20 THEORY OF METAL MACHINING

Review Questions

20.1 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.

20.2 What distinguishes material removal processes from other manufacturing processes?

Answer. In material removal processes, material is cut away from the work part so that the remaining material has the desired part geometry.

20.3 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 part geometries; (3) it can achieve closer tolerances than most other processes; and (4) it can create good surface finishes.

20.4 Name the three most common machining processes.

Answer. The three common machining processes are (1) turning, (2) drilling, and (3) milling.

20.5 What are the two basic categories of cutting tools in machining? Give an example of machining operations that use each tooling type.

Answer. The two categories are (1) single-point tools, used in operations such as turning; and (2) multiple-edge cutting tools, used in operations such as milling and drilling.

20.6 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.

20.7 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.

20.8 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.

20.9 What is an orthogonal cutting operation?

Answer. Orthogonal cutting uses a wedge-shaped tool in which the cutting edge is perpendicular to the direction of speed motion as the tool is forced into the work material.

20.10 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.

20.11 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 separate 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.

20.12 Identify the four forces that act on the chip in orthogonal cutting but cannot be measured directly in an operation.

Answer. The four forces that act on the chip are (1) friction force at the tool-chip interface, (2) normal force to friction, (3) shear force at the shear plane, and (4) normal force to shear.

20.13 Identify the two forces that can be measured in orthogonal cutting.

Answer. The two forces that can be measured in the orthogonal cutting are (1) cutting force in the direction of cutting speed and (2) thrust force, which is perpendicular to cutting force. Thrust force is the force that causes the cutting edge to penetrate beneath the surface of the work.

20.14 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 ($\mu = \tan \beta$).

20.15 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.

20.16 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.

20.17 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.

20.18 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 ($t_o \times w$ in orthogonal cutting or $f \times d$ in turning) decreases.

20.19 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.

Problems

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

Chip Formation and Forces in Machining

20.1 **(A)** (SI units) The rake angle in an orthogonal cutting operation = 10°. The chip thickness before the cut = 0.30 mm, and the resulting chip thickness after the cut = 0.66 mm. Calculate (a) the shear plane angle and (b) the shear strain for the operation.

Solution: (a) $r = t_o/t_c$ = 0.30/0.66 = 0.4545
$\phi = \tan^{-1}(0.4545 \cos 10/(1 - 0.4545 \sin 10)) = \tan^{-1}(0.4829) =$ **25.8°**

(b) Shear strain $\gamma = \tan(25.8 - 10) + \cot 25.8 = 0.283 + 2.069 =$ **2.352**

20.2 (SI units) In the previous problem, suppose the rake angle were changed to 0°, and this results in a chip thickness after the cut = 0.80 mm. Determine (a) the shear plane angle and (b) the shear strain for the operation.

Solution: (a) $r = t_o/t_c$ = 0.30/0.80 = 0.375
$\phi = \tan^{-1}(0.375 \cos 0/(1 - 0.375 \sin 0)) = \tan^{-1}(0.375) =$ **20.6°**

(b) Shear strain $\gamma = \tan(20.6 - 0) + \cot 20.6 = 0.376 + 2.659 =$ **3.035**

20.3 (USCS units) The tool in an orthogonal cutting operation is 0.250 in wide and has a rake angle = 5°. Chip thickness before the cut = 0.012 in, and cutting speed = 100 ft/min. After the cut, the deformed chip thickness = 0.028 in. Calculate (a) the shear plane angle, (b) the shear strain for the operation, and (c) material removal rate.

Solution: (a) $r = t_o/t_c$ = 0.012/0.028 = 0.4286
$\phi = \tan^{-1}(0.4286 \cos 5/(1 - 0.4286 \sin 5)) = \tan^{-1}(0.4678) =$ **25.1°**

(b) Shear strain $\gamma = \tan(25.1 - 5) + \cot 25.1 = 0.366 + 2.135 =$ **2.501**

(c) $R_{MR} = vt_ow$ = 100(12)(0.012)(0.250) = **3.6 in^3/min**

20.4 (SI units) In a turning operation, cutting speed = 1.8 m/s, feed = 0.30 mm/rev, and depth of cut = 2.6 mm. Rake angle = 8°. After the cut, the deformed chip thickness = 0.56 mm. Determine (a) shear plane angle, (b) shear strain, and (c) material removal rate. Use the orthogonal cutting model as an approximation of turning.

Solution: (a) $r = t_o/t_c$ = 0.30/0.56 = 0.536
$\phi = \tan^{-1}(0.536 \cos 8/(1 - 0.536 \sin 8)) = \tan^{-1}(0.5736) =$ **29.8°**

(b) $\gamma = \cot 29.8 + \tan(29.8 - 8) = 1.746 + 0.400 =$ **2.146**

(c) R_{MR} = (1.8 m/s × 10^3 mm/m)(0.3)(2.6) = **1404 mm^3/s**

20.5 **(A)** (USCS units) A turning operation is performed using a rake angle of 15°. Cutting speed = 200 ft/min, feed= 0.012 in/rev, and depth of cut = 0.100 in. The chip thickness ratio measured after the cut = 0.48. Determine (a) chip thickness after the cut, (b) shear angle, (c) friction angle, (d) coefficient of friction, and (e) shear strain.

Solution: (a) Using the orthogonal model, $f = t_o$: $t_c = t_o/r$ = 0.012/0.48 = **0.025 in**

(b) $\phi = \tan^{-1}(0.48 \cos 15/(1 - 0.48 \sin 15)) = \tan^{-1}(0.5294) =$ **27.9°**

(c) $\beta = 2(45) + \alpha - 2(\phi) = 90 + 15 - 2(27.9) =$ **49.2°**

(d) $\mu = \tan 49.2 =$ **1.16**

(e) $\gamma = \tan(27.9 - 15) + \cot 27.9 = 0.229 + 1.889 =$ **2.118**

20.6 **(A)** (USCS units) The turning operation in the previous problem involves a work material whose shear strength = 52,000 lb/in^2. Based on your answers to the previous problem, compute (a) shear force, (b) cutting force, (c) thrust force, and (d) friction force.

Solution: $\phi = 27.9°$ and $\beta = 49.2°$from previous problem.
(a) $A_s = (0.012)(0.100)/\sin 27.9 = 0.00256$ in^2
$F_s = A_s S = 0.00256(52{,}000) =$ **133.4 lb**

(b) $F_c = 133.4 \cos (49.2 - 15)/\cos (27.9 + 49.2 - 15) =$ **236 lb**

(c) $F_t = 133.4 \sin (49.2 - 15)/\cos (27.9 + 49.2 - 15) =$ **160 lb**

(d) $F = 236 \sin 15 + 160 \cos 15 =$ **216 lb**

20.7 (USCS units) The shear strength of a certain work material = 50,000 lb/in^2. An orthogonal cutting operation is performed using a tool with rake angle = 20° at a 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.
$F_s = A_s S = 0.00456(50{,}000) =$ **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**

20.8 (USCS units) Solve the previous problem, except the rake angle is 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.
$F_s = A_s S = 0.00702(50{,}000) =$ **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**

20.9 (USCS units) A carbon-steel bar with diameter = 7.64 in has a tensile strength of 65,000 lb/in^2 and a shear strength of 45,000 lb/in^2. The diameter is reduced in a turning operation at a cutting speed of 350 ft/min. Feed = 0.011 in/rev and depth of cut = 0.120 in. The rake angle on the tool in the direction of chip flow = 13°. The cutting conditions result in a chip ratio of 0.52. Using the orthogonal model as an approximation of turning, determine (a) 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
$F_s = A_s S = 0.00265(45{,}000) =$ **119.3 lb**

(c) $\beta = 2(45) + \alpha - 2\phi = 90 + 10 - 2(29.8) = 43.3°$
$F_c = F_s \cos(\beta - \alpha)/\cos(\phi + \beta - \alpha)$
$F_c = 119.3 \cos(43.3 - 13)/\cos(29.8 + 43.3 - 13) =$ **207 lb**
$F_t = F_s \sin(\beta - \alpha)/\cos(\phi + \beta - \alpha)$
$F_t = 119.3 \sin(43.3 - 13)/\cos(29.8 + 43.3 - 13) =$ **121 lb**
(d) $\mu = \tan \beta = \tan 43.3 =$ **0.942**

20.10 **(A)** (SI units) Low-carbon steel with tensile strength = 300 MPa and shear strength = 220 MPa is turned at a cutting speed = 2.5 m/s. Feed = 0.20 mm/rev and depth of cut = 3.0 mm. Rake angle = 5° in the direction of chip flow. The resulting chip ratio = 0.45. Using the orthogonal model to approximate turning, determine the cutting force and feed force.

Solution: $\phi = \tan^{-1}(0.45 \cos 5/(1 - 0.45 \sin 5)) = \tan^{-1}(0.4666) = 25.0°$
$A_s = t_o w/\sin \phi = (0.2)(3.0)/\sin 25.0 = 1.42$ mm^2.
$F_s = A_s S = 1.42(220) = 312$ N
$\beta = 2(45) + \alpha - 2\phi = 90 + 5 - 2(25.0) = 45.0°$
$F_c = F_s \cos(\beta - \alpha)/\cos(\phi + \beta - \alpha)$
$F_c = 312 \cos(45 - 5)/\cos(25.0 + 45.0 - 5) =$ **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**

20.11 (USCS units) A turning operation is performed with a rake angle of 10°, a feed of 0.010 in/rev, and a depth of cut = 0.100 in. Shear strength of the work metal = 50,000 lb/in^2, and the chip thickness ratio after the cut = 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**

20.12 Show how Equation (20.3) is derived from the definition of chip ratio, Equation (20.2), and Figure 20.6(b).

Solution: The definition of the chip ratio, Equation (20.2): $r = t_o/t_c = \sin \phi/\cos(\phi - \alpha)$
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 ϕ, $r \cos \alpha/\tan \phi + r \sin \alpha = 1$
$r \cos \alpha/\tan \phi = 1 - r \sin \alpha$
Rearranging, $\tan \phi = r \cos \alpha/(1 - r \sin \alpha)$ Q.E.D.

20.13 Show how Equation (20.4) is derived from Figure 20.7.

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.

Power and Energy in Machining

20.14 **(A)** (SI units) In a turning operation on stainless steel, cutting speed = 125 m/min, feed = 0.25 mm/rev, and depth of cut = 6.0 mm. How much power will the lathe draw in performing this operation if its mechanical efficiency = 90%. Use Table 20.2 to obtain the specific energy value.

Solution: From Table 20.2, U = 2.8 N-m/mm^3 = 2.8 J/mm^3
$R_{MR} = vfd$ = (125 m/min)(10^3 mm/m)(0.25 mm)(6 mm) = 187,500 mm^3/min = 3125 mm^3/s
P_c = (3125 mm^3/s)(2.8 J/mm^3) = 8,750 J/s = 8,750 W = 8.75 kW
Accounting for mechanical efficiency, P_g = 8.75/0.90 = **9.72 kW**

20.15 (SI units) In the previous problem, compute the lathe power 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 Equation 20.22, for f = 0.50 mm,
Correction factor $CF = 0.75(0.50)^{-.21} = 0.87$
From Table 20.2, U = 2.8 J/mm^3. With the correction factor, U = 2.8(0.87) = 2.44 J/mm^3.
$R_{MR} = vfd$ = (125 m/min)(10^3)(0.50 mm)(7.5 mm) = 375,000 mm^3/min = 6,250 mm^3/s
P_c = (6,250 mm^3/s)(2.44 J/mm^3) = 15,250 J/s = 15,250 W = 15.25 kW
Accounting for mechanical efficiency, P_g = 15.25/0.90 = **16.9 kW**

20.16 (USCS units) In a turning operation on aluminum, cutting speed = 1000 ft/min, feed = 0.018 in/rev, and depth of cut = 0.250 in. What horsepower is required of the drive motor, if the lathe has a mechanical efficiency = 92%? Use Table 20.2 to obtain the unit horsepower value.

Solution: From Table 20.2, 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 using Equation 20.22. For f = 0.018 in/rev = t_o, Correction factor = $0.38(0.018)^{-.21} = 0.88$
$HP_c = HP_u \times R_{MR}$, $HP_g = HP_c/E$
$R_{MR} = vfd = 1000 \times 12(.018)(0.250) = 54$ in^3/min
HP_c = 0.88(0.25)(54) = 11.88 hp
HP_g = 11.88/0.92 = **12.9 hp**

20.17 (SI units) Plain carbon steel with Brinell hardness of 275 HB is turned at a cutting speed = 200 m/min. Depth of cut = 6.0 mm. The lathe motor is rated at 25 kW (gross), and its mechanical efficiency = 90%. Using the specific energy value from Table 20.2, determine the maximum feed that can be used in this operation.

Solution: From Table 20.2, 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 $P_c = P_g\ E = 25(10^3)(0.90) = 22.5\ (10^3) = 22{,}500$W = 22,500 N-m/s
Required power $P_c = (2.8$ N-m/mm$^3)(\ 20 \times 10^3)\ f = 56{,}000$ 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 turning)

However, for this feed, correction factor using Equation 20.22 must be applied.
Correction factor $CF = 0.75(0.402)^{-.21} = 0.91$
Thus $U = 2.8(0.91) = 2.54$ 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 $P_c = (2.54)(20 \times 10^3)\ f = 50{,}858\ f$
Again setting available power = required power, 22,500 = 50,858 f
f = 22,500/50,858 = 0.442 mm/rev

However, for this feed, the correction factor using Equation 20.22 must be applied.
Correction factor $CF = 0.75(0.442)^{-.21} = 0.89$
$U = 2.8(0.89) = 2.49$ N-m/mm^3
Required $P_c = (2.49)(20 \times 10^3)\ f = 49{,}855\ f$
Again setting available power = required power, 22,500 = 49,855 f
f = 22,500/49,855 = 0.451 mm/rev

Again, this feed requires the correction factor using Equation 20.22.
Correction factor $CF = 0.75(0.451)^{-.21} = 0.89$
$U = 2.8(0.89) = 2.49$ N-m/mm^3
Required $P_c = (2.49)(20 \times 10^3)\ f = 49{,}855\ f$
Again setting available power = required power, 22,500 = 49,855 f
f = 22,500/49,855 = 0.451 mm/rev
The final value is around ***f* = 0.45 mm/rev**

20.18 (USCS units) A rough turning operation is performed on a 20 hp lathe that has a 92% efficiency. The cut is made on alloy steel whose hardness is 325 HB. Cutting speed = 375 ft/min, feed = 0.030 in/rev, and depth of cut = 0.150 in. Based on these values, can the job be performed on the 20 hp lathe? Use Table 20.2 to obtain the unit horsepower value.

Solution: From Table 20.2, $HP_u = 1.3$ hp/(in^3/min)
Since the uncut chip thickness (0.030 in) is different from the value of 0.010, the correction factor must be applied using Equation 20.22.
Correction factor = $0.38(0.030)^{-.21} = 0.79$
Therefore, the corrected $HP_u = 0.79(1.3) = 1.03$ hp/(in^3/min)
$R_{MR} = vfd$ = 375 ft/min(12 in/ft)(0.030 in)(0.150 in) = 20.25 in^3/min
HP_c = (20.25 in^3/min)(1.03 hp/(in^3/min)) = **20.9 hp** required
At efficiency E = 92%, available horsepower = 0.92(20) = **18.4 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.

20.19 (SI units) A turning operation is carried out on aluminum. Based on the specific energy values in Table 20.2, determine material removal rate and cutting power in the operation under the following sets of cutting conditions: (a) Cutting speed = 5.6 m/s, feed = 0.25 mm/rev, and depth of cut = 2.0 mm; and (b) cutting speed = 1.3 m/s, feed = 0.75 mm/rev, and depth = 4.0 mm.

Solution: (a) From Table 20.2, $U = 0.7$ 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) Because feed is greater than 0.25 mm/rev in the table, a correction factor must be applied using Equation 20.22.
Correction factor = $0.75(0.75)^{-.21} = 0.80$
$R_{MR} = vfd = 1.3(10^3)(.75)(4.0) =$ **$3.9(10^3)$ mm^3/s**.
$P_c = U\,R_{MR} = 0.80(0.7)(3.9)(10^3) = 2.184(10^3)$ N-m/s = **2184 W**

Note that although the power in (b) is only about 10% greater than in (a), the metal removal rate is almost 40% greater.

20.20 (USCS units) 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 20.2, determine (a) the horsepower consumed by the turning operation and (b) the horsepower that must be generated by the lathe.

Solution: (a) From Table 20.2, $HP_u = 0.6$ hp/(in^3/min) for low carbon steel
$HP_c = HP_u \times R_{MR}$
$R_{MR} = vfd = 400 \times 12(.010)(0.075) = 3.6$ in^3/min
$HP_c = 0.6(3.6) =$ **2.16 hp**

(b) $HP_g = 2.16/0.85 =$ **2.54 hp**

20.21 **(A)** (USCS units) A cast iron workpiece is turned on a lathe whose mechanical efficiency = 0.87. Cutting speed = 400 ft/min, feed = 0.011 in/rev, and depth of cut = 0.120 in. Cutting force = 250 lb. 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) Given $F_c = 250$ lb, $HP_c = F_c v/33{,}000 = 250(400)/33{,}000 =$ **3.03 hp**

(b) $HP_g = HP_c/E = 3.03/0.87 =$ **3.48 hp**

(c) $R_{MR} = 12\,vfd = (400 \times 12)(0.011)(0.120) = 6.336$ in^3/min
$HP_u = HP_c/R_{MR} = 3.03/6.336 =$ **0.478 hp/(in^3/min)**
$U = F_c v/R_{MR} = 250(400 \times 12)/6.336 =$ **189,394 in-lb/in^3**

20.22 (USCS units) 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. Feed = 0.015 in/rev, depth of cut = 0.125 in, and cutting speed = 300 ft/min. After the cut, the chip thickness ratio = 0.45. (a) Using the appropriate value of specific energy from Table 20.2, compute the horsepower at the drive motor, if the lathe 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 20.2, $U = P_u = 520{,}000$ in-lb/in^3 for this alloy steel of the specified hardness. Because feed is greater than 0.010 in/rev in the table, a correction factor must be applied using Equation 20.22.

Correction factor = $0.38(0.015)^{-.21} = 0.92$
U = 520,000(0.92) = 478,400 in-lb/in^3 = 39,867 ft-lb/in^3
$R_{MR} = 300 \times 12(.015)(0.125) = 6.75$ in^3/min
$P_c = U\, R_{MR}$ = 39,867(6.75) = 269,100 ft-lb/min
Equivalency: 1 hp = 33,000 ft-lb
HP_c = 269,100/33,000 = 8.15 hp
HP_g = 8.15/0.85 = **9.6 hp**

(b) $HP_c = vF_c/33{,}000$. Rearranging, $F_c = 33{,}000\,(HP_c/v)$ = 33,000(8.15/300) = **897 lb**

Check: (a) Use unit horsepower from Table 20.2: HP_u = 1.3 hp/(in^3/min). Applying the correction factor = 0.92, HP_u = 1.196 hp/(in^3/min).
$R_{MR} = 300 \times 12(0.015)(0.125) = 6.75$ in^3/min, same as before
HP_c = 1.196(6.75) = 8.07 hp
HP_g = 8.07/0.85 = **9.5 hp**

(b) F_c = 33,000 (8.3/300) = **888 lb** (Close enough)

20.23 (SI units) In a turning operation on an aluminum alloy workpiece, feed = 0.50 mm/rev, and depth of cut = 4.0 mm. The motor horsepower of the lathe = 20 hp, and it has a mechanical efficiency = 92%. What is the maximum cutting speed that can be used on this job?

Solution: From Table 20.2, P_u = 0.8 N-m/mm^3 for aluminum alloy. Because feed is greater than 0.25 mm/rev in the table, a correction factor must be applied using Equation 20.22.
Correction factor = $0.75(0.50)^{-.21} = 0.87$
$R_{MR} = vfd = 1000v(.50)(4.0) = 2000\,v$ mm^3/s where v = m/s
HP_c = 0.87(0.8 N-m/mm^3)(2000 v mm^3/s) = 1392 v N-m/s = 1392 v W where v = m/s
Equivalency: 1 hp = 745.7 W = 745.7 N-m/s
HP_g = 1392 v /0.92 = 1513 v N-m/s = 20 hp = 20(745.7) = 14,914 N-m/s
v = 14,914/1513 = **9.86 m/s**

20.24 One of the foremen in the machine shop complains of a problem with an operation in the turning section. It seems the lathe has a tendency to slow down or stall in the middle of the cutting operation, indicating that the machine is underpowered for the work material and conditions of the cut. Without knowing any more about the problem, what actions and changes can be made to mitigate this power problem?

Solution: Several changes can be made to avoid this kind of power problem: (1) reduce cutting speed, (2) reduce feed and/or depth of cut, (3) perform the cut on a lathe with higher power capability, (4) use a cutting fluid, and (5) use a cutting tool that has a larger rake angle.

Cutting Temperature

20.25 **(A)** (SI units) 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. Cutting speed = 3.5 m/s, uncut chip thickness = 0.25 mm, and width of cut = 2.2 mm. Cutting force = 950 N. 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 = (2.90×10^{-3}) J/mm^3-°C
K = 0.8 cm^2/s = 80 mm^2/s
$U = F_c v/R_{MR}$ = 950 N × 3.5 m/s/(3500 mm/s × 0.25 mm × 2.2 mm) = 1.727 N-m/mm^3

$T = 0.4U/(\rho C) \times (vt_o/K)^{0.333}$
$T = 22 + (0.4 \times 1.727$ N-m/mm^3/(2.90×10^{-3}) J/mm^3-C) [3500 mm/s $\times$ 0.25 mm/80 mm^2/s]$^{0.333}$
$T = 22 + (0.2382 \times 10^3$ C)$(10.94)^{.333} = 22 + 238.3(2.22) = 22° + 528° =$ **550°C**

20.26 (SI units) Consider a turning operation performed on steel whose hardness = 225 HB at a cutting 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 specific energy value from Table 20.2, compute an estimate of cutting temperature. Assume ambient temperature = 20°C.

Solution: From Table 20.2, 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 4.2, C = 0.11 Cal/g-°C. From note "a" at bottom of 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 Equation (4.3), thermal diffusivity $K = k/\rho C$
K = 0.046 J/s-mm-°C /[(7.87 $\times$ 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**

20.27 (USCS units) 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. Cutting force = 200 lb. Determine the cutting temperature if the ambient temperature = 70°F.

Solution: v = 350 ft/min $\times$ 12 in/ft/60 sec/min = 70 in/sec.
$U = F_c v/vt_o w = 200(70)/(70 \times 0.008 \times 0.100) = 250{,}000$ in-lb/in^3.
$T = 70 + (0.4\text{U}/\rho\text{C})(\text{vt}_\text{o}/\text{K})^{0.333} =$
$T = 70 + (0.4 \times 250{,}000/110)[70 \times 0.008/0.14]^{0.333}$
$= 70 + (909)(4)^{0.333} = 70 + 1436 =$ **1506°F**

20.28 **(A)** (USCS units) An orthogonal machining operation removes metal at 1.8 in^3/min. Cutting force = 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 = 0.010 in and width of cut = 0.100 in, compute the cutting temperature in the operation given that ambient temperature = 70°F.

Solution: $R_{MR} = vt_o w$, $v = R_{MR}/t_o w = 1.8/(0.01 \times 0.100) = 1800$ in/min = 30 in/sec
$U = F_c v/vt_o w = 300(30)/(30 \times 0.010 \times 0.100) = 300{,}000$ in-lb/in^3
$T = 70 + (0.4U/\rho C)(vt_o/K)^{0.333} = 70 + (0.4 \times 300{,}000/124)(30 \times 0.010/0.18)^{0.333}$
$= 70 + (968)(1.667)^{0.333} = 70 + 1147 =$ **1217°F**

20.29 (SI units) 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, Equation (20.24).

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).