Chapter 21

Fundamentals of Machining

QUALITATIVE PROBLEMS

21.14 Are the locations of maximum temperature and crater wear related? If so, explain why.

Although various factors can affect crater wear, the most significant factors in crater wear are diffusion (a mechanism whereby material is removed from the rake face of the tool) and the degree of chemical affinity between the tool and the chip. Thus, the higher the temperature, the higher the wear. Referring collectively to all the figures on pp. 625 and 633, we note that temperature and crater wear indeed are related.

21.15 Is material ductility important for machinability? Explain.

Let's first note that the general definition of machinability (Section 21.7 on p. 583) involves workpiece surface finish and integrity, tool life, force and power required, and chip control. Ductility directly affects the type of chip produced which, in turn, affects surface finish, the nature of forces involved (less ductile materials may lead to tool chatter), and more ductile materials produce continues chips which may not be easy to control.

21.16 Explain why studying the types of chips produced is important in understanding cutting operations.

It is important to study the types of chips produced (see Section 21.2.1 on p. 562) because they significantly influence the surface finish produced, cutting forces, as well as the overall cutting operation. Note, for example, that continuous chips are generally associated with good surface finish and steady cutting forces. Built-up edge chips usually result in poor surface finish; serrated chips can have similar effects. Discontinuous chips usually result in poor surface finish and dimensional accuracy, and involve cutting forces that fluctuate. Thus, the type of chip is a good indicator of the overall quality of the cutting operation.

21.17 Why do you think the maximum temperature in orthogonal cutting is located at about the middle of the tool–chip interface? (*Hint:* Note that the two sources of

heat are (a) shearing in the primary shear plane and (b) friction at the tool–chip interface.)

It is reasonable that the maximum temperature in orthogonal cutting is located at about the middle of the tool-chip interface (see, for example, Fig. 21.12 on p. 572). The chip reaches high temperatures in the primary shear plane, and the temperature would decrease from then on. If no frictional heat was involved, we would expect the highest temperature to occur at the shear plane. After the chip is formed, it slides up the rake face of the tool. The friction at the tool-chip interface is a heat source and thus increases the temperature, and hence the temperature due only to frictional heating would be highest at the end of the tool-chip contact length. These two opposing effects are additive and, as a result, we find that the temperature is highest somewhere in between the tool tip and the end of the tool-chip contact zone.

21.18 Tool life can be almost infinite at low cutting speeds. Would you then recommend that all machining be done at low speeds? Explain.

Tool life can be almost infinite at very low cutting speeds (see Fig. 21.16 on p. 576) but this reason alone would not necessarily justify using low cutting speeds. Most obviously, low cutting speeds remove less material in a given time which, unless otherwise justified, would be economically undesirable. Lower cutting speeds also often also lead to the formation of a built-up edge and discontinuous chips, thus affecting surface finish. (See also Example 21.2 on p. 577.)

21.19 Explain the consequences of allowing temperatures to rise to high levels in cutting.

By the student. There are several consequences of allowing temperatures to rise to high levels in cutting (see also pp. 571-573), such as: (a) Tool wear will be accelerated due to high temperatures. (b) High temperatures will cause dimensional changes in the workpiece, thus reducing dimensional accuracy. (c) Excessively high temperatures in the cutting zone can induce thermal damage and metallurgical changes to the machined surface.

21.20 The cutting force increases with the depth of cut and decreasing rake angle. Explain why.

It is logical that the cutting force increases as the depth of cut increases and rake angle decreases. Deeper cuts remove more material, thus requiring a higher cutting force. As the rake angle, α, decreases, the shear angle, ϕ , decreases [see Eqs. (21.3) and (21.4) on p. 561], and hence shear energy dissipation and cutting forces increase.

21.21 Why is it not always advisable to increase the cutting speed in order to increase the production rate?

The main consideration here is that as the cutting speed increases, tool life decreases. See also Example 21.2 on p. 577 and note that there has to be an optimum cutting speed, as also discussed in Section 25.8 on p. 713.

21.22 What are the consequences if a cutting tool chips?

By the student. Tool chipping has various effects, such as poor surface finish and dimensional control of the part being machined; possible temperature rise; and cutting force fluctuations

and increases. Chipping is indicative of a harmful condition for the cutting tool material, and often is followed by more extreme failure.

21.23 What are the effects of performing a cutting operation with a dull tool? A very sharp tool?

By the student. There are many effects of performing a cutting operation with a dull tool. Note that a dull tool has an increased tip radius (see Fig. 21.22 on p. 582); as the tip radius increases (the tool dulls), the cutting force increases due to the fact that the effective rake angle is decreased. In addition, we can see that shallow depths of cut may not be possible because the tool may simply ride over the surface without producing chips. Another effect is inducing surface residual stresses, tearing, and cracking of the machined surface due to the heat generated by the dull tool tip rubbing against this surface. Dull tools also increase the tendency for BUE formation, which leads to poor surface finish.

21.24 To what factors do you attribute the difference in the specific energies in machining the materials shown in Table 21.2? Why is there a range of energies for each group of materials?

The differences in specific energies observed in Table 21.2 on p. 571, whether among different materials or within types of materials, can be attributed to differences in the mechanical and physical properties of these materials, which affect the cutting operation. For example, as the material strength increases, so does the total specific energy. Differences in frictional characteristics of the tool and workpiece materials would also play a role. Physical properties such as thermal conductivity and specific heat, both of which increase cutting temperatures as they decrease [see Eq. (21.19a) on p. 572], also could be responsible for such differences in practice. These points are confirmed when one closely examines Table 21.2 and observes that the ranges for materials such as steels, refractory alloys, and high-temperature alloys are large, in agreement with our knowledge of the large variety of materials which fall under these categories.

21.25 Explain why it is possible to remove more material between tool resharpenings by lowering the cutting speed.

The main consideration here is that as the cutting speed increases, tool life decreases. See Example 21.4 on p. 577. As the example states, there is, of course, an optimum cutting speed, as also discussed in Section 25.8 on p. 713.

21.26 Noting that the dimension d in Fig. 21.4a is very small, explain why the shear strain rate in metal cutting is so high.

The shear strain rate in metal cutting is high even though the dimension d is very small. Referring to Fig. 21.4 on p. 560, we note that shear-strain rate is defined as the ratio of shear velocity, V_s, to the dimension d in the shear plane. Since V_s is on the same order of magnitude as the cutting speed, V, and the dimension d is very small (on the order of 10^{-2} to 10^{-3} in.), the shear strain rate is very high.

21.27 Explain the significance of Eq. (21.7).

The significance of Eq. (21.7) on p. 567 is that it determines an effective rake angle for oblique cutting (a process of more practical significance in most machining operations), which we

can relate back to the simpler orthogonal cutting models for purposes of analysis. Oblique cutting is extremely complicated otherwise, and certainly cannot be treated effectively in an undergraduate textbook without Eq. (21.7).

21.28 Comment on your observations regarding Figs. 21.12 and 21.13.

By the student. General observations are as follows:

(a) The maximum temperature, both on flank and rake faces, are at a location approximately halfway along the tool-workpiece contact surfaces.

(b) Temperatures and their gradients can be very high.

(c) Cutting speed has a major effect on temperature.

(d) Chip temperatures are much higher than workpiece temperatures.

21.29 Describe the consequences of exceeding the allowable wear land (Table 21.4) for various cutting-tool materials.

The major consequences would be:

(a) As the wear land increases, the wear flat will rub against the machined surface and thus temperature will increase due to friction.

(b) Dimensional control will become difficult and surface damage may result.

(c) Some burnishing may also take place on the machined surface, leading to residual stresses and temperature rise.

(d) Cutting forces will increase because of the increased land, requiring greater power for the same machining operation.

21.30 Comment on your observations regarding the hardness variations shown in Fig. 21.6a.

By the student. What is obvious in Fig. 21.6a on p. 564 is that the chip undergoes a very high degree of strain hardening, as evidenced by the hardness distribution in the chip. Also, there is clearly and not surprisingly an even higher level of cold work in the built-up edge, to as much as three times the workpiece hardness.

21.31 Why does the temperature in cutting depend on the cutting speed, feed, and depth of cut? Explain in terms of the relevant process variables.

Refer to Eq. (21.19a) on p. 572. As cutting speed increases, there is less time for the heat generated to be dissipated, hence temperature increases. As feed increases (such as in turning; see Fig. 21.2 on p. 557) or as the depth of cut increases (such as in orthogonal cutting), the chip is thicker. With larger thickness-to-surface area of the chip, there is less opportunity for the heat to be dissipated, hence temperature increases.

21.32 You will note that the values of a and b in Eq. (21.19b) are higher for high-speed steels than for carbides. Why is this so?

As stated on p. 572, the magnitudes of a and b depend on the type of cutting tool as well as the workpiece materials. Factors to be considered include thermal conductivity and friction at the tool-chip and tool-workpiece interfaces. Carbides have higher thermal conductivity

than high-speed steels (see Table 22.1 on p. 593) and also have lower friction. Consequently, these constants are lower for carbides; in other words, the temperature is less sensitive to speed and feed.

21.33 As shown in Fig. 21.14, the percentage of the total cutting energy carried away by the chip increases with increasing cutting speed. Why?

The reason is due to the fact that as cutting speed increases, the heat generated (particularly that portion due to the shear plane deformation) is carried away at a higher rate. Conversely, if the speed is low, the heat generated will have more time to dissipate into the workpiece.

21.34 Describe the effects that a dull tool can have on cutting operations.

By the student. There are many effects of performing a cutting operation with a dull tool. Note that a dull tool has an increased tip radius (see Fig. 21.22 on p. 582); as the tip radius increases (the tool dulls), the cutting force increases due to the fact that the effective rake angle is decreased. In addition, we can see that shallow depths of cut may not be possible because the tool may simply ride over the surface without producing chips. Another effect is inducing surface residual stresses, tearing, and cracking of the machined surface due to the heat generated by the dull tool tip rubbing against this surface. Dull tools also increase the tendency for BUE formation, which leads to poor surface finish.

21.35 Explain whether it is desirable to have a high or low (a) n value and (b) C value in the Taylor tool-life equation.

As we can see in Fig. 21.17 on p. 576, high n values are desirable because, for the same tool life, we can cut at higher speeds, thus increasing productivity. Conversely, we can also see that for the same cutting speed, high n values give longer tool life. Note that as n approaches zero, tool life becomes extremely sensitive to cutting speed. These trends can also be seen by inspecting Eq. (21.20a) on p. 575. As for the value of C, note that its magnitude is the same as the cutting speed at $T = 1$. Consequently, it is desirable to have high C values because we can cut at higher speeds, as can also be seen in Fig. 21.17.

21.36 The tool-life curve for ceramic tools in Fig. 21.17 is to the right of those for other tool materials. Why?

Ceramic tools are harder and have higher resistance to temperature; consequently, they resist wear better than other tool materials shown in the figure. Ceramics are also chemically inert even at the elevated temperatures of machining. The high hardness leads to abrasive wear resistance, and the chemical inertness leads to adhesive wear resistance.

21.37 Why are tool temperatures low at low cutting speeds and high at high cutting speeds?

At very low cutting speeds, as energy is dissipated in the shear plane and at chip-tool interface, it is conducted through the workpiece and/or tool and eventually to the environment. At higher speeds, conduction cannot take place quickly enough to prevent temperatures from rising significantly. At even higher speeds, however, the heat will be taken away by the chip, hence the workpiece will stay cool. This is one of the major advantages of high speed machining (see Section 25.5 on p. 709).

21.38 Can high-speed machining be performed without the use of a cutting fluid?

Yes, high-speed machining can be done without a cutting fluid. The main purposes of a cutting fluid (see Section 22.12 on p. 607) is to lubricate and to remove heat, usually accomplished by flooding the tool and workpiece by the fluid. In high speed machining, most of the heat is conveyed from the cutting zone through the chip, so the need for a cutting fluid is less (see also Fig. 21.14 on p. 573).

21.39 Given your understanding of the basic metal-cutting process, what are the important physical and chemical properties of a cutting tool?

Physically, the important properties are hardness (especially hot hardness), toughness, thermal conductivity and thermal expansion coefficient. Chemically, it must be inert to the workpiece material at the cutting temperatures.

QUANTITATIVE PROBLEMS

21.40 Let $n = 0.5$ and $C = 90$ in the Taylor equation for tool wear. What is the percent increase in tool life if the cutting speed is reduced by (a) 50% and (b) 75%?

The Taylor equation for tool wear is given by Eq. (21.20a) on p. 575, which can be rewritten as

$$C = VT^n$$

Thus, for the case of $C = 90$ and $n = 0.5$, we have $90 = V\sqrt{T}$.

(a) To determine the percent increase in tool life if the cutting speed is reduced by 50%, let $V_2 = 0.5V_1$. We may then write

$$0.5V_1\sqrt{T_2} = V_1\sqrt{T_1}$$

Rearranging this equation, we find that $T_2/T_1 = 4.0$, hence tool life increases by 300%.

(b) If the speed is reduced by 75%, then use $V_2 = 0.25V_1$, and then the result obtained is $T_2/T_1 = 16$, or an increase in tool life of 1500%.

21.41 Assume that, in orthogonal cutting, the rake angle is 25° and the coefficient of friction is 0.2. Using Eq. (21.3), determine the percentage increase in chip thickness when the friction is doubled.

We begin with Eq. (21.1b) on p. 560 which shows the relationship between the chip thickness and cutting variables. Assuming that the depth of cut (t_c) and the rake angle (α) are constant, we can compare two cases by rewriting this equation as

$$\frac{t_1}{t_2} = \frac{t_1/t_c}{t_2/t_c} = \frac{\cos(\phi_2 - \alpha)\sin\phi_1}{\cos(\phi_1 - \alpha)\sin\phi_2}$$

Now, using Eq. (21.3) on p. 561 we can determine the two shear angles. For Case 1, we have from Eq. (21.4) that $\mu = 0.2 = \tan\beta$, or $\beta = 11.3^\circ$, and hence

$$\phi_2 = 45^\circ + \frac{25^\circ}{2} - \frac{11.3^\circ}{2} = 51.85^\circ$$

and for Case 2, where $\mu = 0.4$, we have $\beta = \tan^{-1} 0.4 = 21.8^\circ$ and hence $\phi_2 = 46.6^\circ$. Substituting these values in the above equation for chip thickness ratio, we obtain

$$\frac{t_1}{t_2} = \frac{\cos(\phi_2 - \alpha)\sin\phi_1}{\cos(\phi_1 - \alpha)\sin\phi_2} = \frac{\cos(46.6^\circ - 25^\circ)\sin 51.85^\circ}{\cos(51.85^\circ - 25^\circ)\sin 46.6^\circ} = 1.13$$

Therefore, the chip thickness increased by 13%.

21.42 Derive Eq. (21.11).

From the force diagram shown in Fig. 21.11 on p. 569, we express the following:

$$F = (F_t + F_c \tan\alpha)\cos\alpha$$

and

$$N = (F_c - F_t \tan\alpha)\cos\alpha$$

Therefore, by definition,

$$\mu = \frac{F}{N} = \frac{(F_t + F_c \tan\alpha)\cos\alpha}{(F_c - F_t \tan\alpha)\cos\alpha}$$

21.43 Taking carbide as an example and using Eq. (21.19b), determine how much the feed should be reduced in order to keep the mean temperature constant when the cutting speed is doubled.

We begin with Eq. (21.19b) on p. 572 which, for our case, can be rewritten as

$$V_1^a f_1^b = (2V_1)^a f_2^b$$

Rearranging and simplifying this equation, we obtain

$$\frac{f_2}{f_1} = 2^{-a/b}$$

For carbide tools, approximate values are given on p. 572 as $a = 0.2$ and $b = 0.125$. Substituting these, we obtain

$$\frac{f_2}{f_1} = 2^{-(0.2/0.125)} = 0.33$$

Therefore, the feed should be reduced by (1-0.33) = 0.67, or 67%.

21.44 Using trigonometric relationships, derive an expression for the ratio of shear energy to frictional energy in orthogonal cutting, in terms of angles α, β, and ϕ only.

We begin with Eqs. (21.13) and (21.17) on p. 570:

$$u_s = \frac{F_s V_s}{w t_o V} \quad \text{and} \quad u_f = \frac{F V_c}{w t_o V}$$

Thus their ratio becomes

$$\frac{u_s}{u_f} = \frac{F_s V_s}{F V_c}$$

The terms involved above can be defined as

$$F = R \sin\beta$$

and from Fig. 21.11 on p. 569,

$$F_s = R\cos(\phi + \beta - \alpha)$$

However, we can simplify this expression further by noting that the magnitudes of ϕ and α are close to each other. Hence we can approximate this expression as

$$F_s = R\cos\beta$$

Also,

$$V_s = \frac{V\cos\alpha}{\cos(\phi - \alpha)}$$

$$V_c = \frac{V\sin\alpha}{\cos(\phi - \alpha)}$$

Combining these expressions and simplifying, we obtain

$$\frac{u_s}{u_f} = \cot\beta\cot\alpha$$

21.45 An orthogonal cutting operation is being carried out under the following conditions: $t_o = 0.1$ mm, $t_c = 0.2$ mm, width of cut = 5 mm, $V = 2$ m/s, rake angle = 10°, $F_c = 500$ N, and $F_t = 200$ N. Calculate the percentage of the total energy that is dissipated in the shear plane.

The total power dissipated is obtained from Eq. (21.13) on p. 570 and the power for shearing from Eq. (21.14). Thus, the total power is

$$\text{Power} = (500)(2) = 1000 \text{ N-m/s}$$

To determine power for shearing we need to determine F_s and V_s. We know that

$$F_s = R\cos(\phi + \beta - \alpha)$$

where

$$R = \sqrt{(500)^2 + (200)^2} = 538 \text{ N}$$

also, ϕ is obtained from Eq. (21.1a) on p. 560 where $r = 0.1/0.2 = 0.5$. Hence

$$\phi = \tan^{-1}\left(\frac{r\cos\alpha}{1 - r\sin\alpha}\right) = \tan^{-1}\left[\frac{(0.5)(\cos 10^\circ)}{1 - (0.5)(\sin 10^\circ)}\right] = 28.4^\circ$$

We can then determine β from the expression (see Fig. 21.11 on p. 569)

$$F_c = R\cos(\beta - \alpha)$$

or,

$$500 = 538\cos(\beta - 10^\circ)$$

Hence

$$\beta = 31.7^\circ$$

Therefore,

$$F_s = 538\cos(28.4^\circ + 31.7^\circ - 10^\circ) = 345 \text{ N}$$

which allows us to calculate V_s using Eq. (21.6a) on p. 562. Hence,

$$V_s = 2\cos 10^\circ / \cos(28.4^\circ - 10^\circ) = 2.08 \text{ m/s}$$

and the power for shearing is (345)(2.08) = 718 N-m/s. Thus, the percentage is 718/1000 = 0.718, or about 72%.

21.46 Explain how you would go about estimating the C and n values for the four tool materials shown in Fig. 21.17.

From Eq. (21.20a) on p. 575 we note that the value of C corresponds to the cutting speed for a tool life of 1 min. From Fig. 21.16 on p. 576 and by extrapolating the tool-life curves to a tool life of 1 min. we estimate the C values approximately as (ranging from ceramic to HSS) 11000, 3000, 400, and 200, respectively. Likewise, the n values are obtained from the negative inverse slopes, and are estimated as: 0.73 (36°), 0.47 (25°), 0.14 (8°), and 0.11 (6°), respectively. Note that these n values compare well with those given in Table 21.3 on p. 575.

21.47 Derive Eqs. (21.1).

Refer to the shear-plane length as l. Figure 21.3a on p. 558 suggests that the depth of cut, t_o, is given by

$$t_o = l\sin\phi$$

Similarly, from Fig. 21.4 on p. 560, the chip thickness is seen to be

$$t_c = l\cos(\phi - \alpha)$$

Substituting these relationships into the definition of cutting ratio [Eq. (21.1b) on p. 560] gives

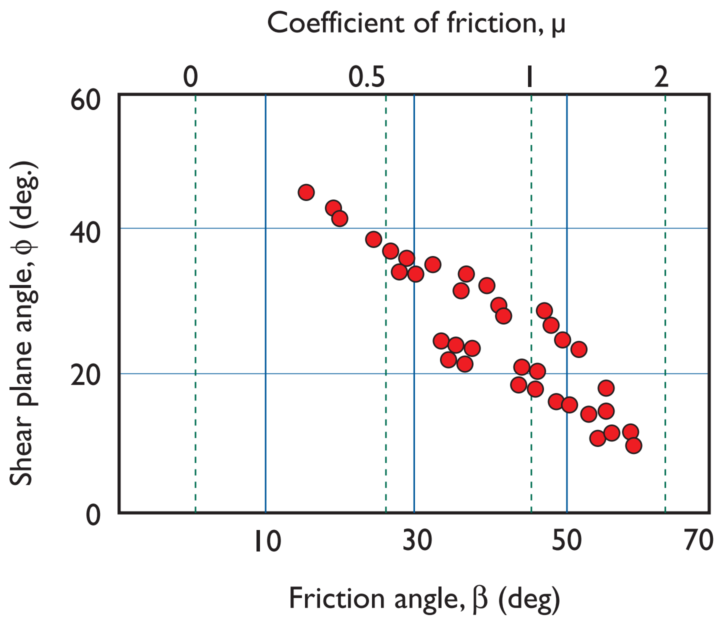
$$r = \frac{t_o}{t_c} = \frac{l\sin\phi}{l\cos(\phi - \alpha)} = \frac{\sin\phi}{\cos(\phi - \alpha)}$$

21.48 Assume that, in orthogonal cutting, the rake angle, is 20° and the friction angle, is 35° at the chip–tool interface. Determine the percentage change in chip thickness when the friction angle is 50°. (*Note*: do not use Eq. (21.3) or Eq. (21.4)).

Since the problem states that we cannot use Eq. (21.3) on p. 561, we have to find a means to determine the shear angle, ϕ, first. This requires further reading by the student to find other shear-angle relationships similar to Eq. (21.3) or Eq. (21.4), with the guidance of the instructor and referring to the Bibliography at the end of this chapter. Note that many researchers have measured shear plane angles and developed shear plane angle relationships; this solution is only one example of an acceptable answer, and students should be encouraged

to find a solution based on their own literature review. Indeed, such a literature review is an invaluable exercise.

This solution will use experimental measurements of the shear plane angle obtained by S. Kobayashi and printed in Kalpakjian, S., *Manufacturing Processes for Engineering Materials*, 3rd ed., 1997:



From this chart, we can estimate that for $\beta = 35°$, ϕ is approximately 25° and if $\beta = 50°$, $\phi = 15°$. We now follow the same approach as in Problem 20.41. We begin with Eq. (21.1b) on p. 560 which shows the relationship between the chip thickness and depth of cut. Assume that the depth of cut and the rake angle are constant, we can rewrite this equation as

$$\frac{t_o}{t_c} = \frac{\cos(\phi_2 - \alpha)\sin\phi_1}{\cos(\phi_1 - \alpha)\sin\phi_2} = \frac{\cos(15° - 25°)\sin 25°}{\cos(25° - 25°)\sin 15°} = 1.60$$

Therefore, the chip thickness increased by 60 percent.

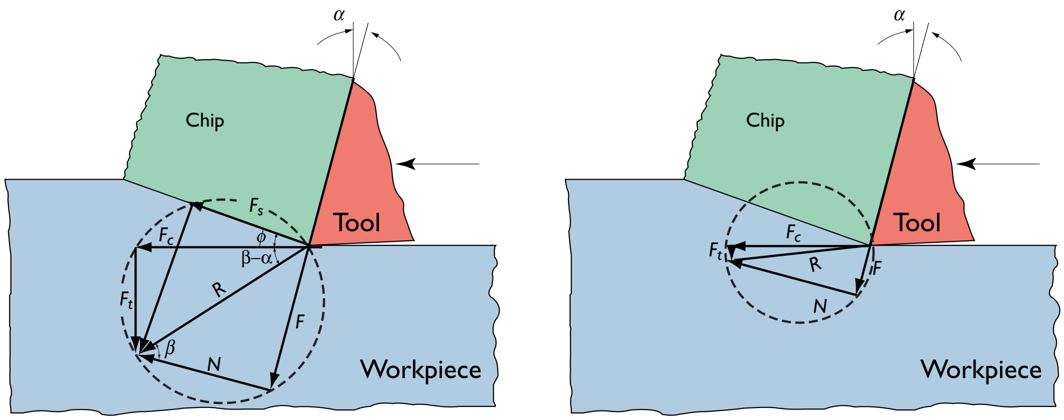
21.49 Show that, for the same shear angle, there are two rake angles that give the same cutting ratio.

By studying Eq. (21.1b) on p. 560, we note that the denominator can give the same value for the angle $(\phi - \alpha)$ that is either positive or negative. Therefore, the statement is correct.

21.50 With appropriate diagrams, show how the use of a cutting fluid can change the magnitude of the thrust force, F_t, in Fig. 21.11.

Note in Fig. 21.11 on p. 569 that the use of a cutting fluid will reduce the friction force, F, at the tool-chip interface. This, in turn, will change the force diagram, hence the magnitude of the thrust force, F_t. Consider the sketch given below. The left sketch shows cutting without an effective cutting fluid, so that the friction force, F is large compared to the normal force, N. The sketch on the right shows the effect if the friction force is a smaller fraction of the

normal force because of this cutting fluid. As can be seen, the cutting force is reduced with the effective fluid. The largest effect is on the thrust force, but there is a noticeable effect on cutting force. This effect becomes larger as the rake angle increases.



21.51 For a turning operation using a ceramic cutting tool, if the speed is increased by 50%, by what factor must the feed rate be modified to obtain a constant tool life? Use $n = 0.5$ and $y = 0.6$.

Equation (21.22) on p. 575 will be used for this problem. Since the tool life is constant, we can write the following:

$$C^{1/n}V_1^{-1/n}d_1^{-x/n}f_1^{-y/n} = C^{1/n}V_2^{-1/n}d_2^{-x/n}f_2^{-y/n}$$

Note that the depth of cut is constant, hence $d_1 = d_2$, and also it is given that $V_2 = 1.5V_1$. Substituting the known values into this equation yields:

$$V_1^{-2}f_1^{-0.6/0.5} = (1.5V_1)^{-2}\,f_2^{-0.6/0.5}$$

or

$$1.5^2 = \left(\frac{f_2}{f_1}\right)^{-1.2}$$

so that

$$\frac{f_2}{f_1} = \left(1.5^2\right)^{-1/1.2} = 0.508 = 50.8\%$$

21.52 In Example 21.3, if the cutting speed V is doubled, will the answer be different? Explain.

Refer to Example 21.3 on p. 630. The values of $n = 0.5$ and $C = 120$ are preserved, and the values of $V_2 = 2V_1$ will be used. The Taylor tool life equation can be written as

$$2V_1\sqrt{T_2} = V_1\sqrt{T_1}$$

Simplifying this expression,

$$\frac{\sqrt{T_2}}{\sqrt{T_1}} = \frac{V_1}{2V_1} = \frac{1}{2} \quad \rightarrow \quad \frac{T_2}{T_1} = 0.25$$

Therefore, the life has been reduced by 75%.

21.53 Using Eq. (21.24), select an appropriate feed for $R = 1$ mm and a desired roughness of 1 μm. How would you adjust this feed to allow for nose wear of the tool during extended cuts? Explain your reasoning.

If $R_a = 1$ μm, and $R = 1$ mm, then

$$f^2 = (1\ \mu\text{m})(8)(1\ \text{mm}) = 8 \times 10^{-9}\ \text{m}^2 \quad \rightarrow \quad f = 0.089\ \text{mm/rev}$$

If nose wear occurs, then the radius will increase. The feed will similarly have to increase, per the equation above.

21.54 With a carbide tool, the temperature in a cutting operation is measured as 650°C when the speed is 90 m/min and the feed is 0.05 mm/rev. What is the approximate temperature if the speed is doubled? What speed is required to lower the maximum cutting temperature to 480°C?

Equation (21.19a) on p. 572 is needed to solve this problem, which is rewritten as:

$$T_{\text{mean}} = \frac{1.2Y_f}{\rho c}\sqrt[3]{\frac{Vt_o}{K}} \quad \rightarrow \quad \frac{T_{\text{mean}}}{\sqrt[3]{V}} = \frac{1.2Y_f}{\rho c}\sqrt[3]{\frac{t_o}{K}}$$

Note that the text warns that appropriate units need to be used. It is reasonable in this case to use °F instead of °R, because, clearly, a cutting speed near zero does not lead to temperatures below room temperature. Therefore, using $T_{\text{mean}} = 650$°C and $V = 90$ m/min yields

$$\frac{T_{\text{mean}}}{\sqrt[3]{V}} = \frac{1.2Y_f}{\rho c}\sqrt[3]{\frac{t_o}{K}} = \frac{650°\text{C}}{\sqrt[3]{90\ \text{m/min}}}$$

For the first part of the problem, we take $V = 180$ m/min, yielding

$$\frac{T_{\text{mean}}}{\sqrt[3]{180}} = \frac{650°\text{C}}{\sqrt[3]{90\ \text{m/min}}}$$

or $T_{\text{mean}} = 819$°C. If the maximum temperature is lowered to 480°C, then we have

$$\frac{480°\text{C}}{\sqrt[3]{V}} = \frac{650°\text{C}}{\sqrt[3]{90\ \text{m/min}}}$$

which is solved as $V = 36$ m/min.

21.55 Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

By the student. This open-ended question requires considerable focus and understanding on the part of students, and has been found to be a very valuable homework problem.

SYNTHESIS, DESIGN, AND PROJECTS

21.56 As we have seen, chips carry away the majority of the heat generated during machining. If chips did not have this capacity, what suggestions would you make in order to be able to carry out machining processes without excessive heat? Explain.

By the student. If chips couldn't carry away the heat, then some other means would be needed to cool the workpiece and the cutting tool. The obvious solution is a generous flood of cutting fluid or more advanced methods such as high-pressure systems or through the cutting tool system, as described on p. 610.

21.57 Tool life is increased greatly when an effective means of cooling and lubrication is implemented. Design methods of delivering this fluid to the cutting zone and discuss the advantages and limitations of your design.

By the student. See pp. 609-610.

21.58 Design an experimental setup whereby orthogonal cutting can be simulated in a turning operation on a lathe.

By the student. This can be done simply by placing a thin-walled tube in the headstock of a lathe (see Fig. 21.2 on p. 557, where the solid bar is now replaced with a tube) and machining the end of the tube with a simple, straight tool. The feed on the lathe will become the depth of cut, to, in orthogonal cutting, and the chip width will be the same as the wall thickness of the tube.

21.59 Describe your thoughts on whether chips produced during machining can be used to make useful products. Give some examples of possible products, and comment on their characteristics and differences if the same products were made by other manufacturing processes. Which types of chips would be desirable for this purpose?

By the student. This can be a challenging problem and many students may conclude (incorrectly) that there are no useful products that can be made from chips. However, the following are some examples:

- Short or discontinuous chips, as well as thin and long chips, can be used as metal reinforcing fibers for nonmetallic materials such as polymers or cement.
- Shaved sheet can be produced from metal, as described in Problem 21.62.
- Metal filters can be produced by compacting the chips into solid shapes, as can be done using powder-metallurgy techniques.
- Novel jewelry can be produced from chips.

21.60 Recall that cutting tools can be designed so that the tool–chip contact length is reduced by recessing the rake face of the tool some distance away from its tip. Explain the possible advantages of such a tool.

By the student. The principal reason is that by reducing the tool-chip contact, the friction force, F, is reduced, thus cutting forces are reduced. Chip morphology may also change. The student is encouraged to search the technical literature regarding this question.

21.61 Recall that the chip-formation mechanism also can be observed by scraping the surface of a stick of butter with a sharp knife. Using butter at different temperatures, including frozen butter, conduct such an experiment. Keep the depth of cut constant and hold the knife at different angles (to simulate the tool rake angle), including oblique scraping. Describe your observations regarding the type of chips produced. Also, comment on the force that your hand feels while scraping and whether you observe any chatter when the butter is very cold.

By the student. This is a simple experiment to perform. By changing the temperature of the stick of butter and the knife angle, one can demonstrate various chip formations and observe the changes that occur when the temperature is changed. Chattering of the knife and how it is related to chip morphology can also be explored.

21.62 Experiments have shown that it is possible to produce thin, wide chips, such as 0.08 mm thick and 10 mm wide, which would be similar to the dimensions of a rolled sheet. Materials have been aluminum, magnesium, and stainless steel. A typical setup would be similar to orthogonal cutting, by machining the periphery of a solid round bar with a straight tool moving radially inward. Describe your thoughts regarding producing thin metal sheets by this method, taking into account the metal's surface characteristics and properties.

By the student. There are some advantages to this material. The material has undergone an intense shear during cutting, and therefore the material develops a fine grained, highly oriented structure. One side (that against the tool) will have a shiny surface finish, while the other side is rough (see chip surfaces in Fig. 21.3a on p. 558 and Fig. 21.5 on p. 562).

21.63 Describe your thoughts regarding the recycling of chips produced during machining in a plant. Consider chips produced by dry cutting versus those produced by machining with a cutting fluid.

By the student. Chips are now recycled more commonly, although cutting-fluid reclamation (removal) is often attempted before melting the chips. Cutting fluids often can cause volatile organic compounds (to be exhausted upon combustion) so this can be an environmental issue. Also, an effort must to be made to keep classes of materials separate; for example, aluminum and steel chips have to be separated for recycling.

Chapter 22

Cutting-Tool Materials and Cutting Fluids

QUALITATIVE PROBLEMS

22.12 Explain why so many different types of cutting-tool materials have been developed over the years. Why are they still being developed further?

The reasons for the availability of a large variety of cutting-tool materials is best appreciated by reviewing the top eight parameters in the first column in Table 22.2 on p. 594. Among various factors, the type of workpiece material machined, the type of operation, and the surface finish and dimensional accuracy required all affect the choice of a cutting-tool material. For example, for interrupted cutting operations such as milling, we need toughness and impact strength. For operations where much heat is generated due, for example, to high cutting speeds, hot hardness is important. If very fine surface finish is desired, then materials such as ceramics and diamond would be highly desirable. These materials continue to be investigated further because, as in all other materials, there is much progress to be made for reasons such as to improve properties, extend their applications, develop new tool geometries, and reduce costs. The students are encouraged to comment further.

22.13 Which tool-material properties are suitable for interrupted cutting operations? Why?

In interrupted cutting operations, it is desirable to have tools with a high impact strength and toughness. From Tables 22.1 and 22.2 on pp. 593-594, the tool materials which have the best impact strength are high speed steels, and to a lesser extent, cast alloys and carbides. Therefore, one would prefer to use high-speed steels and carbides in interrupted cutting operations. In addition, in these operations, the tool is constantly being heated and reheated. It is therefore desirable to utilize materials with low coefficients of thermal expansion and

high thermal conductivity to minimize thermal stresses in the tool which could lead to tool failure.

22.14 Describe the reasons for and advantages of coating cutting tools with multiple layers of different materials.

There are several reasons for applying multiple coatings to a cutting tool, as also described in Section 22.5 on p. 600. One of the most obvious is that a given coating material may not bond well directly to the tool surface. A sandwiched layer of coating to which both the metal and the desired coating can bond successfully will increase the life of the tool. Also, one can combine the benefits from different materials. For example, the outermost layer can be a coating which is best from a hardness or low frictional characteristic to minimize tool wear. The next layer can have the benefit of being thermally insulating, and a third layer may be of a material which bonds well to the tool. Using these multiple layers allows a synergistic result in that the weaknesses of one coating can be compensated for with another layer.

22.15 Make a list of the alloying elements used in highspeed steels. Explain what their functions are and why they are so effective in cutting tools.

Typical alloying elements for high-speed steel are chromium, vanadium, tungsten, and cobalt. These elements impart higher strength and higher hardness at elevated temperatures. See Section 5.5.1 on p. 136 for further details on the effects of various alloying elements in steels.

22.16 As stated in Section 22.1, tool materials can have conflicting properties when used for machining operations. Describe your observations regarding this matter.

The brief discussion below should be viewed as illustrative of the type of answers that can be generated by the students. One well-known example of conflicting properties is the competition between hardness and ductility. Hardness is desirable for good wear resistance (see Section 33.5 on p. 961), and for this reason it is advisable to perform hardening processes such as proper heat treating to high-speed steels. One of the consequences of hardening operations is that the ductility of the tool material may be compromised. If the machining operation is one of interrupted cutting (as in milling), or if chatter occurs, it is better to have good ductility and toughness to prevent premature tool fracture. The students are encouraged to comment further.

22.17 Explain the economic impact of the trend shown in Fig. 22.6.

The obvious economic impact can be deduced when also considering the axiom "time is money." As the cutting time decreases, the production cost decreases. Notice that the ordinate in Fig. 22.6 on p. 601 is a log scale, which indicates that the reduction in time will be an ever decreasing difference with given time increments. However, the trend is still that parts manufactured by machining are less costly as the years progress.

22.18 Why does temperature have such an important effect on tool life?

Temperature has a large effect on the life of a cutting tool for several reasons. First, all materials become weaker and less hard as they become hotter; therefore, higher temperatures will weaken and soften an otherwise ideal material. Second, chemical reactivity typically increases with increasing temperature, as does diffusion between the workpiece and the cutting

tool. Third, the effectiveness of cutting fluids is compromised at excessive temperatures, meaning there is higher friction to overcome, and therefore more tool wear is expected. Finally, in interrupted cutting, there can be excessive thermal shock if the temperatures are high.

22.19 Ceramic and cermet cutting tools have certain advantages over carbide tools. Why, then, are they not completely replacing carbide tools?

Ceramics are preferable to carbides in that they have a lower tendency to adhere to metals being cut, and have a very high abrasion resistance and hot hardness. However, ceramics are generally brittle, and it is not unusual for them to fail prematurely. Carbides are much tougher than ceramics, and are therefore much more likely to perform as expected even when conditions such as chatter occurs. Also, it should be noted that ceramic tools have limits to their geometry; sharp noses are likely to be chipped and high rake angle tools will have suspect strength if made from ceramics. Carbide tools are preferable for these geometries when needed.

22.20 Can cutting fluids have any adverse effects in machining? If so, what are they?

Cutting fluids can have adverse effects on the freshly machined surfaces, as well as various components of the machine tool and the lubricants used on the machines themselves, such as altering their viscosity and lubricating capabilities. If a cutting fluid is very effective as a coolant, it could lead to thermal shock in interrupted cutting operations. Cutting fluids have to be replaced periodically because they degrade, adversely affecting their performance. This degradation can be due to intense shear in the cutting zone, contamination by other materials, or from bacteria attacking the oil (or, more commonly, the emulsifier). If the cutting is no longer effective because of this degradation, workpiece quality will be compromised, but then there is the additional environmental concern associated with fluid disposal. (See also bottom of p. 611.)

22.21 Describe the trends you observe in Table 22.2.

By the student. Table 22.2 on p. 594 lists the cutting-tool materials in the approximate order of their development (from left to right). In terms of mechanical properties of the tool materials, the trend is towards development of harder materials with improved wear resistance. The tradeoff, however, can be a reduction in toughness, impact strength, and chipping resistance. The benefits of the trend is that cutting can take place faster, with greater depths of cut (except for diamond tools) and with better surface finish. Other limitations are the decreasing thermal shock resistance and increasing costs of the tool materials towards the right of the table.

22.22 Why are chemical stability and inertness important in cutting tools?

Chemical stability and inertness are important for cutting tools in order to maintain low friction and wear. One of the causes of friction is the shear stress required to break the microwelds in the interfaces between tool and workpiece materials (see Fig. 33.5 on p. 958). If the tool material is inert, the microwelds are less likely to occur, and friction and wear will thus be reduced. It is also important that the workpiece and the cutting tool not bond chemically; this can lead to diffusion and adhesive wear.

22.23 Titanium-nitride coatings on tools reduce the coefficient of friction at the tool–chip interface. What is the significance of this property?

The tool-chip interface is the major source of friction in cutting, hence a major source of energy dissipation. Also, reducing friction will increase the shear angle and produce thinner chips and requiring less shear energy (see p. 561). These reductions will, in turn, reduce the cutting forces and hence the total energy required to perform the cutting operation. Reducing friction also reduces the amount of heat generated, which results in lower temperatures, with beneficial effects such as extending tool life and maintaining dimensional accuracy. (See also Problem 21.19.)

22.24 Describe the necessary conditions for optimal utilization of the capabilities of diamond and cubic-boronnitride cutting tools.

Because diamond and cBN are brittle, impact due to factors such as cutting-force fluctuations and poor quality of the machine tools used must be minimized. Thus, interrupted cutting (such as milling or turning splines) should be avoided. Machine tools should have sufficient stiffness to avoid chatter and vibrations (see Chapter 25). Tool geometry and setting is also important to minimize stresses and possible chipping. The workpiece material must be suitable for diamond or cBN; for example, carbon is soluble in iron and steels at elevated temperatures as seen in cutting, and diamond would not be suitable for these materials.

22.25 Negative rake angles generally are preferred for ceramic, diamond, and cubic-boron-nitride tools. Why?

Although hard and strong in compression, these materials are brittle and relatively weak in tension. Consequently, negative rake angles (which indicate larger included angle of the tool tip; see, for example, Fig. 21.3 on p. 558) are preferred mainly because of the lower tendency to cause tensile stresses and chipping of the tools.

22.26 Do you think that there is a relationship between the cost of a cutting tool and its hot hardness? Explain.

Generally, as hot hardness increases, the cost of the tool material increases. For example, ceramics have high hot hardness and are generally made of inexpensive raw materials. However, their production into effective and reliable tool materials involves major steps (see Section 18.2 on p. 466) and, hence, expenses (also known as value added; see bottom of p. 2). Likewise, carbides utilize expensive raw materials as well as involving a number of processing steps. Diamond and cubic boron nitride are expensive as well.

22.27 Make a survey of the technical literature, and give some typical values of cutting speeds for high-speed steel tools and for a variety of workpiece materials.

By the student. Good sources for such a literature search are periodicals, trade magazines, and cutting-tool vendors whose product specifications will include recommended cutting speeds and various other useful data. See also Table 23.4 starting on p. 622.

22.28 In Table 22.1, the last two properties listed can be important to the life of a cutting tool. Why?

The last two properties in Table 22.1 on p. 593 are thermal conductivity and coefficient of thermal expansion. These properties are important in thermal cracking or shock of the tool material due to internal thermal stresses developed when subjected to thermal cycling, as in interrupted cutting operations. (See Section 3.6 on p. 93 for details.)

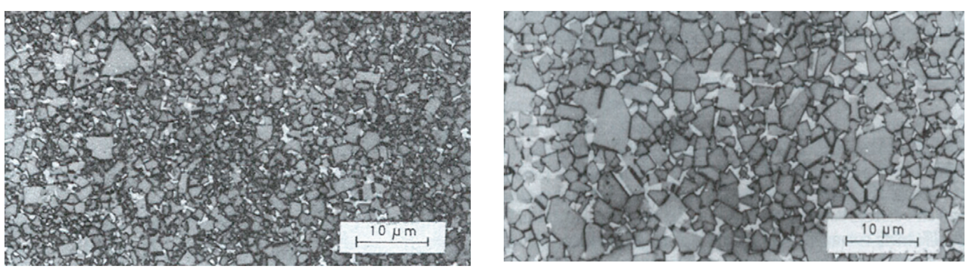
22.29 It has been stated that titanium-nitride coatings allow cutting speeds and feeds to be higher than those for uncoated tools. Survey the technical literature and prepare a table showing the percentage increase of speeds and feeds that would be made possible by coating the tools.

By the student. Good sources for such a literature search are periodicals, trade magazines, and cutting-tool vendors whose product specifications will include data on speeds and feeds. See also Table 23.4 on pp. 622-624.

22.30 Note in Fig. 22.1 that all tool materialsespecially carbideshave a wide range of hardnesses for a particular temperature. Describe each of the factors that are responsible for this wide range.

By the student. There are many reasons for the range of hardnesses, including:

- All of the materials can have variations in their microstructure, and this can significantly affect the hardness. For example, compare the following two micrographs of tungsten carbide, showing a fine-grained (left) and coarse-grained (right) tungsten carbide. (*Source:* Trent, E.M., and Wright, P.K., *Metal Cutting* 4th ed., Butterworth Heinemann, 2000, pp. 178-185).



- There can be a wide range in the concentration of the carbide compared to the cobalt binder in carbide tools.
- For materials such as carbon tool steels, the carbon content can be different, as can the level of case hardening of the tool.
- ‘High speed steels’ and ‘ceramics’ are generic terms with a large range of chemistries.
- Cutting tool materials are available in a wide variety of sizes and geometries, and the hardness will vary accordingly. For example, a large rake angle tool is more susceptible to chipping (see Fig. 22.4 on p. 598), so such tools may be hardened to a lower extent in order to preserve some toughness in the material.

22.31 Referring to Table 22.1, state which tool materials would be suitable for interrupted cutting operations. Explain.

By the student. Interrupted cutting operations basically require cutting-tool materials that have high impact strength (toughness) as well as thermal-shock resistance. Note in Table

22.1 on p. 593 that high-speed steels are by far the toughest; however, their resistance to high temperatures is rather low and have limited tool life in such operations. Consequently, although not as tough, carbides, cermets, and polycrystalline cubic boron nitride and diamond are used widely in interrupted cutting various workpiece materials, as shown in Table 24.2 on p. 670. These tool materials are continuously being developed for increasing toughness and resistance to edge chipping.

22.32 Which of the properties listed in Table 22.1 is, in your opinion, the least important in cutting tools? Explain.

By the student. It would appear that modulus of elasticity and density are not particularly important in cutting. However, as a very low order effect, elastic modulus may have some influence in very high precision machining operations because of the deflections involved. As for density, although the cutting tool itself has a rather small mass compared to other components, in high-speed operations where tool reversals may be involved, inertia effects can be important.

22.33 If a drill bit is intended only for woodworking applications, what material is it most likely to be made from? (*Hint*: Temperatures rarely rise to 400°C in woodworking.) Explain.

Because of economic considerations, woodworking tools are typically made of carbon steels, with some degree of hardening by heat treatment. Note from Fig. 22.1 on p. 592 that carbon steels maintain a reasonably high hardness for temperatures less than 400°F. For drilling metals, however, the temperatures are high enough to soften the carbon steel (unless drilling at very low rotational speeds), thus quickly dulling the drill bit.

22.34 What are the consequences of a coating on a tool having a different coefficient of thermal expansion than the substrate material?

Consider the situation where a cutting tool and the coating are stress-free at room temperature when the tool is inserted. Then consider the situation when the tool is used in cutting and the temperatures are very high. A mismatch in thermal expansion coefficients will cause high thermal strains at the temperatures developed during machining. This can result in a separation (delamination) of the coating from the substrate.

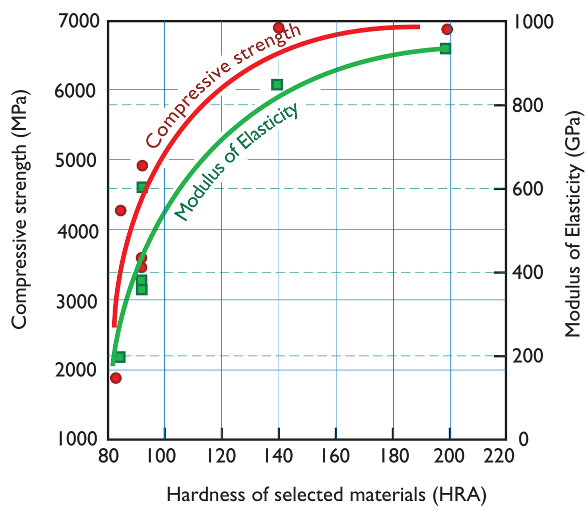
22.35 Discuss the relative advantages and limitations of near-dry machining. Consider all relevant technical and economic aspects.

Refer to Section 22.12.1 on p. 611. The advantages are mostly environmental as there is no cutting fluid which would add to the manufacturing cost, or to dispose of or treat before disposal. This has other implications in that the workpiece doesn't have to be cleaned, so no additional cleaning fluids, such as solvents, have to be used. Also, lubricants are expensive and difficult to control. However, cutting-fluid residue provides a protective oil film on the machined part from the environment, especially with freshly machined metals that begin to rapidly oxidize.

QUANTITATIVE PROBLEMS

22.36 Review the contents of Table 22.1. Plot several curves to show relationships, if any, among parameters such as hardness, transverse rupture strength, and impact strength. Comment on your observations.

By the student. There are many variables that can be selected for study; some will give no apparent relationship but others will give some correlation. For example, below is a plot of hardness compared to compressive strength and elastic modulus. Note that the hardness of cubic boron nitride and diamond have been extrapolated from Fig. 2.15 on p. 73 and are only estimates for illustrative purposes. It should be noted that the plot is restricted to the materials in Table 22.1. In general, there is no trend between hardness and elastic modulus, but Table 22.1 has a small selection of materials suitable for cutting tools.



22.37 Obtain data on the thermal properties of various commonly used cutting fluids. Identify those which are basically effective coolants (such as water-based fluids) and those which are basically effective lubricants (such as oils).

By the student. Most cutting fluids are emulsions (water-based fluids), but they may be provided as a base oil, and the supplier will report data for the base oil only. The actual emulsion produced from this base oil will have higher specific heat and superior thermal properties. Properties such as thermal conductivity and specific heat can be linearly interpolated from the water concentration according to rules of mixtures. This is a challenging problem because thermal properties are usually not readily available. The most common practice for applying the lubricant is flooding (see p. 609), so that most heat is removed by convection. Predicting convection coefficients using well-characterized fluids is extremely difficult.

22.38 The first column in Table 22.2 shows ten properties that are important to cutting tools. For each of the tool materials listed in the table, add numerical data for

each of these properties. Describe your observations, including any data that overlap.

There are many acceptable answers since all of the tool materials in the table have a wide range of values. Also, some of the measures are qualitative, such as chipping resistance and thermal-shock resistance. Cutting speeds depend on the workpiece material and its condition, as well as the quality of surface desired. However, examples of acceptable answers are:

Property	**Material**			
	HSS	**Cast-cobalt alloys**	**Cubic boron nitride**	**Diamond**
Hot hardness	60 HRA	75 HRA	4000 HK	7000 HK
Impact strength, J	4	1	< 0.5	< 0.2
Cutting speed, m/min	90	300	400	760
Thermal conductivity, W/m-K (shock resistance)	40	-	13	500

SYNTHESIS, DESIGN, AND PROJECTS

22.39 Describe in detail your thoughts regarding the technical and economic factors involved in tool-material selection.

By the student. The technical and economic factors are constantly in competition. Among the technical factors are (see pp. 591-592):

- A tool material with sufficiently high hot hardness for strength and wear resistance.
- Chemical stability and inertness for adhesive wear resistance.
- Toughness for fracture prevention.
- High thermal conductivity to minimize severe temperature gradients.

Among the economic factors are:

- Tool cost should be minimized.
- The material should be readily available.

22.40 One of the principal concerns with coolants is degradation due to biological attack by bacteria. To prolong the life of a coolant, chemical biocides often are added, but these biocides greatly complicate the disposal of the coolant. Conduct a literature search concerning the latest developments in the use of environmentally benign biocides in cutting fluids.

By the student. There are a few approaches, such as: (a) Increase the pH to an extent to where no microorganisms can survive. (b) Develop chemical agents which directly kill microorganisms (biocides). (c) Use a chemical which the microorganism ingests and which, in turn, poisons the microbe.

22.41 How would you go about measuring the effectiveness of cutting fluids? Describe your method and explain any difficulties that you might encounter.

By the student. The most effective and obvious method is to test different cutting fluids in actual machining operations. Other methods are to heat the fluids to the temperatures typically encountered in machining, and measure their viscosity and other relevant properties such as lubricity, specific heat, and chemical reactions (see Chapter 34 for details). The students are encouraged to develop their own ideas for such tests.

22.42 Contact several different suppliers of cutting tools, or search their websites. Make a list of the costs of typical cutting tools as a function of various sizes, shapes, and features.

By the student. Very useful websites are those for major suppliers such as Kennametal, Iscar, Sandvik, Carboloy, and Valenite; general product catalogues are also helpful. In comparing costs from older and newer cost data, it will be noted that, as in many other products, costs vary (up or down) by time. (See also Section 40.9 on p. 1156.)

22.43 There are several types of cutting-tool materials available today for machining operations, yet much research and development is being carried out on all these materials. Discuss why you think such studies are being conducted.

By the student. This is a challenging and rich topic for literature studies. For example, students could examine this question based on requirements for cutting-tool materials for machining of new materials such as nanophase materials and composites. The students can also consider this question as an issue of the continued trend in increasing cutting speeds and tool life.

22.44 Assume that you are in charge of a laboratory for developing new or improved cutting fluids. On the basis of the topics presented in this chapter and in Chapter 21, suggest a list of topics for your staff to investigate. Explain why you have chosen those topics.

By the student. For example, one approach would be to direct the students to current conference programs, so that they can examine the technical papers currently being presented. Appropriate sources would be the Society of Tribologists and Lubrication Engineers (www.stle.org) and the American Society of Mechanical Engineers (www.asme.org). Among the major research topics of current interest are:

- The use of environmentally benign cutting fluids, such as vegetable oil-based fluids.
- The use of ionic fluids.
- Elimination of cutting fluids (dry or near-dry machining; see Section 22.12.1 starting on p. 611).
- Formulation of additives, such as detergents, lubricity additives, and alkalinity modifiers.

Chapter 23

Machining Processes Used to Produce Round Shapes: Turning and Hole Making

QUALITATIVE PROBLEMS

23.13 Explain the reasoning behind the various design guidelines for turning.

By the student. The design guidelines, given in Section 23.3.6 on p. 697, are mostly self-explanatory, such as the need to design parts so that they can be easily fixtured. However, some examples of some reasoning are as follows:

- Sharp corners, tapers, steps, and major dimensional variations in the part should be avoided. It's easiest for a lathe to be set up to perform straight turning, thus unnecessary dimensional variations make the lathe operation much more difficult. The difficulty with sharp corners, especially internal corners, is that the minimum corner radius is that of the nose radius of the cutting tool (see Figs. 21.15 on p. 574, 21.23 on p. 582, and 23.4c on p. 619). Also, small nose radii lead to increased likelihood of tool chipping or breakage.
- Blanks to be machined should be as close to the final dimensions as possible; this is, of course, a valuable general concept. It is important in turning because tool life is limited and the number of roughing cuts before a finishing cut is taken should be minimized.

23.14 Note that both the terms "tool strength" and "tool-material strength" have been used in the text. Do you think there is a difference between them? Explain.

By the student. There is a difference between tool-material strength and tool strength. Tool material strength is a property of the material (see Table 22.1 on p. 593); thus, for example, the compressive strength of carbides is higher than that for high-speed steels. The tool

strength, on the other hand, refers to the ability of a particular cutting tool to resist fracture or failure. This depends not only on the tool material itself but also on the tool geometry, as shown in Figs. 22.4 and 22.5 on pp. 598-599.

23.15 List and explain the factors that contribute to poor surface finish in the processes described in this chapter.

By the student. As an example, one factor is explained by Eq. (8.35) on p. 449, which gives the roughness in a process such as turning. Clearly, as the feed increases or as the tool nose radius decreases, roughness will increase. Other factors that affect surface finish are built-up edge (see, for example, Figs. 8.4 and 8.6), dull tools or tool-edge chipping (see Fig. 8.28), or vibration and chatter (Section 8.11.1).

23.16 Explain why the sequence of drilling, boring, and reaming produces a hole that is more accurate than drilling and reaming it only.

The difficulty is largely due to the fact that drilling, because of its inherent flexibility, does not necessarily produce a hole that is accurate in its coordinate, whereas boring is an operation that is better controlled.

23.17 Why would machining operations be necessary even on net-shape or near-net-shape parts made by precision casting, forming, or powder-metallurgy products, as described in preceding chapters? Explain.

By the student. Many applications require better dimensional tolerances or surface finish than those produced by casting, forging, or powder metallurgy. Machining operations can remove unevenness from parts, such as those caused by defects or through uneven deformation and warping upon cooling. Many processes, by their nature, will not impart a sufficiently smooth surface finish to the workpiece, and it is often necessary to machine (or grind, polish, etc.) them for improved dimensional accuracy. Other parts require surface features that cannot be obtained through other manufacturing methods.

23.18 A highly oxidized and uneven round bar is being turned on a lathe. Would you recommend a small or a large depth of cut? Explain.

Because oxides are generally hard and abrasive (see p. 952), consequently, light cuts will cause the tool to wear rapidly. Thus it is highly desirable to cut right through the oxide layer on the first pass. Note that an uneven round bar will cause significant variations in the depth of cut being taken; thus, depending on the degree of eccentricity, it may not always be possible to do so since this can be self-excited vibration and lead to chatter.

23.19 Describe the difficulties that may be encountered in clamping a workpiece made of a soft metal in a three-jaw chuck.

A common problem in clamping any workpiece into a chuck is that the jaws will bite into the workpiece (see, for example, Fig. 23.3b on p. 618), possibly leaving an impression that may be unsightly or functionally unacceptable. Shim stock, made of a softer material, can be used between the jaws and the workpiece to minimize damage to the workpiece surface. Parts may also be designed for convenient clamping into chucks, or provided with flanges or extensions which can be gripped by the chuck, which can later be removed.

23.20 Does the force or torque in drilling change as the hole depth increases? Explain.

The force and torque may increase as the hole depth increases, but not by a significant amount. The factors which would increase the force and torque are contact area between the tool and cylindrical surface of the hole and difficulties in removing chips from the bottom of deep holes and possible clogging. Unless the hole depth is very deep, these are usually considered unimportant and the force and torque can be taken as constant.

23.21 Explain the similarities and differences in the design guidelines for turning and for boring.

By the student. Turning and boring are quite similar operations in terms of dimensional tolerances and surface finish. In both cases, secure clamping is necessary, which is the reason the clamped lengths are similar. Interrupted surfaces in both cases can lead to vibration and chatter. The differences in the two operations are that, in boring, the workpiece size is not critical. Workpieces that are suitable for boring can naturally be held in various fixtures, and vertical boring machines can accommodate very large parts (see, for example, Fig. 23.18 on p. 642). On the other hand, in typical turning operations very large parts can be difficult to mount.

23.22 Describe the advantages and applications of having a hollow spindle in the headstock of a lathe.

The main advantage is the ability to feed stock through the headstock of the lathe (Fig. 23.2 on p. 617). This is particularly important in automatic bar machines (see p. 631).

23.23 Assume that you are asked to perform a boring operation on a large-diameter hollow workpiece. Would you use a horizontal or a vertical boring mill? Explain.

By the student. It is apparent that, because of size and weight limitations, a horizontal setup is desirable. See, for example, Fig. 23.18 on p. 642.

23.24 Explain the reasons for the major trend that has been observed in producing threads by thread rolling as opposed to thread cutting. What would be the differences, if any, in the types of threads produced and in their performance characteristics?

By the student. Thread rolling is described on pp. 329-330. The main advantages of thread rolling over thread cutting are the speeds involved (thread rolling is a very high production rate process) and the fact that the threads will undergo extensive cold working (plastic deformation; see Fig. 13.17c on p. 330), leading to stronger work-hardened threads. Cutting is still used for making threads(see Section 23.3.8 on p. 639) because it is a very versatile operation and much more economical for low production runs (since expensive dies are not required). Note that internal threads also can be rolled, but this is not nearly as common as machining the threads and can be a difficult operation.

23.25 Describe your observations concerning the contents of Tables 23.2 and 23.4, and explain why those particular recommendations are made.

By the student. Some observations are listed below:

- Referring to Table 23.2 on p. 619, note that the side rake angle is high for aluminum but low for titanium. This can be explained by the benefits of maintaining higher compression on the shear plane for titanium (to obtain higher ductility), a situation not needed for aluminum.
- Note from Table 23.4 on p. 622 that the cutting speeds for steels are much lower than those for copper alloys. This can be explained by power requirements associated with machining steels.
- Note that the tools used in Table 23.4 vary by workpiece material. For example, no diamond is listed for steel, explainable by the solubility of carbon in steel at elevated temperatures.

23.26 The footnote to Table 23.11 states that as the hole diameter increases, speeds and feeds in drilling should be reduced. Explain why.

As hole depth increases, elastic recovery in the workpiece causes normal stresses on the surface of the drill, thus the stresses experienced by the drill are higher than they are in shallow holes. These stresses, in turn, cause the torque on the drill to increase and may even lead to its failure. Reduction in feeds and speeds can compensate for these increases.

23.27 In modern manufacturing, which types of metal chips would be undesirable and why?

Referring to Fig. 21.5 on p. 562, we note the following: Continuous chips are not desirable because (a) the machines mostly untended and operate at high speeds, thus chip generation is at a high rate (see also chip collection systems, p. 638) and (b) continuous chips would entangle on spindles and machine components, and thus severely interfere with the cutting operation. Conversely and for that reason, discontinuous chips or segmented chips would be desirable, and indeed are typically produced using chipbreaker features on tools, Note, however, that such chips can lead to vibration and chatter, depending also on the characteristics of the machine tool (see Section 25.4 on p. 706).

23.28 The operational severity for reaming is much lower than that for tapping, even though they both are internal machining processes. Why?

Tapping (Section 23.7 starting on p. 653) produces a significant amount of chips and their removal through the hole being tapped can be difficult as they can get clogged (and can cause tap fracture), thus contributing to the severity of the tapping operation. Control of processing parameters and use of effective cutting fluids are thus important. Chipless tapping, on the other hand, does not present such difficulties.

23.29 Review Fig. 23.6, and comment on the factors involved in determining the height of the zones (cutting speed) for various tool materials.

The main reasons for a range of acceptable cutting speeds shown in Fig. 23.6 on p. 621 are based on tool life and surface finish of the workpiece. One can appreciate that tool life depends not only on the cutting-tool material, but also on the workpiece material and its condition, as well as the particular tool geometry. It is therefore to be expected that there will be a wide range of feeds and speeds for each cutting-tool material.

23.30 Explain how gun drills remain centered during drilling. Why is there a hollow, longitudinal channel in a gun drill?

Gun drills remain centered because of the tip design because, as stated on p. 646, of the presence of bearing pads. The hole in the center of the drill is for pumping the cutting fluid, which cools the workpiece and the tool, lubricates the interfaces, and washes chips from the drilling zone.

23.31 Comment on the magnitude of the wedge angle on the tool shown in Fig. 23.4.

The wedge angle is very important. As shown in Figs. 22.4 and 22.5 on p. 598-599, the wedge angle has a large effect on the strength of the cutting tool, and therefore its resistance to chipping and fracture. (See also Problem 22.21.)

23.32 If inserts are used in a drill bit (see Fig. 23.21), how important is the shank material? If so, what properties are important? Explain.

Recognizing that inserts on a drill bit are rather small (see Fig. 23.21 on p. 645) and the temperature of the inserts will be very high, it is important that the shank material be able to effectively extract heat from the inserts. Also, if the inserts are brazed in place (which is a decreasing practice because they are not indexable and are time-consuming to make), the thermal expansion coefficients of the insert and the shank should be matched to avoid thermal stresses. The shank must provide rigidity and damping to avoid chatter, and must have reasonable cost.

23.33 Refer to Fig. 23.10b, and in addition to the tools shown, describe other types of cutting tools that can be placed in toolholders to perform other machining operations.

By the student. Referring to Fig. 23.1 on p. 616, not that a tool for each of these operations could be included. In addition, reamers, taps, and drills of all types also could be used (see Fig. 23.20 on p. 645).

QUANTITATIVE PROBLEMS

23.34 Calculate the same quantities as in Example 23.1 for high-strength titanium alloy and at N=700 rpm.

The maximum cutting speed is

$$V = \frac{(700)(\pi)(12.5)}{1000} = 27.5 \text{ m/min}$$

and the cutting speed at the machined diameter is

$$V = \frac{(700)(\pi)(12)}{1000} = 26.4 \text{ m/min}$$

The depth of cut is unchanged at 0.25 mm and the feed is given by

$$f = 200/700 = 0.29 \text{ mm/rev}$$

Taking an average diameter of 12.25 mm, the metal removal rate is

$$\text{MRR} = \pi(12.25)(0.25)(0.29)(700) = 1953 \text{ mm}^3/\text{min}$$

The actual time to cut is

$$t = \frac{150}{(0.29)(700)} = 0.74 \text{ min}$$

From Table 21.2 on p. 622 let's take the unit power for titanium alloys as 5 W-s/mm^3, or 2 hp-min/in^3. Note that we used the upper limits of the power because the problem states that the titanium is of high strength. Thus, the power dissipated is

$$\text{Power} = \frac{(5)(1953)}{60} = 163 \text{ W} = 9780 \text{ N-m/min}$$

The torque is given by

$$\text{Torque} = \frac{9780}{(700)(2)(\pi)} = 2.2 \text{ N-m}$$

Therefore the cutting force is

$$F_c = \frac{(2.2)(1000)}{(12.25/2)} = 360 \text{ N}$$

23.35 Estimate the machining time required to rough turn a 0.50-m-long annealed copper-alloy round bar from a 60-mm diameter to a 58-mm diameter, using a high-speed steel tool. (See Table 23.4.) Estimate the time required for an uncoated carbide tool.

Referring to Table 23.4 starting on p. 622, annealed copper alloys can be machined at a maximum cutting speed of 535 m/min=8.9 m/s using uncoated carbides. The footnote to the table states that the speeds for high-speed steels are about one-half the value for uncoated carbides, so the speed will be taken as 268 m/min = 4.46 m/s for HSS. For rough turning, the depth of cut varies, but a mean value is taken from the table as 4.5 mm, or 0.0045 m. The maximum cutting speed is at the outer diameter and is given by (see Table 23.3 on p. 621)

$$V = \pi D_o N \quad \rightarrow \quad 535 \text{ m/min} = (N)(\pi)(0.06 \text{ m})$$

and hence $N = 2840$ rpm for HSS and 1420 rpm for carbide. Because it is rough turning, the feeds can be taken as the higher values in Table 23.4 on p. 622. Using the value of 0.75 mm/rev, or 0.00075 m/rev, for materials with low hardness such as aluminum, the time to cut is obtained from Eq. (23.2) on p. 679 as

$$t = \frac{l}{fN} = \frac{0.5 \text{ m}}{(0.00075 \text{ m/rev})(2840 \text{ rpm})} = .235 \text{ min} = 14.1 \text{ s}$$

The time for carbide is likewise found to be about 7.5 s.

23.36 A high-strength cast-iron bar 200 mm in diameter is being turned on a lathe at a depth of cut d = 1.25 mm. The lathe is equipped with a 12-kW electric motor and has a mechanical efficiency of 80%. The spindle speed is 500 rpm. Estimate the maximum feed that can be used before the lathe begins to stall.

Note that $D_{\text{ave}} = 198.75$ mm. Since the lathe has a 12-kW motor and a mechanical efficiency of 80%, we have (12)(0.8)=9.6 kW available for the cutting operation. For cast irons the specific power required is obtained from Table 21.2 on p. 571 as between 1.1 and 5.4 W.s/mm^3. We will use the average value to obtain a typical number so that the specific power will be taken as 3.3 W.s/mm^3. Therefore, the maximum metal removal rate is

$$\text{MRR} = \frac{(9.6)(1000)\text{W}}{3.3\ \text{Ws/mm}^3} = 2909\ \text{mm}^3/\text{s}$$

The metal removal rate is also given by Eq. (23.1a) on p. 620 as

$$\text{MRR} = \pi D_{\text{ave}} d f N$$

Therefore, the maximum feed, f, is

$$f = \frac{\text{MRR}}{\pi D_{\text{ave}} d N} = \frac{(2909)(60)}{\pi(198.75)(1.25)(500)} = 0.45\ \text{mm/rev}$$

23.37 A 7.5-mm-diameter drill is used on a drill press operating at 300 rpm. If the feed is 0.125 mm/rev, what is the MRR? What is the MRR if the drill diameter is doubled?

The metal removal rate in drilling is given by Eq. (23.3) on p. 647. Thus, for a 7.5-mm drill diameter, with the spindle rotating at 300 rpm and a feed of 0.125 mm/rev, the MRR is

$$\text{MRR} = \left(\frac{\pi D^2}{4}\right)(f)(N) = \left[\frac{(\pi)(7.5)^2}{4}\right](0.125)(300) = 1657\ \text{mm}^3/\text{min}$$

If the drill diameter is doubled, the metal removal rate will be increased fourfold because MRR depends on the diameter squared. The MRR would then be (1657)(4)=6628 mm^3/min.

23.38 In Example 23.4, assume that the workpiece material is high-strength aluminum alloy and the spindle is running at N = 500 rpm. Estimate the torque required for this operation.

If the spindle is running at 500 rpm, the metal removal rate is

$$\text{MRR} = (210)\left(\frac{500}{800}\right) = 131\ \text{mm}^3/\text{s}$$

From Table 21.2 on p. 574, the unit power for high-strength aluminum alloys is estimated as 1 W-s/mm^3. The power dissipated is then

$$\text{Power} = (131)(1) = 131\ \text{W}$$

Since power is the product of the torque on the drill and its rotational speed, the rotational speed is $(500)(2\pi)/60 = 52.3$ rad/s. Hence the torque is

$$\text{Torque} = \frac{131}{52.3} = 2.5\ \text{N-m}$$

23.39 A 150-mm-diameter aluminum cylinder 250 mm in length is to have its diameter reduced to 115 mm. Using the typical machining conditions given in Table 23.4, estimate the machining time if a TiN-coated carbide tool is used.

As we'll show below, this is a subtly complicated and open-ended problem, and a particular solution can significantly deviate from this one. From Table 23.4 on p. 622, the range of parameters for machining aluminum with a TiN-coated carbide tool is:

$$d = 0.25 - 8.8 \text{ mm}$$

$$f = 0.08 - 0.62 \text{ mm/rev}$$

$$V = 60 - 915 \text{ m/min}$$

Since the total depth of cut is to be 17.5 mm, it would be logical to perform three equal roughing cuts, each at $d = 5.6$ mm and a finishing cut at $d = 0.7$ mm. For the roughing cuts, the maximum allowable feed and speed can be used, that is, $f = 0.62$ mm/rev and $V = 915$ m/min. For the finishing cuts, the feed is determined by surface finish requirements, but is assigned the minimum value of 0.08 mm/rev, and the speed is similarly set at a low value of $V = 60$ m/min. The average diameter for the first roughing cut is 144.4 mm, 133.2 mm for the second, and 122.0 mm for the third. The rotational speeds for 1st, 2nd, and 3rd roughing cuts are (from $V = \pi D_{\text{ave}} N$) 2010 rpm, 2180 rpm, and 2380 rpm, respectively. The mean diameter for the finishing cut is 115.7 mm, and with $V = 60$ m/min, the rotational speed is 165 rpm. The total machining time is then

$$\begin{aligned} t = \sum \frac{l}{fN} &= \frac{250 \text{ mm}}{(0.62 \text{ mm/rev})(2010 \text{ rpm})} + \frac{250 \text{ mm}}{(0.62 \text{ mm/rev})(2180 \text{ rpm})} \\ &+ \frac{250 \text{ mm}}{(0.62 \text{ mm/rev})(2380 \text{ rpm})} + \frac{250 \text{ mm}}{(0.08 \text{ m/rev})(165 \text{ rpm})} \end{aligned}$$

or $t = 19.5$ minutes.

23.40 For the data in Problem 23.39, calculate the power required.

This solution depends on the solution given in Problem 23.39. It should be recognized that a number of answers are possible in Problem 23.39, depending on the number of roughing cuts taken and the particular speeds and feeds selected. The power requirement will be determined by the first roughing cut since all other cuts will require less power. The metal removal rate, from Eq. (23.1a) on p. 620, is

$$\text{MRR} = \pi D_{\text{avg}} d f N = \pi(144.4)(5.6)(0.62)(2010) = 3.17 \times 10^6 \text{ mm}^3/\text{min}$$

Using the data from Table 21.1 on p. 571 for aluminum, the power required is

$$P = (3.17 \times 10^6 \text{ mm}^3/\text{min})(1 \text{ Ws/mm}^3)\left(\frac{1 \text{ min}}{60 \text{ s}}\right) = 53 \text{ kW}$$

23.41 Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

By the student. This is a good, open-ended question that requires considerable focus and understanding from the students, and has been found to be a very valuable homework problem.

SYNTHESIS, DESIGN, AND PROJECTS

23.42 Would you consider the machining processes described in this chapter as net-shape processes, thus requiring no further processing? Near-net-shape processing? Explain with appropriate examples.

By the student. This is a challenging question for in-depth discussion and is valuable in clarifying the meaning of the concept of net-shape processing. Briefly, the processes described in this chapter can be classified as either net-shape or near-net shape. Restricting the answer to surfaces that are machined, the workpiece may, as an example, be net-shaped after turning or drilling. However, if the dimensional tolerances or surface finish from turning are not acceptable, the workpiece may need to be ground (Chapter 26). The former is an example where the processes in this chapter are net-shape operations, and the latter is an example of near-net-shape processing.

23.43 Would it be difficult to use the machining processes described in this chapter on various soft nonmetallic or rubberlike materials? Explain your thoughts, commenting on the role of the physical and mechanical properties of such materials with respect to the machining operation and any difficulties that may be encountered in producing the desired shapes and dimensional accuracies.

By the student. This is a very interesting question and an excellent candidate for a technical literature review. Rubberlike materials are difficult to machine mainly because of their low elastic modulus and very large elastic strains that they can undergo under external forces. Care must be taken in properly supporting the workpiece and minimizing the cutting forces. Note also that these materials become stiffer with lower temperatures, which suggests an effective cutting strategy.

23.44 If a bolt breaks in a hole, it typically is removed by first drilling a hole in the bolt shank and then using a special tool to remove the bolt. Inspect such a tool and explain how it functions.

By the student. This is a good problem for students to develop an intuitive feel for the use of bolt extractors, commonly called "easy outs." This can be an inexpensive demonstration as well: A low-strength bolt can be easily sheared in a hole using a wrench and extender (to develop high torque), then asking the students to remove the bolt. Bolt extractors have left-handed threads and wedged sides. Thus, when place into a properly-sized cylinder or pre-drilled hole, the bolt extractor will wedge itself further into the hole as the extracting torque increases. Since it is a left-handed thread, it tightens as the bolt is being withdrawn.

23.45 An important trend in machining operations is the increased use of flexible fixtures. Conduct a search on the 658 Chapter 23 Machining Processes: Turning and Hole Making Internet regarding these fixtures, and comment on their design and operation.

By the student. This is an interesting problem for a literature search. Flexible fixturing (see also Section 37.8 on p. 1107) is economically viable for intermediate production quantities;

for large quantities, dedicated fixtures are more suitable. Manufacturers such as Carr-Lane have systems of components that can be combined to form flexible fixtures.

23.46 Review Fig. 23.7d, and explain if it would be possible to machine eccentric shafts, such as that shown in Fig. 23.12c, on the setup illustrated. What if the part is long compared with its cross section? Explain.

By the student. This is a good problem for students to develop alternatives and setup for machining. Clearly, a simple solution is that a computer-controlled lathe (see Fig. 23.10a on p. 632) can be used that is programmed to accommodate the eccentric shaft. Otherwise, the workpiece can be held in a fixture where the workpiece is mounted eccentrically and the fixture is held in the chuck.

23.47 Boring bars can be designed with internal damping capabilities to reduce or eliminate vibration and chatter during machining (see Fig. 23.17). Referring to the technical literature, describe details of designs for such boring bars.

By the student. This is a good problem for an Internet search. As with other machine tools, the approaches used are to have boring bars that have inherent damping (see Fig. 23.17b on p. 642), such as fiber-reinforced plastics (see Section 9.3 on p. 222) or using bolted joints (as shown in Fig. 25.15 on p. 709).

23.48 Make a comprehensive table of the process capabilities of the machining operations described in this chapter. Using several columns, describe the machine tools involved, type of cutting tools and tool materials used, shapes of parts produced, typical maximum and minimum sizes, surface finish, dimensional tolerances, and production rates.

By the student. This is a challenging and comprehensive problem with many possible solutions. Some examples of acceptable answers are:

Process	Machine tools	Cutting-tool materials	Shapes	Typical sizes
Turning	Lathe	Assorted; see Table 23.4	Axisymmetric	25-300 mm diameter, 100-1200 mm length
Drilling	Lathe, mill drill press	Assorted, usually HSS	Circular holes	1-100 mm (50 μm possible)
Knurling	Lathe, mill	Assorted, usually HSS	Rough surfaces on axisymmetric parts	Same as in turning

Chapter 24

Machining Processes Used to Produce Various Shapes: Milling, Broaching, Sawing, and Filing; Gear Manufacturing

QUALITATIVE PROBLEMS

24.10 Would you consider the machining processes described in this chapter to be near-net or net-shape processing? Explain with appropriate examples.

By the student. This is a good question for in-depth discussion in the classroom and is valuable for clarifying the meaning of the concept of net-shape processing. Briefly, the processes described in this chapter can be classified as either net-shape or near-net shape. Restricting the answer to surfaces that are machined, the workpiece can be net-shaped after milling. However, if the dimensional tolerances or surface finish from milling are not acceptable, the workpiece may have to be subjected to finishing operations such as grinding. The former is an example where the processes in this chapter are net-shape operations; the latter is an example of near-net-shape processing.

24.11 Why is end milling such an important versatile process? Explain with examples.

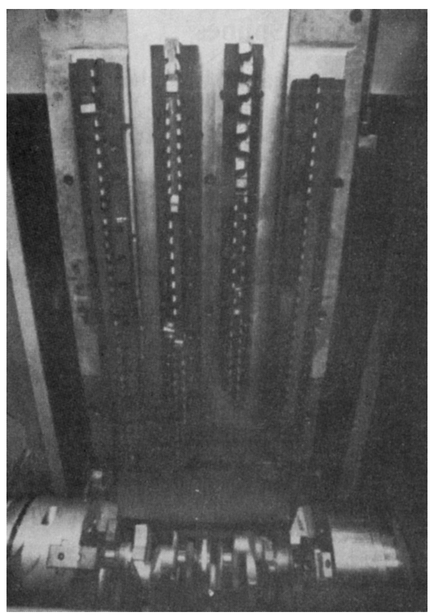
By the student. Note the capability of the relatively high length-to-diameter ratio of end mills that are capable of removing material from small and deep recesses in the workpiece (see Figs. 21.1d on p. 557 and 24.2 on p. 661). For details, see Section 24.2.3 on p. 667.

24.12 List and explain factors that contribute to poor surface finish in the processes described in this chapter.

By the student. Note, for example, Eq. (21.24) on p. 582, which gives the roughness in a process such as turning and milling, clearly indicating that as the feed per tooth increases or as the tool radius decreases, the roughness increases. Other factors that contribute to poor surface finish are built-up edge, tool chipping or fracture, and chatter. Each of these factors can adversely affect any of the processes described in the chapter. (See also Problem 24.19.)

24.13 Explain why broaching crankshaft bearings is an attractive alternative to other machining processes.

Broaching (Section 24.4 on p. 675) has certain advantages such as capability to remove material at high volume rates in one setup and with good surface finish of the product. Turn broaching is the term used for broaching the bearing surfaces of crankshafts and similar parts (see bottom of p. 676) and is an efficient process because multiple broaches can be used and thus production rate is high. For example, the photograph below is Fig. 23.25 of the 4th edition of this text, and shows a number of broaches acting simultaneously on the bearing surfaces of an automotive crankshaft.



24.14 Several guidelines are presented in this chapter for various cutting operations. Discuss the reasoning behind these guidelines.

By the student. Typical design guidelines have been discussed in this chapter for a number of machines. For example, it is suggested that standard milling cutters be used and costly special cutters be avoided; this is reasonable because many CNC milling machines have automatic tool changers (see also Chapter 25) and can rapidly exchange tools. The guidelines that workpieces be rigid to resist deflection from clamping forces and cutting forces are intended to maximize the accuracy of the milling operation. For planing, it is suggested that the operation be designed so that all sides of the workpiece can be machined without having to reposition and reclamp the workpiece. This is important to minimize downtime while parts are being repositioned. Other guidelines have similar practical explanations.

24.15 What are the advantages of helical teeth over straight teeth on cutters for slab milling?

There are a number of advantages, but the main advantages are associated with the fact that there are always multiple teeth in contact, and the transition in contact from one tooth to another is smooth. This has the effect of reducing impact loads and periodic forcing functions (and associated vibration) from the cutting operation.

24.16 Explain why hacksaws are not as productive as band saws.

Hacksaws and band saws both have teeth oriented to remove chips when the saw moves across a workpiece; however, a band saw has continuous motion, whereas a hacksaw reciprocates. About half of the time, the hacksaw is not producing any chips, and thus it is not as productive.

24.17 What similarities and differences are there in slitting with a milling cutter and with a saw?

The milling machine utilizes a rotating cutter with multiple teeth to perform the slitting operation, cutting the material across a small width. Because the cutters are rigid and the process is well controlled, good dimensional accuracy is obtained. The blades in sawing are thinner, hence thin cuts are possible. However, the blade has more flexibility (not only because it is thin but it is also long) and hence control of dimensions can be difficult. It should be noted that are several types of saws and that circular saws have been developed which produce good dimensional accuracy and thickness control (see p. 680).

24.18 Why do machined gears have to be subjected to finishing operations? Which of the finishing processes are not suitable for hardened gear teeth? Why?

Machined gears may be subjected to finishing operations (see Section 24.7.4 on p. 685) for a number of reasons. Since gears are expected to have long lives and, therefore, operate in the high-cycle fatigue range, surface finish is very important. Better surface finish can be obtained by various finishing operations, including inducing surface compressive residual stresses to improve fatigue life. Also, errors in gear-tooth form are corrected, resulting in smaller clearances and tighter fits, and therefore less "play" and noise in a gear train.

24.19 How would you reduce the surface roughness shown in Fig. 24.6? Explain.

By the student. It can readily be seen in Fig. 24.6 on p. 665 that the surface roughness can be improved by means such as (a) reducing the feed per tooth, (b) increasing the corner radius of the insert, and (c) correctly positioning the wiper blade, as shown in Fig. 24.6c.

24.20 Why are machines such as the one shown in Fig. 24.17 so useful?

They are useful because of their versatility; they can perform a number of operations without having to re-clamp or reposition the workpiece (which is a very important consideration for improving productivity). The headstock can be tilted on most models. These machines are also relatively simple to program and the program information for a certain part can be stored on magnetic tape or disc and recalled at a later date. The machine itself can reduce the number of tools needed to perform a given number of operations by utilizing the computer to program the tool paths. (See also Sections 38.3 and 38.4.)

24.21 Comment on your observations concerning the designs illustrated in Fig. 24.20b and on the usefulness of broaching operations.

By the student. The usefulness of broaching lies not only in the complexity of parts which can be economically produced, but also in the high surface quality. These parts would be relatively difficult to produce economically and at high rates by other machining processes.

24.22 Explain how contour cutting could be started in a band saw, as shown in Fig. 24.25d.

Contour cutting, as shown in Fig. 24.25d on p. 679, would best be initiated by first drilling a hole in the workpiece and then inserting the blade into the hole. Note the circle in the part, indicating the position of the drilled hole. (A similar situation exists in wire EDM, described in Section 27.5.1 on p. 772.) Depending on the part, it is also possible to simply start the cut at one of the edges of the blank.

24.23 In Fig. 24.27a, high-speed steel cutting teeth are welded to a steel blade. Would you recommend that the whole blade be made of high-speed steel? Explain your reasons.

By the student. It is desirable to have a hard, abrasion-resistant material such as high-speed steel for the cutting edge and a flexible, thermally conductive material for the bulk of the blade. This is an economical method of producing saws, and to make the whole blade from HSS would be unnecessary and expensive.

24.24 Describe the parts and conditions under which broaching would be the preferred method of machining.

By the student. Broaching is very attractive for producing various external and internal geometric features; it is a high-rate production process and can be highly automated. Although the broach width is generally limited (see Fig. 24.22 on p. 676), typically a number of passes are taken to remove material, such as on the top surface of engine blocks. Producing notches, slots, or keyways are common applications where broaching is very useful.

24.25 With appropriate sketches, explain the differences between and similarities among shaving, broaching, and turn-broaching operations.

By the student. Note, for example, that the similarities are generally in the mechanics of cutting, involving a finite width chip and usually orthogonal cutting. The differences include particulars of tooling design, the machinery used, and workpiece shapes.

24.26 Explain the reason that it is difficult to use friction sawing on nonferrous metals.

As stated on p. 680-681, nonferrous metals have a tendency to stick to the blade. This is undoubtedly caused by adhesion at the high temperatures and is easily attributable to the softness of these materials. Note also that these materials have a characteristically high thermal conductivity, so if any metal is melted (which is possible given the low melting temperatures of nonferrous metals), it will be quickly solidified if the severity of the operation is reduced; this can lead to welding to the blade.

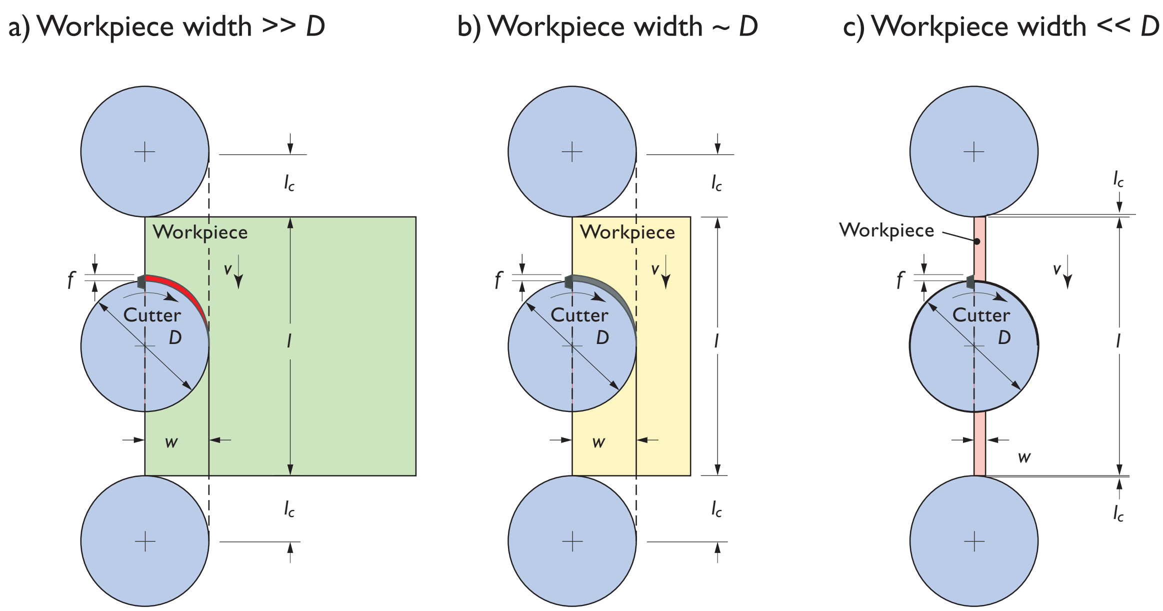
24.27 Would you recommend broaching a keyway on a gear blank before or after machining the gear teeth? Why?

By the student. The keyway can be machined before the teeth is machined. The reason is that in hobbing or related processes (see Section 24.7 on p. 681), the gear blank is indexed. The key-way serves as a natural guide for indexing the blank.

QUANTITATIVE PROBLEMS

24.28 In milling operations, the total cutting time can be significantly influenced by (a) the magnitude of the noncutting distance, l_c, shown in Figs. 24.3 and 24.4, and (b) the ratio of width of cut, w, to the cutter diameter, D. Sketch several combinations of these parameters, give dimensions, select feeds and cutting speeds, etc., and determine the total cutting time. Comment on your observations.

By the student. Students should be encouraged to consider, at a minimum, the following three cases:



Note that l_c needs to be estimated for each case. l_c is shown to be equal to $\sqrt{Dw}$ in Prob. 24.36 for $D \gg w$. For $D \sim w$, it is reasonable to take $l_c = D/2$. For $w \ll D$, it is reasonable to take $l_c = 0$.

24.29 A slab-milling operation is being performed at a specified cutting speed (surface speed of the cutter) and feed per tooth. Explain the procedure for determining the table speed required.

Combining Eqs. (24.1) and (24.3) on pp. 726-727, we obtain the expression for the table speed, v, as

$$v = \frac{fVn}{pD}$$

Since all quantities are known, we can calculate the table speed.

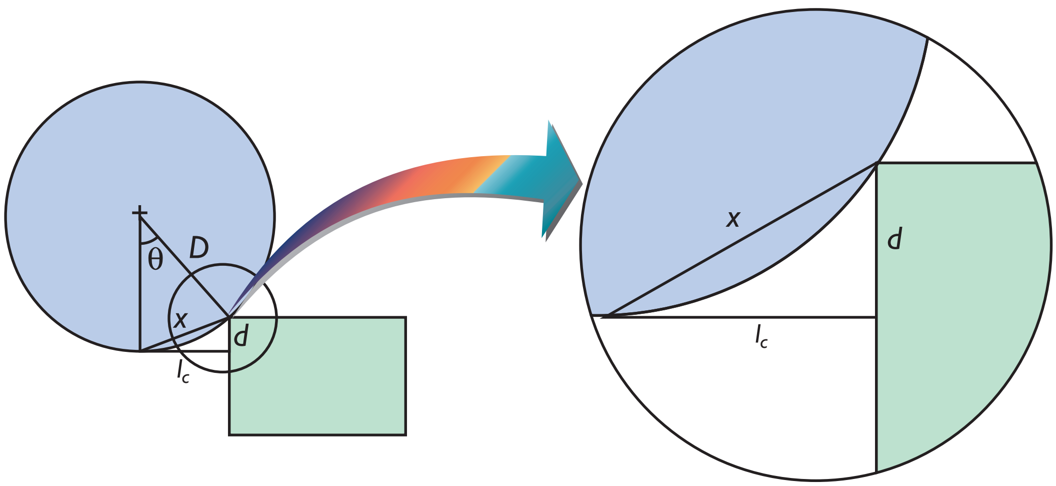
24.30 Show that the distance in slab milling is approximately equal to $\sqrt{Dd}$ for situations where $D \gg d$. (See Fig. 24.3c.)

Referring to the figure below, the hypotenuse of the right triangle on the figure to the right is assigned the value of x, and is approximately equal to $D\theta$. Also, from the right triangle, $\theta = d/x$. Substituting for θ, we get $x^2 = Dd$. From the Pythagorean theorem

$$l_c^2 + d^2 = x^2$$

Since d is assumed to be first order small, the squared term can be assumed to be negligible. Thus,

$$l_c = x = \sqrt{Dd}$$



24.31 In Example 24.1, which of the quantities will be affected when the feed is increased to f = 0.5 mm/tooth?

If the feed is doubled to 0.5 mm/tooth, the workpiece speed will double to 1000 mm/min. The metal removal rate will become 313 cm^3/min, the power will double to 15.64 kW, and the cutting time will be halved to 19 s.

24.32 Calculate the chip depth of cut, t_c, and the torque in Example 24.1.

The chip depth of cut is given by Eq. (24.2) on p. 663:

$$t_c = 2f\sqrt{\frac{d}{D}} = 2(0.25)\sqrt{\frac{3.13}{50}} = 0.125 \text{ mm}$$

Since power is the product of torque and rotational speed, we find the torque to be

$$\text{Torque} = \frac{(7820)(60 \text{ N-m/min})}{(2\pi)(100 \text{ rpm})} = 747 \text{ N-m}$$

24.33 Estimate the time required to face mill a 250-mm- long, 25-mm-wide brass block with a 150-mm-diameter cutter with 10 high-speed steel inserts.

From Table 24.2 on p. 670, let's take a cutting speed for copper alloys (noting that brass has good machinability; see top of p. 586) of 230 m/min. From the same table, let's take a feed per tooth of 0.2 mm. The rotational speed of the cutter is then calculated from

$$V = \pi D N$$

Hence,

$$N = \frac{V}{\pi D} = \frac{230}{\pi(0.15)} = 488 \text{ rpm}$$

The workpiece speed can be obtained from Eq. (24.3) on p. 727:

$$v = fNn = (0.2 \text{ mm/rev})(488 \text{ rev/min})(10) = 976 \text{ mm/min}$$

The cutting time is given by Eq. (24.4) on p. 663 as

$$t = \frac{l + l_c}{v} = \frac{250 + 75}{976} = 0.333 \text{ min} = 20 \text{ s.}$$

24.34 A 300-mm-long, 25-mm-thick plate is being cut on a band saw at 45 m/min. The saw has 480 teeth per m. If the feed per tooth is 0.075 mm, how long will it take to saw the plate along its length?

The workpiece speed, v, is the product of the number of teeth (480 per m), the feed per tooth (0.075 mm), and band saw linear speed (45 m/min). Thus the workpiece speed is

$$v = (480)(0.075)(45) = 1620 \text{ mm/min} = 27 \text{ mm/s}$$

Hence, for a 300-mm long plate, the cutting time is 300/27 = 11.1 s.

24.35 A single-thread hob is used to cut 40 teeth on a spur gear. The cutting speed is 35 m/min and the hob is 75 mm in diameter. Calculate the rotational speed of the spur gear.

If a single-thread hob is used to cut 40 teeth, the hob and the blank must be geared so that the hob makes 40 revolutions while the blank makes one. The surface cutting speed of the hob is

$$V = \pi D N$$

hence

$$N = \frac{V}{\pi D}$$

Since the cutting speed is 35 m/min, or 35,000 mm/min, we have

$$N = \frac{35{,}000}{\pi(75)} = 148.5 \text{ rpm}$$

Therefore, the rotational speed of the spur gear is 148.5/40 = 3.71 rpm.

24.36 Assume that in the face-milling operation shown in Fig. 24.4 the workpiece dimensions are 100 mm by 250 mm. The cutter is 150 mm in diameter, has eight teeth, and rotates at 300 rpm. The depth of cut is 3 mm and the feed is 0.125 mm/tooth. Assume that the specific energy requirement for this material is 5 W-s/mm^3 and that only 75% of the cutter diameter is engaged during cutting. Calculate (a) the power required and (b) the material-removal rate.

From the information given, we note that the material removal rate is

$$\text{MRR} = (0.125 \text{ mm/tooth})(8 \text{ teeth/rev})(300 \text{ rev/min})(3 \text{ mm})(0.75)(100 \text{ mm})$$

or MRR = 67,500 mm^3. Since the specific energy of material removal is given as 5 W-s/mm^3, we have

$$\text{Power} = 67,500 \text{ mm}^3/\text{min} \left(\frac{\text{min}}{60 \text{ s}} \right) \frac{5 \text{ W-s}}{\text{mm}^3} = 5.6 \text{ kW}$$

24.37 A slab-milling operation will take place on a part 300 mm long and 40 mm wide. A helical cutter 75 mm in diameter with 10 teeth will be used. If the feed per tooth is 0.2 mm/tooth and the cutting speed is 0.75 m/s, find the machining time and metal-removal rate for removing 6 mm from the surface of the part.

From Eq. (24.1) on p. 662, the rotational speed, N, of the cutter can be calculated as:

$$V = \pi D N \quad \rightarrow \quad N = \frac{V}{\pi D} = \frac{0.75 \text{ m/s}}{\pi (0.075 \text{ m})} = 3.18 \text{ rev/s} = 190 \text{ rpm}$$

The linear speed of the cutter is given by Eq. (24.3) on p. 663 as:

$$f = \frac{v}{Nn} \quad \rightarrow \quad v = fNn = (0.2 \text{ mm})(190 \text{ rpm})(10) = 0.38 \text{ m/min}$$

If $l_c \ll l$, then $t = l/v = 0.30/0.38 = 0.789$ min = 47.4 s. The metal removal rate is given by Eq. (24.5) as

$$\begin{aligned} \text{MRR} &= wdv = (0.040 \text{ m})(0.006 \text{ m})(0.38 \text{ m/min}) = 9.12 \times 10^{-5} \text{ m}^3/\text{min} \\ &= 91,200 \text{ mm}^3/\text{min} \end{aligned}$$

24.38 Explain whether the feed marks left on the workpiece by a face-milling cutter (as shown in Fig. 24.13a) are segments of true circles. Describe the parameters you consider in answering this question.

They are not true circles, although they may appear to be circular. Consider the fact that a point on an insert is rotating about an axis (the cutter center). If the cutter is stationary, the insert traces a true circle. If the cutter translates, the path becomes elongated, so that it is no longer circular. Deriving an expression for the path of an insert is an interesting but advanced problem in kinematics.

24.39 In describing the broaching operations and the design of broaches, we have not given equations regarding feeds, speeds, and material-removal rates, as we have done in turning and milling operations. Review Fig. 24.21 and develop such equations.

There are many forms for these expressions, and the simple derivation below should be recognized as an example of an acceptable solution. Referring to Fig. 24.21a on p. 676, we note that the volume of material removed by each tooth is

$$V_i = t_i w l$$

where t_i is the depth of cut for tooth i, w is the broach width, and l is the length of cut. We can take the derivative with respect to time to obtain the metal removal rate per tooth as

$$\text{MRR}_i = t_i w v$$

We can say that the total metal removal rate is simply the sum of all tooth actions, or

$$\text{MRR} = \sum_{i=1}^{n} t_i w v = w v \sum_{i=1}^{n} t_i$$

If we divide the broach into roughing, semifinishing, and finishing zones (see Fig. 24.23 on p. 677),

$$\text{MRR} = w v \left(\sum_{i=1}^{n_r} t_{ri} + \sum_{i=1}^{n_s} t_{si} + \sum_{i=1}^{n_f} t_{fi} \right)$$

where an r subscript denotes a roughing cut, s for semifinishing, and f for finishing. A simplification can be obtained if one assumes that the depth of cut for all but the roughing zones can be neglected.

SYNTHESIS, DESIGN, AND PROJECTS

24.40 The part shown in Fig. 24.1f is to be machined from a rectangular blank. Suggest the machine tool(s) required, the fixtures needed, and the types and sequence of operations to be performed. Discuss your answer in terms of the workpiece material, such as aluminum versus stainless steel.

By the student. This is an open-ended problem and a number of solutions are acceptable. The main challenge with the part shown is in designing a fixture that allows all of the operations to be performed. Clearly, a milling machine will be required for milling the stepped cavity and the slots; the holes could be done in the milling machine as well, although a drill press may be used instead. Note that one hole is drilled on a milled surface, so drilling and tapping have to follow milling. If the surface finish on the exterior is not critical, a chuck or vise can be used to grip the surface at the corners, which is plausible if the part height is large enough. The grips usually have a rough surface, so they will leave marks which will be more pronounced in the aluminum than in stainless steel.

24.41 In Problem 24.40, would you prefer to machine this part from a preformed blank (near-net shape) rather than a rectangular blank? If so, how would you prepare such a blank? How would the number of parts required influence your answer?

By the student. This is an open-ended problem and a number of solutions are acceptable. Although starting with a near-net shape blank is always preferable for machining, it can sometimes be difficult or expensive to obtain a near-net shape, especially when production quantities are low. Regardless, obtaining a near-net shaped blank is challenging in this case because of the slots and stepped cavity. This shape is very difficult to forge, and the cross-section is not uniform to be extruded and cut to length; however, a blank can be cast fairly easily. The tapped holes are features that would be very difficult cast, but a dimple for the drill bit (in order to avoid the drill bit wandering from the intended spot) can be incorporated into the cast part. Proper machining allowances should be incorporated on all surfaces and features that have stringent surface finish or dimensional tolerance requirements.

24.42 If expanded honeycomb panels (see Section 16.12) were to be machined in a form-milling operation, what precautions would you take to keep the sheet metal from buckling due to tool forces? Think up as many solutions as you can.

By the student. This is an open-ended problem can be interpreted in two ways: That the honeycomb itself is being pocket machined, or that a fabricated honeycomb is being contoured. Either problem is a great opportunity to challenge students to develop creative solutions. Acceptable approaches include:

(a) high-speed machining with properly chosen processing variables,

(b) using alternative processes such as chemical machining,

(c) filling the cavities of the honeycomb structure with a low-melting-point metal (to provide strength to the thin layers of material being machined) which is then melted away after the machining operation has been completed, and

(d) filling the cavities with wax, or with water which is then frozen, and melted after the machining operation.

24.43 Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare two quantitative problems and supply the answers.

By the student. This is an outstanding, open-ended question that requires considerable focus and understanding from the students, and has been found to be a very valuable homework problem.

24.44 Suggest methods whereby milling cutters of various designs (including end mills) can incorporate carbide inserts.

By the student. This is an open-ended problem and various solutions would be acceptable. There are several ways to incorporate carbide inserts, some of which are depicted in the text. In Fig. 24.5 on p. 665, for example, inserts are shown mounted on a face-milling cutter, and inserts for ball-nose end mills are shown in Fig. 24.10 on p. 668. These figures show inserts being installed in place with screws, but clamps or brazing also are options for affixing inserts as well, although brazing of carbide inserts is not usually done.

24.45 Prepare a comprehensive table of the process capabilities of the machining processes described in this chapter. Using several columns, list the machines involved, types of tools and tool materials used, shapes of blanks and parts produced, typical maximum and minimum sizes, surface finish, dimensional tolerances, and production rates.

By the student. This is an open-ended problem and a number of responses are acceptable. For example, the following can be a portion of a more complete table:

Machine tool	**Tool materials**	**Typical part shapes**	**Typical surface finish** (μm)	**Typical production rates** (parts/hr)
Milling machine, column and knee type	Carbide, coated carbide, cermets, SiN, PCD, etc. (see Table 24.2 on p. 736)	No limit; typically moderate aspect ratio	1-2	1-20
Broaching machines	High speed steels, carbide inserts	Short width, constant cross-sections, linear surface lay	1.5	20-200
Gear generator	Carbide	Gears	1	10-30

24.46 On the basis of the data developed in Problem 24.45, describe your thoughts regarding the procedure to be followed in determining what type of machine tool to select when machining a particular part.

By the student. In this open-ended problem, the discussions should include the part shape as well as the material, the surface finish and dimensional tolerances required, the production quantity and production rate specified. Also, in practice, this determination is usually constrained by machine or vendor availability, as well as machine backlog.

24.47 Make a list of all the processes that can be used in manufacturing gears, including those described in Parts II and III of this text. For each process, describe the advantages, limitations, and quality of gears produced.

By the student. This is an open-ended problem and an example of an acceptable answer would be:

- Form cutting: The advantages are the relatively simple design of machinery and tooling, and the ability to rapidly produce spur gears; However, surface finish is limited.
- Hobbing: Allows production of a wide variety of gears including worm gears; surface finish is limited.
- Grinding: Produces superior surface finish, but is a relatively slow process.

Chapter 25

Machining Centers, Advanced Machining Concepts and Structures, and Machining Economics

QUALITATIVE PROBLEMS

25.10 Explain the technical and economic factors that led to the development of machining centers.

Machining centers (p. 694), as a manufacturing concept, serve two purposes: (a) save time by rapid tool changes and eliminating part handling and mounting in between processes, and (b) rapid changeover for new production runs. The text gives the example of automobile engine blocks which require drilling, boring, tapping, etc., to be performed. Normally, much time would be spent transferring and handling the workpiece between different machine tools. Machining centers eliminate or reduce the need for part handling and, consequently, reduce manufacturing time and costs. Also, a variety of parts can be produced in small lots.

25.11 Spindle speeds in machining centers vary over a wide range. Explain why this is so, giving specific applications.

Spindle speeds vary over a wide range for a number of reasons; the most obvious is the optimization of cutting time. A small drill, for example, is operated at higher spindle speeds than for larger drills to obtain the same surface cutting speed. Since the speed of the cutting operation is important (because different workpiece materials require different cutting speeds for optimum tool life and surface finish) spindles must therefore be capable of operating in a wide range of rotational speeds.

25.12 Explain the importance of stiffness and damping of machine tools. Describe how they are implemented.

High stiffness in machine tools results in lowering the dynamic force/excitation ratios, thus it is important in reducing, or at least controlling, chatter. Also, stiffness is important to minimize tool deflections during machining. By minimizing deflections, one can improve dimensional accuracy and reduce dimensional tolerances. Stiffness typically can be improved by using materials with high elastic modulus, optimizing the section moduli of components, and by improving the type of joints and sliding machine elements. (See Section 25.4 on p. 706.)

25.13 Are there machining operations described in Chapters 23 and 24 that cannot be performed in machining and turning centers? Explain, with specific examples.

By the student. Machining centers can easily perform operations which involve a rotating tool (milling, drilling, tapping, and honing) and not the workpiece (other than during indexing or positioning). Consequently, it would be difficult to perform operations such as turning, broaching, sawing, or grinding on a machining center. The students are encouraged to investigate further the machining processes in the two chapters for their suitability for machining centers.

25.14 How important is the control of cutting-fluid temperature in operations performed in machining centers? Explain.

The control of cutting-fluid temperature is very important in operations where high dimensional accuracy is essential. As expected, the fluid heats up during its service throughout the day (due to the energy dissipated during machining), its temperature begins to rise. This, in turn, raises the temperature of the workpiece and fixtures, and adversely affects dimensional accuracy. Temperature-control units are available for maintaining a constant temperature in cutting-fluid systems. (See also Section 22.12.)

25.15 Review Fig. 25.10 on modular machining centers, and describe some workpieces and operations that would be suitable on such machines.

By the student. The main advantages to the different modular setups shown in Fig. 25.10 on p. 702 are that various workpiece shapes and sizes can be accommodated can be changed, and the tool support can made stiffer by minimizing the overhang. (See Section 25.2.4 on p. 701 for the benefits of reconfigurable machines.)

25.16 Describe the adverse effects of vibration and chatter in machining operations.

By the student. The adverse effects of chatter are discussed on p. 707 and are summarized briefly below:

- Poor surface finish, as shown in the right central region of Fig. 25.13 on p. 707.
- Loss of dimensional accuracy of the workpiece.
- Premature tool wear, chipping, and failure, a critical consideration with brittle tool materials, such as ceramics, some carbides, and diamond.
- Possible damage to the machine-tool components from excessive vibration and chatter.
- Objectionable noise, particularly if it is of high frequency, such as the squeal heard when turning brass on a lathe with a less rigid setup.

25.17 Describe some specific situations in which thermal distortion of machine-tool components would be important.

When high precision is required (see, for example, Fig. 25.17 on p. 712), thermal distortion is very important and must be eliminated or minimized. As shown in Problem 25.36, this is a serious concern, as even a few degrees of temperature rise can cause sufficient thermal expansion to compromise dimensional accuracy.

25.18 Explain the differences in the functions of a turret and of a spindle in turning centers.

By the student. A turret (see Figs. 23.9 and 23.10 on p. 632) accommodates multiple tools which can be indexed quickly. Spindles (see Fig. 25.8 on p. 699) typically accommodate the workpiece, although they can be equipped with drill bits depending on the design of the machine. The students may investigate this topic further as a project.

25.19 Explain how the pallet arrangements shown in Fig. 25.4a and b would be operated in using these machines on a shop floor.

In Fig. 25.4a on p. 696, the pallets are taken from the cue in a first in, first out (FIFO) manner. The pallet pool can have individual pallets added, or else the gray shaded region shown with a number of pallets can be added at one time. In Fig. 25.4b, the pallets service two machining centers. These can be arranged identically to Fig. 25.4a, where dedicated pallets are assigned to each machine. However, another approach is to have both machines operate on the same pallet cue. This makes the machining process less susceptible to delays due to machine service.

25.20 Review the tool changer shown in Fig. 25.5. Are there any constraints on making their operations faster in order to reduce the tool changing time? Explain.

By the student. This question would make a good design project. Tool changers (Fig. 25.5 on p. 697) are very fast for the obvious reason of reducing the noncutting time in machining (see p. 714). Making them faster can involve significant costs by virtue of the more powerful motors required to overcome inertial forces, the adverse effects of these dynamic forces on machine components, and the higher wear rates of the components. The larger motors and the design changes will also increase the bulk of the automatic tool changers as well, making them more difficult to place in the machine where space is a premium.

25.21 In addition to the number of joints in a machine tool (see Fig. 25.15), what other factors influence the rate at which damping increases? Explain.

In addition to the number of joints and components in a machine tool (as shown in Fig. 25.15 on p. 701) other factors that influence damping is the nature and roughness of the joint interfaces, clamping force, and the presence of lubricants and other fluids at the interfaces.

25.22 Describe types and sizes of workpieces that would not be suitable for machining on a machining center. Give specific examples.

By the student. There are few workpieces that cannot be produced on machining centers, as by their nature they are very flexible. Some of the acceptable answers would be:

- Workpieces that are required in much higher quantities than can be performed economically on machining centers.
- Parts that are too large for the machining-center workspace, such as large forging or castings.
- Parts that need specialized machines, such as rifling of gun barrels.

25.23 Other than the fact that they each have a minimum, are the overall shapes and slopes of the total-cost and totaltime curves in Fig. 25.17 important? Explain.

By the student. Note that the shape of the total cost curve can be sharper or shallower than that shown in Fig. 24.18a on p. 674. If sharper, a small difference in the cutting speed can make a large difference in cost because of the steeper slopes of the curve. If shallower, the cutting speed would have less influence. With numerical data obtained, students can determine the extent of these effects.

25.24 Explain the advantages and disadvantages of machine-tool frames made of gray-iron castings.

The advantages of cast machine-tool frames are that it is easy and relatively inexpensive to produce complex and large structures. Gray irons have high internal damping capacity (see pp. 110 and 306). Because of lower elastic modulus, these structures have relatively low stiffness compared to welded-steel frames; however, using larger cross-sections will greatly improve this situation (as is the common practice). Also, the very limited ductility and toughness of cast irons (see Fig. 12.4f on p. 303) may make them unsuitable for high impact situations.

25.25 What are the advantages and disadvantages of (a) welded-steel frames, (b) bolted steel frames, and (c) adhesively bonded components of machine tools? Explain.

By the student. This problem can be an interesting project for students, requiring considerable efforts in literature search. Briefly:

(a) The advantages of welded-steel frames (see Part VI) are their high stiffness (due to the high elastic modulus of steels) as well as ease of fabrication since various components can be welded into complex shapes and the overall stiffness can be optimized. However, welded structures cannot be disassembled and thermal distortions during welding can present difficulties.

(b) The advantage to bolted frames is their fairly high stiffness, with some damping capability associated with a bolted joint (see also Fig. 25.15 on p. 709). The disadvantages include the time required for preparation of surfaces to be joined, holes, and fasteners, and possible corrosion at interfaces by time (crevice corrosion).

(c) Adhesive bonding (see Section 32.4 on p. 931) has major advantages of ease of assembly, fewer problems with corrosion at the interfaces of assembled components, and some capacity for damping vibrations. Among disadvantages are the time required for assembly, reliability of the joints, and the difficulty of disassembly.

25.26 What would be the advantages and limitations of using concrete or polymer–concrete in machine tools?

Concrete and polymer concretes (see p. 703) can play an important role in reducing vibration in steel-framed machine tools. Concrete is poured inside the machine frame in various configurations (including sandwich construction) to provide damping as well as mass, thereby reducing vibrations. Also, vibration-isolating machine supports also can be produced which are very effective. (Note also that concrete canoes have been built.) Among disadvantages are relatively low stiffness and poor thermal conductivity of these materials (important in reducing thermal distortions in machine tools).

25.27 Explain how you would go about reducing each of the cost factors in machining operations. What difficulties would you encounter in doing so?

By the student. As can be seen on p. 714, the total machining cost per piece consists of four factors (see also Chapter 40 for further details):

(a) Nonproductive cost. This includes labor, overhead, and setup costs. These costs can be reduced through application of automation to reduce labor, especially using CNC machines and machining centers to reduce setup time and costs.

(b) Machining cost. This cost can be reduced not only by automation to reduce labor, but also by selection of appropriate cutting-tool materials, cutting fluids, and machining parameters.

(c) Tool-change cost. This can be reduced through the application of automatic tool changers and fixtures which allow rapid exchange of tools, thus eliminating or reducing manual labor.

(d) Cost of cutting tool. Advanced tool materials are more expensive, thus the tool cost can be reduced through use of more conventional materials. However, the use of less expensive tool materials will likely result in higher tool wear, more frequent tool changes, and the need for lower cutting speeds, thus increasing the machining costs and tool-change costs.

QUANTITATIVE PROBLEMS

25.28 A machining-center spindle and tool extend 250 mm from their machine-tool frame. Calculate the temperature change that can be tolerated in order to maintain a tolerance of 0.0025 mm or 0.025 mm in machining. Assume that the spindle is made of steel.

The extension due to a change in temperature is given by

$$\Delta L = \alpha \Delta T L$$

where α is the coefficient of thermal expansion which, for carbon steels, is $\alpha = 12 \times 10^{-6}/°\text{C}$. If $\Delta L = 0.0025$ mm and $L = 250$ mm, then ΔT can easily be calculated to be 0.8°C; also for $\Delta L = 0.025$ mm, we have $\Delta T = 8°\text{C}$. Noting that the temperatures involved are quite small, this example clearly illustrates the importance of environmental controls in precision manufacturing operations, where dimensional tolerances are extremely small (see Fig. 25.17).

25.29 Using the data given in the example, estimate the time required to manufacture the parts in Example 25.1 with conventional machining and with high-speed machining.

This is an open-ended problem and various answers would be acceptable because the number of roughing and finishing cuts have not been specified in the statement of the problem. The following would be examples of calculations:

1. Finish turning. The outer diameter is given as 91 mm, so to obtain a cutting speed of 95 m/min, the required rotational speed is

$$N = \frac{V}{\pi D_o} = \frac{95}{\pi(0.091)} = 332 \text{ rpm}$$

For determining the feed, we review Table 23.4 starting on p. 622 and note that for high-carbon steel the low value of typical feeds is 0.15 mm/rev, which we can use since this is a finishing operation. Thus, using $l = 25$ mm, we have

$$t = \frac{l}{fN} = \frac{25}{(0.15)(332)} = 0.50 \text{ min}$$

2. Boring on inside diameter. Here the ID is 75.5 mm, so to obtain a linear speed of 95 m/min requires a rotational speed of

$$N = \frac{V}{\pi D_o} = \frac{95}{\pi(0.0755)} = 400 \text{ rpm}$$

Therefore, the time required using the same feed of $f = 0.15$ mm/rev is

$$t = \frac{l}{fN} = \frac{25}{(0.15)(400)} = 0.41 \text{ min}$$

The students are encouraged to obtain estimates for the remaining machining steps and investigate incorporating roughing and finishing cuts into each step.

SYNTHESIS, DESIGN, AND PROJECTS

25.30 If you were the chief engineer in charge of the design of advanced machining and turning centers, what changes and improvements would you recommend on existing models? Explain.

By the student. Among several others, the following research topics are suggested:

(a) Expansion of tool-magazine capabilities.

(b) Development of hardware and software to facilitate programming without sacrificing reliability, as discussed further in Part IX, including holonic manufacturing integration.

(c) Improving the stiffness of the machine tool but without compromising the damping capability of the machine frame.

(d) Alternate materials and optimum structural designs. (See also Section I.11 on p. 41.)

25.31 Review the technical literature and outline the trends in the design of modern machine tools. Explain why there are those trends.

By the student. The trend in machine tools is towards increased computer control and increased stiffness, while attempting to maintain good damping characteristics. Note that stiffness and damping are mutually exclusive when using conventional materials. Gray cast iron, which has been used on machine structures for hundreds of years, has good damping characteristics. Steel is being used more and more because of stiffness considerations, but it lacks the inherent damping capability of gray iron. The increase in the use of steel is based upon the need to increase the stiffness of the machine tool for improved dimensional accuracy and reduction of chatter, and also offering greater flexibility in design. Research and development efforts are being directed at utilizing stiffer materials in the construction of machine tools as well as improving damping. Communication between machines and host computers is being continually improved and expanded to allow for better control of the manufacturing enterprise. (See also Section I.11 on p. 34.)

25.32 Make a list of components of machine tools that could be made of ceramics, and explain why ceramics would be suitable.

By the student. To review the characteristics of ceramics and their processing, refer to Sections 8.2 and 8.3 on pp. 197 and 201, and Section 18.2 on p. 466. Typical candidates are members that reciprocate at high speeds or members that move at high speeds and are brought to rest in a short time. Bearing components are also suitable applications by virtue of the hardness, resistance, and low density (hence low inertial forces) of ceramics.

25.33 Survey the company literature from various machinetool manufacturers, and prepare a comprehensive table indicating the capabilities, sizes, power, and costs of machining and turning centers. Comment on your observations.

By the student. This is a challenging project. To obtain costs, students should identify machinery dealers and not manufacturers, because in practice it is rare that a manufacturer will have cost data readily available. It is advisable that the instructor assign a number of machines, such as five machines with different capabilities, since a wide variety of equipment and capacities are commercially available.

25.34 The cost of machining and turning centers is considerably higher than for traditional machine tools. Since many operations performed by machining centers also can be done on conventional machines, how would you go about justifying the high cost of these centers? Explain with appropriate examples.

By the student. This is an open-ended problem and a variety of answers would be acceptable. The justification needs to be economic, and it is usually tied to increased capabilities, flexibility, and production rates that can be achieved with machining centers. Also, modern machines have much better capabilities to integrate into a computer-controlled manufacturing enterprise, so that part-description recollection and inventory control can be better accomplished. (See also Table 40.6 on p. 1157.)

25.35 In your experience using tools or other devices, you may have come across situations in which where you experienced vibration and chatter. Describe your experience and explain how you would go about minimizing the vibration and chatter.

By the student. The particular answers will vary based on the student's experience. A student answering "no" to this question obviously is not being sufficiently creative because vibrations are commonly experienced, such as in sounds produced by string and percussion instruments, automobile suspensions, and trampolines. Chatter has, for example, been commonly experienced by all students in the way of the annoying scratching sound of a chalk while writing on a chalkboard. Minimizing vibration and chatter can be accomplished in several ways, including increasing damping (as in replacing faulty struts on an automobile), and increasing stiffness or process parameters.

25.36 Describe your thoughts on whether or not it is feasible to include grinding operations (see Chapter 26) in machining centers. Explain the nature of any difficulties that may be encountered.

By the student. This is a challenging problem for students who have not yet read Chapter 26, although may have been exposed to grinding of a kitchen knife or scissors. It can be a good problem when an instructor is covering these two chapters in an assignment. Note, however, that grinding would be difficult to incorporate into machining centers primarily because the processing parameters are different and the debris from the grinding operation would cause serious damage and wear of the machine components. On the other hand, it is quite conceivable that a "grinding center" could be developed, as has been done in die-sinking machining centers (see Section 27.5 on p. 771).

25.37 The following experiment is designed to better demonstrate the effect of tool overhang on vibration and chatter: With a sharp tool, scrape the surface of a piece of soft metal by holding the tool with your arm fully outstretched. Repeat the experiment, this time holding the tool as close to the workpiece as possible. Describe your observations regarding the tendency for the tool to vibrate. Repeat the experiment with different types of metallic and nonmetallic materials.

By the student. This would be an interesting experiment to perform. This clearly shows the effect of stiffness on chatter. The same experiment can be demonstrated in a classroom with chalk on a chalkboard.

Chapter 26

Abrasive Machining and Finishing Operations

QUALITATIVE PROBLEMS

26.13 Explain why grinding operations may be necessary for components that have previously been machined.

The grinding processes described in this chapter are necessary for a number of reasons, as stated at the beginning of Section 26.1 on p. 719. Students are encouraged to articulate further, giving specific examples. Basically, the answer is that the processes described cannot produce the required dimensional accuracy and surface finish for a part.

26.14 Why is there such a wide variety of types, shapes, and sizes of grinding wheels?

By the student. There are many different types and sizes of grinding wheels because of numerous factors: The shape and type of a grinding wheel depend upon the workpiece material and its shape, the surface finish and geometry desired, rate of production, heat generation during the process, economics of wheel wear, and type of grinding fluids used. Each grinding wheel must be chosen for a particular application while considering all of these factors.

26.15 Explain the reasons for the large difference between the specific energies involved in machining (Table 21.2) and in grinding (Table 26.2).

Specific energies in grinding as compared to machining (see pp. 571 and 729) are much higher principally due to the presence of wear flats (causing high friction) and due to the large negative rake angles typically found in abrasives (hence the chips formed during grinding must undergo more deformation, and therefore require more energy). Also, since the chips in grinding are very small, there is more surface area for frictional losses per volume of material removed when compared with machining. Size effect (due to very small chips produced) also may be a contributing factor. Students may investigate this topic further as a project.

26.16 The grinding ratio, G, depends on the type of grinding wheel, workpiece hardness, wheel depth of cut, wheel and workpiece speeds, and the type of grinding fluid. Explain.

By the student. The grinding ratio, G, decreases as the grain force increases (see Section 26.3.2 on p. 732) and is associated with high attritious wear of the wheel. The type of wheel will have an effect on wheel wear; for example, vitrified wheels generally wear slower than resinoid wheels. Workpiece hardness will reduce G because of increased wear, if all other process parameters are kept constant. Depth of cut has a similar effect. Wheel and workpiece speed affect wheel wear in opposite ways; higher wheel speeds and lower workpiece speeds reduce the force on the grains [see Eq. (26.3) on p. 729] which, in turn, reduces wheel wear.

26.17 What are the consequences of allowing the temperature to rise during grinding? Explain.

Refer also to Problem 21.19. Temperature rise can have major effects in grinding, including:

(a) If excessive, it can cause metallurgical burn and heat checking.

(b) The workpiece may distort due to thermal gradients.

(c) With increasing temperature, the part will expand and hence the actual depth of cut will be greater; thus, upon cooling, the part will contract and the dimensional tolerances will not be within the desired range.

26.18 Explain why speeds are much higher in grinding than in machining operations.

Grinding is an operation that typically involves very small chips being removed from the workpiece surface by individual grains along the grinding surface of the wheel (see pp. 727-728). Consequently, to remove material at a reasonably high rate for productivity, wheel speeds have to be very high. Note also that high wheel speeds have no particularly adverse effects on the overall grinding operation (unless the wheels cannot withstand the stresses developed). In fact, the trend has been to increase spindle speeds on grinders and develop wheels with higher burst strengths. Recall also that higher removal rates are typically obtained in creep-feed grinding, which is an important industrial process (see p. 815).

26.19 It was stated that ultrasonic machining is best suited for hard and brittle materials. Explain.

In ultrasonic machining (p. 744) the stresses developed from particle impact should cause damage sufficient to spall the workpiece, which involves fracture on a very small scale. If the workpiece is soft and ductile, the impact force will simply deform the workpiece locally (as does the indenter in a hardness test), instead of causing fracture.

26.20 Explain why parts with irregular shapes, sharp corners, deep recesses, and sharp projections can be difficult to polish.

By the student. Students are likely to have had some experience relevant to this question. The basic reason why these shapes may be difficult to polish is that it is difficult to have a polishing medium to properly follow an intricate surface, to penetrate depths, or be able apply equal pressure on all surfaces for uniform polishing.

26.21 List the finishing operations commonly used in manufacturing operations. Why are they necessary? Explain why they should be minimized.

There are a large number of finishing operations, including abrasive machining operations such as grinding, polishing, buffing, lapping, chemical mechanical polishing, electrochemical grinding, electrochemical polishing; coating operations such as electroplating, CVD and PVD; cleaning operations; deburring operations, etc. These are necessary to obtain required surface finish and dimensional tolerance requirements as well as to impart desirable characteristics to workpieces.

26.22 Referring to the preceding chapters on processing of materials, list the operations in which burrs can develop on workpieces.

Burrs can develop in a large number of operations, including shearing operations on sheet metal or in removing the flash from forgings; machining operations such as turning, milling or drilling; and piercing operations. Students should be encouraged to elaborate on the mechanisms of burr creation.

26.23 Explain the reasons that so many deburring operations have been developed over the years.

By the student. There are many deburring operations because (as described on pp. 825-826) of the wide variety of workpiece materials, characteristics, shapes, and surface features and textures involved. There is a also the requirement for different levels of automation in deburring.

26.24 What precautions should you take when grinding with high precision? Comment on the machine, process parameters, grinding wheel, and grinding fluids.

When grinding for high precision (see also Fig. 25.16 on p. 712), it is essential that the forces involved remain low so that workpiece and machine deflections are minimal. As can be seen from Eq. (26.3) on p. 729, to minimize grinding forces, hence minimize deflections, the wheel speed should preferably be high, the workpiece speed should be low, and the depth of cut should be small. The machine used should have high stiffness with good bearings. The temperature rise, as given by Eq. (26.4) on p. 730, should be minimized. (In comparing the two equations cited, note how the processing parameters have contradicting effects; this is situation where the parameters have to be optimized.)

The grinding wheel should also have fine grains and the abrasive should be inert to the workpiece material to avoid any adverse reactions. The grinding fluid should be selected to provide low wheel loading and wear, and also to provide for effective cooling. Automatic dressing capabilities should be included and the wheel should be dressed often.

26.25 Describe the factors involved in a grinding wheel acting "soft" or acting "hard."

An individual grinding wheel can act soft or hard depending on the particular grinding conditions. The greater the force on the grinding wheel grains, the softer the wheel acts; thus, a grinding wheel will act softer as the workpiece material strength, work speed, and depth of cut increase. It will act harder as the wheel speed and wheel diameter increase. Equation (9.6) gives the relationship between grain force and the process parameters. See also Section 9.5.2.

26.26 What factors could contribute to chatter in grinding? Explain.

Grinding chatter (see p. 743) is similar to chatter in machining and the factors involved are similar to those discussed in Section 25.4 on p. 706. Factors that contribute to chatter are: stiffness of machine tool and damping of vibration, irregular grinding wheels, dressing techniques, uneven wheel wear, high-grade wheels, high material-removal rates, eccentricity in wheels and or in mounting them on machine spindles, vibrations from nearby machinery, and inadequate support of the workpiece. Sources of regenerative chatter, such as material inhomogeneity and surface irregularities in wheels also can cause chatter in grinding.

26.27 Generally, it is recommended that, in grinding hardened steels, the grinding be wheel of a relatively soft grade. Explain.

By the student. The use of a soft wheel on hardened steels is effective because when the abrasive grains develop wear flats (see Fig. 26.8b on p. 727), the wheels should be sufficiently soft so that the grains can be dislodged, thereby reducing workpiece surface damage. By using softer wheels, adverse effects such as burning and heat checking of the workpiece surface and residual stresses can be controlled. Note, however, that soft wheels will wear faster, but this is acceptable as long as workpiece quality is improved. Soft wheels would also reduce the tendency for chatter.

26.28 In Fig. 26.4, the proper grinding faces are indicated for each type of wheel. Explain why the other surfaces of the wheels should not be used for grinding and what the consequences may be in doing so.

By the student. The proper grinding faces, identified in Fig. 26.4 on p. 723, should be utilized because the wheels are designed to resist grinding forces on these faces. Note, for example, that if grinding forces act normal to the plane of a thin straight wheel (Type 1 in the figure), the wheel will flex and may eventually fracture. Thus, from a functional standpoint, grinding wheels are more made stiff in the directions in which they are intended to be used. There are serious safety and functional considerations involved. For example, an operator who grinds with the side surface of a flared-cup wheel causes wear to take place such that the flange thickness is significantly reduced. It may eventually fracture, exploding with violent force and potentially causing serious injury or death.

26.29 Describe the effects of a wear flat on the overall grinding operation.

By the student. A wear flat (see Figs. 26.3 and 26.8 on pp. 723 and 727, respectively) causes dissipation of frictional energy and thus increases the temperature of the operation. Wear flats are undesirable because they provide no useful action (they play no obvious role in deforming the chip) but they increase the frictional forces at the wheel-workpiece interface and cause surface damage. Recall that in orthogonal cutting, flank wear (see Fig. 21.15a on p. 574) is equivalent to a wear flat in grinding.

26.30 What difficulties, if any, could you encounter in grinding thermoplastics? Thermosets? Ceramics?

Refer to Section 26.3.4 on p. 734 on grindability of materials and wheel selection, and also compare with Section 21.7.3 on p. 586. Some of the difficulties encountered are:

(a) Thermoplastics (p. 180) have a low melting point and have a tendency to soften (and become gummy) and thus tend to bond to grinding wheels (by mechanical locking). An effective coolant, including cool air jet, must be used to keep temperatures low. Furthermore, the low elastic modulus of thermoplastics (see Table 7.1 on p. 172) can make it difficult to hold dimensional tolerances during grinding.

(b) Thermosets (p. 184) are harder and do not soften with temperature (although they decompose and crumble at high temperatures), consequently grinding, using appropriate wheels and processing parameters, is relatively easy.

(c) Grinding of ceramics (p. 197) is now relatively easy, using diamond wheels and appropriate processing parameters, and implementing ductile-regime grinding (see p. 808). Note also the development of machinable ceramics.

26.31 Observe the cycle patterns shown in Fig. 26.20 and comment on why they follow those particular patterns.

The particular patterns are discussed in Example 26.3 on p. 739. The particular cycle patterns have been developed for a number of reasons, and each can be closely examined to obtain insight as to their design. For example, consider the pattern identified with the label '3'. The grinding wheel penetrates the workpiece normally, is removed, translates along the cylinder axis, then penetrates again, etc. After this sequence of operations, the grinding wheel traverses the entire length of the cylinder two times. The reasons for this are relatively easy to understand: the first stages of normal approach are large material removal rate operations with large feeds. Lateral motion cannot be done since the penetration of the wheel into the workpiece is large. After these stages, the material removal rate and depth of penetration are lowered in order to establish final tolerances and surface finish. Note that it is relatively easy to understand why the particular patterns are followed, but a more demanding problem is associated with planning the pattern.

26.32 Which of the processes described in this chapter are suitable particularly for workpieces made of (a) ceramics, (b) thermoplastics, and (c) thermosets? Why?

By the student. It will be noted that, as described in Chapter 26, most of these materials can be machined through conventional means. Consider the following processes:

(a) Ceramics: water-jet machining, abrasive-jet machining, chemical machining.

(b) Thermoplastics: water-jet and abrasive-jet machining; electrically-conducting polymers may be candidates for EDM processing.

(c) Thermosets: similar consideration as for thermoplastics.

26.33 Grinding can produce a very fine surface finish on a workpiece. Is this finish necessarily an indication of the quality of a part? Explain.

The answer is not necessarily so because surface integrity includes factors in addition to surface finish (which is basically a geometric feature). As stated on p. 133, surface integrity includes several mechanical and metallurgical parameters which, in turn, can have adverse effects on the performance of a ground part, such as its strength, hardness, and fatigue life. The students are encouraged to explore this topic further.

26.34 Jewelry applications require the grinding of diamonds into desired shapes. How is this done, since diamond is the hardest material known?

By the student. Grinding is done with fine diamond abrasives on polishing wheels, and very high quality diamond surfaces can be generated in this manner. This topic could be made into a project.

26.35 List and explain factors that contribute to poor surface finish in the processes described in this chapter.

There are a number of factors that can lead to poor surface finish, including:

- Vibration. As described on p. 743, chatter can be regenerative or self-excited, and results in chatter marks on surfaces.
- Excessive temperature. When temperatures become very large, the surface will display heat checks, or surface cracks, that compromise the surface finish.
- Loaded grinding wheels can result in smeared surfaces, or else this can lead to high temperatures and heat checking or even burning of the surface.
- If speeds and feeds are too high, there will be machining marks that lead to excessively high surface roughness.

QUANTITATIVE PROBLEMS

26.36 Calculate the chip dimensions in surface grinding for the following process variables: D = 250 mm, d = 0.025 mm, v = 30 m/min, V = 1500 m/min, C = 1 per mm^2, and r = 20.

The undeformed chip length, l, is given approximately by the expression

$$l = \sqrt{Dd} = \sqrt{(250)(0.025)} = 2.5 \text{ mm}$$

and the undeformed chip thickness, t, is given by Eq. (26.2) on p. 728. Thus,

$$t = \sqrt{\left(\frac{4v}{VCr}\right)\sqrt{\frac{d}{D}}} = \sqrt{\left[\frac{4(30)}{(1200)(1)(20)}\right]\sqrt{\frac{0.025}{250}}} = 0.006 \text{ mm}$$

Note that these quantities are very small compared to those in typical machining operations.

26.37 If the strength of the workpiece material is doubled, what should be the percentage decrease in the wheel depth of cut, d, in order to maintain the same grain force, with all other variables being the same?

Using Eq. (26.3) on p. 729, we note that if the workpiece-material strength is doubled, the grain force is doubled. Since the grain force is dependent on the square root of the depth of cut, the new depth of cut would be one-fourth of the original depth of cut. Thus, the reduction in the wheel depth of cut will be 75%.

26.38 Assume that a surface-grinding operation is being carried out under the following conditions: D = 200 mm, d = 0.1 mm, v = 40 m/min, and V = 2000 m/min. These conditions are then changed to the following: D = 150 mm, d = 0.1 mm, v = 30 m/min, and V = 2500 m/min. How different is the temperature rise from the rise that occurs with the initial conditions?

The temperature rise is given by Eq. (26.4) on p. 730. We can obtain a relative change even if we don't know a constant of proportionality in the equation, which we will identify as A. Thus, for the initial cutting conditions, we have

$$\Delta T = AD^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{1/2} = A(200)^{1/4}(0.1)^{3/4}\left(\frac{2000}{40}\right)^{1/2} = 4.73A$$

and for the new conditions, we have

$$\Delta T = AD^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{1/2} = A(150)^{1/4}(0.1)^{3/4}\left(\frac{2500}{30}\right)^{1/2} = 5.68A$$

Therefore, the modified conditions have a temperature rise which is slightly higher than the original temperature rise by about 20%.

26.39 Estimate the percent increase in the cost of the grinding operation if the specification for the surface finish of a part is changed from 6.4 to 0.8 μm.

Referring to Fig. 26.35 on p. 754, we note that changing the surface finish from 6.4 μm to 0.8 μm would involve an increased cost of about 250/50-1 or 5-1=400%. This is a very significant increase in cost, and is a good example of the importance of the statement made throughout the book that dimensional accuracy and surface finish should be specified as broadly as is permissible in order to minimize manufacturing costs (see also Fig. 40.5 on p. 1151).

26.40 Assume that the energy cost for grinding an aluminum part with a specific energy requirement of 8 W-s/mm^3 is \$1.50 per piece. What would be the energy cost of carrying out the same operation if the workpiece material were T15 tool steel?

From Table 26.2 on p. 729 we note that the power requirement for T15 tool steel ranges from 17.7 to 82 W-s/mm^3. Consequently, the costs would range from 2.5 to 11.7 times that for the aluminum. This means an energy cost between \$2 and \$9.36 per part.

26.41 In describing grinding processes, we have not given the type of equations regarding feeds, speeds, materialremoval rates, total grinding time, etc., as we did in the turning and milling operations discussed in Chapters 23 and 24. Study the quantitative relationships involved and develop such equations for grinding operations.

By the student. This is a challenging problem and a good topic for a project. The students should refer to various texts in the Bibliography, including texts by S. Malkin and M.C. Shaw.

26.42 What would be the answers to Example 26.1 if the workpiece is high-strength titanium and the width of cut is w = 20 mm? Give your answers in newtons.

By the student. Refer to Example 26.1 on p. 729. For high-strength titanium, let's assume that the specific energy from Table 26.2 on p. 729 is 50 W-s/mm^3. Since the width, w, is now

20 mm, the MRR will be (0.05)(20)(1500)=1500 mm^3/min. The power is then $(\frac{50}{60})(1500) =$ 1.25 kW, which is that same as that in the example; hence the answer to be unchanged, that is, $F_c = 25$ N, and $F_t = 32$ N.

26.43 It is known that, in grinding, heat checking occurs when grinding is done with a spindle speed of 5,000 rpm, a wheel diameter of 200 mm, and a depth of cut of 0.04 mm for a feed rate of 15 m/min. For this reason, the standard operating procedure is to keep the spindle speed at 3,500 rpm. If a new, 250-mm-diameter wheel is used, what spindle speed can be used before heat checking occurs? What spindle speed should be used to keep the same grinding temperatures as those encountered with the existing operating conditions?

To solve this problem, let's assume that the workpiece initial temperature is the same for both cases. Consider the first case, where the wheel radius is 4 in. and speed is 5000 rpm. The temperature rise for heat checking to occur is given by Eq. (26.4) on p. 730 (and using A as the constant for proportionality) as

$$\Delta T = AD^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{1/2} = A(200)^{1/4}(0.04)^{3/4}\left[\frac{(5000)\pi(0.2)}{15}\right]^{1/2} = 4.87A$$

The temperature rise for the "safe" operating condition with the 200-mm wheel is

$$\Delta T = AD^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{1/2} = A(200)^{1/4}(0.04)^{3/4}\left[\frac{(3500)\pi(0.2)}{15}\right]^{1/2} = 4.07A$$

With a new, 250-mm wheel and the same depth of cut and feed, heat checking occurs at

$$\Delta T = 0.131A = AD^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{1/2} = A(250)^{1/4}(0.04)^{3/4}\left[\frac{N\pi(0.25)}{15}\right]^{1/2}$$

or, solving for N we obtain $N = 3580$ rpm. To maintain the same safe surface temperatures, we need

$$\Delta T = 4.07A = A(250)^{1/4}(0.04)^{3/4}\left[\frac{N\pi(0.25)}{15}\right]^{1/2}$$

or $N = 2500$ rpm.

26.44 A grinding operation takes place with a 250-mm grinding wheel with a spindle speed of 4,000 rpm. The workpiece feed rate is 15 m/min and the depth of cut is 0.05 mm. Contact thermometers record an approximate maximum temperature of 980°C. If the workpiece is steel, what is the temperature if the speed is increased to 5,000 rpm? What if the speed is 10,000 rpm?

Assuming that the workpiece is at room temperature, Eq. (26.4) on p. 730 can be used to calculate the temperature rise. The temperature rise for the initial state lets one calculate the proportionality constant as

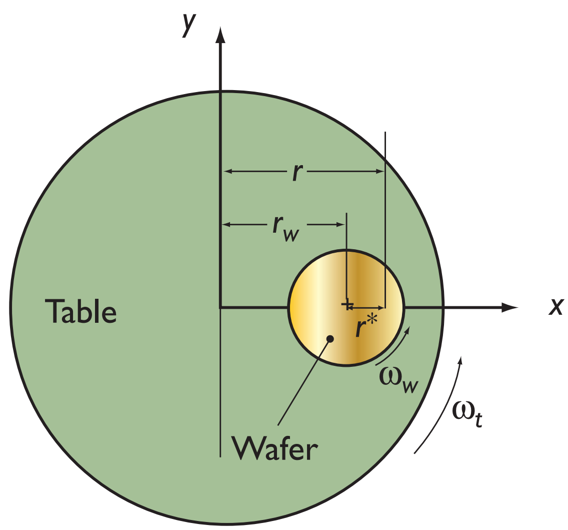
$$\Delta T = AD^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{1/2} = A(250)^{1/4}(0.05)^{3/4}\left[\frac{(4000)\pi(0.25)}{15}\right]^{1/2} = 980$$

which is solved as $A = 161$. If the speed is 5000 rpm, then

$$\Delta T = AD^{1/4}d^{3/4}\left(\frac{V}{v}\right)^{1/2} = (161)(250)^{1/4}(0.05)^{3/4}\left[\frac{(5000)\pi(0.25)}{15}\right]^{1/2} = 1088^\circ\text{C}$$

If the speed is 10,000 rpm, the same equation gives 1549°C; note however that steel melts at around 1370°C (see Table 3.1 on p. 103). When the steel melts, the grinding process mechanics change dramatically, hence this temperature should be regarded as the maximum temperature rise.

26.45 Derive an expression for the angular velocity of the wafer shown in Fig. 26.30b as a function of the radius and angular velocity of the pad in chemical–mechanical polishing.



By the student. Refer to the figure above and consider the case where a wafer is placed on the x-axis as shown. Along this axis there is no velocity in the x-direction. The y-component of the velocity has two sources: rotation of the table and the rotation of the carrier. Considering the table movement only, we can express the velocity distribution as

$$V_y = r\omega_t$$

and for the carrier

$$V_y = r^*\omega_w$$

where r^* can be positive or negative, and is shown positive in the figure. Note that $r = r_w + r^*$, so that we can substitute this equation into V_y and combine the velocities to obtain the total velocity as

$$V_{y,\text{tot}} = (r_w + r^*)\omega_t + r^*\omega_w$$

If $\omega_w = -\omega_t$, then $V_{y,\text{tot}} = r_w\omega_t$. Since the location of the wafer and the angular velocity of the carrier are fixed, it means that the y-component of velocity is constant across the wafer.

SYNTHESIS, DESIGN, AND PROJECTS

26.46 With appropriate sketches, describe the principles of various fixturing methods and devices that can be used for the processes described in this chapter.

By the student. This is an open-ended problem that would also be suitable for a project. The students are encouraged to conduct literature search on the topic a well as recalling the type of fixtures used and described throughout the chapters. See especially Section 37.8 starting on p. 1081.

26.47 Make a comprehensive table of the process capabilities of abrasive-machining operations. Using several columns, describe the features of the machines involved, the type of abrasive tools used, the shapes of blanks and parts produced, typical maximum and minimum sizes, surface finish, tolerances, and production rates.

By the student. This is a very challenging problem. The following should be considered as an example of the kinds of information that can be contained in such a table.

Process	**Abrasives used**	**Part shapes**	**Maximum size**	**Typical surface finish** (μm)
Grinding	Al_2O_3 SiC, cBN Diamond	Flat, round or circular	Flat: no limit. Round: 300 mm Circular: 300 mm	0.2
Barrel finishing	Al_2O_3, SiC	Limited aspect ratio	150 mm	0.2
Chemical-mechanical polishing	Al_2O_3, SiC	Flat surfaces	330 mm	0.05 and lower
Shot blasting	Sand, SiO_2	All types	No limit	1-10

26.48 Vitrified grinding wheels (also called ceramic wheels) use a glasslike bond to hold the abrasive grains together. Given your understanding of ceramic-part manufacture (as described in Chapter 18), list methods of producing vitrified wheels.

By the student. The students should refer to the literature on wheel production, as a project on this topic. The basic process involves blending the abrasive grains with powdered glass, pressing the mixture into various wheel shapes (see Fig. 26.4 on p. 723), firing the green wheels, cooling them (which, for large wheels such as those used in foundries, can take hours to eliminate residual stresses and possible cracking), and truing and balancing the wheel.

26.49 Assume that you are an instructor covering the topics described in this chapter and you are giving a quiz on the numerical aspects to test the understanding of the students. Prepare three quantitative problems and supply the answers.

By the student. This is an challenging, open-ended question and has been found to be a very valuable homework problem.

26.50 Conduct a literature search, and explain how observing the color, brightness, and shape of sparks produced in grinding can be a useful guide to identifying the type of material being ground and its condition.

By the student. Various charts, showing photographs or sketches of the type and color of sparks produced, have been available for years as a useful but general guide for material identification at the shop level, especially for steels. Some of these charts can be found in textbooks, such as in Fig. 24.15 on p. 458 of *Machining Fundamentals*, by J.R. Walker.

26.51 Visit a large hardware store and inspect the grinding wheels that are on display. Make a note of the markings on the wheels and, on the basis of the marking system shown in Fig. 26.6, comment on your observations, including the most common types of wheels available in the store.

By the student. This is a good opportunity to encourage students to gain some exposure to grinding wheels. The markings on the grinding wheels will have the type of information shown in Fig. 26.6 on p. 724. It will also be noted that the most common grinding wheels are basically the same as those shown in Fig. 26.4 on p. 723. Those shown in Fig. 26.5 are less common and also more expensive.

26.52 Obtain a small grinding wheel or a piece of a large wheel. (a) Using a magnifier or a microscope, observe its surfaces and compare them with Fig. 26.9. (b) Rub the abrasive wheel by pressing it hard against a variety of flat metallic and nonmetallic materials. Describe your observations regarding the surfaces produced.

By the student. This is a good project, and can become a component of a laboratory course.

26.53 In reviewing the abrasive machining processes in this chapter, you will note that some use bonded abrasives while others involve loose abrasives. Make two separate lists for these processes and comment on your observations.

By the student. This is an open-ended problem and the following table should be regarded as only an illustration of an answer. The students should give further details, based on a study of each of the processes cover in the chapter.

Process	Comments
Bonded abrasives	
Grinding Belt grinding Sanding Honing Superfinishing	These processes are basically similar to each other and with a wide range abrasive sizes, the material removal rates, surface finish, and lay (see Fig. 33.2 on p. 954).
Loose abrasives	
Ultrasonic machining Chemical-mechanical polishing Barrel finishing Abrasive-flow machining	A random surface lay is most common for these processes.

26.54 Obtain pieces of sandpaper and emery cloth of different coarseness. Using a magnifier or a microscope, observe their surface features and compare them with Fig. 26.25.

By the student. This is a valuable exercise and simple to perform. The illustration in Fig. 26.25 on p. 746 is only a cross-section (side view) of the coated abrasive. The top view should also be viewed, which can be done easily using a magnifier or a simple microscope. The students should comment on the shape and distribution of the abrasives grains and other features that they could observe of the product.

26.55 On the basis of the contents of this chapter, describe your thoughts on whether or not it would be possible to design and build a "grinding center." (See Chapter 25.) Comment on any difficulties that may be encountered in such machines and operations.

By the student. There are now grinding centers commercially available, although the distinction between a machine and a center is not a clear as it is in machining centers. A study of grinding centers and their features would be an interesting topic for a student project.

Chapter 27

Advanced Machining Processes

QUALITATIVE PROBLEMS

27.12 Give technical and economic reasons that the processes described in this chapter might be preferred over those described in the preceding chapters.

The reasons for these considerations are outlined in the introduction to Section 27.1 on p. 759. Students are encouraged to give specific examples after studying each of the individual processes.

27.13 Why is the preshaping or premachining of parts sometimes desirable in the processes described in this chapter?

By the student. Most of the processes described in this chapter are slow and costly, thus they are economically feasible if the volume to be removed is low. Consequently, preshaping of the parts is very important. Note also the concept of net- or near-net shape manufacturing described on p. 25.

27.14 Explain why the mechanical properties of workpiece materials are not significant in most of the processes described in this chapter.

Mechanical properties such as hardness, yield strength, ultimate strength, ductility, and toughness are not important because the principles of these operations do not done involve mechanical means, unlike traditional machining processes. For example, hardness (which is an important factor in conventional machining processes) is unimportant in chemical machining because it does not adversely affect the ability of the chemical to react with the workpiece and remove material. The students should give several other examples of properties and their relevance to specific advanced processes.

27.15 Why has electrical-discharge machining become so widely used in industry?

With increasing strength and toughness and various other properties of advanced engineering materials, there was a need to develop processes that were not sensitive to these properties. Because EDM basically involves electrical properties and is capable of removing material in a variety of configurations, it was one of the most important developments and continues to do so. As in all other processes, it has its advantages as well as limitations, regarding particularly the material-removal rate and possible surface damage which could significantly reduce fatigue life.

27.16 Describe the types of parts that are suitable for wire EDM.

The wire EDM process is most suitable for flat parts, with or without constant thickness. The machines (see p. 773) most commonly have two-degree or three-degree freedom, with the latter capable of producing tapered walls and complex die contours. The major competing process is blanking (see Section 16.2 on p. 382), provided the workpiece is sufficiently thin.

27.17 Which of the advanced machining processes would cause thermal damage? What is the consequence of such damage to workpieces?

The advanced machining processes which cause thermal damage are obviously those that involve high levels of heat, that is, EDM, and laser-beam and electron-beam machining. The thermal effect is to cause the material to develop a heat-affected zone, thus adversely affecting hardness and ductility (see also *heat-affected zone*, p. 884). For the effects of temperature in machining and grinding, see pp. 571-574 and pp. 730-731.

27.18 Which of the processes described in this chapter require a vacuum? Explain why.

By the student. It will be noted from Table 27.1 on p. 761 that the only process that requires a vacuum is electron-beam machining. This is because the electron-beam gun, shown in Fig. 27.15 on p. 777, requires a vacuum to operate.

27.19 Describe your thoughts regarding the laser-beam machining of nonmetallic materials. Give several possible applications, including their advantages compared with other processes.

By the student. Most nonmetallic materials, including polymers and ceramics, can be laser-beam machined (see p. 775) using different types of lasers. The presence of a major heat source and its various adverse effects on a particular material and workpiece must of course be considered. Some materials can have additional concerns; wood, for example, is flammable and may require an oxygen-free environment.

27.20 Are deburring operations still necessary for some parts made by advanced machining processes? Explain and give several specific examples.

By the student. Deburring operations, described on Section 26.8 on p. 750, may be necessary for many of the advanced machining processes described in this chapter. This would be a good topic for the student to conduct research and write a paper. A good reference is *Deburring and Edge Finishing Handbook* by L. Gillespie.

27.21 List and explain factors that contribute to a poor surface finish in the processes described in this chapter.

By the student. Many factors are involved in poor surface finish, depending on the particular process used, each of which has its own set of parameters. A brief outline of the major factors is as follows:

(a) Chemical machining: preferential etching and intergranular attack.

(b) Electrochemical machining and grinding: improper selection of electrolyte, process variables, and abrasives.

(c) Electrical-discharge machining: high rates of material removal and improper selection of electrodes, dielectric fluids, and process variables.

(d) Laser-beam and electron-beam machining: improper selection of process variables, development of heat-affected zones,

(e) Water-jet and abrasive water-jet machining: machining: improper selection of process variables.

27.22 What is the purpose of the abrasives in electrochemical grinding?

The purpose of the abrasives in electrochemical grinding are described on pp. 769-769; namely, they act as insulators and, in the finishing stages, produce a surface with good surface finish and dimensional accuracy.

27.23 Which of the processes described in this chapter are suitable for producing very small and deep holes? Explain.

The answer depends on what is meant by the relative terms “small” and “deep.” Tungsten-wire electrodes as small as 0.1 mm in diameter have been used in EDM, producing depth-to-hole diameter ratios of up to 400:1 (see p. 771 and Fig. 27.10d on p. 770). Laser beams can also be used, and are capable of producing holes at ratios as high as 50:1 (see p. 775). Sub-micron deep holes can only be produced through reactive ion etching.

27.24 Is kerf width important in wire EDM? Explain.

The kerf developed in wire EDM is important primarily because it affects dimensional tolerances, as can be seen in Fig. 27.12 on p. 772.

27.25 Comment on your observations regarding Fig. 27.4.

There are a large number of acceptable observations, and students should be encouraged to develop their own answers based on their background and education. However, examples of observations associated with Fig. 27.4 on p. 764 include:

(a) Note that the surface roughness is presented on a log scale, so that each of the processes shown has a very wide range of possible surface roughness and tolerance that can be achieved.

(b) Note that it is very difficult to obtain surface roughnesses lower than 4 μin, but it is possible.

(c) The processes have not been sorted according to best obtainable roughness or tolerance, but instead are organized by type of process. An enterprising student may reorganize the figure so that the processes resulting in the best surface roughness or tolerance is at the top, etc.

27.26 Why may different advanced machining processes affect the fatigue strength of materials to different degrees?

Fatigue is a complex phenomenon which accounts for the vast majority of component failures, including dies and tooling (see Section 2.7 on p. 74). Fatigue failures are known to initiate and propagate as cracks through the part. Because these cracks usually (but not necessarily) start at the workpiece surface and grow with repeated cyclic loadings, the surfaces should be as smooth as possible (see Fig. 2.29 on p. 80). As described throughout the chapter, various chemical, electrical, and thermal mechanisms are involved in each process (with some mechanical interactions as in electrical-discharge grinding and abrasive water-jet machining). Thus, as expected, each process will produce a surface with its own texture and characteristics, and hence the fatigue life of a component will depend on the particular process employed.

QUANTITATIVE PROBLEMS

27.27 A 200-mm-deep hole that is 30 mm in diameter is being produced by electrochemical machining. A high production rate is more important than machined surface quality. Estimate the maximum current and the time required to perform this operation.

From Table 27.1 on p. 761 we find that the maximum current density is 8 A/mm^2. The area of the hole is

$$\text{Area} = \frac{\pi D^2}{4} = \frac{\pi(30 \text{ mm})^2}{4} = 707 \text{ mm}^2$$

The current is the product of the current density and the cathode area. Thus,

$$(8 \text{ A/mm}^2)(707 \text{ mm}^2) = 5650 \text{ A}$$

From Table 27.1, we also find that the maximum material-removal rate (given in terms of penetration rate) is 12 mm/min. Since the hole is 200 mm deep, the machining time is 200/12 = 16.7 min.

27.28 If the operation in Problem 27.27 were performed on an electrical-discharge machine, what would be the estimated machining time?

Refer to the volume and area calculations in Problem 27.27. With electrical-discharge machining, the maximum material-removal rate is typically 0.15 cm^3/min = 150 mm^3/min. Since the problem states that high production rate rather than surface quality is important, let's assume that the material-removal rate is twice this amount, that is, 300 mm^3/min. The volume to be removed is

$$V = \pi \left[\frac{30^2}{4}\right](200) = 141,000 \text{ mm}^3$$

Therefore, the machining time is

$$\text{Time} = \frac{141,000}{300} = 470 \text{ min.}$$

27.29 A cutting-off operation is being performed with a laser beam. The workpiece being cut is 12 mm thick and 380 mm long. If the kerf is 2.4 mm wide, estimate the time required to perform this operation.

From Table 27.1 on p. 761, the range of cutting speeds for laser-beam machining is between 0.5 and 7.5 m/min. Because the workpiece is rather thick, only large capacity lasers will be suitable for this operation, but we will calculate the range of speeds. The time to traverse 0.380 m is between 0.76 min (46 s) and 0.051 min (3.0 s).

27.30 A 20-mm-thick copper plate is being machined by wire EDM. The wire moves at a speed of 1.2 m/min and the kerf width is 1.6 mm. What is the required power? Note that it takes 1550 J to melt one gram of copper.

The metal-removal rate is calculated as MRR=(1/16 in.)(0.8 in.)(48 in./min)=2.4 in^3/min. Since the density of copper is 8970 kg/m^3 (from Table 3.1 on p. 89), the mass removal rate is

$$\dot{m} = \rho(\text{MRR}) = \left(8970 \text{ kg/m}^3\right)\left(2.40 \text{ in}^3/\text{min}\right)\left(\frac{1 \text{ m}}{39.37 \text{ in.}}\right)^3 = 0.35 \text{ kg/min}$$

Therefore, the power required is

$$P = (1550 \text{ J/g})\dot{m} = (1550 \text{ J/g})(0.35 \text{ kg/min}) = 547 \text{ kJ/min} = 9.1 \text{ kJ/s}$$

SYNTHESIS, DESIGN, AND PROJECTS

27.31 Explain why it is difficult to produce sharp profiles and corners with some of the processes described in this chapter.

By the student. Some of the processes are functionally constrained and cannot easily provide very small radii. Consider water-jet machining: the minimum radius which can be cut will depend on the ability to precisely focus the water jet. With wire EDM, the minimum radius depends on the wire diameter. Small radii are possible with small wires, but small wires have low current-carrying capacity, thus compromising the speed of the process. With laser-beam cutting, radii are adversely affected by material melting away from the cutting zone, as well as beam diameter. Similar problems exist in chemical machining as the chemical tends to remove a wider area than that required for sharp profiles.

27.32 Make a list of the processes described in this chapter in which the following properties are relevant: (a) mechanical, (b) chemical, (c) thermal, and (d) electrical. Are there processes in which two or more of these properties are important? Explain.

By the student. Because "relevant" is a subjective term, the students should be encouraged to deviate from this answer if they can articulate a rationale for their decisions. Also, the problem can be interpreted as properties that are important in the workpiece or the phenomenon that is the basic principle of the advanced machining process. An acceptable answer is shown below:

Mechanical: Electrochemical grinding, water-jet machining, abrasive-jet machining.
Chemical: Chemical machining, electrochemical machining, electrochemical grinding.
Thermal: Chemical machining, electrochemical machining, electrochemical grinding, plunge EDM, wire EDM, laser-beam machining, electron-beam machining.
Electrical: Electrochemical machining, electrochemical grinding, plunge EDM, wire EDM, electron-beam machining.

Clearly, there are processes (such as chemical machining) where two properties that are important: the chemical reactivity of workpiece and reagents, and the corrosion processes (which is the principle of chemical machining) which are temperature dependent.

27.33 Would the processes described in this chapter be difficult to perform on various nonmetallic or rubberlike materials? Explain your thoughts, commenting on the influence of various physical and mechanical properties of workpiece materials, part geometries, etc.

By the student. Some materials will be difficult for some of the processes. For example, a chemically inert material will obviously be difficult to machine chemically. An electrically-insulating material is impossible for EDM; a tough material can be difficult to cut with a water jet; and a shiny or transparent material is difficult to machine by laser beams. Note that it is rare that a workpiece material has all of these properties simultaneously.

27.34 Describe the types of parts that would be suitable for hybrid machining. Consider one such part and make a preliminary sketch for a hybrid machine to produce that part.

By the student. Hybrid machining systems are described in Section 27.10 starting on p. 780. Candidate parts for hybrid machines are those that utilize two or more processes and are needed in quantities large enough to warrant such capital equipment investment. Perhaps the most common hybrid machine involves combining turning and milling for applications such as automotive pistons.

27.35 Describe your thoughts as to whether the processes described in (a) Chapters 13 through 16, and (b) Chapters 23 and 24 can be suitable for a hybrid system of making parts. Give a preliminary sketch of a machine for the two groups of processes listed.

By the student. This is an open-ended and challenging but valuable exercise. The particular answer will depend on the individual processes selected for a combination. As an expanded project, students could be encouraged to develop such a design and prepare a brochure, describing the characteristics and capabilities of the machine (as well as its limitations) to venture capitalists, requesting funds to begin producing such machines.

27.36 Make a list of machining processes that may be suitable for each of the following materials: (a) ceramics, (b) cast iron, (c) thermoplastics, (d) thermosets, (e) diamond, and (f) annealed copper.

By the student. It will be noted that, as described in Chapters 23 through 26, most of these materials can be machined through conventional means. Restricting our attention to the processes described in Chapter 27 (although the student is encouraged to extend the discussion to previous chapters), the following processes would be suitable:

(a) Ceramics: water-jet machining, abrasive-jet machining, chemical machining (see etching of silicon, Section 28.8 starting on p. 808).

(b) Cast iron: chemical machining, electrochemical machining, electrochemical grinding, EDM, laser-beam and electron-beam machining, and water- and abrasive-jet machining.

(c) Thermoplastics: water-jet and abrasive-jet machining; electrically-conducting polymers (see p. 183) may be candidates for EDM processing.

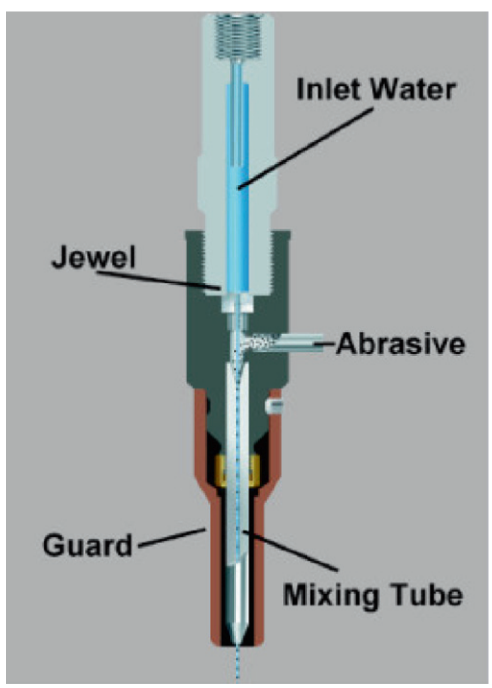
(d) Thermosets: similar consideration as for thermoplastics.

(e) Diamond: None, because diamond would not be responsive to any of the methods described in this chapter.

(f) Annealed copper: Chemical and electrochemical processes, EDM, and laser-beam machining.

27.37 At what stage is the abrasive in abrasive water-jet machining introduced into the water jet? Survey the available literature, and then prepare a schematic illustration of the equipment involved.

The abrasive water-jet machining process is shown in Fig. 27.17 on p. 857 which also indicates the location where the abrasive powder is introduced. Further information can be obtained by surveying manufacturers on the Internet. A very good site is www.waterjets.org; the figure below is from this site.



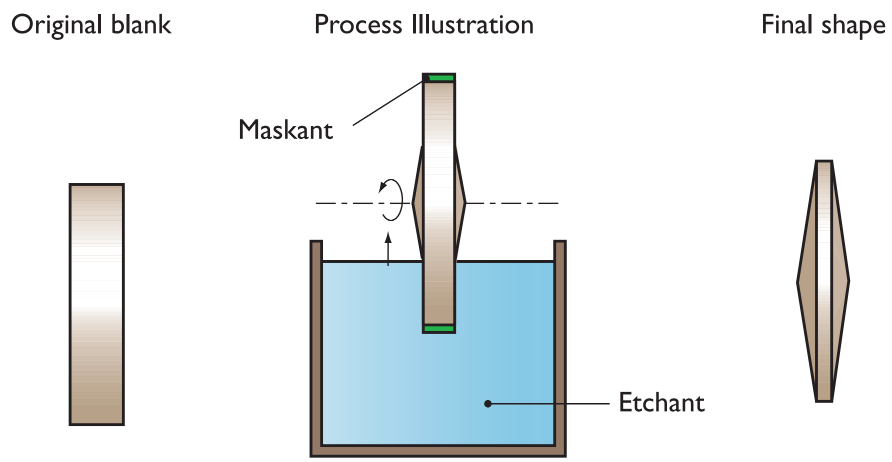
27.38 How would you manufacture a large-diameter, conical, round metal disk with a thickness that decreases from the center outward? Make appropriate sketches.

By the student. The following methods would be suitable.

(a) Machine the part on a CNC milling machine, and supporting it (if thin) with a backup plate or fixture.

(b) Electrochemical machining is a simple method, although it would take longer to produce the part. Take a round blank with a constant thickness and supported at its center, and insert it fully into the tank containing the electrolyte (see pp. 765-766 and the figure below). Begin to withdraw the blank slowly at a constant rate, whereby the outer portions of the part will remain in the tank longer and thus become thinner.

(c) A version of chemical etching can be used, as shown in the figure below. In this setup, a constant-thickness disk is immersed into a chemical etching solution, and is rotated as it is slowly withdrawn from the tank. A mask is applied to the blank periphery to ensure that the outside diameter doesn't change.



27.39 Describe the similarities and differences among the various design guidelines for the processes described in this chapter.

By the student. The major guidelines are listed on pp. 765, 767, 769, 772, and 776.

27.40 Describe any workpiece size limitations in advanced machining processes. Give examples.

By the student. As expected, size limitations vary from process to process, and the students are encouraged to investigate this topic based on data from various sources. For example, processes such as water-jet machining (Fig. 27.16b on p. 779) and laser-beam machining is limited only by the material handling equipment (Fig. 27.14d on p. 774), and sheet size can be quite large. As an actual illustration, bulldozer manufacturers use laser-beam machining of the plate that forms the support of an operator's cab; it measures approximately 6 m × 4.5 m with a 75 mm thickness. In a process such as chemical machining workpiece sizes are limited by tank size, which can be as large as 1.5 m × 3 m × 3 m, but more commonly are about 0.6 m × 1.2 m × 1.2 m. In electrical-discharge machining, workpiece sizes can be large so as to accommodate large dies for various metalworking operations. Conversely, in

electron-beam machining, the vacuum chamber size is limited, and, thus, large workpieces cannot be accommodated. This topic would make a good student project.

27.41 Suggest several design applications for the types of parts shown in Fig. 27.5. (See also Fig. 27.16c.)

The types of parts shown can be used for a number of applications, including electrical connections, filters, plates in optical comparators, and in assembly of microsatellites as described in Case Study 27.2 on p. 781. Students should be encouraged to obtain other answers based on their experience and education, or even based on an Internet search.

27.42 Based on the topics covered in Parts III and IV, make a comprehensive table of hole-making processes. Describe the advantages and limitations of each method, and comment on the quality and surface integrity of the holes produced.

By the student. This is an ambitious and challenging problem topic for students. The problem implies that holes are to generated on a sheet or a block of solid material, and that it does not include finishing processes for existing holes. From the contents of Parts II and IV, it can be seen that hole-making processes include (a) piercing, (b) punching, (c) drilling and boring, (d) chemical machining, (e) electrochemical machining, (f) electrical-discharge machining, (g) laser-beam and electron-beam machining, and (h) water-jet and abrasive water-jet machining. The students can prepare a comprehensive answer, based on the study of these processes in the chapter.

27.43 Review Example 27.1 and explain the relevant parameters involved; then design a system whereby both processes can be used in combination to produce parts from sheet metal.

By the student. Since punching capability will be a feature of such a machine, the main advantage is the use of a laser beam to soften the workpiece material prior to punching, thereby reducing the punch force. Another possibility is nibbling of flat sheets (see p. 387) to produce contoured sections, in which the laser beam reduces forces, can remove burrs from the punching operation (see Fig. 16.2 on p. 384), and provide means for markings while the part is being processed. The students are encouraged to further develop these concepts.

27.44 Marking surfaces with numbers and letters for partidentification purposes can be done with a variety of mechanical and nonmechanical methods. Based on the processes described throughout this book thus far, make a list of these methods, explaining their advantages, limitations, and typical applications.

By the student. Some methods include

(a) laser beams (where the laser path is computer controlled to produce the desired shapes of marks),

(b) etching (where a droplets of an etchant are placed in a fashion similar to ink jet printers),

(c) machining with a small end mill on a CNC milling machine,

(d) embossing (see p. 412, provided that the material is thin), and

(e) using punches with numbers and letters, in a punching operation, similar to coining, as has been done traditionally.

27.45 *Precision engineering* **is a term that is used to describe manufacturing high-quality parts with close dimensional tolerances and good surface finish. Based on their process capabilities, make a list of advanced machining processes with decreasing order of the quality of parts produced. Comment on your observations.**

By the student. Refer also to Fig. 25.16 on p. 712. The order in such a listing will depend on the size of the parts to be produced, the quantity required, the workpiece materials, and the dimensional tolerances and surface finishes. An approximate ranking would be as follows: (1) Chemical etching, (2) Electrochemical grinding, (3) Electrochemical machining, (4) Chemical blanking, (5) Electron-beam machining, (6) Laser-beam machining, (7) Electrical-discharge machining, (8) Abrasive-jet machining, and (9) Water jet machining. The students should add comments on each of these items.

27.46 With appropriate sketches, describe the principles of various work-holding methods and work-holding devices that can be used for the processes described in this chapter.

By the student. This important and challenging topic can be discussed in several ways. For example, specific fixture designs with strategies of fixturing of flanges versus holes can be examined, or the fixture material and its compatibility with the workpiece material and the process can be explored. The fixturing approach as a function of workpiece shape is also important. Fixturing can involve flexible devices, powered devices, or hard fixtures constructed for a particular workpiece shape. This topic would be a good project, based also on the contents of Section 37.8 on p. 1081.

27.47 Make a table of the process capabilities of the advanced machining processes described in this chapter. Use several columns and describe the machines involved, the type of tools and tool materials used, the shapes of blanks and parts produced, the typical maximum and minimum sizes, surface finish, tolerances, and production rates.

By the student. This is an ambitious problem, as locating the sources of dimensional tolerance and production rate data can be particularly difficult. Students should be allowed some leeway in the numbers that are generated, and it is probably reasonable to restrict their consideration to a subset of processes discussed in the chapter. An example of an answer is as follows:

Process	**Tool material**	**Workpiece material**	**Typical shape**	**Typical part thickness and size**
Chemical etching	None (chemical etchant)	Any	Any; most commonly etched cavities on silicon.	No limit; usually < 300 mm
Laser-beam machining	None (light source)	Any, mostly metals	Usually planar blanks	No limit; usually < 25 mm
Wire EDM	Tungsten or copper	Electrically-conducting, mostly metals	Usually planar blanks	No limit; typical workspace is 1.2 m × 1.2 m
Plunge EDM	Tungsten or graphite	Electrically-conducting, mostly metals	Complex die cavities	Typical workspace is 1.2 m × 1.2 m

27.48 One of the general concerns regarding advanced machining processes is that, in spite of their many advantages, they generally are slower than conventional machining operations. Conduct a survey of the speeds, machining times, and production rates involved, and prepare a table comparing their respective process capabilities.

By the student. This is a good opportunity to perform an Internet search for machinery suppliers. It should be noted that it is difficult to obtain consistent numbers for comparison purposes because of the differences in material, dimensional tolerances required, etc. Nevertheless, a benchmark for all of these processes can be found in Table 27.1 on p. 761.

27.49 It can be seen that several of the processes described in Part IV of this book can be employed, either singly or in combination, to make or finish dies for metal-working operations. Write a brief technical paper on these methods, describing their advantages, limitations, and typical applications.

By the student. This is also a good problem for an Internet search.

Chapter 28

Fabrication of Microelectronic Devices

QUALITATIVE PROBLEMS

28.11 Comment on your observations regarding the contents of Fig. V.1.

Figure V.1 on p. 788 has many features that can inspire comments, and students should be encouraged to develop their own observations. Examples of observations regarding this figure include:

- Most manufacturing experience in human history is associated with parts that are in macromanufacturing, and indeed are on the order of the human in size.
- Most biological activities and growth of living organisms takes place fundamentally at nanoscales, with the individual cells being a few tens of micrometers in diameter.
- The manufacturing processes shown use plastic deformation or casting for large scales, but lithography for small length scales. Lithography is not economical for macromanufacturing and forging is not economical for micromanufacturing.
- While not highlighted in Fig. V.1, note that the features in an integrated circuit are impressive, but they are not nearly as elaborate as the three-dimensional shapes that can be achieved in living tissue.

28.12 Describe how n-type and p-type dopants differ.

The difference is whether or not they donate or take an electron from the (usually) silicon into which they are doped.

28.13 How is epitaxy different from other techniques used for deposition? Explain.

Epitaxial layers are grown from the substrate, as described in Section 13.5. Other films are externally applied without consuming the substrate.

28.14 Note that, in a horizontal epitaxial reactor (see Fig. P28.14), the wafers are placed on a stage (susceptor) that is tilted by a small amount, usually 1° to 3°. Explain why this is done.

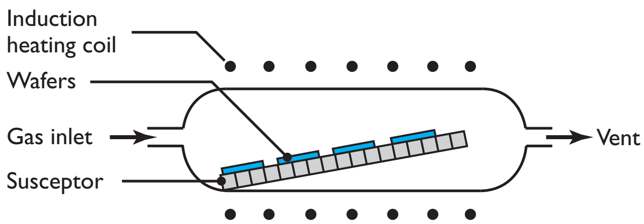


FIGURE P28.14

The stage in the horizontal epitaxial reactor is usually tilted by a small amount to provide equal amounts of reactant gases in both the front and back of the chamber. If the stage were not tilted, the reactant gases would be partially used up (on the wafers in the front of the chamber) before reaching the wafers at the back end of the chamber, causing a nonuniformity in the film deposition.

28.15 The table that follows describes three wafer manufacturing changes: increasing the wafer diameter, reducing the chip size, and increasing process complexity. Complete the table by filling in "increase," "decrease," or "no change," and indicate the effect that each change would have on the wafer yield and on the overall number of functional chips.

Change	Wafer yield	Number of functional chips
Increase wafer diameter		
Reduce chip size		
Increase process complexity		

The effects of manufacturing changes are tabulated below:

Change	Wafer yield	Number of functional chips
Increase wafer diameter	No change	Increase
Reduce chip size	Increase	Increase
Increase process complexity	Decrease	Decrease

28.16 The speed of a transistor is directly proportional to the width of its polysilicon gate; thus, a narrower gate results in a faster transistor and a wider gate in a slower transistor. Knowing that the manufacturing process has a certain variation for the gate width (say, $\pm$ 0.1 μm), how would a designer modify the gate size of a critical circuit in order to minimize its variation in speed? Are there any negative effects of this change?

In order to minimize the speed variation of critical circuits, gate widths are typically designed at larger than the minimum allowable size. As an example, if a gate width is 0.5 μm and the

process variation is ±0.1 μm, a ±20% variation in speed would be expected. However, if the gate width is increased to 0.8 μm, the speed variation reduces to ±12.5%. The penalty for this technique is a larger transistor size (and in turn a larger die area) and a slower transistor.

28.17 A common problem in ion implantation is channeling, in which the high-velocity ions travel deep into the material via channels along the crystallographic planes before finally being stopped. How could this effect be avoided? Explain.

A simple and common method of stopping ion channeling during implantation is to tilt the crystal material by a few degrees (typically 4 to 7°) so that the incident ion beam is not coincident with the crystallographic planes of the material.

28.18 Examine the hole profiles shown in Fig. P28.18 and explain how they might be produced.

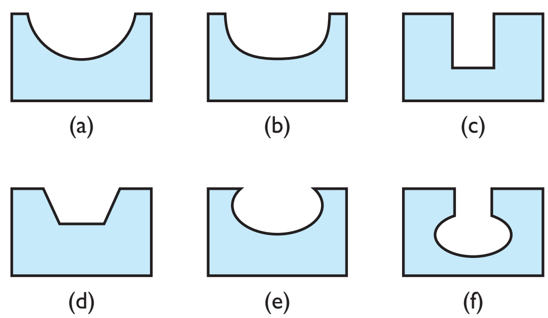


FIGURE P28.18

(a) This profile shows an isotropic etch with no preferential etch direction; this type occurs in wet etching for polycrystalline materials.

(b) This profile shows an almost isotropic etch; note, however, the extended flat region. This can be done with wet etching on a polycrystalline material, where the hole did not have an initial circular profile.

(c) The vertical sidewalls in this profile suggest that ion etching was performed (see Fig. 28.18 on p. 811).

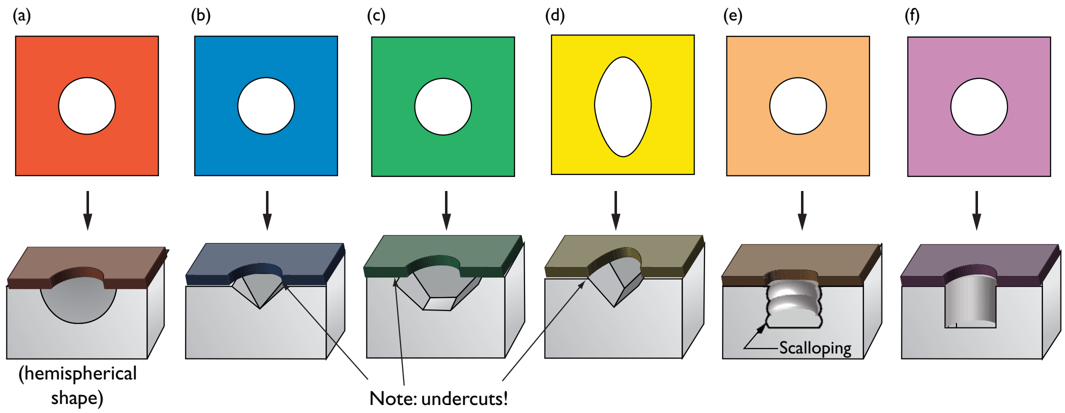
(d) This type is indicative of wet etching on a single-crystal workpiece by sputtering.

(e) This profile is indicative of wet etching, possibly on a dry-etched hole. Note that the surface is undercut, which requires an isotropic etchant.

(f) This profile can be explained as a hole produced with ion etching with an inhibitor layer, followed by isotropic (wet) etching.

28.19 Referring to Fig. 28.23, sketch the shape of the holes generated from a circular mask.

The challenge to this problem is that conical sections are difficult to sketch. Note, however, that some etching processes will expose crystallographic planes, resulting in an undercut of the circular mask in places. The sketches are given below.



QUANTITATIVE PROBLEMS

28.20 A certain wafer manufacturer produces two equalsized wafers, one containing 500 chips and the other containing 200. After testing, it is observed that 50 chips on each wafer are defective. What are the yields of these two wafers? Can any relationship be drawn between chip size and yield?

The yield for the 500 chip wafer is (500-50)/500 = 90.0%, and for the 200 chip wafer it is (200-50)/200 = 75%. Thus, given the same number of defects per wafer, the wafer with smaller chips (more chips per wafer) will have a higher yield because the same number of defects are spread over a larger number of chips, making the number of unacceptable chips a smaller percentage. The relationship between chip size and yield is for this circumstance is

$$\text{Yield} = \frac{N - x}{N}$$

where N is the number of chips on the wafer and x the number of defects per wafer. If a chip has a certain size, l, then the number of chips on a wafer of diameter d is given by

$$N \sim \frac{A_{\text{wafer}}}{A_{\text{chip}}} = \frac{\left(\frac{\pi}{4}d^2\right)}{l^2} = C\left(\frac{d}{l}\right)^2$$

where C is a constant that takes into account the fact that there will be wasted space on a wafer. For a wafer of a given diameter, it can be seen that the number of chips that can be placed on the wafer is approximately inversely proportional to its size.

28.21 A chlorine-based polysilicon etching process displays a polysilicon-to-resist selectivity of 5:1 and a polysiliconto- oxide selectivity of 60:1. How much resist and exposed oxide will be consumed in etching 3500 Å of polysilicon? What would the polysilicon-to-oxide selectivity have to be in order to reduce the loss to only 40 Å of exposed oxide?

The etch rate of the resist is 1/5 that of polysilicon; therefore, etching 3500 Å of polysilicon will result in (3500)(1/5) = 700 Å of resist being etched. Similarly, the amount of exposed oxide etched away will be (3500)(1/60) = 58.3 Å. To remove only 40 Å of exposed oxide, the polysilicon-to-oxide selectivity would be 3500/40 = 88:1.

28.22 During a processing sequence, three silicondioxide layers are grown by oxidation to 2500 Å, 4000 Å, and 1500 Å, respectively. How much of the silicon substrate is consumed?

The total oxide thickness = 2500 Å+ 4000 Å+ 1500 Å= 8000 Å. From Section 28.6 on p. 799, the ratio of oxide to the amount of silicon consumed is found to be 1:0.44. Therefore, to grow 8000 Å of oxide, approximately (0.44)(8000 Å) = 3520 Å of the silicon substrate will be consumed.

28.23 A certain design rule calls for metal lines to be no less than wide. If a thick metal layer is to be wet etched, what is the minimum photoresist width allowed (assuming that the wet etching is perfectly isotropic)? What would be the minimum photoresist width if a perfectly anisotropic dry-etching process is used?

A perfectly isotropic wet-etch process will etch equally in the vertical and horizontal directions. Therefore, the wet-etch process requires a minimum photoresist width of 2 μm, plus 1 μm per side, to allow for the undercutting, hence a total width of 4 μm. The perfectly anisotropic dry-etch process displays no undercutting and hence requires a photoresist width of only 2 μm.

SYNTHESIS, DESIGN, AND PROJECTS

28.24 Describe products that would not exist today without the knowledge and techniques described in this chapter. Explain.

By the student. This topic would be a good project. Clearly, a wide variety of modern products could not exist without using the processes described in this chapter. Certainly, the presence of the integrated circuit has had a profound impact on the lives of everyone, and any product that contains an integrated circuit would either not exist or it would be more expensive and less reliable. Personal computers, television sets, and cellular phones are other major examples of products that could not exist (or exist in a vastly different form) without integrated circuits are televisions, automobiles, and music players. The students are encouraged to comment further, with numerous other examples.

28.25 Inspect various electronic and computer equipment, take them apart as much as you can, and identify components that may have been manufactured by the techniques described in this chapter.

This is a good problem and one that can be inexpensively performed, as most schools and individuals have obsolete electronic devices that can be harvested for their components. Some

interesting and fun projects also can arise from this experiment. One fun project would be to microscopically examine the chips to observe the manufacturer's logos, as graphical icons are often imprinted on chip surfaces. See http://www.microscopy.fsu.edu/micro/gallery.html.

28.26 Describe your understanding of the important features of clean rooms and how they are maintained.

Clean rooms are described in Section 28.2 starting on p. 793. Students should be encouraged to search for additional information, such as the design features of HEPA filters, the so-called bunny suits, and humidity controls. It should be noted, however, that any discussion of clean rooms has to recognize the sources of contaminants (mostly people and their clothing) and the strategies used to control them.

28.27 Make a survey of the necessity for clean rooms in various industries, including the medical, pharmacological, and aerospace industries, and what their requirements are.

By the student. This is a challenging task, because the terminology "clean room" is not always used in these industries, even though the end result is a clean room.

28.28 Review the technical literature, and give further details regarding the type and shape of the abrasive wheel used in the wafer-cutting process shown in Step 2 in Fig. 28.2. (See also Chapter 26.)

By the student. The main source for such information would be manufacturers and distributors of abrasive wheels. It should be noted that the wheel is contoured, hence the wafer does not have a vertical wall. This means that the wafer will have a barrel shape, which is beneficial for avoiding chipping.

28.29 List and discuss the technologies that have enabled the manufacture of the products described in this chapter.

This is an open-ended problem that can be answered in a number of ways. For example, students may wish to list technologies with a historical perspective, or by function, or as associated with a particular product. It is also possible to ask a student to write a summary of the chapter, as this also would serve to answer this question.

28.30 Microelectronic devices may be subjected to hostile environments, such as high temperature, humidity, and vibration, as well as physical abuse, such as being dropped onto a hard surface. Describe your thoughts on how you would go about testing these devices for their endurance under these conditions. Are there any industry standards regarding such tests? Explain.

By the student. This is a good topic for students to study and develop testing methods for electronic devices. It will be helpful to have students refer to ASTM standards and various other sources to find standardized test procedures, and evaluate if they are sufficient for the difficulties encountered.

28.31 Review the specific devices, shown in Fig. V.2. Choose any one of these devices, and investigate what they are, what their characteristics are, how they are manufactured, and what their costs are.

By the student. This is an open-ended problem and the answer will of course vary depending on which component the student wishes to study. Note that the air bag sensor, for example, is described in Case Study 29.2 on p. 851.

Chapter 29

Fabrication of Microelectromechanical Devices and Systems (MEMS)

QUALITATIVE PROBLEMS

29.10 Describe the difference between isotropic etching and anisotropic etching.

In isotropic etching, material is chemically machined in all directions at the same rate, as shown in Fig. 28.18a on p. 811. Anisotropic etching involves chemical machining where one direction etches faster than another, with the extreme being vertical etching (Fig. 28.18c) where material is only removed in one direction.

29.11 Lithography produces projected shapes, so true three dimensional shapes are more difficult to produce. What lithography processes are best able to produce three-dimensional shapes, such as lenses? Explain.

Making three dimensional shapes is very difficult. A shape with a smooth surface is especially challenging, since a stepped surface can be produced by multilayer lithography. Three-dimensional objects can be produced by isotropic etching, but the surface won't necessarily have the desired contour. The best lithography-based process for producing three dimensional surfaces is stereolithography or microstereolithography, which can be combined with electroforming (see p. 986) or other processes (such as LIGA, see p. 844).

29.12 Which process or processes in this chapter allow the fabrication of products from polymers?

By the student. It will be noted that polymers are most easily produced from LIGA and solid freeform fabrication processes. They can be produced through surface micromachining, but in practice, it is very difficult because of the presence of surface residual stresses and the lack of high selectivity in etchants. Polymer products can also be produced from microstereolithography or additive approaches.

29.13 What is the difference between chemically reactive ion etching and dry-plasma etching?

Chemically assisted ion etching is one type of dry plasma etching. In chemically assisted ion-etching, described on pp. 814-815, a chemically reactive species is used along with the impact of ions onto a surface to remove material. This is a form of dry-plasma etching because no liquids are used in the process. However, the general category of 'dry plasma etching' also includes processes such as sputter etching (see p. 812) and cryogenic dry etching (see p. 815).

29.14 The MEMS devices discussed in this chapter are applicable to macroscale machine elements, such as spur gears, hinges, and beams. Which of the following machine elements can or cannot be applied to MEMS, and why? (a) ball bearings, (b) bevel gears, (c) worm gears, (d) cams, (e) helical springs, (f) rivets, and (g) bolts.

Although, in principle, most of these machine elements can be manufactured, it is extremely difficult to manufacture ball bearings, helical springs, worm gears, and bolts (and use them in micromechanical systems). The main reason is that these components are three dimensional, and the current MEMS manufacturing processes are best suited for 2D, or at best, 2-1/2 D devices.

29.15 Explain how you would produce a spur gear if its thickness was one-tenth of its diameter and its diameter was (a) 10 μm (b) 100 μm (c) 1 mm, (d) 10 mm, and (e) 100 mm

The answer depends on the material, but let's assume the material is silicon.

(a) 10-μm spur gear could be produced through surface micromachining.

(b) 100 μm spur gear could be produced through micromachining (p. 833). If silicon is not the desired material, LIGA is an option (p. 844).

(c) 1-mm gear can be produced through LIGA, chemical blanking or chemical etching from foil (p. 763).

(d) 10 mm gear can be blanked or chemically blanked.

(e) 100 mm gear should be machined or hobbed (p. 684).

29.16 List the advantages and disadvantages of surface micromachining compared with bulk micromachining.

By the student. This is an open-ended problem and the students should be encouraged to develop answers that may deviate from this partial list.

Advantages of surface micromachining:

- Multilayer objects can be produced.
- Very good dimensional tolerances can be maintained.
- Complex shapes can be produced in multiple layers.
- A mature technology which is fairly robust.
- Not restricted to single-crystal materials.

Disadvantages of surface micromachining:

- Additional manufacturing steps are required to deposit and remove spacer layers.
- The process is effectively limited to silicon as the substrate material.
- Wet etchants can result in structures that fail to separate from surfaces, as shown in Fig. 29.5 on p. 836.

29.17 What are the main limitations to the LIGA process? Explain.

LIGA is an acronym from the German *X ray Lithographie, Galvanoformung und Abformung* (meaning x-ray lithography, electroforming and molding, as shown in Fig. 29.16 on p. 845). LIGA has the capability of producing MEMS and micromechanical devices with very large aspect ratios, and it also allows the production of polymer MEMS devices and the mass production of these devices (since the LIGA-produced structure is a mold for further processing). The main limitations of LIGA are cost-based: collimated x-rays are obtained only with special equipment, currently available only at selected U.S. National Laboratories; thus, the cost of parts produced is very high.

29.18 Other than HEXSIL, what process can be used to make the microtweezers shown in Fig. 29.22? Explain.

The HEXSIL tweezers shown in Fig. 29.22 on p. 850 are difficult, but not impossible, to produce through other processes. The important features to be noted in these tweezers are the high aspect ratios and the presence of lightening holes in the structure, resulting in a compliant and lightweight structure. Although processes such as SCREAM can be used, the required aspect ratio will be difficult to achieve. LIGA also can be used, but it is expensive. For each of these processes, the tweezers shown in Fig. 29.22 would require redesign of the microtweezers. For example, in LIGA, it would be desirable to have a draft in the vertical members to aid in molding. However, a structure that serves the same function can be produced, even though vertical sidewalls cannot be produced.

QUANTITATIVE PROBLEMS

29.19 The atomic-force microscope probe shown in Fig. 29.29 has a stainless steel cantilever that is 450 $\times$ 40 $\times$ 2 μm. Using equations from solid mechanics, estimate the stiffness of the cantilever, and the force required to deflect the end of the cantilever by 1 μm.

From a textbook on solid mechanics, the folllowing expression can be found for the stiffness of a cantilever:

$$k = \frac{F}{\delta} = \frac{3EI}{L^3}$$

The elastic modulus of stainless steel is, from Table 2.1 on p. 59, around 200 GPa. The cross section of the cantilever is 40 $\times$ 2 μm, so that the moment of inertia of the cross section is

$$I = \frac{1}{12}bh^3 = \frac{1}{12}(40 \times 10^{-6}\text{ m})(2 \times 10^{-6}\text{ m})^3 = 2.67 \times 10^{-23}\text{ m}^4$$

Since the length of the cantilever is 450×10^{-6} m, the stiffness is found to be

$$k = \frac{3EI}{L^3} = \frac{3(200 \times 10^9 \text{ N/m}^2)(2.67 \times 10^{-23} \text{ m}^4)}{(450 \times 10^{-6} \text{ m})^3} = 0.176 \text{ N/m}$$

Therefore, the force needed to cause a deflection of $\delta = 1 \times 10^{-6}$ m is 1.76×10^{-7} N.

29.20 Estimate the natural frequency of the cantilever in Problem 29.19. ***Hint*: See Problem 3.21.**

Problem 3.21 gives the natural frequency of a cantilever as

$$f = 0.56\sqrt{\frac{EIg}{wL^4}}$$

As was shown in the solution to Problem 29.19, $E = 200$ GPa, $I = 2.67 \times 10^{-23}$ m^4, and $L = 450 \times 10^{-6}$ m. The acceleration of gravity is $g = 9.81$ m/s^2. As given in Table 3.1 on p. 89, the density of steel has a wide range; however, a value of $\rho = 7800$ kg/m^3 is reasonable for martensitic stainless steels, although other values may be used by the student. Therefore, w is obtained as

$$w = g\rho A = (9.81 \text{ m/s}^2)(7800 \text{ kg/m}^3)(2 \times 10^{-6} \text{ m})(40 \times 10^{-6} \text{ m}) = 6.12 \times 10^{-6} \text{ N/m}$$

Therefore, the natural frequency of the cantilever is

$$f = 0.56\sqrt{\frac{EIg}{wL^4}} = f = 0.56\sqrt{\frac{(200 \times 10^9)(2.67 \times 10^{-23})(9.81)}{(6.12 \times 10^{-6})(450 \times 10^{-6})^4}} = 8090 \text{ Hz}$$

29.21 Tapping-mode probes for the atomic-force microscope are produced from etched silicon and have typical dimensions of 125 μm in length, 30 μm in width, and 3 μm in thickness. Estimate the stiffness and natural frequency of such probes.

This is a complicated problem because the orientation of the silicon crystal is unknown, and the Young's modulus of silicon depends greatly on orientation. For this problem, a value of 130 GPa will be used, which corresponds to the {100} direction (see Fig. 28.7). Thus, using the same approach as in Problems 29.19 and 29.20,

$$I = \frac{1}{12}bh^3 = \frac{1}{12}(30 \times 10^{-6} \text{ m})(3 \times 10^{-6} \text{ m})^3 = 6.75 \times 10^{-23} \text{ m}^4$$

So that the stiffness is

$$k = \frac{3EI}{L^3} = \frac{3(130 \times 10^9 \text{ N/m}^2)(6.75 \times 10^{-23} \text{ m}^4)}{(125 \times 10^{-6} \text{ m})^3} = 13.4 \text{ N/m}$$

From Table 3.1 on p. 89, the density of silicon is $\rho = 2330$ kg/m^3 so that

$$w = g\rho A = (9.81 \text{ m/s}^2)(2330 \text{ kg/m}^3)(3 \times 10^{-6} \text{ m})(30 \times 10^{-6} \text{ m}) = 2.05 \times 10^{-6} \text{ N/m}$$

Therefore, the natural frequency of the cantilever is

$$f = 0.56\sqrt{\frac{EIg}{wL^4}} = f = 0.56\sqrt{\frac{(130 \times 10^9)(6.75 \times 10^{-23})(9.81)}{(2.05 \times 10^{-6})(125 \times 10^{-6})^4}} = 232 \text{ kHz}$$

29.22 Using data from Chapter 28, derive the time needed to etch the hinge shown in Fig. 29.7 as a function of the hinge thickness.

This problem may have a number of answers, depending on the etching solution selected by the students. The problem aslks to determine the etching time; note that the etching takes place in phosphosilicate glass. There are deposition steps, but these are not considered in this problem. Reviewing Table 28.3 on p. 810, note that concentrated hydrofluoric acid results in an etch rate of 3600 nm/min for phosphosilicate glass, and does not etch polysilicon. This is preferable to buffered HF solutions, where the selectivity and glass etch rates are not as advantageous. Therefore, the etch time is given as $t = x/(3600 nm/min)$ where x is the combined thickness of spacer layers 1 and 2.

Note that the etch time will undoubtedly be longer than this calculation suggests, because it will be difficult to etch material from beneath the Poly1 and Poly2 shapes.

SYNTHESIS, DESIGN, AND PROJECTS

29.23 List similarities and differences between IC technologies described in Chapter 28 and miniaturization technologies presented in this chapter.

By the student. There are many similarities, and the student is encouraged to produce more than given in the short list provided here.

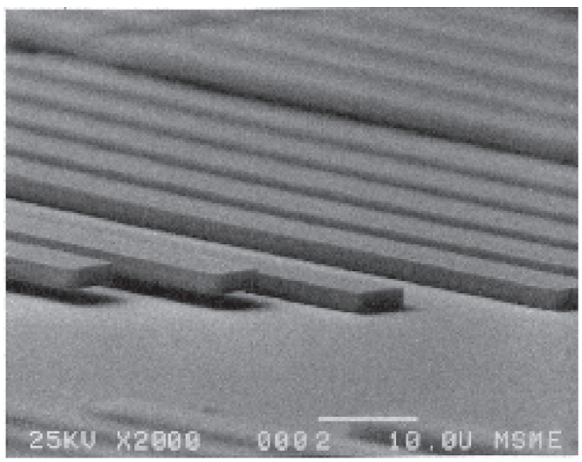
- Microelectronics and MEMS both depend on etching, wet and dry.
- Both use predominantly silicon as the main substrate material.
- Both use similar packaging strategies.
- Both require clean rooms for manufacture.
- Both use batch production techniques.

29.24 Figure I.8 in the General Introduction shows a mirror that is suspended on a torsional beam and can be inclined through electrostatic attraction by applying a voltage on either side of the micromirror at the bottom of the trench. Make a flowchart of the manufacturing operations required to produce this device.

The device shown in Fig. I.8b on p. 24 was produced at the University of California at Berkeley Sensor and Actuator Center. As can be seen, the layer below the mirror is very deep and has near vertical sidewalls, so clearly this device was produced through a dry (plasma) etching approach. Note also that the device was machined from the top since the sidewall slope is slightly inclined. However, a high-quality mirror cannot be produced in this manner. The only means of producing this micromirror is (a) to perform deep reactive ion etching on the lower portion, (b) traditional surface micromachining on the top layer, and (c) joining the two layers through silicon fusion bonding. (See Fig 29.13 on p. 842 for further examples of this approach.)

29.25 Referring to Fig. 29.5, design an experiment to find the critical dimensions of an overhanging cantilever that will not stick to the substrate.

By the student. There are several potential solutions and approaches to this problem. An experimental investigation, pursued by K. Komvopolous, Department of Mechanical Engineering at the University of California at Berkeley, is to produce a series of cantilevers of different aspect ratios on a wafer. After production through surface micromachining followed by rinsing, some of the cantilevers attach to the substrate while others remain suspended. The figure below shows the transition. Based on beam theory from the mechanics of solids, a prediction of the adhesive forces can be determined.



29.26 Design an accelerometer by using (a) the SCREAM process and (b) the HEXSIL process.

By the student. This is an open-ended problem and thus many solutions are possible. The students should draw upon the manufacturing sequence shown in Figs. 29.26 through 29.28 on pp. 853-855, and consider the capability of the SCREAM and HEXSIL processes to produce large, overhanging structures.

29.27 Design a micromachine or device that allows the direct measurement of the mechanical properties of a thin film.

By the student. This is an interesting problem, and since it does not specify a length scale, there are a number of designs. Currently, a number of devices, including nanoindenters and atomic force microscopes are used to obtain the mechanical properties (such as stiffness and strength) of thin films. The student should consider the very small lengths involved; actuators must be extremely sensitive and hence their proper control is essential.

Chapter 30

Fusion-Welding Processes

QUALITATIVE PROBLEMS

30.14 Explain the reasons that so many different welding processes have been developed over the years.

A wide variety of welding processes have been developed for several reasons (see also top of p. 866). Among these are:

(a) There are many types of metals and alloys with a wide range of mechanical, physical, and metallurgical properties and characteristics.

(b) There are numerous applications involving a wide variety of part shapes and thicknesses. For example, small or thin parts which cannot be arc welded can be resistance welded, and for aerospace applications, where strength-to-weight ratio is a major consideration, laser-beam welding or diffusion bonding are attractive processes.

(c) The workpiece is often not suitable for in-plant welding, and the welding process and equipment must be brought to the site, such as in large construction. When the workpiece is available for in-plant welding, less mobile welding processes are necessary.

30.15 Explain why some joints may have to be preheated prior to welding.

Some joints may have to be preheated prior to welding in order to:

(a) control and reduce the cooling rate, especially for metals with high thermal conductivity, such as aluminum and copper,

(b) control and reduce residual stresses developed in the joint, and

(c) for more effective wave soldering (p. 778).

30.16 Describe the role of filler metals in welding.

30.17 What is the effect of the thermal conductivity of the workpiece on kerf width in oxyfuel–gas cutting? Explain.

In oxyfuel-gas cutting, it is desirable to melt as small a width (kerf) as possible. If the workpiece has high thermal conductivity (see Table 3.1 on p. 89), the heat will be dissipated throughout the workpiece more rapidly, resulting in a wider kerf. Low thermal conductivity results in a more localized heating and, hence, a smaller kerf. For this reason, processes that involve a highly localized application of heat, such as laser-beam or electron-beam welding, can be used with much smaller kerfs than other processes. (See, for example, Fig. 30.16 on p. 883.)

30.18 Describe the differences between oxyfuel–gas cutting of ferrous and of nonferrous alloys. Which properties are significant?

In oxyfuel-gas cutting of ferrous alloys, the cutting process takes place mainly by oxidation and burning of the ferrous metal, with some melting also taking place. In nonferrous alloys, on the other hand, the cutting action is mainly by melting; oxidation and burning are usually less important factors; in fact, iron fluxes are often introduced in the flame to localize the melting zone. This method is not effective with ferrous alloys because iron fluxes consume some of the available oxygen and actually hinder the cutting process. The temperature at which welding takes place varies significantly among ferrous and nonferrous alloys, and is it usually higher for ferrous alloys. This phenomenon affects the selection of process parameters such as fuel and oxygen flow rates and welding speed.

30.19 Could you use oxyfuel–gas cutting for a stack of sheet metals? (*Note*: For stack cutting, see Fig. 24.25e.) Explain.

A major problem in cutting a stack of sheet metal is that if the cutting is predominantly through melting, the sheets may be welded together. To minimize this effect, the cutting speed should be as high as possible and at as high a heat-input rate as possible. To further limit the welding of the individual sheets, oxyfuel-gas cutting should be limited to ferrous alloys where the welding is predominantly through oxidation and burning, and not melting. Another problem with stack cutting is that the cut size of the top and bottom sheets can be different (depending on how many layers there are and their thickness, as well as how well the process parameters are controlled) because the heat source is maintained after the top sheets have been cut.

30.20 What are the advantages of electron-beam and laser-beam welding compared with arc welding?

The main advantages of these processes are associated with the very small weld kerf, and the localized energy input and small heat-affected zone. Weld failures, especially by fatigue, occur in the heat-affected zone; thus, minimizing this volume reduces the likelihood of large flaws and rapid crack growth. Also, the low energy input means that thermal distortions and warping associated with these processes will be much lower than with arc welding (see also Figs. 30.23 and 30.25 on pp. 889-890).

30.21 Describe the methods by which discontinuities in welding can be avoided.

Discontinuities in welds are discussed on pp. 885-888. Some of the common defects are porosity, inclusions, incomplete fusion/penetration, underfilling, undercutting, overlaps, and cracks (see Fig. 30.21 on p. 888). The methods by which they can be avoided are discussed on p. 888. Basically, they involve modifying the process parameters (usually modifying welding speed) or preheating the workpiece.

30.22 Explain the significance of the stiffness of the components being welded on both weld quality and part shape.

The effect of stiffness on weld defects is primarily through the thermal stresses that develop during heating and cooling of the weld joint. As shown in Fig. 30.22 on p. 888, for example, not allowing contraction (such as due to a very stiff system) may cause cracks in the joint due to thermal stresses. (See also Section 30.9.1 on p. 885.)

30.23 Comment on the factors that influence the size of the two weld beads shown in Fig. 30.14.

The important factor is the intensity and rate of energy supplied to the workpiece. Other important factors are the shape of the weld bead, and, of course, the thermal conductivity of the material.

30.24 Which of the processes described in this chapter are not portable? Can they be made so? Explain.

While some welding processes are very portable, and this is extremely valuable for field repairs, other processes are not portable. Examples are plasma arc welding, submerged arc welding, electrogas welding, and laser-beam and electron-beam welding. These processes are difficult to make into portable versions, mostly because of the bulkiness of the power supplies required. However, since there are so many portable processes, there is little need to adapt these approaches to make them portable.

30.25 Describe your observations concerning the contents of Table 30.1.

By the student. There are many possible answers to this question, depending on the interpretation and experiences of the student. This problem and others like it have been found to be useful aides in lectures; it can be modified by asking the students to list additional advantages, or the possibility of extending operation from manual to automatic for some processes. Students should be encouraged to develop an answer to this problem that demonstrates they read and studied the information.

30.26 What determines whether a certain welding process can be used for workpieces in horizontal, vertical, or upside down positions–or, for that matter, in any position? (See Table 30.1.) Explain and give examples of appropriate applications.

Note the contents of Table 30.1 on p. 866. Submerged arc welding is the only process listed that requires a flat and horizontal surface, and this is because the flux would not remain in place otherwise. This problem can be repeated as Chapters 31-32 are covered as well to increase the number of operations that are limited in terms of their position.

30.27 Comment on the factors involved in electrode selection in arc-welding processes.

By the student. Electrodes are chosen for the particular process and workpiece. For example, with high-strength workpieces, a stronger electrode may be desired (such as an E110XX series) while for ductile, low-carbon steels, an E60XX series would be adequate. The alloy content can be selected to closely match the alloys being welded to improve fusion.

30.28 In Table 30.1, the column on the distortion of welded components is ordered from lowest distortion to highest. Explain why the degree of distortion varies among different welding processes.

By the student. The main reason distortion varies greatly between processes is the amount of heating involved. Some processes, such as laser-beam machining, apply heat to a very small volume and, therefore, there is much less distortion than, say, oxyacetylene welding where a large volume is heated.

30.29 Explain the significance of residual stresses in welded structures.

By the student. This is an open-ended problem, and students should be encouraged to develop additional or expanded solutions compared to the one given here. Residual stresses (see p. 966) are important for several reasons, including:

- They can lead to warpage, especially if a portion of the weldment is later machined or ground.
- Tensile residual stresses usually result in a reduction of fatigue life.
- Residual stresses require larger dimensional tolerances in design.

30.30 Rank the processes described in this chapter in terms of (a) cost and (b) weld quality.

By the student. Refer to Table 30.1 on p. 866. It will be noted that the weld quality and process costs follow the same trends. Also, cost data given in Table 30.1 relates to equipment costs. While the cost per weld will follow the same trends as the equipment costs, it should be noted that high production rates can justify higher capital equipment expenditures, whereas low production rates cannot make this justification. Geometry and material to be welded also have an effect on economy and quality. Thus, for one weld, the lowest cost process could be shielded metal arc or oxyfuel welding, depending on the material. For higher production rates, an automatic process such as laser welding may actually cost less per weld, even though the capital equipment costs are much higher.

30.31 Must the filler metal be made of the same composition as the base metal that is to be welded? Explain.

It is not necessary for the filler metal, rod, or wire to be the same as the base metal to be welded. Many filler metals are chosen for the favorable alloying properties that they impart to the weld zone. The only function the filler metal must fulfill is to fill in the gaps; whether it diffuses into the base metal is not a requirement, although it is usually beneficial. The filler metal is typically an alloy of the same metal, due to the fact that the workpiece and the filler should melt at reasonably close temperatures. To visualize why this is the case, consider a copper filler used with a material with a much higher melting temperature, such as steel. When the copper melts, the steel workpiece is still solid, and the interface will be adhesion-based, with no diffusion between the copper and steel.

30.32 Describe your observations concerning Fig. 30.18.

By the student. Many observations can be made, such as:

(a) The microstructures can be explained by drawing upon the principles of metal casting, as discussed in Chapter 10.

(b) The hardness contours match the volumes that are expected to be significantly heated as a result of the welding process.

(c) See the solution to Problem 30.34 for a plot of the hardness as a function of distance from the surface.

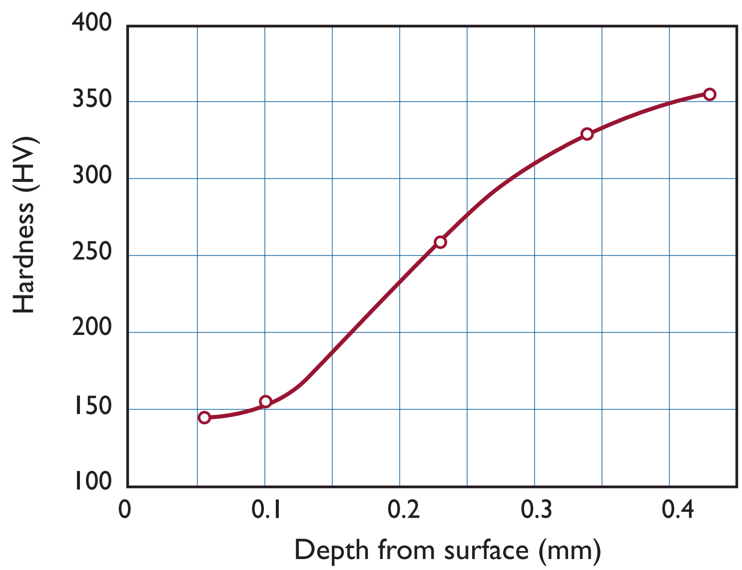
30.33 If the materials to be welded are preheated, is the likelihood for porosity increased or decreased? Explain.

Weld porosity arises from a number of sources, including micropores similar to those found in castings, entrained or evolved gases, and bridging and cracking. If the part is preheated, bridging and cracking are reduced and the cooling rate is lower, therefore large shrinkage pores are less likely. However, since cooling is slower with preheat, soluble gases may be more likely to be entrained unless effective shielding gases are used.

QUANTITATIVE PROBLEMS

30.34 Plot the hardness in Fig. 30.18d as a function of the distance from the top surface, and discuss your observations.

The plot is shown below:



30.35 A welding operation will take place on carbon steel. The desired welding speed is around 20 mm/s. If an arcwelding power supply is used with a voltage of 12 V, what current is needed if the weld width is to be 5 mm?

Assuming that we have a T-joint (see Fig. VI.4 on p. 939), the weld cross-sectional area is

$$A = \frac{1}{2}bh = \frac{1}{2}(5)(5) = 12.5 \text{ mm}^2 = 1.25 \times 10^{-5} \text{ m}^2$$

which assumes that the cross-section is triangular. If all the energy is used to melt the weld metal, we can write,

$$H = \frac{\rho V C \, \Delta T}{l}$$

Also, From Eq. (30.3) on p. 870, $H = EI/v$. Therefore, we can now write, noting that $V = Al$, where l is the weld length,

$$\frac{EI}{v} = \frac{\rho V C \, \Delta T}{l} = \frac{\rho A L C \, \Delta T}{l} = \rho A C \, \Delta T$$

So that the current required is solved as

$$I = \frac{\rho A C v \, \Delta T}{E}$$

From Table 3.1 on p. 89, $\rho = 7860$ kg/m^3, $C = 460$ J/kg-K, and $T_{\text{melt}} = 1450$°C (using mid-range values for steels). Therefore, $\Delta T = 1425$°C. The current is then obtained as

$$I = \frac{(7860)(1.25 \times 10^{-5})(460)(1425)(0.02)}{(12)} = 107 \text{ A}$$

30.36 In Fig. 30.24b, assume that most of the top portion of the top piece is cut horizontally with a sharp saw. The residual stresses will now be disturbed and the part will change its shape, as was described in Section 2.11. For this case, how do you think the part will distort: curved downward or upward? Explain. (See also Fig. 2.30d.)

In this problem, the portion of the material with a compressive residual stress is removed; as a result, the object in Fig. 30.24 on p. 889 is no longer in equilibrium. Note that the original tensile portion has to have the same area as both of the compressive areas combined for initial equilibrium. When the top portion is removed, the bar has excess tension, and it will distort to relieve this stress. Therefore, it will curve downward.

SYNTHESIS, DESIGN, AND PROJECTS

30.37 Comment on workpiece size and shape limitations for each of the processes described in this chapter.

By the student. Some obvious examples are that oxyacetylene welding requires thin workpieces, stick welding requires shapes that allow access to the intended area, and in electron-beam welding workpieces must be small enough to fit into the vacuum chamber.

30.38 Review the types of welded joints shown in Fig. 30.27 and give an application for each.

By the student. This is an open-ended problem, with various possible answers based on the experience of the students. Some examples are:

- Single square-groove weld: pressure vessel walls, tailor welded blanks.
- Single V-groove weld: pressure vessel walls, ship construction.
- Single-flare, V-groove weld: crane booms and lattice structures.

30.39 Comment on the design guidelines given in various sections of this chapter.

By the student. This is an open-ended problem, and several acceptable answers can be given based on the experience of the students. The design guidelines given on pp. 893-896 are fairly straightforward, but the students are encouraged to develop creative answers of their own to this problem.

30.40 You are asked to inspect a welded structure for a critical engineering application. Describe the procedure that you would follow in order to determine the safety of the structure.

By the student. Refer to Sections 36.10 and 36.11 on pp. 1040 and 1044, respectively. Visual examination can detect some defects such as undercuts and toe cracks; however, underbead cracks or incomplete fusion cannot be detected visually. There are nondestructive techniques for evaluating a weld, acoustic and x-ray techniques being the most common for determining porosity and large inclusions. Proof stressing a weld is a destructive approach, but is certainly suitable since defective welds cannot be placed in service safely.

30.41 Discuss the need for, and the role of, work-holding devices in the welding operations described in this chapter.

By the student. The reasons for using fixtures are basically to assure proper alignment of the components to be joined, reduce warpage, and help develop good joint strength. The fixtures can also be a part of the electrical circuit in arc welding, where a high clamping force reduces the contact resistance. See also Section 14.11.1.

30.42 Make a list of welding processes that are suitable for producing (a) butt joints, where the weld is in the form of a line or line segment, (b) spot welds, and (c) both butt joints and spot welds. Comment on your observations.

This solution restricts discussion to the processes in Chapter 30; this problem can be expanded to include processes in Chapters 31 and 32.

(a) For butt joints, a number of operations can be used, including shielded metal arc welding, submerged arc welding, gas metal arc welding, gas tungsten arc welding, fluxed-core arc welding, oxyfuel welding, and electron and laser beam welding.

(b) Spot welds can be crudely made by all of the processes in part (a), but of the processes in Chapter 30, electron beam and laser welding are best suited for spot welds.

(c) All of the processes described in part (a) can make good butt joints and crude spot welds, but only electron beam and laser welding can produce high quality butt and spot welds.

30.43 Explain the factors that contribute to the differences in properties across a welded joint.

There are several factors that can contribute to property differences across a weld joint. The mechanics of casting, covered in Chapter 10, describes clearly that the weld microstructure, which is essentially a cast microstructure, will not be uniform (see Fig. 30.18a and b on p. 885) and that the alloy element concentration will vary within the weld. Also, porosity will be present due to entrained gases and shrinkage that may be concentrated in local areas of the weld.

30.44 Explain why preheating the components to be welded is effective in reducing the likelihood of developing cracks.

Preheating the components prior to welding is helpful because it reduces thermal stresses which could lead to fracture. Consider that the weld solidifies at the melting temperature of the electrode, which can be over 1400°C for steels. When the molten-metal pool solidifies at this temperature, it is stress-free, but the stresses can begin to develop as it contracts, until the part reaches room temperature. However, if the workpiece is preheated, then it will contract with the weld and the resulting built-up stresses will be lower.

30.45 Review the poor and good joint designs shown in Fig. 30.29, and explain why they are labeled so.

By the student. This is an open-ended problem, and various answers are acceptable based on the experience of the students. Students should be encouraged to develop their own answers to this problem. However, examples of acceptable answers are:

- In Fig. 30.29a on p. 895, the loading labeled "Poor" is eccentric and causes a bending moment to the weld; the loading labeled "Good" leads to welds that undergo no stress.
- In (b), the loading has similar effects as in (a).
- In (c), the T-joint on the left is not square, hence it will stress the weld more than a vertical member that is cut square.
- In (d), the burr creates the same type of situation as in (c).
- In (e), the purpose of the design change is to move the welds away from the main body so as to reduce the adverse effect of stress concentration, especially in a location within the heat-affected zone.

- In (f), the design change is to avoid having to machine a weld bead, which can present problems.

30.46 In building large ships, there is a need to weld thick and large sections of steel together to form a hull. Consider each of the welding operations discussed in this chapter, and list the benefits and drawbacks of that particular joining operation for this application.

By the student. This is an open-ended problem and the students should be encouraged to develop their own opinions. The following are examples of points that can be made:

- Submerged arc welding can be used for joining some sections but is not suitable for assembly of the sections into the hull.
- Electroslag welding is probably best suited for this application because it can produce very thick and high-quality welds in one pass; however, the setup is complicated.

30.47 Inspect various parts and components in (a) an automobile, (b) a major appliance, and (c) kitchen utensils, and explain which, if any, of the processes described in this chapter has been used in joining them.

By the student. There are many examples of welding processes described in this chapter that are used in automobiles. Other examples also can be found, depending on the persistence of students (e.g., whether they would crawl under their car and look up). Much of the structure has been arc welded or gas metal arc welded, depending on whether or not robots were used.

30.48 Comment on whether there are common factors that affect the weldability, castability, formability, and machinability of metals, as described in various chapter of this book. Explain with appropriate examples.

By the student. Note that there are some common factors, involving physical and mechanical properties, energy requirements, thermal considerations, and warping.

30.49 If you find a flaw in a welded joint during inspection, how would you go about determining whether or not the flaw is significant?

By the student. This is a challenging task and will require students to search the literature. Some calculations on flaw behavior and crack propagation in metal structures can be attempted, probably with finite-element methods or by using advanced concepts for crack propagation. Proof-testing is another approach. An understanding of the loads and the resulting stresses often determines whether or not a flaw is important. For example, if the defect is on a weld at the neutral axis of a beam in bending, then the stresses are not likely to be high and the flaw is not likely to be critical. On the other hand, a defect in a highly loaded area or in a stress concentration would raise concerns.

30.50 Lattice booms for cranes are constructed from extruded cross sections (see Fig. 15.2) that are welded together. Any warpage that causes such a boom to deviate from straightness will severely reduce its lifting capacity. Conduct a literature search on the approaches used to minimize distortion due to welding and how to correct it, specifically in the construction of lattice booms.

By the student. Lattice booms are constructed in typically 20-ft sections, are checked with an indicator as shown in Fig. 35.4a on p. 1003, and, if necessary, are bent to straightness over the length of the section before welding them. This approach results in a section that, after welding, is sufficiently straight to properly support the intended loads. This is assured by making certain that welds are done in a proper sequence and are balanced everywhere on the boom.

30.51 A common practice in repairing expensive broken or worn parts (such as may occur when a fragment is broken from a forging) is to fill the area with layers of weld beads and then to machine the part back to its original dimensions. Make a list of the precautions that you would suggest to someone who uses this approach.

By the student. Examples are that the weld bead will have different properties than the substrate, so machining may result in vibration and chatter (Section 25.4 on p. 706). The weld material may cause the cutting tools to wear more quickly. The weld material may fracture during machining and compromise the part strength. The weld material may have insufficient ductility for the application.