.

35.3 What is the difference between a track and a land on a printed circuit board?

Answer. A track is a copper-conducting path on a PCB, while a land is a small copper area for electrically attaching components.

35.4 Define what a printed circuit board (PCB) is.

Answer. A PCB is a laminated flat panel of insulating material to which electronic components are attached and electrically interconnected.

35.5 Name the three principal types of printed circuit board.

Answer. The three types are (1) single-sided board, (2) double-sided board, and (3) multilayer board.

35.6 What is a via hole in a printed circuit board?

Answer. A via hole is a hole in the printed circuit board whose sides are plated with copper to serve as a conducting path from one side of a PCB to the other or between intermediate layers in a multilayer board.

35.7 What are the two basic methods by which the circuit pattern is transferred to the copper surface of the boards?

Answer. The two methods are (1) screening, such as silk screening, and (2) photolithography.

35.8 What is etching used for in PCB fabrication?

Answer. Etching is used to remove copper cladding on the PCB surface to define the tracks and lands of the circuit.

35.9 What is continuity testing, and when is it performed in the PCB fabrication sequence?

Answer. Continuity testing is an electrical test in which contact probes are brought into contact with track and land areas to insure the existence of electrical conduction paths. Continuity tests are generally used (1) after the bare board has been fabricated and (2) again after the board has been populated with components.

35.10 What are the two main categories of printed circuit board assemblies, as distinguished by the method of attaching components to the board?

Answer. The two categories are (1) pin-in-hole technology, also known as through-hole technology, and (2) surface mount technology.

35.11 What are some of the reasons and defects that make rework an integral step in the PCB fabrication sequence?

Answer. Rework is required to correct the following types of defects: (1) replace defective components, (2) insert missing components, (3) repair faulty solder joints, and (4) repair of copper film that has lifted from the substrate surface.

35.12 Identify some of the advantages of surface-mount technology over conventional through-hole technology.

Answer. Advantages of SMT include (1) smaller components, (2) higher packing densities, (3) components can be mounted on both sides of the board, (4) smaller PCBs are possible for the same function, (5) reduced number of holes drilled in the board, and (6) certain undesirable electrical effects are reduced, such as spurious surface capacitances and inductances.

35.13 Identify some of the limitations and disadvantages of surface-mount technology?

Answer. Limitations and disadvantages of SMT include (1) components are more difficult for humans to handle, (2) SMT components are generally more expensive than THT components, (3) inspection, testing, and rework are more difficult, and (4) certain types of components are not available in SMT.

35.14 What are the two methods of component placement and soldering in surface-mount technology?

Answer. The two methods are (1) adhesive bonding and wave soldering and (2) solder paste and reflow soldering.

35.15 What is a solder paste?

Answer. A solder paste is a suspension of solder powders in a flux binder. The flux binder includes an adhesive that attaches the SMT components to the board surface. The solder constitutes about 85% of the total volume of the paste.

35.16 Identify the two basic methods of making electrical connections.

Answer. The two methods are (1) soldering, and (2) pressure connections.

35.17 Define crimping in the context of electrical connections.

Answer. Crimping involves the mechanical forming of a terminal barrel to create a permanent connection with the stripped end of a conductor wire.

35.18 What is press fit technology in electrical connections?

Answer. A press fit technology in the context of electrical connections is an interference fit between a terminal pin and the plated hole into which it is inserted.

35.19 What is a terminal block?

Answer. A terminal block consists of a series of evenly spaced receptacles that allow connection of individual wires or terminals.

35.20 What is a pin connector?

Answer. A pin connector is a connector with multiple pins or blades that are inserted into the holes of a mating receptacle to establish electrical contact.

Multiple Choice Quiz

There are 14 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and

each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

35.1 The second level of packaging refers to which one of the following: (a) component to printed circuit board, (b) IC chip to package, (c) intraconnections on the IC chip, or (d) wiring and cabling connections?

Answer. (a).

35.2 Surface-mount technology is included within which one of the following levels of packaging: (a) zeroth, (b) first, (c) second, (d) third, or (e) fourth?

Answer. (c).

35.3 Card-on-board (COB) packaging refers to which one of the following levels in the electronics packaging hierarchy: (a) zeroth, (b) first, (c) second, (d) third, or (e) fourth?

Answer. (d).

35.4 Which of the following polymeric materials is commonly used as an ingredient in the insulation layer of a printed circuit board (two correct answers): (a) copper, (b) E-glass, (c) epoxy, (d) phenolic, (e) polyethylene, and (f) polypropylene?

Answer. (c) and (d).

35.5 Typical thickness of the copper layer in a printed circuit board is which one of the following: (a) 0.100 inch, (b) 0.010 inch, (c) 0.001 inch, or (d) 0.0001 inch?

Answer. (c).

35.6 Photolithography is widely used in PCB fabrication. Which of the following is the most common resist type used in the processing of PCBs: (a) negative resists or (b) positive resists?

Answer. (a).

35.7 Which of the following plating processes has the higher deposition rate in PCB fabrication: (a) electroless plating or (b) electroplating?

Answer. (b).

35.8 In addition to copper, which one of the following is another common metal plated onto a PCB: (a) aluminum, (b) gold, (c) nickel, or (d) tin?

Answer. (b).

35.9 Which of the following are the soldering processes used to attach components to printed circuit boards in through-hole technology (two best answers): (a) hand soldering, (b) infrared soldering, (c) reflow soldering, (d) torch soldering, and (e) wave soldering?

Answer. (a) and (e).

35.10 In general, which of the following technologies results in greater problems during rework: (a) surface-mount technology, or (b) through-hole technology?

Answer. (a).

35.11 Which of the following electrical connection methods produce a separable connection (two correct answers): (a) crimping of terminals, (b) press fitting, (c) soldering, (d) terminal blocks, and (e) sockets?

Answer. (d) and (e).

36 MICROFABRICATION TECHNOLOGIES

Review Questions

36.1 Define microelectromechanical system.

Answer: A microelectromechanical system (MEMS) is a miniaturized system consisting of both electronic and mechanical components.

36.2 What is the approximate size scale in microsystem technology?

Answer: Product features in MST are measured in microns.

36.3 Why is it reasonable to believe that microsystem products would be available at lower costs than products of larger, more conventional size?

Answer: Because less material is used in microsystem products.

36.4 What is a hybrid microsensor?

Answer: A hybrid microsensor is a sensing element (transducer) combined with electronic components in the same device.

36.5 What are some of the basic types of microsystem devices?

Answer: The text indicates four classifications: (1) microsensors, (2) microactuators, (3) microstructures and microcomponents, and (4) microsystems and micro-instruments.

36.6 Name some products that represent microsystem technology.

Answer: The text discusses ink-jet printing heads, thin-film magnetic heads, compact discs (CDs), digital versatile discs (DVDs), and various automotive sensors.

36.7 Why is silicon a desirable work material in microsystem technology?

Answer: Reasons given in the text are (1) the microdevices in MST often include electronic circuits, so both the circuit and the microdevice can be fabricated in combination on the same substrate; (2) in addition to its desirable electronic properties, silicon also possesses useful mechanical properties, such as high strength and elasticity, good hardness, and relatively low density; (3) the technologies for processing silicon are well-established, owing to their widespread use in microelectronics; and (4) use of single-crystal silicon permits the production of physical features to very close tolerances.

36.8 What is meant by the term aspect ratio in microsystem technology?

Answer: The aspect ratio is the height-to-width ratio of the features produced in the MST device.

36.9 What is the difference between bulk micromachining and surface micromachining?

Answer: Bulk micromachining refers to a relatively deep wet etching process into a single-crystal silicon substrate (Si wafer). Surface micromachining refers to the planar structuring of the substrate surface using much more shallow layering processes.

36.10 What are the three steps in the LIGA process?

Answer: The three steps in the LIGA process are (1) lithography, specifically X-ray lithography, (2) electroforming or electrodeposition, and (3) plastic molding.

Multiple Choice Quiz

There are 14 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

36.1 Microsystem technology includes which of the following (three best answers): (a) LIGA technology, (b) microelectromechanical systems, (c) micromachines, (d) nanotechnology, (e) and precision engineering?

Answer: (a), (b), and (c).

36.2 Which of the following are current applications of microsystem technology in modern automobiles (three best answers): (a) air-bag release sensors, (b) alcohol blood level sensors, (c) driver identification sensors for theft prevention, (d) oil pressure sensors, and (e) temperature sensors for cabin climate control?

Answer: (a), (d), and (e).

36.3 The polymer used to make compact discs (CDs) and digital versatile discs (DVDs) is which one of the following: (a) amino resin, (b) epoxy resin, (c) polyamides, (d) polycarbonate, (e) polyethylene, or (f) polypropylene?

Answer: (d).

36.4 The most common work material used in microsystem technology is which one of the following: (a) boron, (b) gold, (c) nickel, (d) potassium hydroxide, or (e) silicon?

Answer: (e).

36.5 The aspect ratio in microsystem technology is best defined by which one of the following: (a) degree of anisotropy in etched features, (b) height-to-width ratio of the fabricated features, (c) height-to-width ratio of the MST device, (d) length-to-width ratio of the fabricated features, or (e) thickness-to-length ratio of the MST device?

Answer: (b).

36.6 Which of the following forms of radiation have wavelengths shorter than the wavelength of ultraviolet light used in photolithography (two correct answers): (a) electron beam radiation, (b) natural light, and (c) X-ray radiation?

Answer: (a) and (c).

36.7 Bulk micromachining refers to a relatively deep wet etching process into a single-crystal silicon substrate: (a) true or (b) false?

Answer: (a).

36.8 In the LIGA process, the letters LIGA stand for which one of the following: (a) let it go already, (b) little grinding apparatus, (c) lithographic applications, (d) lithography, electrodeposition, and plastic molding, or (e) lithography, grinding, and alteration?

Answer: (d).

36.9 Photofabrication is the same process as photolithography. (a) true or (b) false?

Answer: (b). Photofabrication is an industrial process in which ultraviolet exposure through a pattern mask causes a significant increase in the chemical solubility of an optically clear material, thus permitting a suitable etchant to remove the exposed regions much more rapidly. This is not the same as photolithography, in which resists are used to determine the regions to be etched.

38 Nanofabrication Technologies

Review Questions

38.1 What is the range of feature sizes of entities associated with nanotechnology?

Answer: The features sizes range from less than 1 nm to 100 nm.

38.2 Identify some of the present and future products associated with nanotechnology.

Answer: Products mentioned in the text include computers, flat screen displays, and batteries based on carbon nanotubes; nanodots and nanowires as reinforcing agents in composite materials; cancer drugs designed to match the genetic profile of cancer cells; surface films that absorb more solar energy than current photovoltaic receptacles; nanoscale coatings to increase scratch resistance of surfaces and stain resistance of fabrics; portable medical laboratories, and light sources that are more energy efficient.

38.3 What is a buckyball?

Answer: A buckyball is the carbon molecule C_{60}, a molecule containing exactly 60 carbon atoms and shaped like a soccer ball. The 60 atoms are arranged symmetrically into 12 pentagonal faces and 20 hexagonal faces to form a ball.

38.4 What is a carbon nanotube?

Answer: A carbon nanotube is another molecular structure of carbon atoms possessing the shape of a tube. It has a typical size of a few nm in diameter and a length of 100 nm or so. Of interest are its mechanical and electrical properties. It can possess strength and stiffness properties exceeding those of steel, and it can be a conductor of electricity or a semiconductor.

38.5 What are the scientific and technical disciplines associated with nanoscience and nanotechnology?

Answer: The main disciplines include chemistry, physics, various engineering disciplines, computer science, biology, and medical science.

38.6 Why is biology so closely associated with nanoscience and nanotechnology?

Answer: The close association of biology derives from the fact that the building blocks of biological organisms are in the same size range. For example, proteins range in size between about 4 nm and 50 nm.

38.7 The behavior of nanoscale structures is different from macroscale and even microscale structures due to two factors mentioned in the text. What are those two factors?

Answer: The two factors mentioned in the text that differentiate nanoscale objects from much larger ones are (1) surface properties become much more important because a much higher proportion of a nanoscale object's atoms or molecules are at the surface, whereas in a larger object the internal atoms and molecules are relatively much more numerous; and (2) material behavior of nanoscale objects is influenced by quantum mechanics rather than bulk properties.

38.8 What is a scanning probe instrument, and why is it so important in nanoscience and nanotechnology?

Answer: A scanning probe instrument uses a very sharp probe, whose tip approaches the size of an atom, that moves along the surface of the specimen at a distance of only one nanometer in order to measure properties of the surface. This type of instrument is important because it permits images of the surface to be constructed that are on the scale of the surface atoms.

38.9 What is tunneling, as referred to in the scanning tunneling microscope?

Answer: Tunneling is a quantum mechanics phenomenon in which individual electrons in a solid material jump beyond the surface of the solid into space. The probability of electrons being in this space beyond the surface decreases exponentially in proportion to the distance from the surface. This sensitivity to distance is exploited in the scanning tunneling microscope by positioning the probe tip very close to the surface and applying a small voltage between the two. This causes electrons of surface atoms to be attracted to the small positive charge of the tip, and they tunnel across the gap to the probe.

38.10 What are the two basic categories of approaches used in nanofabrication?

Answer: The two basic categories are (1) top-down approaches, which adapt the microfabrication techniques to nanoscale object sizes and (2) bottom-up approaches, in which atoms and molecules are manipulated and combined into larger structures.

38.11 Why is photolithography based on visible light not used in nanotechnology?

Answer: Because the wavelength of visible light is 400 to 700 nm, well beyond nanoscale.

38.12 What are the lithography techniques used in nanofabrication?

Answer: The lithography techniques discussed in the text are (1) extreme ultraviolet lithography, (2) electron beam lithography, (3) x-ray lithography, and (4) nano-imprint lithography.

38.13 How is nano-imprint lithography different from micro-imprint lithography?

Answer: Nano-imprint lithography is the same basic process as micro-imprint lithography except the deformed features of the resist are of nanoscale proportions.

38.14 What are the limitations of scanning tunneling microscope in nanofabrication that inhibit its commercial application?

Answer: The limitations of STM include (1) they must be carried out in a very high vacuum environment to prevent stray atoms or molecules from interfering with the process and (2) the surface of the substrate must be cooled to temperatures approaching absolute zero (-273°C or -460°F) in order to reduce thermal diffusion that would gradually distort the atomic structure being formed. These limitations make it a very slow and expensive process.

38.15 What is self-assembly in nanofabrication?

Answer: Self-assembly is a process in which entities at the atomic and/or molecular level combine on their own into larger entities, proceeding in a constructive manner toward the creation of some deliberate thing.

38.16 What are the desirable features of atomic or molecular self-assembly processes in nanotechnology?

Answer: The desirable features of atomic or molecular self-assembly processes include the following: (1) they can be carried out rapidly, (2) they occur automatically and do not require any central control, (3) they exhibit massive replication, and (4) they can be performed at or near atmospheric pressure and room temperature.

Multiple Choice Quiz

There are 18 correct answers in the following multiple choice questions (some questions have more than one correct answer). To achieve a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the total score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. The percentage score on the quiz is based on the total number of correct answers.

38.1 Nanotechnology refers to the fabrication and application of entities whose feature sizes are in which of the following ranges (one best answer): (a) 0.1 nm-10 nm, (b) 1 nm-100 nm, or (c) 100 nm-1000 nm?

Answer: (b).

38.2 One nanometer is equivalent to which of the following (two correct answers): (a) 1 x 10^{-3} μm, (b) 1 x 10^{-6} m, (c) 1 x 10^{-9} m, and (d) 1 x 10^{6} mm.

Answer: (a) and (c).

38.3 NNI stands for which one of the following: (a) Nanoscience Naval Institute, (b) Nanoscience Nonsense and Ignorance, (c) National Nanotechnology Initiative, or (d) Nanotechnology News Identification?

Answer: (c).

38.4 The surface-to-volume ratio of a cube that is 1 x 10^{-6} m on each edge is significantly greater than the surface-to-volume ratio of a cube that is 1 m on each edge: (a) true or (b) false?

Answer: (b). The surface-to-volume ratios of the two cubes are equal.

38.5 The proportion of surface molecules relative to internal molecules is significantly greater for a cube that is 1 x 10^{-6} m on each edge than for a cube that is 1 m on each edge: (a) true or (b) false?

Answer: (a).

38.6 Which one of the following microscopes can achieve the greatest magnification: (a) electron microscope, (b) optical microscope, or (c) scanning tunneling microscope?

Answer: (c).

38.7 Which of the following are correct statements about a buckyball (three best answers): (a) it contains 60 atoms, (b) it contains 100 atoms, (c) it contains 600 atoms, (d) it is a carbon atom, (e) it is a carbon molecule, (f) it is shaped like a basketball, (g) it is shaped like a tube, and (h) it is shaped like a volleyball?

Answer: (a), (e), and (h).

38.8 Which of the following are considered techniques that fall within the category called top-down approaches to nanofabrication (three best answers): (a) biological evolution, (b) electron-beam lithography, (c) micro-imprint lithography, (d) scanning probe techniques, (e) self-assembly, and (f) X-ray lithography?

Answer: (b), (c), and (f).

38.9 Which of the following are considered techniques that fall within the category called bottom-up approaches to nanofabrication (three best answers): (a) electron beam lithography, (b) extreme ultraviolet lithography, (c) chemical vapor deposition to produce carbon nanotubes, (d) nano-imprint lithography, (e) scanning probe techniques, (f) self-assembly, and (g) X-ray lithography?

Answer: (c), (e), and (f).

38.10 Dip-pen nanolithography uses which one of the following techniques and/or devices: (a) atomic force microscope, (b) chemical vapor deposition, (c) electron beam lithography, (d) nano-imprint lithography, or (e) self-assembly?

Answer: (a).

38.11 A self-assembled monolayer has a thickness that is which one of the following: (a) one micrometer, (b) one millimeter, (c) one molecule, or (d) one nanometer?

Answer: (c).

38 AUTOMATION TECHNOLOGIES FOR MANUFACTURING SYSTEMS

Review Questions

38.1 Define the term *manufacturing system*.

Answer. The text defines manufacturing system as a collection of integrated equipment and human resources that performs one or more processing and/or assembly operations on a starting work material, part, or set of parts. The integrated equipment consists of production machines, material handling and positioning devices, and computer systems.

38.2 What are the three basic components of an automated system?

Answer. The three basic components of an automated system, according to the text, are (1) power, (2) a program of instructions, and (3) a control system to carry out the instructions.

38.3 What are some of the advantages of using electrical power in an automated system?

Answer. Advantages listed in the text are (1) it is widely available, (2) it can be readily converted to other forms of power such as mechanical, (3) it can be used at lower power levels for signal processing, communication, and data storage, and (4) it can be stored in long-life batteries.

38.4 What is the difference between a closed-loop control system and an open-loop control system?

Answer. The difference is that a closed-loop control system includes feedback of data related to the output of the process that is used to make control adjustments. An open-loop system does not have this feedback loop.

38.5 What is the difference between fixed automation and programmable automation?

Answer. In fixed automation, the processing or assembly steps and their sequence are fixed by the equipment configuration. The program of instructions is determined by the equipment design and cannot be easily changed. In programmable automation, the equipment is designed with the capability to change the program of instructions to allow production of different parts or products.

38.6 What is a sensor?

Answer. A sensor is a device that converts a physical stimulus or variable of interest (e.g., temperature, force, pressure, or other characteristic of the process) into a more convenient physical form (e.g., electrical voltage) for the purpose of measuring the variable. The conversion allows the variable to be interpreted as a quantitative value.

38.7 What is an actuator in an automated system?

Answer. In automated systems, an actuator is a device that converts a control signal into a physical action, which usually refers to a change in a process input parameter. The action is typically mechanical, such as a change in position of a worktable or rotational speed of a motor.

38.8 What is a contact input interface?

Answer. As defined in the text, a contact input interface is a device that reads binary data into the computer from an external source.

38.9 What is a programmable logic controller?

Answer. As defined in the text, a programmable logic controller (PLC) is a microcomputer-based controller that uses stored instructions in programmable memory to implement logic, sequencing, timing, counting, and arithmetic control functions, through digital or analog input/output modules, for controlling various machines and processes.

38.10 Identify and briefly describe the three basic components of a numerical control system.

Answer. The three basic components are: (1) part program, (2) machine control unit, and (3) processing equipment. The part program is the detailed set of commands to be followed by the processing equipment. The machine control unit in modern NC technology is a microcomputer that stores the program and executes it by converting each command into actions by the processing equipment, one command at a time. The processing equipment accomplishes the sequence of processing steps to transform the starting workpart into a completed part.

38.11 What is the difference between point-to-point and continuous path in a motion control system?

Answer. In point-to-point, the motion is from one location in space to the next with no regard for the path taken between starting and final locations. In continuous path, the trajectory of the movement is controlled.

38.12 What is the difference between absolute positioning and incremental positioning?

Answer. In absolute positioning, the locations are defined relative to the origin of the axis system. In incremental positioning, each succeeding location is defined relative to the previous location.

38.13 What is the difference between an open-loop positioning system and a closed-loop positioning system?

Answer. In a closed loop system, measurements of the output (position) are fed back to verify that it corresponds to the desired input value. In an open loop system, there is no feedback of the output value.

38.14 Under what circumstances is a closed-loop positioning system preferable to an open-loop system?

Answer. When there is a significant reaction force resisting the motion of the positioning system, a closed loop system is preferred.

38.15 Explain the operation of an optical encoder.

Answer. An optical encoder is a sensor for measuring angular position and rotational velocity. It consists of a light source, a photodetector, and a disk containing a series of slots through which the light source can shine to energize the photodetector. The disk is connected, either directly or through a gear train, to a rotating shaft whose angular position and velocity are to be measured. As the shaft rotates, the slots cause the light source to be seen by the photocell as a series of flashes, which are converted into an equivalent series of electrical pulses. By counting the pulses and computing the frequency of the pulse train, angular position and rotational speed can be determined.

38.16 Why should the electromechanical system rather than the controller storage register be the limiting factor in control resolution?

Answer. Because the control resolution in the controller storage register can be increased simply by increasing the number of bits used to define the axis location.

38.17 What is manual data input in NC part programming?

Answer. Manual data input refers to a method of programming in which the machine tool operator accomplishes the programming of the NC machine using a menu-driven procedure. Programming is simplified to minimize the amount of training required by the operator.

38.18 Identify some of the non-machine tool applications of numerical control.

Answer. The applications include (1) arc welding and resistance welding, (2) electronic component insertion, (3) electrical wire wrap machines, (4) drafting, (5) tape laying for fiber reinforced polymer composites, and (6) coordinate measuring machines.

38.19 What are some of the benefits usually cited for NC compared to using manual alternative methods?

Answer. Advantages of NC include (1) reduced non-productive time, (2) lower manufacturing lead times, (3) simpler fixtures, (4) greater flexibility, (5) improved accuracy, and (6) reduced human error.

38.20 What is an industrial robot?

Answer. An industrial robot is a programmable machine possessing certain anthropomorphic features. The most common feature is a manipulator (arm) that can be programmed to perform industrial tasks.

38.21 How is an industrial robot similar to numerical control?

Answer. They are both positioning systems that can be programmed and reprogrammed.

38.22 What is an end effector?

Answer. An end effector is the special tooling that is attached to the robot's wrist to perform a particular application. A gripper is one form of end effector.

38.23 In robot programming, what is the difference between powered leadthrough and manual leadthrough?

Answer. In powered leadthrough, a teach pendant that controls the drive motors of the individual joints is used to move the manipulator into the desired joint positions, which are then recorded into memory. In manual leadthrough, the manipulator is physically moved through the desired sequence of positions, which are recorded into memory for later execution.

Multiple Choice Quiz

There are 21 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

38.1 The three components of an automated system are which of the following: (a) actuators, (b) communication system, (c) control system, (d) feedback loop, (e) humans, (f) power, (g) program of instructions, and (h) sensors?

Answer. (c), (f), and (g).

38.2 The three basic types of automated systems used in manufacturing are fixed automation, programmable automation, and flexible automation. Flexible automation is an extension of programmable automation in which there is virtually no lost production time for setup changes or reprogramming: (a) true or (b) false.

Answer. (a).

38.3 The input/output relationship of a sensor is called which one of the following: (a) analog, (b) converter, (c) sensitivity, or (d) transfer function?

Answer. (d).

38.4 A stepper motor is which one of the following types of devices: (a) actuator, (b) interface device, (c) pulse counter, or (d) sensor?

Answer. (a).

38.5 A contact input interface is a device that reads analog data into the computer from an external source: (a) true of (b) false?

Answer. (b). The data is binary, not analog.

38.6 A programmable logic controller (PLC) normally replaces which one of the following in control applications: (a) computer numerical control, (b) distributed process control, (c) humans, (d) industrial robots, or (e) relay control panel?

Answer. (e).

38.7 The standard coordinate system for numerical control machine tools is based on which one of the following: (a) Cartesian coordinates, (b) cylindrical coordinates, or (c) polar coordinates?

Answer. (a).

38.8 Identify which of the following applications are point-to-point and not continuous path operations (three correct answers): (a) arc welding, (b) drilling, (c) hole punching in sheet metal, (d) milling, (e) spot welding, and (f) turning?

Answer. (b), (c), and (e).

38.9 The ability of a positioning system to return to a previously defined location is measured by which one of the following terms: (a) accuracy, (b) control resolution, or (c) repeatability?

Answer. (c).

38.10 The APT command GORGT is which of the following (two best answers): (a) continuous path command, (b) geometry statement involving a volume of revolution about a central axis, (c) name of the humanoid in the latest Star Wars movie, (d) point-to-point command, and (e) tool path command in which the tool must go right in the next move?

Answer. (a) and (e).

38.11 The arm-and-body of a robot manipulator generally performs which one of the following functions in an application: (a) holds the end effector, (b) orients the end effector within the work volume, or (c) positions the wrist within the work volume?

Answer. (c).

38.12 A SCARA robot is normally associated with which one of the following applications: (a) arc welding, (b) assembly, (c) inspection, (d) machine loading and unloading, or (e) resistance welding?

Answer. (b).

38.13 In robotics, spray-painting applications are classified as which of the following: (a) continuous path operation or (b) point-to-point operation?

Answer. (a).

38.14 Which of the following are characteristics of work situations that tend to promote the substitution of a robot in place of a human worker (three best answers): (a) frequent job changeovers, (b) hazardous work environment, (c) repetitive work cycle, (d) multiple work shifts, and (e) task requires mobility?

Answer. (b), (c), and (d).

Problems

Open-Loop Positioning Systems

38.1 A leadscrew with a 7.5 mm pitch drives a worktable in an NC positioning system. The leadscrew is powered by a stepping motor which has 200 step angles. The worktable is programmed to move a distance of 120 mm from its present position at a travel speed of 300 mm/min. Determine (a) the number of pulses required to move the table the specified distance and (b) the required motor speed and pulse rate to achieve the desired table speed.

Solution: (a) $\alpha = 360/n_s = 360/200 = 1.8°$
$n_p = 360x/p\alpha = 360(120)/(7.5 \text{ x } 1.8) =$ **3200 pulses**

(b) $N_m = v_t/p$ = (300 mm/min)/(7.5 mm/rev) = **40 rev/min**
$f_p = v_t n_s/60p = 300(200)/(60 \text{ x } 7.5) =$ **133.33 Hz**

38.2 Referring to Problem 38.1, the mechanical inaccuracies in the open-loop positioning system can be described by a normal distribution whose standard deviation = 0.005 mm. The range of the worktable axis is 500 mm, and there are 12 bits in the binary register used by the digital controller to store the programmed position. For the positioning system, determine (a) control resolution, (b) accuracy, and (c) repeatability. (d) What is the minimum number of bits that the binary register should have so that the mechanical drive system becomes the limiting component on control resolution?

Solution: (a) $CR_1 = p/n_s$ = 7.5 mm/200 = 0.0375 mm.
$CR_2 = L/2^B = 500/2^{12} - 1 = 500/4095 = 0.122$ mm.
$CR = \text{Max}\{CR_1, CR_2\} = \text{Max}\{0.0375, 0.122\} =$ **0.122 mm**.

(b) Accuracy = $0.5\ CR + 3\sigma = 0.5(0.122) + 3(0.005) =$ **0.076 mm**.

(c) Repeatability = $\pm\ 3\sigma = \pm\ 3(0.005) =$ **± 0.015 mm.**

(d) In order for the mechanical errors to be the limiting factor in control resolution in this problem, set $CR_1 = CR_2$.
Thus, $0.0375 = 500/(2^B - 1)$
$2^B - 1 = 500/0.0375 = 13{,}333.33$
$2^B = = 13{,}334.33$
$B \ln 2 = \ln 13{,}334.33$
$0.69315\ B = 9.498$
$B = 13.703$ Use ***B* = 14 bits**

38.3 A stepping motor has 200 step angles. Its output shaft is directly coupled to leadscrew with pitch = 0.250 in. A worktable is driven by the leadscrew. The table must move a distance of 5.00 in from its present position at a travel speed of 20.0 in/min. Determine (a) the number of pulses required to move the table the specified distance and (b) the required motor speed and pulse rate to achieve the specified table speed.

Solution: (a) $\alpha = 360/n_s = 360/200 = 1.8°$
$n_p = 360x/p\alpha = 360(5.0)/(0.25 \text{ x } 1.8) =$ **4000 pulses**

(b) $N_m = v_t/p$ = (20 in/min)/(0.25 in/rev) = **80 rev/min**
$f_p = v_t n_s/60p = 20(200)/(60 \text{ x } 0.25) =$ **266.67 Hz**

38.4 A stepping motor with 100 step angles is coupled to a leadscrew through a gear reduction of 9:1 (9 rotations of the motor for each rotation of the leadscrew). The leadscrew has 5 threads/in. The worktable driven by the leadscrew must move a distance = 10.00 in at a feed rate of 30.0 in/min.

Determine (a) number of pulses required to move the table, and (b) the required motor speed and pulse rate to achieve the desired table speed.

Solution: (a) $\alpha = 360/n_s = 360/100 = 3.6°$
$n_p = 360\ r_g\ x/p\alpha = 360(9)(10)/(0.2 \text{ x } 3.6) =$ **45,000 pulses**

(b) $N_m = r_g\ f_r/p = 9(30 \text{ in/min})/(0.2 \text{ in/rev}) =$ **1350 rev/min**
$f_p = r_g f_r n_s/60p = 9(30)(100)/(60 \text{ x } 0.2) =$ **2250 Hz**

38.5 The drive unit for a positioning table is driven by a leadscrew directly coupled to the output shaft of a stepping motor. The pitch of the leadscrew = 0.18 in. The table must have a linear speed = 35 in/min, and a positioning accuracy = 0.001 in. Mechanical errors in the motor, leadscrew, and table connection are characterized by a normal distribution with standard deviation = 0.0002 in. Determine (a) the minimum number of step angles in the stepping motor to achieve the accuracy, (b) the associated step angle, and (c) the frequency of the pulse train required to drive the table at the desired speed.

Solution: (a) Accuracy = 0.5 CR + 3 σ
0.001 = 0.5 CR + 3(0.0002) = 0.5 CR + 0.0006
0.001 - 0.0006 = 0.0004 = 0.5 CR
CR = 0.0008 in
Assume $CR = CR_1$
$CR_1 = 0.0008 = p/n_s = 0.18/n_s$
$n_s = 0.18/0.0008 =$ **225 step angles**

(b) $\alpha = 360/225 =$ **1.6°**

(c) $f_p = v_t\ n_s/60p = 35(225)/(60 \text{ x } 0.18) =$ **729.167 Hz**

38.6 The positioning table for a component insertion machine uses a stepping motor and leadscrew mechanism. The design specifications require a table speed of 40 in/min and an accuracy = 0.0008 in. The pitch of the leadscrew = 0.2 in, and the gear ratio = 2:1 (2 turns of the motor for each turn of the leadscrew). The mechanical errors in the motor, gear box, leadscrew, and table connection are characterized by a normal distribution with standard deviation = 0.0001 in. Determine (a) the minimum number of step angles in the stepping motor, and (b) the frequency of the pulse train required to drive the table at the desired maximum speed.

Solution: (a) Accuracy = 0.5 CR + 3σ
0.0008 = 0.5 CR + 3(0.0001) = 0.5 CR + 0.0003
0.0008 - 0.0003 = 0.0005 = 0.5 CR
CR = 0.001 in
Assume $CR = CR_1$
$CR_1 = 0.001 = p/(r_g n_s) = 0.2/2n_s$
Minimum $n_s = 0.2/(2 \text{ x } 0.001) =$ **100 step angles**

(b) $f_p = r_g v_t n_s/60p = 2(40)(100)/(60 \text{ x } 0.2) =$ **667.67 Hz**

38.7 The drive unit of a positioning table for a component insertion machine is based on a stepping motor and leadscrew mechanism. The specifications are for the table speed to be 25 mm/s over a 600 mm range and for the accuracy to be 0.025 mm. The pitch of the leadscrew = 4.5 mm, and the gear ratio = 5:1 (5 turns of the motor for each turn of the leadscrew). The mechanical errors in the motor, gear box, leadscrew, and table connection are characterized by a normal distribution with standard deviation = 0.005 mm. Determine (a) the minimum number of step angles in the stepping motor, and (b) the frequency of the pulse train required to drive the table at the desired maximum speed for the stepping motor in part (a).

Solution: (a) Accuracy = 0.5 CR + 3σ

$0.025 = 0.5\,CR + 3(0.005) = 0.5\,CR + 0.015$
$0.025 - 0.015 = 0.010 = 0.5\,CR$
$CR = 0.02$ mm.
Assume $CR = CR_1$
$CR_1 = p/(r_g n_s)$
Minimum $n_s = 4.5/(5 \times 0.02) =$ **45 step angles**

(b) $f_p = r_g v_t n_s / 60p = 5(25)(45)/4.5 =$ **1250 Hz**

38.8 The two axes of an *x-y* positioning table are each driven by a stepping motor connected to a leadscrew with a 10:1 gear reduction. The step angle on each stepping motor is 7.5°. Each leadscrew has a pitch = 5.0 mm and provides an axis range = 300.0 mm. There are 16 bits in each binary register used by the controller to store position data for the two axes. (a) What is the control resolution of each axis? (b) What are the required rotational speeds and corresponding pulse train frequencies of each stepping motor in order to drive the table at 600 mm/min in a straight line from point (25, 25) to point (100, 150)? Ignore acceleration.

Solution: (a) $n_s = 360/7.5 = 48$ step angles
$CR_1 = p/r_g n_s = 5.0/(10 \times 48) = 0.0104$ mm
$CR_2 = L/(2^B - 1) = 300/(2^{16} - 1) = 300/65{,}535 = 0.00458$ mm
$CR = \text{Max}\{0.0104, 0.00458\} =$ **0.0104 mm**

(b) $v_t = 600$ mm/min from (25, 25) to (100, 150)
$\Delta x = 100 - 25 = 75$ mm, $\Delta y = 150 - 25 = 125$ mm
Angle $A = \tan^{-1}(125/75) = 59°$
$v_{tx} = 600 \cos 59 = 308.7$ mm/min
$N_{mx} = r_g v_{tx}/p = 10(308.7)/5.0 =$ **617.4 rev/min**
$f_{px} = N_{mx} n_s/60 = 617.4(48)/60 =$ **493.92 Hz**
$v_{ty} = 600 \sin 59 = 514.5$ mm/min
$N_{my} = r_g v_{ty}/p = 10(514.5)/5.0 =$ **1029 rev/min**
$f_{px} = N_{my} n_s/60 = 1029(48)/60 =$ **823.2 Hz**

38.9 The *y*-axis of an *x-y* positioning table is driven by a stepping motor that is connected to a leadscrew with a 3:1 gear reduction (3 turns of the motor for each turn of the leadscrew). The stepping motor has 72 step angles. The leadscrew has 5 threads per inch and provides an axis range = 30.0 in. There are 16 bits in each binary register used by the controller to store position data for the axis. (a) What is the control resolution of the *y*-axis? Determine (b) the required rotational speed of the *y*-axis stepping motor and (c) the corresponding pulse train frequency to drive the table in a straight line from point ($x = 20$ in, $y = 25$ in) to point ($x = 4.5$ in, $y = 7.5$ in) in exactly 30 sec. Ignore acceleration.

Solution: (a) pitch $p = 1/5 = 0.200$ in.
$CR_1 = p/r_g n_s = 0.20/(3 \times 72) = 0.000926$ in
$CR_2 = L/(2^B - 1) = 30.0/(2^{16} - 1) = 30/65{,}535 = 0.000458$ in
$CR = \text{Max}\{0.000926, 0.000458\} =$ **0.000926 in**

(b) $\Delta x = 20 - 4.5 = 15.5$ in, $\Delta y = 25 - 7.5 = 17.5$ in
$v_{fy} = 17.5$ in $/0.5$ min $= 35$ in/min
$N_{my} = r_g v_{ty}/p = 3(35)/0.20 =$ **525 rev/min**

(c) $f_{px} = N_{my} n_s/60 = 525(72)/60 =$ **630 Hz**

38.10 The two axes of an *x-y* positioning table are each driven by a stepping motor connected to a leadscrew with a 4:1 gear reduction. The number of step angles on each stepping motor is 200. Each leadscrew has a pitch = 5.0 mm and provides an axis range = 400.0 mm. There are 16 bits in each binary register used by the controller to store position data for the two axes. (a) What is the control resolution of each axis? (b) What are the required rotational speeds and corresponding pulse train frequencies of each stepping motor in order to drive the table at 600 mm/min in a straight line from point (25,25) to point (300,150)? Ignore acceleration.

Solution: (a) $CR_1 = p/r_g n_s = 5.0/(4 \text{ x } 200) = 0.00625$ mm
$CR_2 = L/(2^B - 1) = 400/(2^{16} - 1) = 400/65{,}535 = 0.00610$ mm
$CR = \text{Max}\{0.00625, 0.00610\} =$ **0.00625 mm**

(b) $v_t = 600$ mm/min from (25, 25) to (300, 150)
$\Delta x = 300 - 25 = 275$ mm, $\Delta y = 150 - 25 = 125$ mm
Angle $A = \tan^{-1}(125/275) = 24.44°$
$v_{tx} = 600 \cos 24.44 = 546.22$ mm/min
$N_{mx} = r_g v_{tx}/p = 4(546.22)/5.0 =$ **436.98 rev/min**
$f_{px} = N_{mx} n_s/60 = 436.98(200)/60 =$ **1456.6.8 Hz**
$v_{ty} = 600 \sin 24.44 = 248.28$ mm/min
$N_{my} = r_g v_{ty}/p = 4(248.28)/5.0 =$ **198.63 rev/min**
$f_{px} = N_{my} n_s/60 = 198.63(200)/60 =$ **662.1 Hz**

Closed-Loop Positioning Systems

38.11 An NC machine tool table is powered by a servomotor, leadscrew, and optical encoder. The leadscrew has a pitch = 5.0 mm and is connected to the motor shaft with a gear ratio of 16:1 (16 turns of the motor for each turn of the leadscrew). The optical encoder is connected directly to the leadscrew and generates 200 pulses/rev of the leadscrew. The table must move a distance = 100 mm at a feed rate = 500 mm/min. Determine (a) the pulse count received by the control system to verify that the table has moved exactly 100 mm; and (b) the pulse rate and (c) motor speed that correspond to the feed rate of 500 mm/min.

Solution: (a) $x = pn_p/n_s$; rearranging, $n_p = xn_s/p = 100(200)/5 =$ **4000 pulses**

(b) $f_p = f_r n_s/60p = 500(200)/60(5) =$ **333.3 Hz**

(c) $N_m = r_g f_r/p = 16 \text{ x } 500/5 =$ **1600 rev/min**

38.12 The worktable of a numerical control machine tool is driven by a closed-loop positioning system which consists of a servomotor, leadscrew, and optical encoder. The leadscrew has 4 threads/in and is coupled directly to the motor shaft (gear ratio = 1:1). The optical encoder generates 200 pulses per motor revolution. The table has been programmed to move a distance of 7.5 in at a feed rate = 20.0 in/min. (a) How many pulses are received by the control system to verify that the table has moved the programmed distance? What are (b) the pulse rate and (c) motor speed that correspond to the specified feed rate?

Solution: (a) $x = pn_p/n_s$;Rearranging, $n_p = xn_s/p = 7.5(200)/0.25 =$ **6000 pulses.**

(b) $f_p = f_r n_s/60p = 20(200)/60(0.25) =$ **266.67 Hz**

(c) $N_m = f_r/p = 20/0.25 =$ **80 rev/min**

38.13 A leadscrew coupled directly to a dc servomotor is used to drive one of the table axes of an NC milling machine. The leadscrew has 5 threads/in. The optical encoder attached to the leadscrew emits 100 pulses/rev of the leadscrew. The motor rotates at a maximum speed of 800 rev/min. Determine (a) the control resolution of the system, expressed in linear travel distance of the table axis; (b) the frequency of the pulse train emitted by the optical encoder when the servomotor operates at maximum speed; and (c) the travel speed of the table at the maximum rpm of the motor.

Solution: (a) $CR = p/n_s = 0.2/100 =$ **0.002 in**

(b) $N_m = N_{ls} = 800$ rev/min because the motor is connected directly to the leadscrew.

$f_p = N_{ls}n_s/60$ = 800(100)/60 = **1333.3 Hz**

(c) $v_t = N_{ls}\,p$ = 800(0.2) = **160 in/min**

38.14 Solve the previous problem only the servomotor is connected to the leadscrew through a gear box whose reduction ratio = 12:1 (12 revolutions of the motor for each revolution of the leadscrew).

Solution: (a) $CR = p/n_s$ = 0.2/100 = **0.002 in**

(b) $f_p = N_m\, n_s/60r_g$ = 800(100)/60(12) = **111.1 Hz**

(c) $v_t = N_m\, p/r_g$ = 800(0.2)/12 = **13.33 in/min**

38.15 A leadscrew connected directly to a DC servomotor is the drive system for a positioning table. The leadscrew pitch = 4 mm. The optical encoder attached to the leadscrew emits 250 pulses/rev of the leadscrew. Determine (a) the control resolution of the system, expressed in linear travel distance of the table axis, (b) the frequency of the pulse train emitted by the optical encoder when the servomotor operates at 14 rev/s, and (c) the travel speed of the table at the operating speed of the motor.

Solution: (a) $CR_1 = p/n_s$ = 4/250 = **0.016 mm**.

(b) $N_m = N_{ls}$ = 14 rev/sec because the motor is connected directly to the leadscrew.
$f_p = N_m\, n_s$ = 14(250) = **3500 Hz**

(c) $v_t = N_m\, p$ = 14(4) = **56 mm/s**

38.16 A milling operation is performed on an NC machining center. Total travel distance = 300 mm in a direction parallel to one of the axes of the worktable. Cutting speed = 1.25 m/s and chip load = 0.05 mm. The end milling cutter has four teeth and its diameter = 20.0 mm. The axis uses a DC servomotor whose output shaft is coupled to a leadscrew with pitch = 6.0 mm. The feedback sensing device connected to the leadscrew is an optical encoder that emits 250 pulses per revolution. Determine (a) feed rate and time to complete the cut, and (b) rotational speed of the motor and the pulse rate of the encoder at the feed rate indicated.

Solution: (a) Spindle speed $N = (1.25 \times 10^3$ mm/s)/(20π mm/rev) = 19.89 rev/s
$f_r = N\, f\, n_t$ = 19.89(0.05)(4) = **3.978 mm/s.**
T_m = 300/3.978 = **75.4 s = 1.26 min**

(b) $N_m = f_r/p$ = (3.978 mm/s)/(6 mm/rev) **= 0.663 rev/s**
$f_p = n_s\, N_m$ = 250(0.663) = **165.75 Hz**

38.17 An end milling operation is carried out along a straight line path that is 325 mm long. The cut is in a direction parallel to the *x*-axis on an NC machining center. Cutting speed = 30 m/min and chip load = 0.06 mm. The end milling cutter has two teeth and its diameter = 16.0 mm. The *x*-axis uses a DC servomotor connected directly to a leadscrew whose pitch = 6.0 mm. The feedback sensing device is an optical encoder that emits 400 pulses per revolution. Determine (a) feed rate and time to complete the cut, and (b) rotational speed of the motor and the pulse rate of the encoder at the feed rate indicated.

Solution: (a) Spindle speed $N = (30 \times 10^3$ mm/min)/(16π mm/rev) = 596.8 rev/min
$f_r = N\, f\, n_t$ = 596.8(0.06)(2) = **71.62 mm/min**
T_m = 325/71.62 = **4.54 min**

(b) $N_m = f_r/p$ = (71.62 mm/min)/(6.0 mm/rev) **= 11.94 rev/min**
$f_p = N_m\, n_s/60$ = 400(11.94)/60 = **79.58 Hz**

38.18 A DC servomotor drives the *x*-axis of a NC milling machine table. The motor is coupled to the table lead screw using a 4:1 gear reduction (4 turns of the motor for each turn of the lead screw). The lead screw pitch = 6.25 mm. An optical encoder is connected to the lead screw. The optical encoder emits 500 pulses per revolution. To execute a certain programmed instruction, the table must move from point (x = 87.5 mm, y = 35.0) to point (x = 25.0 mm, y = 180.0 mm) in a straight-line trajectory at a feed rate = 200 mm/min. Determine (a) the control resolution of the system for the x-axis only, (b) the corresponding rotational speed of the motor, and (c) frequency of the pulse train emitted by the optical encoder at the desired feed rate.

Solution: (a) $CR_1 = p/n_s$ = (6.25 mm/rev)/(500 pulse/rev) = **0.0125 mm**

(b) Move from (87.5, 35.0) to (25.0, 180.0) at f_r = 200 mm/min
Δx = 25.0 - 87.5 = -62.5, Δy = 180.0 - 35.0 = 145.0, Angle $A = \tan^{-1}(145/-62.5) = 113.32°$

f_{rx} = 200 cos 113.32 = 200(-0.3958) = -79.19 mm/min
$N_m = r_g f_{rx}/p$ = 4(-79.17 mm/min)/(6.25 mm/rev) = **-50.677 rev/min**

(c) $f_p = n_sN_{ls}/60 = n_sN_m/60r_g = \dfrac{500(50.677)}{60(4)}$ = **105.58 Hz**

38.19 A DC servomotor drives the y-axis of a NC milling machine table. The motor is coupled to the table lead screw with a gear reduction of 2:1 (2 turns of the motor shaft for each single rotation of the lead screw). There are 2 threads per cm in the lead screw. An optical encoder is directly connected to the lead screw (1:1 gear ratio). The optical encoder emits 100 pulses per revolution. To execute a certain programmed instruction, the table must move from point (x = 25.0 mm, y = 28.0) to point (x = 155.0 mm, y = 275.0 mm) in a straight-line trajectory at a feed rate = 200 mm/min. For the y-axis only, determine: (a) the control resolution of the mechanical system, (b) rotational speed of the motor, and (c) frequency of the pulse train emitted by the optical encoder at the desired feed rate.

Solution: (a) With 2 threads per cm, pitch p = 0.5 cm = 5 mm.
One pulse of the optical encoder = $1/n_s$ rotation of the leadscrew.
$CR_1 = p/n_s$ = 5.0/100 = 0.050 mm

(b) Move from (25, 28) to (155, 275) at 200 mm/min
Δx = 155 – 25 = 130 mm, Δy = 275 – 28 = 247 mm
Angle $A = \tan^{-1}(247/130) = \tan^{-1}(1.9) = 62.24°$

f_{ry} = 200 sin 62.24 = 200(0.8849) = 176.98 mm/min
Leadscrew $N_{lsy} = f_{ry}/p$ = 176.98/5 = 35.396 rev/min
Motor $N_{my} = r_g f_{ry}/p$ = 2(176.98)/5 = 70.792 rev/min

(c) Pulse frequency corresponds to rotational speed of leadscrew:
$f_p = n_sN_{lsy}/60$ = 100(35.396)/60 = 58.99 Hz

Industrial Robotics

38.20 The largest axis of a Cartesian coordinate robot has a total range of 750 mm. It is driven by pulley system capable of a mechanical accuracy = 0.25 mm and repeatability = ±0.15 mm. Determine the minimum number of bits required in the binary register for the axis in the robot's control memory.

Solution: Repeatability = $\pm 3\sigma$ = 0.15 mm
σ = 0.15/3 = 0.05 mm
Accuracy = 0.25 mm = 0.5 CR + 3σ = 0.5 CR + 0.15
0.5 CR = 0.25 - 0.15 = 0.10
CR = 0.20
$CR = CR_2 = L/(2^B - 1) = 750/(2^B - 1)$
$750/(2^B - 1) = 0.20$
$2^B - 1 = 750/0.20 = 3750$

$2^B = 3751$
$B \ln 2 = \ln 3751$
$0.69315\, B = 8.22978$ **$B = 11.87 \rightarrow$ 12 bits**

38.21 A stepper motor serves as the drive unit for the linear joint of an industrial robot. The joint must have an accuracy of 0.25 mm. The motor is attached to a leadscrew through a 2:1 gear reduction (2 turns of the motor for 1 turn of the leadscrew). The pitch of the leadscrew is 5.0 mm. The mechanical errors in the system (due to backlash of the leadscrew and the gear reducer) can be represented by a normal distribution with standard deviation = ±0.05 mm. Specify the number of step angles that the motor must have in order to meet the accuracy requirement.

Solution: Repeatability = $\pm 3\sigma = \pm 3(0.05) = \pm 0.15$ mm
Accuracy = 0.25 mm = $0.5\, CR + 3\sigma = 0.5\, CR + 0.15$
$0.5\, CR = 0.25 - 0.15 = 0.10$
$CR = 0.20$ mm
Assume $CR = CR_1 = p/r_g n_s$
$n_s = p/(r_g\, CR) = 5.0/(2 \text{ x } 0.20) = 12.5 \rightarrow$ **n_s = 13 step angles**

38.22 The designer of a polar configuration robot is considering a portion of the manipulator consisting of a rotational joint connected to its output link. The output link is 25 in long and the rotational joint has a range of 75°. The accuracy of the joint-link combination, expressed as a linear measure at the end of the link which results from rotating the joint, is specified as 0.030 in. The mechanical inaccuracies of the joint result in a repeatability error = ±0.030° of rotation. It is assumed that the link is perfectly rigid, so there are no additional errors due to deflection. (a) Show that the specified accuracy can be achieved, given the repeatability error. (b) Determine the minimum number of bits required in the binary register of the robot's control memory to achieve the specified accuracy.

Solution: (a) Repeatability = $\pm 3\sigma = \pm\ 0.030°$.
$0.030° = 2\pi(0.030)/360 = 0.0005236$ rad.
End-of-link movement = $L\, A$ where A = angle of movement in radians
$L\, A = 25(0.0005236) = 0.0131$ in
Accuracy = $0.5\, CR + 3\sigma = 0.5\, CR + 0.0131$
Specified accuracy = 0.030
$0.030 = 0.5\, CR + 0.0131$
$0.5\, CR = 0.030 - 0.0131 = 0.0169$
$CR = 0.0169/0.5 = 0.0338$ in
Since CR is positive, the specified accuracy should be possible to achieve.

(b) Given $CR = 0.0338$ from part (a), total range = 75°
Converting this to an arc distance, range = $(2\pi(75)/360) \text{ x } 25 = 32.725$ in
$CR = L/(2^B - 1) = 0.0338$
$32.725/(2^B - 1) = 0.0338$
$2^B - 1 = 32.725/0.0338 = 968.2$
$2^B = 969.2$
$B \ln 2 = \ln 969.2$
$0.6931\, B = 6.876$ **$B = 9.92 \rightarrow$ 10 bits**

39 INTEGRATED MANUFACTURING SYSTEMS

Review Questions

39.1 What are the main components of an integrated manufacturing system?

Answer. As stated in the text, the main components of an integrated manufacturing system are (1) workstations and/or machines, (2) material handling equipment, and (3) computer control. In addition, human workers are required to manage the system, and workers may be used to operate the individual workstations and machines.

39.2 What are the principal material handling functions in manufacturing?

Answer. The principal material handling functions in manufacturing are (1) loading and positioning work units at each workstation, (2) unloading work units from the station, and (3) transporting work units between workstations.

39.3 Name the five main types of material transport equipment.

Answer. The five main types of material transport equipment are (1) industrial trucks, which includes fork lift trucks, (2) automated guided vehicles, (3) rail-guided vehicles, (4) conveyors, and (5) hoists and cranes.

39.4 What is the difference between fixed routing and variable routing in material transport systems?

Answer. In ***fixed routing***, all of the work units are moved through the same sequence of stations, which means that the processing sequence required on all work units is either identical or very similar. In ***variable routing***, different work units are moved through different workstation sequences, meaning that the manufacturing system processes or assembles different types of parts or products.

39.5 What is a production line?

Answer. A production line is a sequence of workstations at which individual tasks are accomplished on each work unit as it moves from one station to the next to progressively make the product.

39.6 What are the advantages of a mixed model line over a batch model line for producing different product styles?

Answer. Advantages of the mixed model line include (1) no downtime between the different models due to line changeovers; (2) production rates can be matched to demand rates for the different models, and thus (3) inventory fluctuations can be avoided in which there are high inventories of some models while there are stock-outs of other models.

39.7 What are some of the limitations of a mixed model line compared to a batch model line?

Answer. Limitations of a mixed model line include (1) the line balancing problem is more complex, (2) scheduling the models is more difficult, and (3) getting the right parts to each workstation is more complicated because more parts are involved.

39.8 Describe how manual methods are used to move parts between workstations on a production line.

Answer. The manual methods include (1) work units are simply passed by hand along a flat worktable from one station to the next, (2) work units are collected in boxes and then passed between stations, and (3) work units are pushed along a non-powered conveyor between stations.

39.9 Briefly define the three types of mechanized workpart transfer systems used in production lines.

Answer. The three work transfer systems are (1) continuous transfer, in which parts move on a conveyor at a steady speed; (2) synchronous transfer, in which parts all move simultaneously from station-to-station with a stop-and-go action; and (3) asynchronous transfer, in which parts move independently between stations with a stop-and-go action.

39.10 Why are parts sometimes fixed to the conveyor in a continuous transfer system in manual assembly?

Answer. Because the parts are big and/or heavy and cannot be conveniently removed from the transfer system by a human worker.

39.11 Why must a production line be paced at a rate higher than that required to satisfy the demand for the product?

Answer. Because all production lines suffer a certain amount of nonproductive time due to reliability problems.

39.12 Repositioning time on a synchronous transfer line is known by a different name; what is that name?

Answer. The repositioning time is called the transfer time; it is the time to move parts from one station to the next.

39.13 Why are single station assembly cells generally not suited to high-production jobs?

Answer. The entire work cycle is performed at one station, so single station cells usually operate at relatively slow production rates.

39.14 What are some of the reasons for downtime on a machining transfer line?

Answer. Reasons for downtime on a machining transfer line include tool changes, unpredictable mechanical and electrical failures, and normal wear and tear on the equipment.

39.15 Define group technology.

Answer. GT is a general approach in which similarities among parts are identified and exploited in design and manufacturing.

39.16 What is a part family?

Answer. A part family is a collection of parts that share similar design and/or manufacturing attributes.

39.17 Define cellular manufacturing.

Answer. Cellular manufacturing involves the production of part families using groups of machines (generally manually operated) to produce a certain part family or a limited set of part families.

39.18 What is the composite part concept in group technology?

Answer. In GT, a composite part is a hypothetical part that includes all of the design and/or manufacturing attributes of a given part family. The concept is useful in designing cells to produce the part family.

39.19 What is a flexible manufacturing system?

Answer. A flexible manufacturing system (FMS) is an automated group technology cell consisting of processing stations interconnected by an automated handling system and controlled by a computer.

39.20 What are the criteria that should be satisfied to make an automated manufacturing system flexible?

Answer. The flexibility criteria for an FMS are (1) the system must process different part styles in non-batch mode; (2) the system must be able to accept changes in the production schedule, (3) the system must deal gracefully with equipment breakdowns, and (4) the system must be able to accommodate new part style introductions.

39.21 Name some of the FMS software and control functions.

Answer. FMS software and control functions include (1) NC part programming, (2) NC part program download, (3) production control, (4) machine control, (5) workpart control, (6) tool management, (7) work transport control, and (8) general system management.

39.22 What are the advantages of FMS technology, compared to conventional batch operations?

Answer. Advantages include (1) higher machine utilization, (2) reduced work-in-process, (3) lower manufacturing lead times, and (4) greater flexibility in production scheduling.

39.23 Define computer integrated manufacturing.

Answer. Computer integrated manufacturing (CIM) refers to the pervasive use of computer systems throughout a manufacturing organization, not only to monitor and control the operations, but also to design the product, plan the manufacturing processes, and accomplish the business functions related to production.

Multiple Choice Quiz

There are 21 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

39.1 Material handling is usually not associated with transportation between facilities that involves rail, truck, air, or waterway delivery of goods: (a) true or (b) false?

Answer. (a).

39.2 Fixed routing is associated with which of the following types of manufacturing systems (two best answers): (a) automated production lines, (b) automated storage systems, (c) cellular manufacturing systems, (d) flexible manufacturing systems, (e) job shops, and (f) manual assembly lines?

Answer. (a) and (f).

39.3 Which of the following types of material handling equipment are typically used in a process type layout (two best answers): (a) conveyors, (b) cranes and hoists, (c) fork lift trucks, and (d) rail-guided vehicles?

Answer. (b) and (c).

39.4 Batch model production lines are most suited to which one of the following production situations: (a) job shop, (b) mass production, or (c) medium production?

Answer. (c).

39.5 Precedence constraints are best described by which one of the following: (a) launching sequence in a mixed model line, (b) limiting value of the sum of element times that can be assigned to a worker or station, (c) order of workstations along the line, or (d) sequence in which the work elements must be done?

Answer. (d).

39.6 Which of the following phrases are most appropriate to describe the characteristics of tasks that are performed at automated workstations (three best answers): (a) complex, (b) consists of multiple work elements, (c) involves a single work element, (d) involves straight-line motions, (e) requires sensory capability, and (f) simple?

Answer. (c), (d), and (f).

39.7 The transfer line is most closely associated with which one of the following types of production operations: (a) assembly, (b) automotive chassis fabrication, (c) machining, (d) pressworking, or (e) spot welding?

Answer. (c).

39.8 A dial indexing machine uses which one of the following types of workpart transfer: (a) asynchronous, (b) continuous, (c) parts passed by hand, or (d) synchronous?

Answer. (d).

39.9 Production flow analysis is a method of identifying part families that uses data from which one of the following sources: (a) bill of materials, (b) engineering drawings, (c) master schedule, (d) production schedule, or (e) route sheets?

Answer. (e).

39.10 Most parts classification and coding systems are based on which of the following types of part attributes (two best answers): (a) annual production rate, (b) date of design, (c) design, (d) manufacturing, and (e) weight?

Answer. (c) and (d).

39.11 What is the dividing line between a manufacturing cell and a flexible manufacturing system: (a) two machines, (b) four machines, or (c) six machines?

Answer. (b).

39.12 A machine capable of producing different part styles in a batch mode of operation qualifies as a flexible manufacturing system: (a) true or (b) false?

Answer. (b). A flexible manufacturing system does not normally operate in a batch mode.

39.13 The physical layout of a flexible manufacturing system is determined principally by which one of the following: (a) computer system, (b) material handling system, (c) part family, (d) processing equipment, or (e) weight of parts processed?

Answer. (b).

39.14 Industrial robots can, in general, most easily handle which one of the following part types in a flexible machining system: (a) heavy parts, (b) metal parts, (c) nonrotational parts, (d) plastic parts, or (e) rotational parts?

Answer. (e).

39.15 Flexible manufacturing systems and cells are generally applied in which one of the following areas: (a) high-variety, low-volume production, (b) low variety, (c) low volume, (d) mass production, (e) medium-volume, medium-variety production?

Answer. (e).

39.16 Which one of the following technologies is most closely associated with flexible machining systems: (a) lasers, (b) machine vision, (c) manual assembly lines, (d) numerical control, or (f) transfer lines?

Answer. (d).

Problems

Manual Assembly Lines

39.1 A manual assembly line is being designed for a product with annual demand = 100,000 units. The line will operate 50 wks/year, 5 shifts/wk, and 7.5 hr/shift. Work units will be attached to a continuously moving conveyor. Work content time = 42.0 min. Assume line efficiency = 0.97, balancing efficiency = 0.92, and repositioning time = 6 sec. Determine (a) hourly production rate to meet demand, (b) number of workers required, and (c) the number of workstations required if the estimated manning level is 1.4.

Solution: (a) R_p = 100,000/(50 x 5 x 7.5) = **53.33 units/hr**

(b) $T_c = E/R_p$ = 60(.97)/53.33 = 1.09125 min
$T_s = T_c - T_r$ = 1.09125 - 0.1 = 0.99125 min
w = Min Int ≥ 42.0/(.92 x 0.99125) = 46.06 → **47 workers**

(c) $n = w/M$ = 47/1.4 = 33.6 → **34 stations**

39.2 A manual assembly line produces a small appliance whose work content time = 25.9 min. Desired production rate = 50 units/hr. Repositioning time = 6 sec, line efficiency = 95%, and balancing efficiency is 93%. How many workers are on the line?

Solution: $T_c = E/R_p$ = 60(0.95)/50 = 1.14 min
$T_s = T_c - T_r$ = 1.14 - 0.1 = 1.04 min
w = Min Int ≥ 25.9/(0.93 x 1.04) = 26.78 → **27 workers**

39.3 A single model manual assembly line produces a product whose work content time = 47.8 min. The line has 24 workstations with a manning level = 1.25. Available shift time per day = 8 hr, but downtime during the shift reduces actual production time to 7.6 hr on average. This results in an average daily production of 256 units/day. Repositioning time per worker is 8% of cycle time. Determine (a) line efficiency, (b) balancing efficiency, and (c) repositioning time.

Solution: (a) E = 7.6/8.0 = **0.95**

(b) R_p = 256/8 = 32 units/hr on average which includes line stops
R_c = 256/7.6 = 33.684 units/hr when line is running; thus, E = 32/33.68 = 0.95
T_c = 60(0.95)/33.684 = 1.6922 min
$T_s = T_c - T_r = T_c - 0.08T_c = 0.92\ T_c$ = 0.92(1.6922) = 1.5568 min
w = 24(1.25) = 32 workers
$E_b = T_{wc}/wT_s$ = 47.8/(32 x 1.5568) = **0.9595**

(c) T_r = 0.08(1.6922) = 0.1354 min = **8.12 sec**

39.4 A final assembly plant for a certain automobile model is to have a capacity of 240,000 units annually. The plant will operate 50 weeks/yr, 2 shifts/day, 5 days/week, and 8.0 hours/shift. It will be divided into three departments: (1) body shop, (2) paint shop, (3) trim-chassis-final department. The body shop welds the car bodies using robots, and the paint shop coats the bodies. Both of these departments are highly automated. Trim-chassis-final has no automation. There are 15.5 hours of direct labor content on each car in this department, where cars are moved by a continuous conveyor. Determine (a) hourly production rate of the plant, (b) number of workers and workstations required in trim-chassis-final if no automated stations are used, the average manning level is 2.5, balancing efficiency = 93%, proportion uptime = 95%, and a repositioning time of 0.15 min is allowed for each worker.

Solution: (a) R_p = 240,000/(50 x 10 x 8) = **60.0 units/hr**

(b) $T_c = E/R_p$ = 60(0.95)/60 = 0.95 min

$T_s = T_c - T_r = 0.95 - 0.15 = 0.8$ min
w = Min Int $\geq T_{wc}/E_bT_s = 15.5 \times 60/(0.93 \times .8) =$ **1250 workers**
$n = w/M = 1250/2.5 =$ **500 stations**

39.5 A product whose total work content time = 50 minutes is to be assembled on a manual production line. The required production rate is 30 units per hour. From previous experience with similar products, it is estimated that the manning level will be close to 1.5. Assume that the uptime proportion and line balancing efficiency are both = 1.0. If 9 seconds will be lost from the cycle time for repositioning, determine (a) the cycle time and (b) the numbers of workers and stations that will be needed on the line.

Solution: (a) $T_c = E/R_p = 1.0(60)/30 = 2.0$ min/unit

(b) $T_s = T_c - T_r = 2.0 - 0.15 = 1.85$ min
w = Min Int $\geq T_{wc}/E_bT_s = 50/(1.0 \times 1.85) = 27.03 \rightarrow$ **28 workers**

$n = 28/1.5 = 18.67 \rightarrow$ **19 stations**

39.6 A manual assembly line has 17 workstations with one operator per station. Total work content time to assemble the product = 22.2 minutes. The production rate of the line = 36 units per hour. A synchronous transfer system is used to advance the products from one station to the next, and the transfer time = 6 seconds. The workers remain seated along the line. Proportion uptime = 0.90. Determine the balance efficiency.

Solution: $T_c = E/R_p = 60(0.90)/36 = 1.50$ min
$T_s = T_c - T_r = 1.50 - 0.1 = 1.40$ min
$E_b = T_{wc}/wT_s = 22.2/(17 \times 1.40) =$ **0.933 = 93.3%**

39.7 A production line with four automatic workstations (the other stations are manual) produces a certain product whose total assembly work content time = 55.0 min of direct manual labor. The production rate on the line is 45 units/hr. Because of the automated stations, uptime efficiency = 89%. The manual stations each have one worker. It is known that 10% of the cycle time is lost due to repositioning. If the balancing efficiency = 0.92 on the manual stations, find (a) cycle time, (b) number of workers and (c) workstations on the line. (d) What is the average manning level on the line, where the average includes the automatic stations?

Solution: (a) $T_c = E/R_p = 60(0.89)/45 =$ **1.1867 min**

(b) $T_s = T_c - T_r = 0.9\mathrm{T}_c = 0.9(1.1867) = 1.068$ min
$w = T_{wc}/E_bT_s = 55.0/(0.92 \times 1.068) = 55.97 \rightarrow$ **56 workers**

(c) $n = 56 + 4 =$ **60 stations**

(d) $M = 56/60 =$ **0.933**

39.8 Production rate for a certain assembled product is 47.5 units per hour. The total assembly work content time = 32 minutes of direct manual labor. The line operates at 95% uptime. Ten workstations have two workers on opposite sides of the line so that both sides of the product can be worked on simultaneously. The remaining stations have one worker. Repositioning time lost by each worker is 0.2 min/cycle. It is known that the number of workers on the line is two more than the number required for perfect balance. Determine (a) number of workers, (b) number of workstations, (c) the balancing efficiency, and (d) average manning level.

Solution: (a) $T_c = E/R_p = 0.95(60)/47.5 = 1.2$ min
$T_s = T_c - T_r = 1.2 - 0.2 = 1.0$ min
If perfect balance, then $E_b = 1.0$ and w = Min Int $\geq T_{wc}/E_bT_s = 32/(1.0 \times 1.0) = 32$ workers
But with 2 additional workers, $w = 32 + 2 =$ **34 workers**

(b) $n = 10 + (34 - 2 \times 10) = 10 + 14 =$ **24 stations**

(c) $E_b = T_{wc}/wT_s = 32/(34 \times 1.0) =$ **0.941**

(d) $M = w/n = 34/24 =$ **1.417**

39.9 The total work content for a product assembled on a manual production line is 48 min. The work is transported using a continuous overhead conveyor that operates at a speed of 3 ft/min. There are 24 workstations on the line, one-third of which have two workers; the remaining stations each have one worker. Repositioning time per worker is 9 sec, and uptime efficiency of the line is 95%. (a) What is the maximum possible hourly production rate if line is assumed to be perfectly balanced? (b) If the actual production rate is only 92% of the maximum possible rate determined in part (a), what is the balance efficiency on the line?

Solution: (a) $E_b = 1.0$, $w = 0.333(24) \times 2 + 0.667(24) \times 1 = 32$ workers
$w = T_{wc}/E_bT_s$, $T_s = T_{wc}/wE_b = 48/32 = 1.5$ min
$T_c = T_s + T_r = 1.5 + .15 = 1.65$ min
$T_p = T_c/E = 1.65/.95 = 1.737$ min
$R_p = 60/T_p = 60/1.737 =$ **34.55 units/hr**

(b) Actual $R_p = 0.92(34.55) = 31.78$ units/hr
$T_c = 60E/R_p = 60(.95)/31.78 = 1.7935$ min
$T_s = 1.7935 - .15 = 1.6435$ min
$E_b = T_{wc}/wT_s = 48/(32 \times 1.6435) =$ **0.9127**

Automated Production Lines

39.10 An automated transfer line has 20 stations and operates with an ideal cycle time of 1.50 min. Probability of a station failure = 0.008 and average downtime when a breakdown occurs is 10.0 minutes. Determine (a) the average production rate and (b) the line efficiency.

Solution: (a) $F = np = 20(0.008) = 0.16$
$T_p = 1.50 + 0.16(10.0) = 1.50 + 1.60 = 3.10$ min
$R_p = 60/\mathrm{T_p} = 60/3.1 =$ **19.35 units/hr**

(b) $E = T_c/T_p = 1.5/3.1 =$ **0.484**

39.11 A dial-indexing table has 6 stations. One station is used for loading and unloading, which is accomplished by a human worker. The other five perform processing operations. The longest process takes 25 sec and the indexing time = 5 sec. Each station has a frequency of failure = 0.015. When a failure occurs it takes an average of 3.0 min to make repairs and restart. Determine (a) hourly production rate and (b) line efficiency.

Solution: (a) Assume $p = 0$ at the manual station
$F = np = 1(0) + 5(.015) = 0.075$
$T_p = 0.5 + 0.075(3.0) = 0.5 + .225 = 0.725$ min
$R_p = 60/0.725 =$ **82.76 units/hr**

(b) $E = T_c/T_p = 0.5/0.725 =$ **0.690**

39.12 A 7-station transfer line has been observed over a 40-hour period. The process times at each station are as follows: station 1, 0.80 min; station 2, 1.10 min; station 3, 1.15 min; station 4, 0.95 min; station 5, 1.06 min; station 6, 0.92 min; and station 7, 0.80 min. The transfer time between stations = 6 sec. The number of downtime occurrences = 110, and hours of downtime = 14.5 hours. Determine (a) the number of parts produced during the week, (b) the average actual production rate in parts/hour, and (c) the line efficiency. (d) If the balancing efficiency were computed for this line, what would its value be?

Solution: (a) $T_c = 1.15 + 0.10 = 1.25$ min
$EH = 40E = 40 - 14.5 = 25.5$ hrs
$Q = 25.5(60)/1.25 =$ **1224 pc** during the 40 hour period.

(b) $R_p = 1224/40 =$ **30.6 pc/hr**

(c) $40E = 25.5$ $E = 25.5/40$ **= 0.6375**

(d) $T_{wc} = \Sigma\, T_s = 0.80 + 1.10 + 1.15 + 0.95 + 1.06 + 0.92 + 0.80 = 6.78$ min
n(maximum T_s) = 7(1.15) = 8.05 min
$E_b = 6.78/8.05 =$ **0.842**

39.13 A 12-station transfer line was designed to operate with an ideal production rate = 50 parts/hour. However, the line does not achieve this rate, since the line efficiency = 0.60. It costs $75/hour to operate the line, exclusive of materials. The line operates 4000 hours per year. A computer monitoring system has been proposed that will cost $25,000 (installed) and will reduce downtime on the line by 25%. If the value added per unit produced = $4.00, will the computer system pay for itself within one year of operation? Use expected increase in revenues resulting from the computer system as the criterion. Ignore material costs in your calculations.

Solution: $T_c = 60/R_c = 60/50 = 1.2$ min
$T_p = T_c/E = 1.2/.6 = 2.0$ min
$R_p = 60/T_p = 60/2.0 = 30$ pc/hr

In the current system:
Annual production $Q = 4000R_p = 4000(30) = 120{,}000$ units/yr
Revenues = 4.00Q$ = $4.00(120,000) = $480,000/yr.
Cost to operate line = 75H$ = $75(4000) = $300,000/yr

With computer monitoring system:
$T_c = 1.2$ min and $T_p = 2.0$ min. $FT_d = T_p - T_c$. This is reduced by 25% with new system.
$FT_d = (1 - 25\%)(2.0 - 1.2) = 0.75(0.8) = 0.6$ min
$T_p = 1.2 + 0.6 = 1.8$ min
$R_p = 60/1.8 = 33.33$ pc/hr
Annual production $Q = 4000(33.33) = 133{,}333$ units/yr
Revenues = $4.00(133,333) = $533,333/yr.
Cost to operate line = same as in current system (neglecting increased cost of new system)

Difference in revenues = $533,333 - $480,000 = **$53,333**. This is more than enough to justify the $25,000 investment.

39.14 An automated transfer line is to be designed. Based on previous experience, the average downtime per occurrence = 5.0 min, and the probability of a station failure that leads to a downtime occurrence $p = 0.01$. The total work content time = 9.8 min and is to be divided evenly amongst the workstations, so that the ideal cycle time for each station = $9.8/n$. Determine (a) the optimum number of stations on the line n that will maximize production rate, and (b) the production rate and proportion uptime for your answer to part (a).

Solution: (a) Maximizing R_p is equivalent to minimizing T_p.
$T_p = T_c + Ft_d = 9.8/n + n(0.01)(5.0) = 9.8/n + 0.05n$
$dT_p/dn = -9.8/n^2 + 0.05 =$ zero at minimum point
$n^2 = 9.8/0.05 = 196$
$n = (196)^{.5} =$ **14 stations**

(b) $T_p = 9.8/14 + 0.05(14) = 0.7 + 0.7 = 1.4$ min
$R_p = 60/1.4 =$ **42.86 pc/hr** $E = 0.7/1.4 =$ **0.50**

40 MANUFACTURING ENGINEERING

Review Questions

40.1 Define manufacturing engineering.

Answer. Manufacturing engineering is a technical staff department responsible for planning the manufacturing processes for a product and its components.

40.2 What are the principal activities in manufacturing engineering?

Answer. Principal activities in manufacturing engineering are (1) process planning, (2) technical problem solving and continuous improvement, and (3) advising the product designers in design for manufacturability.

40.3 Identify some of the details and decisions that are included within the scope of process planning.

Answer. Table 40.1 lists the following details and decisions in process planning: (1) the processes required and the sequence in which they are performed; (2) equipment selection; (3) tools, dies, molds, fixtures, and gages that will be needed; (4) cutting tools and cutting conditions for machining operations; (5) methods for manual operations (e.g., assembly) and manual portions of machine cycles (e.g., loading and unloading a production machine); (6) time standards for each operation; and (7) estimates of production costs. Not all of these details and decisions are the exclusive responsibility of the manufacturing engineering department.

40.4 What is a route sheet?

Answer. A route sheet is a listing of the production operations and their sequence required to make a given part. It also lists the equipment and special tooling that is required.

40.5 What is the difference between a basic process and a secondary process?

Answer. A basic process establishes the starting geometry of the work material; e.g., casting, rolled sheet metal, drawn metal bar. Secondary processes are used to refine the starting geometry and transform the material into final shape and size; machining and sheet metal pressworking are common secondary processes.

40.6 What is a precedence constraint in process planning?

Answer. A precedence constraint is a limitation on the order in which processing or assembly operations can be performed on a given workpart; for example, a hole must be drilled before it can be tapped.

40.7 In the make or buy decision, why is it that purchasing a component from a vendor may cost more than producing the component internally, even though the quoted price from the vendor is lower than the internal price?

Answer. Because purchasing the component may cause idle equipment and staff in the factory that the company must still pay for.

40.8 Identify some of the important factors that should enter into the make or buy decision.

Answer. The factors in the make or buy decision include (1) cost, (2) whether the process is available internally, (3) production quantity, (4) product life, (5) whether or not the component is a standard commercially available hardware item, (6) supplier reliability, and (7) possible need for alternative sources.

40.9 Name three of the general principles and guidelines in design for manufacturability.

Answer. Table 40.5 lists the following DFM principles and guidelines: (1) Minimize number of components. (2) Use standard commercially available components. (3) Use common parts across product lines. (4) Design for ease of part fabrication. (5) Design parts with tolerances that are within process capability. (6) Design the product to be foolproof during assembly. (7) Minimize flexible components. (8) Design for ease of assembly. (9) Use modular design. (10) Shape parts and products for ease of packaging. (11) Eliminate or reduce adjustment required.

40.10 What is concurrent engineering and what are its important components?

Answer. Concurrent engineering is an approach used by companies to reduce the time to bring a new product to market. It includes (1) design for manufacturability, (2) design for quality, (3) design for life cycle, and (4) design for cost. It also includes certain organizational changes that attempt to bring different functions in the company together during product design to consider all possible aspects of the product.

40.11 What is meant by the term design for life cycle?

Answer. Design for life cycle means that factors relating to the product after it has been manufactured should be taken into consideration in design. These factors include ease of installation, reliability, maintainability, serviceability, upgradeability, and disposability.

Multiple Choice Quiz

There are 19 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

40.1 The manufacturing engineering department in an organization is best described as which one of the following: (a) branch of the sales department, (b) concurrent engineers, (c) management, (d) product designers, (e) production supervisors, or (f) technical staff function?

Answer. (f).

40.2 Which of the following are the usual responsibilities of the manufacturing engineering department (four best answers): (a) advising on design for manufacturability, (b) facilities planning, (c) marketing the product, (d) plant management, (e) process improvement, (f) process planning, (g) product design, (h) solving technical problems in the production departments, and (i) supervision of production workers?

Answer. (a), (e), (f), and (h).

40.3 Which of the following are considered basic processes, as opposed to secondary processes (four correct answers): (a) annealing, (b) anodizing, (c) drilling, (d) electroplating, (e) forward hot extrusion to produce aluminum bar stock, (f) impression die forging, (g) rolling of sheet steel, (h) sand casting, (i) sheet-metal stamping, (j) spot welding, (k) surface grinding of hardened steel, (l) tempering of martensitic steel, and (m) turning?

Answer. (e), (f), (g), and (h).

40.4 Which of the following would be considered secondary processes, as opposed to basic processes (four correct answers): (a) annealing, (b) arc welding, (c) drilling, (d) electroplating, (e) extrusion to produce steel automotive components, (f) impression die forging, (g) painting, (h) plastic injection molding, (i) rolling of sheet steel, (j) sand casting, (k) sheet-metal stamping, (l) sintering of pressed ceramic powders, and (m) ultrasonic machining?

Answer. (c), (e), (k), and (m).

40.5 Which of the following are operations to enhance physical properties (three correct answers): (a) annealing, (b) anodizing, (c) die casting, (d) drilling, (e) electroplating, (f) rolling of nickel alloys, (g) sheet metal drawing, (h) sintering of pressed ceramic powders, (i) surface grinding of hardened steel, (j) tempering of martensitic steel, (k) turning, and (l) ultrasonic cleaning?

Answer. (a), (h), and (j).

40.6 A route sheet is a document whose principal function is which one of the following: (a) continuous improvement, (b) design for manufacturability, (c) provides authorization for material handlers to move the part, (d) quality inspection procedure, (e) specifies the process plan, or (f) specifies the detailed method for a given operation?

Answer. (e).

40.7 In a make or buy situation, the decision should always be to purchase the component if the vendor's quoted price is less than the in-house estimated cost of the component: (a) true or (b) false?

Answer. (b).

40.8 Which one of the following types of computer-aided process planning relies on parts classification and coding in group technology: (a) generative CAPP, (b) retrieval CAPP, (c) traditional process planning, or (d) none of the preceding?

Answer. (b).

41 PRODUCTION PLANNING AND CONTROL

Review Questions

41.1 What is meant by the term make-to-stock production?

Answer. Make-to-stock is the case in which the company produces to replenish inventories of products. Production rate is greater than demand rate, and it is appropriate to carry inventory.

41.2 How does aggregate planning differ from the master production scheduling?

Answer. Aggregate planning is scheduling by general product line; the master production schedule indicates how many and when of each product model within the product line are to be produced.

41.3 What are the product categories usually listed in the master production schedule?

Answer. The categories are (1) firm customer orders, (2) sales forecasts, and (3) spare parts.

41.4 What is the difference between dependent and independent demand for products?

Answer. Independent demand means that the demand or consumption of the item is unrelated to demand for other items. End products and spare parts experience independent demand. Dependent demand refers to the fact that demand for the item is directly related to demand for something else, usually because the item is a component of an end product subject to independent demand.

41.5 Define reorder point inventory system.

Answer. In a reorder point system, an order to restock is issued when the inventory level for the given stock item declines to some point defined as the reorder point.

41.6 In MRP, what are common use items?

Answer. Common use items are materials, components, or subassemblies that are used for more than one item in the next level above in the product structure; for example, a starting material such as sheet metal stock that is used on more than one component, or a component that is used on more than one product.

41.7 Identify the inputs to the MRP processor in material requirements planning.

Answer. The inputs to MRP are (1) master production schedule, (2) bill-of-materials file for product structure, and (3) inventory record file.

41.8 What are some of the resource changes that can be made to increase plant capacity in the short run?

Answer. Short term adjustments to increase capacity include (1) increase employment levels, (2) increase shift hours, (3) authorize overtime, (4) increase number of shifts, and (5) subcontracting work to outside vendors.

41.9 Identify the principal objective in just-in-time production.

Answer. The principal objective in just-in-time production is reduction of in-process inventory.

41.10 How is a pull system distinguished from a push system in production and inventory control?

Answer. In a pull system, authorization to produce parts originates from downstream stations. Parts are "ordered" from upstream stations. A push system, by contrast, operates by supplying parts to each station in the plant, in effect driving the work from upstream stations to downstream stations. An MRP system operates as a push system.

41.11 What are the three phases in shop floor control?

Answer. The three phases are (1) order release, (2) order scheduling, and (3) order progress.

Multiple Choice Quiz

There are 15 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

41.1 Which one of the following terms best describes the overall function of production planning and control: (a) inventory control, (b) manufacturing logistics, (c) manufacturing engineering, (d) mass production, or (e) product design?

Answer. (b).

41.2 Which of the following are the three categories of items usually listed in the master production schedule: (a) components used to build the final products, (b) firm customer orders, (c) general product lines, (d) orders for maintenance and spare parts, (e) sales forecasts, and (f) spare tires?

Answer. (b), (d), and (e).

41.3 Inventory carrying costs include which of the following (two best answers): (a) equipment downtime, (b) interest, (c) production, (d) setup, (e) spoilage, (f) stock-out, and (g) storage?

Answer. (b) and (g).

41.4 Which of the following are the three terms in the economic order quantity formula: (a) annual demand rate, (b) batch size, (c) cost per piece, (d) holding cost, (e) interest rate, and (f) setup cost?

Answer. (a), (d), and (f).

41.5 Order point inventory systems are intended for which of the following (two best answers): (a) dependent demand items, (b) independent demand items, (c) low production quantities, (d) mass production quantities, and (e) mid-range production quantities?

Answer. (b) and (e).

41.6 With which of the following manufacturing resources is capacity requirements planning primarily concerned (two best answers): (a) component parts, (b) direct labor, (c) inventory storage space, (d) production equipment, and (e) raw materials?

Answer. (b) and (d).

41.7 The word kanban is most closely associated with which one of the following: (a) capacity planning, (b) economic order quantity, (c) just-in-time production, (d) master production schedule, or (e) material requirements planning?

Answer. (c).

41.8 Machine loading refers most closely to which one of the following: (a) assigning jobs to a work center, (b) floor foundation in the factory, (c) managing work-in-process in the factory, (d) releasing orders to the shop, or (e) sequencing jobs through a machine?

Answer. (a).

Problems

Inventory Control

41.1 A product is made to stock. Annual demand is 86,000 units. Each unit costs \$9.50 and the annual holding cost rate is 22%. Setup cost to produce this product is \$800. Determine (a) economic order quantity and (b) total inventory costs for this situation.

Solution: (a) $EOQ = (2D_aC_{su}/C_h)^{0.5} = (2 \text{ x } 86{,}000 \text{ x } 800/(0.22 \text{ x } 9.50))^{0.5}$ = **8114 units**

(b) $TIC = C_hQ/2 + C_{su}D_a/Q = 0.22(9.50)(8114/2) + 800(86{,}000/8114) = 8479 + 8479$ = **\$16,958**

41.2 Given that annual demand for a product is 20,000 units, cost per unit = \$6.00, holding cost rate = 2.5%/month, changeover (setup) time between products averages 2.0 hr, and downtime cost during changeover = \$200/hr, determine (a) economic order quantity and (b) total inventory costs for this situation.

Solution: (a) $EOQ = (2D_aC_{su}/C_h)^{0.5} = (2 \text{ x } 20{,}000 \text{ x } 2 \text{ x } 200/(12 \text{ x } .025 \text{ x } 6.00))^{0.5}$ = **2981 units**

(b) $TIC = C_hQ/2 + C_{su}D_a/Q = 12 \text{ x } 0.025(6.00)(2981/2) + 2 \text{ x } 200(20{,}000/2981)$
= 2683 + 2684 = **\$5367**

41.3 A product is produced in batches. Batch size = 2000 units. Annual demand = 50,000 units, and unit cost of the product = \$4.00. Setup time to run a batch = 2.5 hr, cost of downtime on the affected equipment is figured at \$250/hr, and annual holding cost rate = 30%. What would the annual savings be if the product were produced in the economic order quantity?

Solution: Current $TIC = C_hQ/2 + C_{su}D_a/Q = 0.30(4.00)(2000/2) + 2.5 \text{ x } 250(50{,}000/2000)$
= 1200 + 15,625 = \$16,825
$EOQ = (2D_aC_{su}/C_h)^{0.5} = (2 \text{ x } 50{,}000 \text{ x } 2.5 \text{ x } 250/(0.30 \text{ x } 4.00))^{0.5} = 7217$ units
TIC at $EOQ = C_hQ/2 + C_{su}D_a/Q = 0.30(4.00)(7217/2) + 2.5 \text{ x } 250(50{,}000/7217)$
= 4330 + 4330 = \$8660
Savings = 16,825 - 8660 = **\$8165**

41.4 Assembly of a product requires that a component part be ordered and stocked. Demand for the product is constant throughout the year at 7800 units annually. The cost to place an order is \$95. The cost of the part is \$56 and the holding cost rate is 22%. When units are ordered, they take two weeks to arrive. Determine (a) the economic order quantity and (b) the reorder point. (c) The parts are prepackaged in multiples of 100. It saves the supplier unpacking and repackaging time if they can ship in multiples of 100. The supplier has offered to reduce the price by \$1 per unit if even multiples of 100 are purchased. How much would be saved (if anything) by taking this offer?

Solution: (a) $EOQ = (2D_aC_{su}/C_h)^{0.5} = (2 \text{ x } 7800 \text{ x } 95/(0.22 \text{ x } 56))^{0.5} = 346.83$ = **347 units**

(b) Weekly demand is 7800/52 = 150 units/wk. If it takes 2 weeks for an order to arrive, you must reorder when the supply reaches 2*150 = **300 units**

(c) Since total cost is not a linear function, you must check the cost both above and below the EOQ. Also, since the item cost is lower, you must calculate total cost instead of total inventory cost.

$TC_{EOQ} = D_aC_p + C_hQ/2 + C_{su}D_a/Q = 7800(56) + (56)(0.22)(347)/2 + 95(7800)/347$

$TC_{EOQ} = 436{,}800 + 2137.52 + 2134.45 = \$\ 441{,}073$

$TC_{300} = 7800(55) + (55)(0.22)(300)/2 + 95(7800)/300 = 429000 + 1815 + 2470 = \$\ 433{,}285$

$TC_{400} = 7800(55) + (55)(0.22)(400)/2 + 95(7800)/400 = 429000 + 2420 + 1852.50$ = **\$ 433,273**

It is cheapest to buy 400 units at a time. That will save **\$7800 per year**

41.5 A certain piece of production equipment is used to produce various components for an assembled product. To keep in-process inventories low, it is desired to produce the components in batch sizes of 150 units. Demand for each product is 2500 units per year. Production downtime costs an estimated $200/hr. All of the components made on the equipment are of approximately equal unit cost, which is $9.00. Holding cost rate = 30%/yr. In how many minutes must the changeover between batches be completed in order for 150 units to be the economic order quantity?

Solution: $EOQ = (2D_aC_{su}/C_h)^{0.5}$
$(EOQ)^2 = 2D_aC_{dt}T_{su}/hC_p$
$T_{su} = hC_p(EOQ)^2/2D_a\,C_{dt}$ = 0.3(9.00)(150)^2/(2 x 2500 x 200) = **0.06075 hr = 3.65 min.**

41.6 Current setup time on a certain machine is 3.0 hr. Cost of downtime on this machine is estimated at $200/hr. Annual holding cost per part made on the equipment, C_h = $1.00. Annual demand for the part is 15,000 units. Determine (a) *EOQ* and (b) total inventory costs for this data. Also, determine (c) *EOQ* and (d) total inventory costs, if the changeover time could be reduced to six minutes.

Solution: (a) $EOQ = (2D_aC_{su}/C_h)^{0.5}$ = (2 x 15,000 x 3.00 x 200/1.00)$^{0.5}$ = **4243 pc**

(b) $TIC = C_hQ/2 + C_{su}D_a/Q$ = 1.00(4243/2) + 3.00 x 200(15,000/4243)
= 2121.50 + 2121.14 = **$4242.64**

(c) If T_{su} = 6 min = 0.1 hr, $C_{su} = C_{dt}T_{su}$ = 200(0.1) = $20.
EOQ = (2 x 15,000 x 20/1.00)$^{0.5}$ = **775 pc**

(d) *TIC* = 1.00(775/2) + 20(15,000/775) = 387.50 + 387.10 = **$774.60**

41.7 The two-bin approach is used to control inventory for a particular low-cost component. Each bin holds 1200 units. The annual usage of the component is 45,000 units. Cost to order the component is around $70. (a) What is the imputed holding cost per unit for this data? (b) If the actual annual holding cost per unit is only 7 cents, what lot size should be ordered? (c) How much more is the current two-bin approach costing the company annually, compared to the economic order quantity?

Solution: (a) $EOQ = (2D_aC_{su}/C_h)^{0.5}$
1200 = (2 x 45,000 x 70/C_h)$^{0.5}$
C_h = 2 x 45,000 x 70/1200^2 = $4.38 annually

(b) Given C_h = $0.07, *EOQ* = (2 x 45,000 x 70/0.07)$^{0.5}$ = 9486.83 → **9487 pc**

(c) For the two-bin approach in which *Q* = 1200, TIC = 0.07(1200/2) + 70(45,000/1200)
= 42 + 2625 = $2667.00
For the *EOQ* = 9487, *TIC* = 0.07(9487/2) + 70(45,000/9487) = 332.05 + 332.03 = $664.08
Additional cost = 2667.00 – 664.08 = **$2002.92**

Material Requirements Planning

41.8 Quantity requirements are to be planned for component C2 in product P1. Required deliveries for P1 are given in Table 41.1. Ordering, manufacturing, and assembly lead times are as follows: for P1 and C2, the lead time is one week; and for S1 and M2, the lead time is two weeks. Given the product structure in Figure 41.4, determine the time-phased requirements for M2, C2, and S1 to meet the master schedule for P1. Assume no common use items and all on-hand inventories and scheduled receipts are zero. Use a format similar to Table 41.2 and develop a spreadsheet calculator to solve. Ignore demand for P1 beyond period 10.

Solution:

Period	1	2	3	4	5	6	7	8	9	10
P1 Requirements								50	75	100
Order Release							50	75	100	

S1 Requirements							50	75	100	
Order Release					50	75	100			
C2 Requirements					200	300	400			
Order Release				200	300	400				
M2 Requirements				200	300	400				
Order Release		200	300	400						

41.9 Requirements are to be planned for component C5 in product P1. Required deliveries for P1 are given in Table 41.1. Ordering, manufacturing, and assembly lead times are as follows: for P1 and S2, the lead time is one week; for C5, the lead time is three weeks; and for M5, the lead time is 2 weeks. Given the product structure in Figure 41.4, determine the time-phased requirements for M5, C5, and S2 to meet the master schedule for P1. Assume no common use items. On-hand inventories are 200 units for M5 and 100 units for C5, zero for S2. Use a format similar to Table 41.2 and develop a spreadsheet calculator to solve. Ignore demand for P1 beyond period 10.

Solution:

Period	1	2	3	4	5	6	7	8	9	10
P1 Requirements								50	75	100
On-hand: 0										
Net Requirements								50	75	100
Order Release							50	75	100	
S2 Requirements							100	150	200	
On hand: 0										
Net Requirements							100	150	200	
Order Release						100	150	200		
C5 Requirements						200	300	400		
On hand: 100						100				
Net Requirements						100	300	400		
Order Release			100	300	400					
M5 Requirements			100	300	400					
On hand: 200			100	100						
Net Requirements			0	200	400					
Order Release	0	200	400							

41.10 Solve Problem 41.9 except that the following is known in addition to the information given: scheduled receipts of M5 are 250 units in period (week) 3 and 50 units in period (week) 4.

Solution:

Period	1	2	3	4	5	6	7	8	9	10
P1 Requirements								50	75	100
On-hand: 0										
Net Requirements								50	75	100
Order Release							50	75	100	
S2 Requirements							100	150	200	
On hand: 0										
Net Requirements							100	150	200	
Order Release						100	150	200		

C5 Requirements						200	300	400		
On hand: 100						100				
Net Requirements						100	300	400		
Order Release			100	300	400					
M5 Requirements			100	300	400					
Scheduled Receipts			250	50						
On hand: 200			450	350	100					
Net Requirements			-350	-100	300					
Order Release	0	0	300							

Order Scheduling

41.11 Four products are to be manufactured in Department A, and it is desired to determine how to allocate resources in that department to meet the required demand for these products for a certain week. For product 1, demand = 750/wk, setup time = 6 hr, and operation time = 4.0 min. For product 2, demand = 900/wk, setup time = 5 hr, and operation time = 3.0 min. For product 3, demand = 400/wk, setup time = 7 hr, and operation time = 2.0 min. For product 4, demand = 400/wk, setup time = 6 hr, and operation time = 3.0 min. The plant normally operates one shift (7.0 hours per shift), five days per week and there are currently 3 work centers in the department. Propose a way of scheduling the machines to meet the weekly demand.

Solution: Determine time to produce each product, assuming a single setup for each product:
Product 1: Time per batch = 6.0 + 750(4/60) = 6 + 50 = 56 hr.
Product 2: Time per batch = 5.0 + 900(3/60) = 5 + 45 = 50 hr
Product 3: Time per batch = 7.0 + 400(2/60) = 7 + 13.333 = 20.333 hr
Product 4: Time per batch = 6.0 + 400(3/60) = 6 + 20 = 26 hr
Total hours for all four products = 56 + 50 + 20.333 + 26 = 152.333 hr.

Available hours per week on 3 work centers if normal hours are assumed = 3 x (5 x 7) = 105 hr. This is fewer than the number of hours required. To meet the weekly production, overtime must be used. The following schedule is proposed:

Work center	Product	Quantity	Setup hours	Run hours	Hrs/product	Hrs/wk center
I	1	750	6.0	50.0	56.0	56.0
II	2	900	5.0	45.0	50.0	50.0
III	3	400	7.0	13.333	20.333	
	4	400	6.0	20.0	26.0	46.333
Totals			24.0	128.333	152.333	152.333

41.12 In the previous problem, propose a way of scheduling to meet the weekly demand if there were four machines instead of three.

Solution: Time to produce each product is the same as given in the preceding solution, under the assumption that a single setup is required for each product. Available hours per week on 4 work centers if normal hours are assumed = 4 x (5 x 7) = 140 hr. This is fewer than the number of hours required. To meet the weekly production, overtime must be used. In order to equalize the workload among machines as much as possible, let us propose to produce products 1 and 3 on work centers 1 and 2 and Products 2 and 4 on work centers 3 and 4. In both cases, this will require an additional setup

We want to equalize the workload on work centers I and II with Products 1 and 3.
Work center I: $T_I = 6.0 + Q_I(4/60) = 6.0 + 0.06667Q_I$
Work center II: $T_{II} = 6.0 + 0.06667(750 - Q_I) + 7.0 + 400(2/60) = 76.333 - 0.06667Q_I$
Setting $T_I = T_{II}$: $6.0 + 0.06667Q_I = 76.333 - 0.06667Q_I$

$2(0.06667\ Q_I) = 0.13334\ Q_I = 76.333 - 6.0 = 70.333$
$Q_I = 70.333/0.13334 = 528$
$T_I = 6.0 + 0.06667(528) = 41.20$ hr
$T_{II} = 76.333 - 0.06667(528) = 41.133$ hr.

We next want to equalize the workload on work centers III and IV with Products 2 and 4.
Work center III: $T_{III} = 5.0 + Q_{III}(3/60) = 5.0 + 0.05\ Q_{III}$
Work center IV: $T_{IV} = 5.0 + 0.05(900 - Q_{III}) + 6.0 + 400(3/60) = 76.0 - 0.05\ Q_{III}$
Setting $T_{III} = T_{IV}$: $5.0 + 0.05\ Q_{III} = 76.0 - 0.05Q_{III}$
$2(0.05\ Q_{III}) = 0.10\ Q_I = 76.0 - 5.0 = 71.0$
$Q_I = 71.0/0.10 = 710$
$T_I = 5.0 + 0.05(710) = 40.50$ hr
$T_{II} = 76.0 - 0.05(710) = 40.50$ hr.

The following table summarizes the production at each work center:

Work center	Product	Quantity	Setup hours	Run hours	Hrs/product	Hrs/wk center
I	1	528	6.0	35.20	41.20	41.20
II	1	222	6.0	14.80	20.80	
	3	400	7.0	13.33	20.33	41.13
III	2	710	5.0	35.50	40.50	40.50
IV	2	190	5.0	9.50	14.50	
	4	400	6.0	20.00	26.00	40.50
Totals			35.0	128.33	163.33	163.33

41.13 The current date in the production calendar is day 14. There are three orders (A, B, and C) to be processed at a particular work center. The orders arrived in the sequence A-B-C at the work center. For order A, the remaining process time = 8 days, and the due date is day 24. For order B, the remaining process time = 14 days, and the due date is day 33. For order C, the remaining process time = 6 days, and the due date is day 26. Determine the sequence of the orders that would be scheduled using (a) first-come-first-serve, (b) earliest due date, (c) shortest processing time, (d) least slack time, and (e) critical ratio.

Solution: (a) FCFS: sequence = **A - B - C**

(b) Earliest due date: sequence = **A - C - B**

(c) Shortest processing time: sequence = C **- A - B**

(d) Least slack time:
Order A slack time = (24 - 14) - 8 = 2
Order B slack time = (33 - 14) - 14 = 5
Order C slack time = (26 - 14) - 6 = 6
Sequence = **A - B - C**

(e) Critical ratio:
Order A critical ratio = (24 - 14)/8 = 1.25
Order B critical ratio = (33 - 14)/14 = 1.357
Order C critical ratio = (26 - 14)/6 = 2.0
Sequence = **A - B - C**

41.14 Five jobs are waiting to be scheduled on a machine. For order A, the remaining process time = 5 days, and the due date is day 8. For order B, the remaining process time = 7 days, and the due date is day 16. For order C, the remaining process time = 11 days, and the due date is day 22. For order D, the remaining process time = 9 days, and the due date is day 31. For order E, the remaining process time = 10 days, and the due date is day 26. Determine a production schedule based on (a) shortest processing time, (b) earliest due date, (c) critical ratio, and (d) least slack time. All times are listed in days.

Solution: (a) SPT: The schedule is: **A – B – D – E – C**

(b) EDD: The schedule is: **A – B – C – E – D**

(c) Critical Ratio:

A critcal ratio 8/5 = 1.6
B critical ratio 16/7 = 2.29
C critical ratio 22/11 = 2.0
D critical ratio 31/9 = 3.44
E critical ratio 26/10 = 2.6

The schedule is: **A – C – B – E – D**

(d) Least Slack Time

A Slack Time 8 – 5 = 3
B Slack Time 16 – 7 = 9
C Slack Time 22 – 11 = 11
D Slack Time 31 – 9 = 22
E Slack Time 26 – 10 = 16

The schedule is: **A – B – C – E – D**

42 QUALITY CONTROL AND INSPECTION

Review Questions

42.1 What are the two principal aspects of product quality?

Answer. The two quality aspects are (1) product features and (2) freedom from deficiencies.

42.2 How is a process operating in statistical control distinguished from one that is not?

Answer. The process in statistical control is characterized by only random variations. A process that is out of control exhibits additional variation that is not normal, called assignable variation. This indicates that something is wrong with the process.

42.3 Define process capability.

Answer. Process capability is the limits of the random variations of the process when it is in statistical control. The limits are defined as the process mean ± 3 standard deviations.

42.4 What are the natural tolerance limits?

Answer. The natural tolerance limits are when the tolerance on a part is set equal to the process capability; that is $\pm 3\sigma$ of the process mean.

42.5 What is the difference between control charts for variables and control charts for attributes?

Answer. In control charts for variables, measurements of the characteristic of interest are made. In control charts for attributes, the characteristic of interest is identified as being acceptable of not acceptable.

42.6 Identify the two types of control charts for variables.

Answer. The two charts are (1) $\bar{x}$ chart for sample means and (2) R chart for ranges.

42.7 What are the two basic types of control charts for attributes?

Answer. The two charts are (1) p chart for proportion of defects in a sample, and (2) c chart for count of defects in a sample.

42.8 When interpreting a control chart, what does one look for to identify problems?

Answer. Problems are indicated by the following: (1) $\bar{x}$ or R lie outside their respective LCL or UCL limits; (2) trends or cyclical patterns in the data; (3) sudden changes in average; and (4) points consistently near the upper or lower limits.

42.9 What are the three main goals in total quality management (TQM)?

Answer. The three main goals in TQM are (1) achieving customer satisfaction, (2) encouraging the involvement of the entire workforce, and (3) continuous improvement.

42.10 What is the difference between external customers and internal customers in TQM?

Answer. External customers are those who purchase the company's products and services. Internal customers are inside the company, such as the company's final assembly department which is the customer of the parts production departments.

42.11 At what company was the Six Sigma quality program first used?

Answer. Motorola Corporation.

42.12 Why is the Normal statistical table used in a Six Sigma program different from the standard normal tables found in textbooks on probability and statistics?

Answer. The Normal statistical tables used in a Six Sigma program differ from the standard normal tables in the following two ways: (1) the Six Sigma table includes only one tail of the normal distribution and (2) the Six Sigma table is shifted by 1.5σ, so that 6σ in the Six Sigma table is the same as 4.5σ in the standard normal tables.

42.13 A Six Sigma program uses three measures of defects per million (DPM) to assess the performance of a given process. Name the three measures of DPM.

Answer. The three measures of DPM are (1) defects per million opportunities, (2) defects per million units, and (3) defective units per million units.

42.14 What is meant by robust design, as defined by Taguchi?

Answer. Robust design means that a product or process is designed so that its function and performance are relatively insensitive to variations in design and manufacturing parameters that are bound to occur.

42.15 Automated inspection can be integrated with the manufacturing process to accomplish certain actions. What are these possible actions?

Answer. Possible actions discussed in text are (1) parts sortation and (2) feedback of data to adjust the process.

42.16 Give an example of a noncontact inspection technique.

Answer. Non-contact inspection techniques include machine vision, laser measuring methods, and electrical field techniques.

42.17 What is a coordinate measuring machine?

Answer. A CMM is an automated measuring machine consisting of a contact probe and a means to position the probe in three dimensions relative to workpart features and surfaces; when the probe contacts the part, the x-y-z coordinates are recorded.

42.18 Describe a scanning laser system.

Answer. The scanning laser system uses a laser beam deflected by a rotating mirror to produce a beam of light that sweeps past an object. A photodetector on the far side of the object senses the light beam during its sweep except for the short time when it is interrupted by the object. This time period can be measured quickly with great accuracy. A microprocessor system measures the time interruption that is related to the size of the object in the path of the laser beam, and converts from time to a linear dimension.

42.19 What is a binary vision system?

Answer. In a binary vision system, the light intensity of each pixel is reduced to either of two values (black or white, 0 or 1).

42.20 Name some of the nonoptical noncontact sensor technologies available for inspection.

Answer. The technologies include electrical fields (capacitance, inductance), radiation (X-ray), and ultrasonic techniques (high frequency sound).

Multiple Choice Quiz

There are 23 correct answers in the following multiple choice questions (some questions have multiple answers that are correct). To attain a perfect score on the quiz, all correct answers must be given. Each correct answer is worth 1 point. Each omitted answer or wrong answer reduces the score by 1 point, and

each additional answer beyond the correct number of answers reduces the score by 1 point. Percentage score on the quiz is based on the total number of correct answers.

42.1 Which of the following quality aspects would be classified as examples of freedom from deficiencies rather than product features (two correct answers): (a) components within tolerance, (b) location of ON/OFF switch, (c) no missing parts, (d) product weight, (e) reliability, and (f) reputation of the company?

Answer. (a) and (c).

42.2 If the product tolerance is set so that the process capability index = 1.0, then the percentage of parts that are within tolerance will be closest to which one of the following when the process is operating in statistical control: (a) 35%, (b) 65%, (c) 95%, (d) 99%, or (e) 100%?

Answer. (e).

42.3 In a control chart, the upper control limit is set equal to which one of the following: (a) process mean, (b) process mean plus three standard deviations, (c) upper design tolerance limit, or (d) upper value of the maximum range R?

Answer. (b).

42.4 The R chart is used for which one of the following product or part characteristics: (a) number of rejects in the sample, (b) number of reworked parts in a sample, (c) radius of a cylindrical part, or (d) range of sample values?

Answer. (d).

42.5 Which one of the following best describes the situations for which the c chart is most suited: (a) control of defective parts, (b) mean value of part characteristic of interest, (c) number of defects in a sample, or (d) proportion of defects in a sample?

Answer. (c).

42.6 Which of the following identify a likely out-of-control condition in a control chart (three correct answers): (a) consistently increasing value of $\bar{x}$, (b) points near the central line, (c) points oscillating back and forth across the central line, (d) R outside the control limits of the R chart, (e) sample points consistently slightly above the central line, and (f) $\bar{x}$ outside the control limits of the $\bar{x}$ chart?

Answer. (a), (d), and (f).

42.7 Which of the following are the three main goals in a total quality management (TQM) program: (a) achieving customer satisfaction, (b) computing defects per million, (c) continuous improvement, (d) developing robust product and process designs, (e) encouraging the involvement of the entire workforce, (f) forming worker teams, (g) statistical process control, and (h) zero defects?

Answer. (a), (c), and (e).

42.8 Which one of the following measures in a Six Sigma program allows products of different complexity to be directly compared: (a) defects per million units, (b) defects per million opportunities, or (c) defective units per million units?

Answer. (b).

42.9 Which of the following principles and/or approaches are generally credited to G. Taguchi (two correct answers): (a) acceptance sampling, (b) control charts, (c) loss function, (d) Pareto priority index, and (e) robust design?

Answer. (c) and (e).

42.10 Which of the following phrases relating to ISO 9000 are correct (three correct answers): (a) certified by the International Standards Office located in Geneva, Switzerland, (b) developed by the International Organization for Standardization located somewhere in Europe, (c) establishes standards for the quality systems and procedures used by a facility, (d) establishes standards for the products and services delivered by a facility, and (e) registration in ISO 9000 obtained through a third-party agency that certifies the facility's quality systems?

Answer. (b), (c), and (e).

42.11 The two basic types of inspection are inspection by variables and inspection by attributes. The second of these inspections uses which one of the following: (a) destructive testing, (b) gaging, (c) measuring, or (d) nondestructive testing?

Answer. (b).

42.12 Automated 100% inspection can be integrated with the manufacturing process to accomplish which of the following (two best answers): (a) better design of products, (b) feedback of data to adjust the process, (c) 100% perfect quality, and (d) sortation of good parts from defects?

Answer. (b) and (d) are mentioned in the text.

42.13 Which one of the following is an example of contact inspection: (a) coordinate measuring systems, (b) machine vision, (c) radiation techniques, (d) scanning laser systems, and (e) ultrasonic techniques?

Answer. (a).

42.14 Which one of the following is the most important application of vision systems: (a) inspection, (b) object identification, (c) safety monitoring, or (d) visual guidance and control of a robotic manipulator?

Answer. (a).

Problems

Note: Problems identified with an asterisk (*) in this set require the use of statistical tables not included in this text.

Process Capability and Tolerances

42.1 An automatic turning process is set up to produce parts with a mean diameter = 6.255 cm. The process is in statistical control and the output is normally distributed with a standard deviation = 0.004 cm. Determine the process capability.

Solution: Process capability $PC = \mu \pm 3\sigma = 6.255 \pm 3(0.004) =$ **6.255 ± 0.012 cm**
The upper and lower limits of the process capability range are: 6.243 to 6.267 cm

42.2 * In Problem 42.1, the design specification on the part is: diameter = 6.250 ±0.013 cm. (a) What proportion of parts fall outside the tolerance limits? (b) If the process were adjusted so that its mean diameter = 6.250 cm and the standard deviation remained the same, what proportion of parts would fall outside the tolerance limits?

Solution: (a) Given process mean $\mu = 6.255$ cm and $\sigma = 0.004$ cm and tolerance limits 2.237 to 2.263. On the lower side of the tolerance limit, using the standard normal distribution,
$z = (6.237 - 6.255)/0.004 = -4.50$. Conclusion: there are virtually no defects on the lower side of the tolerance. On the upper side of the tolerance limit, $z = (6.263 - 2.255)/0.004 = +2.00$
Using tables of the standard normal distribution, $\Pr(z > 2.00) = 0.0227$
The proportion of defects with the current process mean = **0.0227 = 2.27%.**

(b) Given process mean μ = 6.250 cm and σ = 0.004 cm and tolerance limits 6.237 to 6.263. On the lower side of the tolerance limit, z = (6.237 - 6.250)/0.004 = -3.25. Using tables of the standard normal distribution, Pr(z < -3.25) = 0.0006. On the upper side of the tolerance limit, z = (6.263 - 6.250)/0.004 = +3.25.
Using tables of the standard normal distribution, Pr(z > 3.25) = 0.0006
The proportion of defects with the current process mean = 0.0006 + 0.0006 = **0.0012 = 0.12%.**

42.3 A sheet-metal bending operation produces bent parts with an included angle = 92.1°. The process is in statistical control and the values of included angle are normally distributed with a standard deviation = 0.23°. The design specification on the angle = 90 ± 2°. (a) Determine the process capability. (b) If the process could be adjusted so that its mean = 90.0°, determine the value of the process capability index.

Solution: (a) PC = 92.1 ± 3(0.23) = 92.1° ± 0.69°.
The upper and lower limits of the process capability range are: 91.41° to 92.79°.

(b) If μ = 90°
T = 92° - 88° = 4°
PCI = 4°/(6 x 0.23°) = **2.9** → virtually no defects.

42.4 A plastic extrusion process produces round extrudate with a mean diameter = 28.6 mm. The process is in statistical control and the output is normally distributed with standard deviation = 0.53 mm. Determine the process capability.

Solution: Process capability $PC = \mu \pm 3\sigma$ = 28.6 ± 3(0.53) = **28.6 ± 1.59 mm**
The upper and lower limits of the process capability range are: 27.01 to 30.19 mm.

42.5 * In Problem 42.4, the design specification on the diameter is 28.0 ± 2.0 mm. (a) What proportion of parts fall outside the tolerance limits? (b) If the process were adjusted so that its mean diameter = 28.0 mm and the standard deviation remained the same, what proportion of parts would fall outside the tolerance limits? (c) With the adjusted mean at 28.0 mm, determine the value of the process capability index.

Solution: (a) Given process mean μ = 28.6 mm and σ = 0.53 mm and tolerance limits 26.0 to 30.0 mm. On the lower side of the tolerance limit, using the standard normal distribution,
z = (26.0 - 28.6)/0.53 = -4.01. Conclusion: there are virtually no defects on the lower side of the tolerance.
On the upper side of the tolerance limit, z = (30.0 - 28.6)/0.53 = +2.64
Using tables of the standard normal distribution, Pr(z > 2.64) = 0.0041
The proportion of defects with the current process mean = **0.0041 = 0.41%.**

(b) Given process mean μ = 28.0 mm and σ = 0.53 mm and tolerance limits 26.0 to 30.0 mm.
On the lower side of the tolerance limit, z = (26.0 - 28.0)/0.53 = -3.77. Using tables of the standard normal distribution, Pr(z < -3.77) = approx. 0.0001
On the upper side of the tolerance limit, z = (30.0 - 28.0)/0.53 = +3.77
Using tables of the standard normal distribution, Pr(z > 3.77) = approx. 0.0001
The proportion of defects with the current process mean = 0.0001 + 0.0001 = **0.0002 = 0.02%.**

(c) Process capability index PCI = 4.0/(6 x 0.53) = **1.258**

Control Charts

42.6 In 12 samples of size n = 7, the average value of the sample means is $\bar{\bar{x}}$ = 6.860 cm for the dimension of interest, and the mean of the ranges of the samples is $\bar{R}$ = 0.027 cm. Determine (a) lower and upper control limits for the $\bar{x}$ chart and (b) lower and upper control limits for the *R* chart. (c) What is your best estimate of the standard deviation of the process?

Solution: (a) $\bar{x}$ chart: $\bar{x}$ = 6.860 cm = CL

LCL = $\bar{x} - A_2\bar{R}$ = 6.860 - 0.419(0.027) = **6.8487 cm**

UCL = $\bar{x} + A_2\bar{R}$ = 6.860 + 0.419(0.027) = **6.8713 cm**

(b) R chart: $\bar{R}$ = 0.027 = CL

LCL = $D_3\bar{R}$ = 0.076(0.027) = **0.0205 cm**

UCL = $D_4\bar{R}$ = 1.924(0.027) = **0.0519 cm**

(c) The $\bar{x}$ chart is based on $\pm 3\ \sigma_x/\sqrt{n}$

Therefore, $A_2\bar{R} = 3\ \sigma_x/\sqrt{n}$

$\sigma_x = A_2\bar{R}\sqrt{n}/3 = 0.419(0.027)\sqrt{7}/3$ = **0.00998 cm**

42.7 In nine samples of size n = 10, the grand mean of the samples is $\bar{\bar{x}}$ = 100 for the characteristic of interest, and the mean of the ranges of the samples is $\bar{R}$ = 8.5. Determine (a) lower and upper control limits for the $\bar{x}$ chart and (b) lower and upper control limits for the *R* chart. (c) Based on the data given, estimate the standard deviation of the process?

Solution: (a) $\bar{x}$ chart: $\bar{x}$ = 100 = CL

LCL = $\bar{x} - A_2\bar{R}$ = 100 - 0.308(8.5) = **102.618**

UCL = $\bar{x} + A_2\bar{R}$ = 100 + 0.308(8.5) = **97.382**

(b) R chart: $\bar{R}$ = 8.5 = CL

LCL = $D_3\bar{R}$ = 0.223(8.5) = **1.8955**

UCL = $D_4\bar{R}$ = 1.777(8.5) = **15.1045**

(c) The $\bar{x}$ chart is based on $\pm 3\ \sigma_x/\sqrt{n}$

Therefore, $A_2\bar{R} = 3\ \sigma_x/\sqrt{n}$

$\sigma_x = A_2\bar{R}\sqrt{n}/3 = 0.308(8.5)\sqrt{10}/3$ = **2.7596**

42.8 Ten samples of size n = 8 have been collected from a process in statistical control, and the dimension of interest has been measured for each part. The calculated values of $\bar{x}$ for each sample are (mm) 9.22, 9.15, 9.20, 9.28, 9.19, 9.12, 9.20, 9.24, 9.17, and 9.23. The values of *R* are (mm) 0.24, 0.17, 0.30, 0.26, 0.26, 0.19, 0.21, 0.32, 0.21, and 0.23, respectively. (a) Determine the values of the center, LCL, and UCL for the $\bar{x}$ and *R* charts. (b) Construct the control charts and plot the sample data on the charts.

Solution: $\bar{\bar{x}} = \Sigma\,\bar{x}/\mathrm{m} = \Sigma\,\bar{x}/10$

= (9.22 + 9.15 + 9.20 + 9.28 + 9.19 + 9.12 + 9.20 + 9.24 + 9.17 + 9.23)/10 = 9.20

$\bar{R} = \Sigma\,R/10$ = (0.24 + 0.17 + 0.30 + 0.26 + 0.27 + 0.19 + 0.21 + 0.32 + 0.21 + 0.23)/10 = 0.24

(a) $\bar{x}$ chart: $\bar{x}$ = **9.20 mm = CL**

LCL = $\bar{x} - A_2\bar{R}$ = 9.20 - 0.373(0.24) = **9.1105 mm.**

UCL = $\bar{x} + A_2\bar{R}$ = 9.20 + 0.373(0.24) = **9.2895 mm.**

R chart: $\bar{R}$ = **0.024 = CL**

LCL = $D_3\bar{R}$ = 0.136(0.24) = **0.0326 mm.**

UCL = $D_4\bar{R}$ = 2.114(0.0133) = **0.4474 mm.**

(b) Student exercise.

42.9 Seven samples of 5 parts each have been collected from an extrusion process that is in statistical control, and the diameter of the extrudate has been measured for each part. The calculated values of $\bar{x}$ for each sample are (inch) 1.002, 0.999, 0.995, 1.004, 0.996, 0.998, and 1.006. The values of R are (inch) 0.010, 0.011, 0.014, 0.020, 0.008, 0.013, and 0.017, respectively. (a) Determine the values of the center, LCL, and UCL for $\bar{x}$ and R charts. (b) Construct the control charts and plot the sample data on the charts.

Solution: $\bar{\bar{x}} = \Sigma\bar{x}/7$ = (1.002 + 0.999 + 0.995 + 1.004 + 0.996 + 0.998 + 1.006)/7 = 1.000

$\bar{R} = \Sigma R/7$ = (0.010 + 0.011 + 0.014 + 0.020 + 0.008 + 0.013 + 0.017)/7 = 0.0133

(a) $\bar{x}$ chart: $\bar{x}$ = **1.000 in = CL**

LCL = $\bar{x} - A_2\bar{R}$ = 1.000 - 0.577(0.0133) = **0.9923 in**

UCL = $\bar{x} + A_2\bar{R}$ = 1.000 + 0.577(0.0133) = **1.0077 in**

R chart: $\bar{R}$ = **0.0133 = CL**

LCL = $D_3\bar{R}$ = 0(0.0133) = **0**

UCL = $D_4\bar{R}$ = 2.114(0.0133) = **0.0281 in**

(b) Student exercise.

42.10 A p chart is to be constructed. Six samples of 25 parts each have been collected, and the average number of defects per sample was 2.75. Determine the center, LCL and UCL for the p chart.

Solution: $\bar{p}$ = 2.75/25 = **0.11 = CL**

LCL = $\bar{p} - 3\sqrt{p(1-p)/n}$ = $0.11 - 3\sqrt{0.11(0.89)/25}$ = 0.11 - 3(0.0626) = **-0.078 → 0**

UCL = $\bar{p} + 3\sqrt{p(1-p)/n}$ = $0.11 + 3\sqrt{0.11(0.89)/25}$ = 0.11 + 3(0.0626) = **0.298**

42.11 Ten samples of equal size are taken to prepare a p chart. The total number of parts in these ten samples was 900 and the total number of defects counted was 117. Determine the center, LCL and UCL for the p chart.

Solution: $\bar{d}$ = 117/10 = 11.7.

$\bar{p}$ = 11.7/90 = **0.13 = CL**

LCL = $\bar{p} - 3\sqrt{p(1-p)/n}$ = $0.13 - 3\sqrt{0.13(0.87)/90}$ = 0.13 - 3(0.03545) = **0.024**

UCL = $\bar{p} + 3\sqrt{p(1-p)/n}$ = $0.11 + 3\sqrt{0.13(0.87)/90}$ = 0.11 + 3(0.03545) = **0.236**

42.12 The yield of good chips during a certain step in silicon processing of integrated circuits averages 91%. The number of chips per wafer is 200. Determine the center, LCL, and UCL for the p chart that might be used for this process.

Solution: Use p = 1 - 0.91 = **0.09 = CL**

LCL = $\bar{p} - 3\sqrt{p(1-p)/n}$ = $0.09 - 3\sqrt{0.09(0.91)/90}$ = 0.09 - 3(0.0202) = **0.0293**

UCL = $\bar{p} + 3\sqrt{p(1-p)/n}$ = $0.11 + 3\sqrt{0.09(0.91)/90}$ = 0.09 + 3(0.0202) = **0.1507**

42.13 The upper and lower control limits for a *p* chart are: LCL = 0.19 and UCL = 0.24. Determine the sample size *n* that is used with this control chart.

Solution: $\bar{p}$ = 0.5(UCL + LCL) = 0.5(.24 + .10) = 0.17

UCL - LCL = 0.24 - 0.10 = 0.14 = $6\sqrt{p(1-p)/n}$ = $6\sqrt{0.17(0.83)/n}$

$(0.14)^2 = 6^2$ (0.17 x 0.83/*n*)

0.0196 = 36(0.17)(0.83)/*n* = 5.0796/*n*

n = 5.0796/0.0196 = 259.2 → **259**

42.14 The upper and lower control limits for a *p* chart are: LCL = 0 and UCL = 0.20. Determine the minimum possible sample size *n* that is compatible with this control chart.

Solution: *p* = 0.5(UCL + LCL) = 0.5(.20 + 0) = 0.10

LCL = *p* - $3\sqrt{p(1-p)/n}$ = 0

Therefore, *p* = $3\sqrt{p(1-p)/n}$

0.10 = $3\sqrt{0.10(0.90)/n}$

$(0.10)^2 = 0.01 = 3^2$ (0.10)(0.90)/*n* = 0.81/*n*

n = 0.81/0.01 = **81**

42.15 Twelve cars were inspected after final assembly. The number of defects found ranged between 87 and 139 defect per car with an average of 116. Determine the center and upper and lower control limits for the *c* chart that might be used in this situation.

Solution: **CL = 116**

LCL = $\bar{c} - 3\sqrt{\bar{c}}$ = $116 - 3\sqrt{116}$ = **83.7 → 83**

UCL = $\bar{c} + 3\sqrt{\bar{c}}$ = $116 + 3\sqrt{116}$ = **148.3 → 148**

Quality Programs

42.16 A foundry that casts turbine blades inspects for eight features that are considered critical-to-quality. During the previous month, 1,236 castings were produced. During inspection, 47 defects among the eight features were found, and 29 castings had one or more defects. Determine DPMO, DPM, and DUPM in a Six Sigma program for these data and convert each to its corresponding sigma level.

Solution: Summarizing the data, N_u = 1236, N_o = 8, N_d = 47, and N_{du} = 29. Thus,

$$DPMO = 1{,}000{,}000\frac{47}{1236(8)} = 4753$$

The corresponding sigma level is about 4.1 from Table 42.3.

$$DPM = 1{,}000{,}000\frac{47}{1236} = 38{,}026$$

The corresponding sigma level is about 3.3.

$$DUPM = 1{,}000{,}000\frac{29}{1236} = 23{,}463$$

The corresponding sigma level is about 3.4.

42.17 In the previous problem, if the foundry desired to improve its quality performance to the 5.0 sigma level in all three measures of DPM, how many defects and defective units would they produce in an annual production quantity of 15,000 castings? Assume the same eight features are used to assess quality.

Solution: Summarizing the data, N_u = 15,00, N_o = 8, and N_d and N_{du} are unknown. To achieve a 5.0 sigma level, they would produce 233 dpm. Thus, for defects per million opportunities,

$$DPMO = 1{,}000{,}000 \frac{N_d}{15000(8)} = 233$$

Rearranging, N_d = 233(15,000)(8)/1,000,000 = 27.96, rounded up to 28 defects in 15,000 total castings.

Similarly, if the 5.0 sigma criterion were used for defects per million units,

$$DPM = 1{,}000{,}000 \frac{N_d}{15000} = 233$$

Rearranging, N_d = 233(15,000)/1,000,000 = 3.495 defects in 15,000 total castings.

Finally, if the 5.0 sigma criterion were used for defective units per million units,

$$DUPM = 1{,}000{,}000 \frac{N_{du}}{15000} = 233$$

N_{du} = 233(15,000)/1,000,000 = 3.495 defective units in 15,000 total castings.

42.18 The inspection department in an automobile final assembly plant inspects cars coming off the production line against 55 quality features considered important to customer satisfaction. The department counts the number of defects found per 100 cars, which is the same type of metric used by a national consumer advocate agency. During a one-month period, a total of 16,582 cars rolled off the assembly line. These cars included a total of 6045 defects of the 55 features, which translates to 36.5 defects per 100 cars. In addition, a total of 1955 cars had one or more of the defects during this month. Determine DPMO, DPM, and DUPM in a Six Sigma program for these data and convert each to its corresponding sigma level.

Solution: Although the inspection department uses number of defects per 100 cars, a Six Sigma program uses defects per million as its metric. Summarizing the data, N_u = 16,582, N_o = 55, N_d = 6045, and N_{du} = 1955. Thus,

$$DPMO = 1{,}000{,}000 \frac{6045}{16582(55)} = 6628$$

The corresponding sigma level is about 4.0 from Table 42.3.

$$DPM = 1{,}000{,}000 \frac{6045}{16582} = 364{,}552$$

The corresponding sigma level is about 1.8.

$$DUPM = 1{,}000{,}000 \frac{1955}{16582} = 117{,}899$$

The corresponding sigma level is about 2.7.

42.19 A company produces a certain part whose most important dimension is 37.50 ±0.025 in. If the tolerance is exceeded, the customer will return the part to the manufacturer at a cost of $200 in rework and replacement expenses. (a) Determine the constant k in the Taguchi loss function, Eq. (42.13). (b) The company can add a finish grinding operation that will allow the tolerance to be reduced to ±0.010 in. Using the loss function from part (a) what is the value of the loss associated with this new tolerance?

Solution: (a) In Eq. (42.13), the value of (x – N) is the tolerance 0.025 in. The loss is the expected cost of rework and replacement, which is $200. Using this cost in the loss function, the value of k can be determined as follows:

$$200 = k(0.025)^2 = 0.000625k$$

$$k = 200/0.000625 = \$320{,}000$$

Accordingly, the Taguchi loss function is $L(x) = 320{,}000(x - N)$.

(b) The value of the loss for a tolerance of 0.010 is $L(x) = 320{,}000(0.010)^2 = \$32.00$

42.20 The additional operation in the preceding problem will add $2.00 to the current cost of the part, which is $13.50. If the rate of returns from the customer at the tolerance of ±0.025 in is 2.1%, and it is expected to drop to zero returns using the new tolerance, should the company add the finish grinding operation to the manufacturing sequence for the part? Answer this question using the basic cost and return rate data without consideration of the Taguchi loss function.

Solution: The basic cost and return rate data are that 2.1% of the parts are returned, and it costs $200 for each one that is returned. Comparing the cost per part with and without the grinding operation, we have

Without the grinding operation, cost/pc = $13.50 + 0.021($200) = 13.50 + 4.20 = $17.70

With the added operation, cost/pc = 13.50 + 2.00 = $15.50

The calculation favors the addition of the grinding operation.

Laser Measurement Technologies

42.21 A laser triangulation system has the laser mounted at a 35° angle from the vertical. The distance between the worktable and the photodetector is 24.0000 in. Determine (a) the distance between the laser and the photodetector when no part is present and (b) the height of a part when the distance between the laser and photo-detector is 12.0250 in.

Solution: (a) L with no part when $D = 0$: $D = H - L \cot A$;
$0 = H - L \cot A$; $L = H/\cot A = H \tan A$
$L = 24.0000 \tan(35) =$ **16.8050 in**

(b) $D = H - L \cot A = 24.0000 - 12.0250 \cot(35)$
$D = 24.0000 - 12.0250(1.42815) =$ **6.8265 in**

42.22 A laser triangulation system is used to determine the height of a steel block. The system has a photosensitive detector that is located 750.000 mm above the working surface and the laser is mounted at a 30.00° angle from the vertical. With no part on the worktable, the position of the laser reflection on the photo sensor is recorded. After a part is placed on the worktable, the laser reflection shifts 70.000 mm toward the laser. Determine the height of the object.

Solution: Need to find the distance of the reflection from the laser.
L with no part when $D=0$: $D = H - L \cot A$; $0 = H - L \cot A$; $L = H/\cot A = H \tan A$
$L = 750 \tan(30) = 433.0127$ mm
L with part $= 433.0127 - 70 = 363.0127$ mm
$D = H - L \cot A = 750 - 363.0127 \cot(30) = 750 - 363.0127(1.732) =$ **121.262 mm**