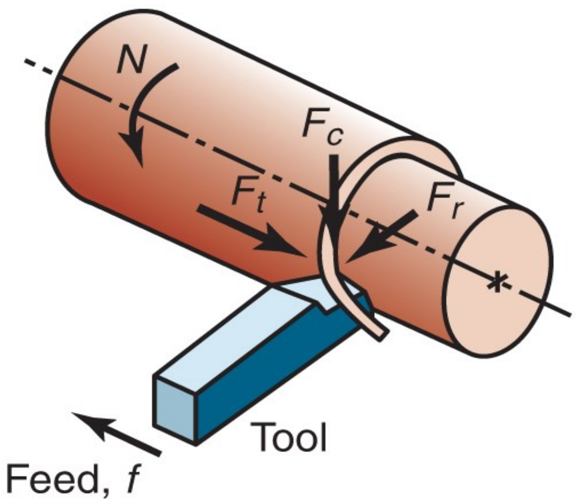
THE UNIVERSITY OF ZAMBIA
SCHOOL OF ENGINEERING
DEPARTMENT OF MECHANICAL ENGINEERING

MEC 3102 PRODUCTION ENGINEERING I AND ELECTRICITY & ELECTRONICS II

MODULE 1: MATERIAL REMOVAL PROCESSES- Lecture Notes



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MODULE OUTLINE

- **Unit 1. Overview of Metal Machining**
- **Unit 2. Overview of Machining Technology**
- **Unit 3. Theory of Chip Formation in Metal Machining**
- **Unit 4. Orthogonal Cutting Model**
- **Unit 5. Actual Chip Formation**
- **Unit 6. Force Relationships and the Merchant Equation under the following:**
  - ***6.1 Forces in Metal Cutting***
  - ***6.2 The Merchant Equation***
- **Unit 7. Power and Energy Relationships in Machining**
- **Unit 8. Power and Energy Relationships in Cutting Temperature under the following**
  - ***8.1 Analytical Methods to Compute Cutting***
  - ***Temperatures.***
  - ***8.2 Measurement of Cutting Temperature.***

Unit 1.OVERVIEW OF METAL MACHINING

- **The material removal processes are a family of shaping operations in which excess material is removed from a starting work part so that what remains is the desired geometry. The "family tree" is shown in Figure 20.1.**
- **The most important branch of the family is *conventional machining*, in which a sharp cutting tool is used to mechanically cut the material to achieve the geometry.**
- **The three most common machining processes are *turning, drilling, and milling*. The "other machining operations" in Figure 20.1 include *shaping*, *planing*, *broaching*, *and* *sawing*. These will be covered in module 2.**
- **This lecture begins the coverage of machining.**

Unit 1.OVERVIEW OF METAL MACHINING(continued)

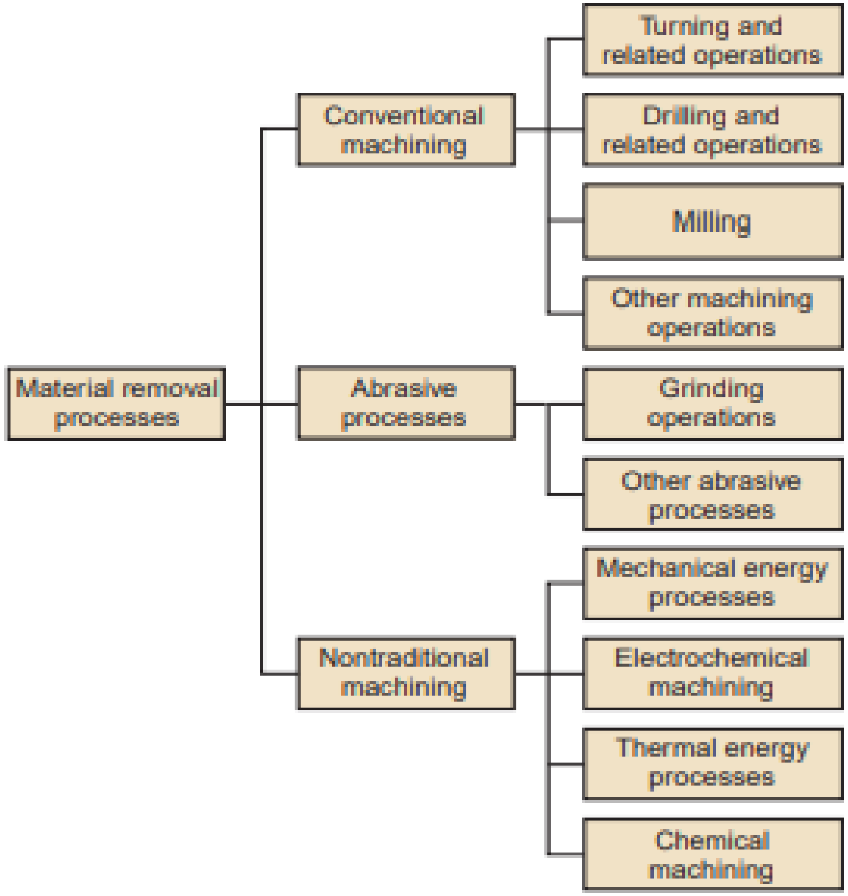


Figure 20.1: Classification of material removal processes.

Unit 1.OVERVIEW OF METAL MACHINING(Continued)

- **Another group of material removal processes is abrasive processes, which mechanically remove material by the action of hard, abrasive particles.**

- **This process group, which includes grinding, will also be covered later in another module.**

- **The "other abrasive processes" in Figure 20.1 include *honing, lapping, and superfinishing.***

- **Finally, there are the non-traditional processes, which use various energy forms and tools other than a sharp cutting tool or abrasive particles to remove material.**

- **The energy forms include *mechanical, electrochemical, thermal, and chemical.***

Unit 1.OVERVIEW OF METAL MACHINING(Continued)

- **The predominant cutting action in machining is *shear deformation of the work material* to form a chip; as the chip is removed by the cutting edge of the tool, a new surface is exposed.**

- **Machining is most frequently applied to metals. The process is diagrammed in Figure 20.2.**

- **Machining is one of the most important manufacturing processes.**

Unit 1.OVERVIEW OF METAL MACHINING(Continued)

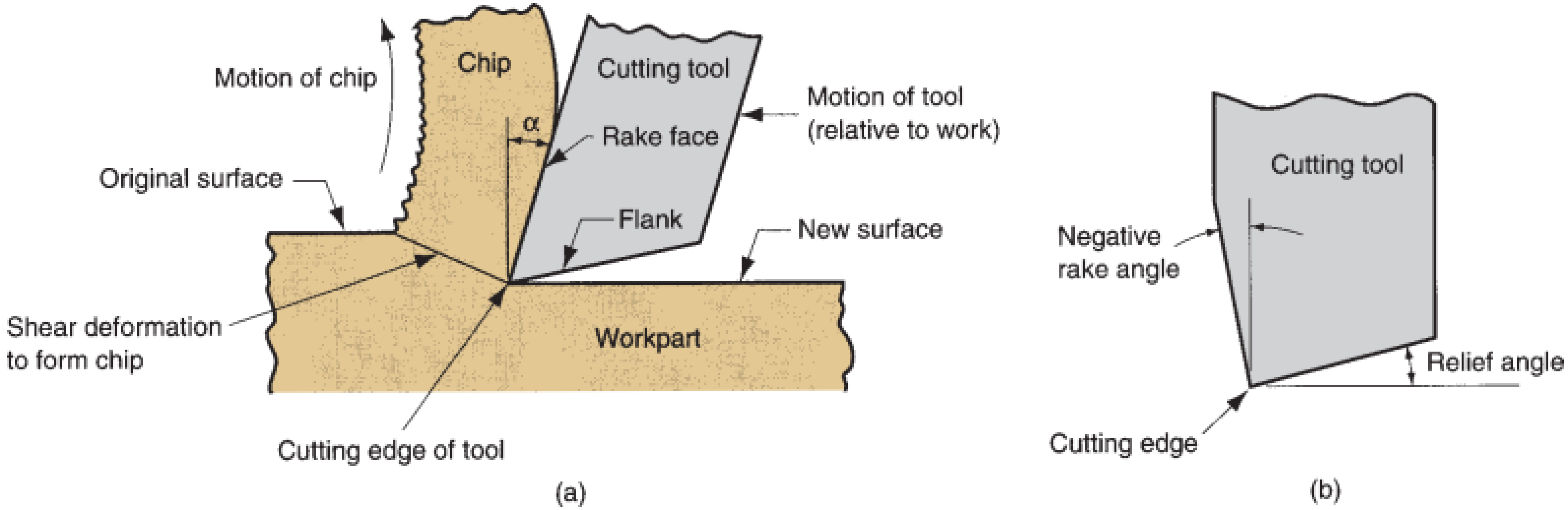


Figure 20.2 (a) A cross-sectional view of the machining process. (b) Tool with negative rake angle; compare with positive rake angle in (a).

Unit 1.OVERVIEW OF METAL MACHINING(Continued)

Machining is important commercially and technologically for several reasons:

- ***Variety of work materials.***

  Machining can be applied to a wide variety of work materials. Virtually all solid metals can be machined. Plastics and plastic composites can also be cut by machining. Ceramics pose difficulties because of their high hardness and brittleness; however, the abrasive machining processes can successfully cut most ceramics.

- ***Dimensional accuracy.***

  Machining can produce dimensions to very close tolerances. Some machining processes can achieve tolerances of ±0.025 mm (±0.001 in), much more accurate than most other processes.

- ***Good surface finishes.***

  Machining is capable of creating very smooth surface finishes. Roughness values less than 0.4 microns (16 μin) can be achieved in conventional machining operations. Some abrasive processes can achieve even better finishes.

Unit 1.OVERVIEW OF METAL MACHINING (Continued)

On the other hand, certain *disadvantages* are associated with machining and other material removal processes:

- ***Wasteful of material.*** **Machining is inherently wasteful of material. The chips generated in a machining operation are wasted material. Although these chips can usually be recycled, they represent waste in the unit operation.**
- ***Time-consuming.*** **A machining operation generally takes more time to shape a given part than alternative shaping processes such as casting or forging.**
  - ***Machining is generally performed after other manufacturing processes such as casting or bulk deformation (e.g., forging, bar drawing). The other processes create the general shape of the starting work part, and machining provides the final geometry, dimensions, and finish.***

Unit 2.OVERVIEW OF MACHINING TECHNOLOGY

- **Machining is not just one process; it is a group of processes.**
- **The common feature is the use of a cutting tool to form a chip that is removed from the work part.**
- **To perform the operation, relative motion is required between the tool and work.**
- **This relative motion is achieved in most machining operations by means of a primary motion, called the *cutting speed*, and a secondary motion, called the *feed*.**
- **The shape of the tool and its penetration into the work surface, combined with these motions, produce the desired geometry of the resulting work surface.**

Unit 2.1 TYPES OF MACHINING OPERATIONS(continued)

- **There are many kinds of machining operations, each of which is capable of generating a certain part geometry and surface texture. The three most common types:** ***turning, drilling, and milling,*** **illustrated in Figure 20.3.**

- In ***turning***, **a cutting tool with a single cutting edge is used to remove material from a rotating workpiece to generate a cylindrical shape, as in Figure 20.3(a).**

- **The speed motion in turning is provided by the rotating work part, and the feed motion is achieved by the cutting tool moving slowly in a direction parallel to the axis of rotation of the workpiece.**

- ***Drilling*** **is used to create a round hole, using a rotating tool that is fed in a direction parallel to its axis of rotation into the work, as in Figure 20.3(b). The tool, called a** ***drill bit***, typically has two cutting edges.

Unit 2.1 TYPES OF MACHINING OPERATIONS(Continued)

- **In *milling*, a rotating tool with multiple cutting edges is fed slowly across the work material to generate a plane or straight surface.**
- **The direction of the feed motion is perpendicular to the tool's axis of rotation. The speed motion is provided by the rotating milling cutter.**
- The two basic forms of milling are ***peripheral milling and face milling***, as in Figure 20.3(c) and (d).
- **Other conventional machining operations include *shaping, planing, broaching, and sawing* (Section 21.6). In addition, *grinding* and similar abrasive operations are often included within the category of machining.**
- **The abrasive processes commonly follow conventional machining and are used to achieve a superior surface finish on the work part.**

Unit 2.1 TYPES OF MACHINING OPERATIONS (Continued)

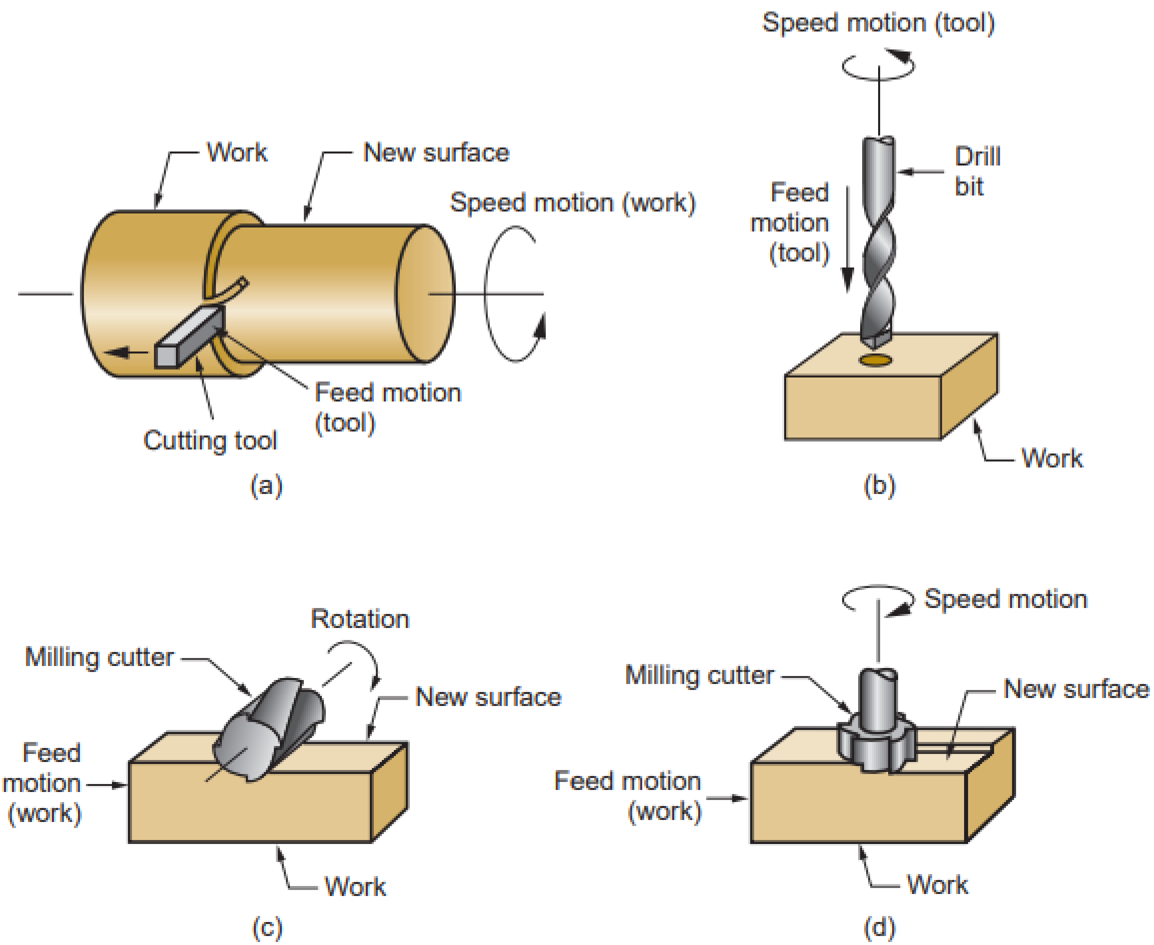


Figure 20.3: The three most common types of machining processes: (a) turning, (b) drilling, and two forms of milling: (c) peripheral milling and (d) face milling.

Unit 2.2 THE CUTTING TOOL

- **A cutting tool has one or more sharp cutting edges and is made of a material that is harder than the work material.**
- **The cutting edge serves to separate a chip from the parent work material, as in Figure 20.2.**
- **Connected to the cutting edge are two surfaces of the tool: the *rake face* and the *flank*. The rake face, which directs the flow of the newly formed chip, is oriented at a certain angle called the *rake angle* α. It is measured relative to a plane perpendicular to the work surface.**
- The rake angle can be positive, as in ***Figure 20.2(a)***, or negative, as in (b).
- **The flank of the tool provides a clearance between the tool and the newly generated work surface, thus protecting the surface from abrasion, which would degrade the finish. This flank surface is oriented at an angle called the relief angle.**

Unit 2.2 THE CUTTING TOOL

- **Most cutting tools in practice have more complex geometries than those in Figure 20.2.**
- **There are two basic types, examples of which are illustrated in Figure 20.4: (a) *single-point tools* and (b) *multiple-cutting-edge tools.***
- **A single-point tool has one cutting edge and is used for operations such as turning.**

Unit 2.2 THE CUTTING TOOL

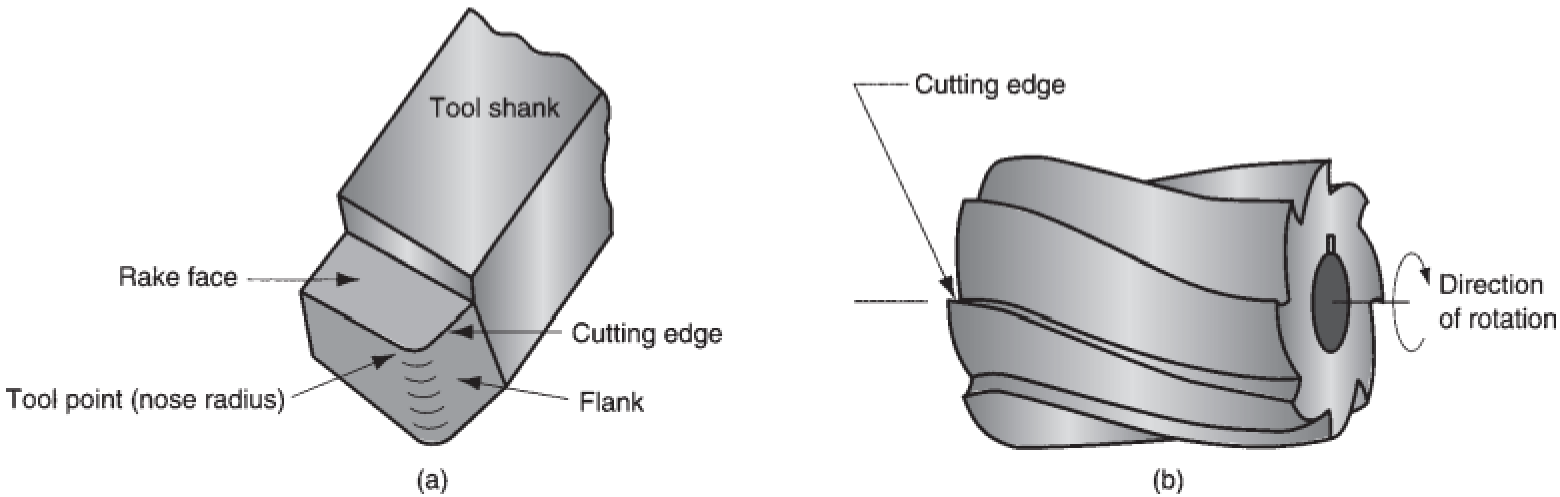


Figure 20.4 (a) A single-point tool showing rake face, flank, and tool point; and (b) a helical milling cutter, representative of tools with multiple cutting edges.

Unit 2.2 THE CUTTING TOOL

- **In addition to the tool features shown in Figure 20.2, there is one tool point from which the name of this cutting tool is derived.**

- **During machining, the point of the tool penetrates below the original work surface of the part.**

- **The point is usually rounded to a certain radius, called the *nose radius.***

- **Multiple-cutting-edge tools have more than one cutting edge and usually achieve their motion relative to the work part by rotating. Drilling and milling use rotating multiple cutting-edge tools.**

Unit 2.2 THE CUTTING TOOL

- Figure 20.4(b) shows a helical milling cutter used in peripheral milling.
- Although the shape is quite different from a single-point tool, many elements of tool geometry are similar.

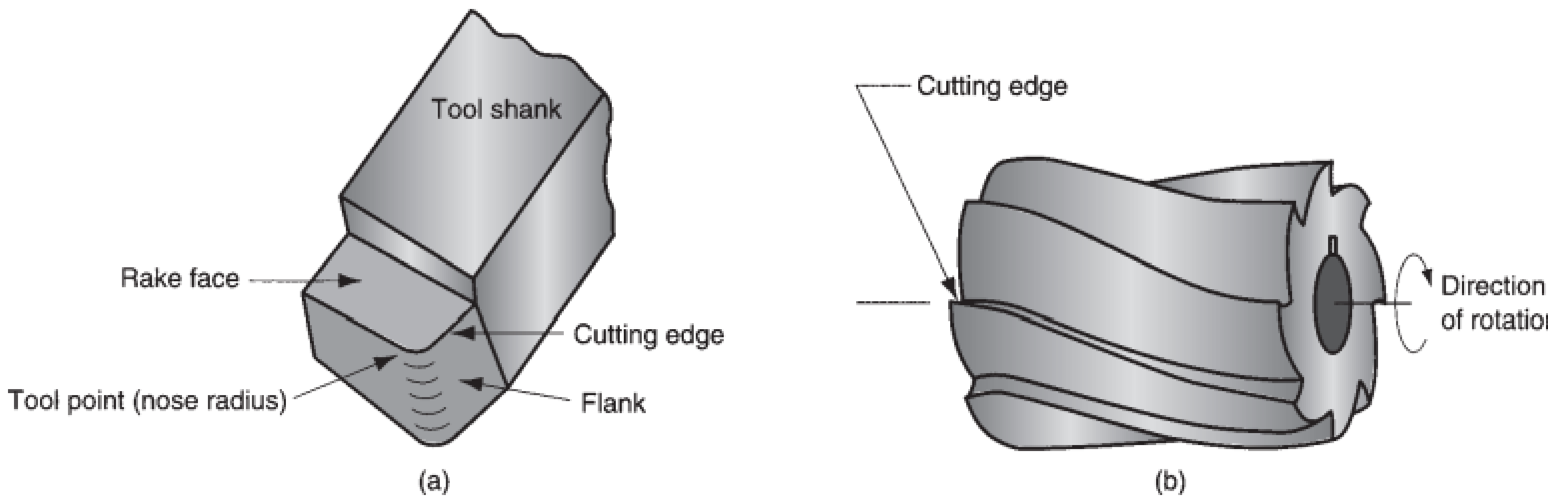


Figure 20.4 (a) A single-point tool showing rake face, flank, and tool point; and (b) a helical milling cutter, representative of tools with multiple cutting edges.

Unit 2.3 CUTTING CONDITIONS

- **Relative motion is required between the tool and work to perform a machining operation. The primary motion is accomplished at a certain cutting speed *v*.**
- **In addition, the tool must be moved laterally across the work. This is a much slower motion, called the *feed f*. The remaining dimension of the cut is the penetration of the cutting tool below the original work surface, called the *depth* of cut *d*.**
- **Collectively; *speed, feed,* and *depth of cut* are called the *cutting conditions*. They form the *three dimensions* of the machining process, and for certain, operations (e.g., most single-point tool operations) they can be used to calculate the material removal rate for the process:**
- $$R_{MR} = vfd$$

Where R_{MR} = material removal rate, $\mathrm{mm^3/s\,(in^3/min)}$; v = cutting speed, $\mathrm{m/s\ (ft/min)}$ which is converted to $\mathrm{mm/s(\ in/min\ )}$; f = feed, mm (in); and d = depth of cut, mm (in).

Unit 2.3 CUTTING CONDITIONS

- **The cutting conditions for a turning operation are depicted in Figure 20.5.**
- **Typical units for *cutting speed* are m/s or m/min (ft/min).**
- ***Feed* in turning is expressed in mm/rev (in/rev), and *depth of cut* is expressed in mm (in).**
- **In other machining operations, interpretations of the cutting conditions may differ. For example, in a drilling operation, depth is interpreted as *the depth of the drilled hole.***

Unit 2.3 CUTTING CONDITIONS

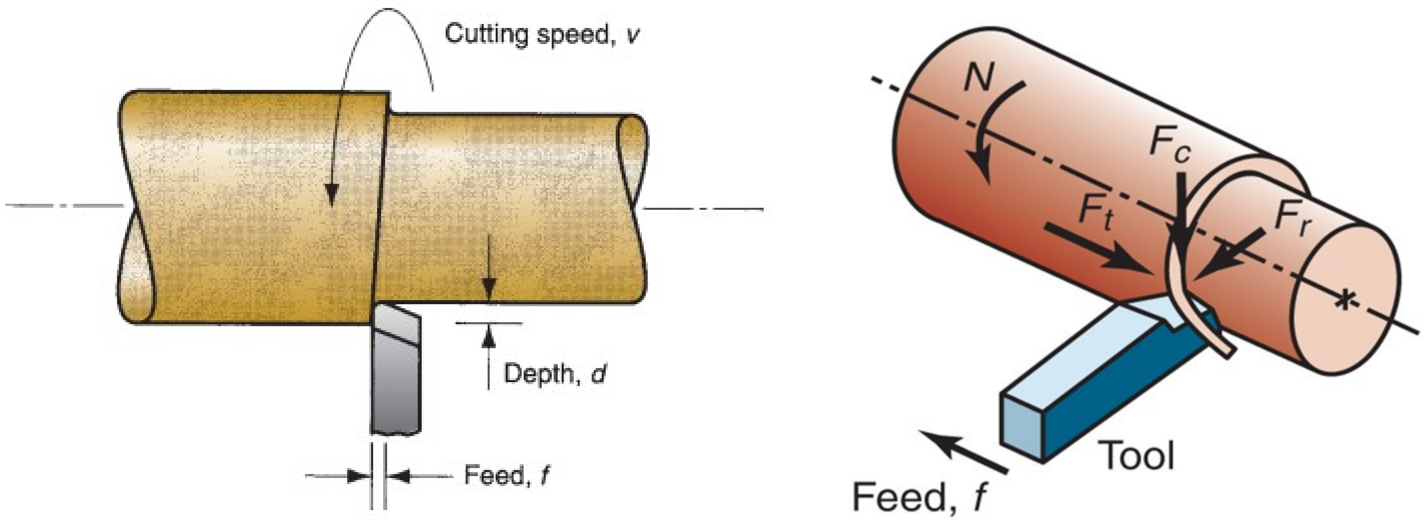
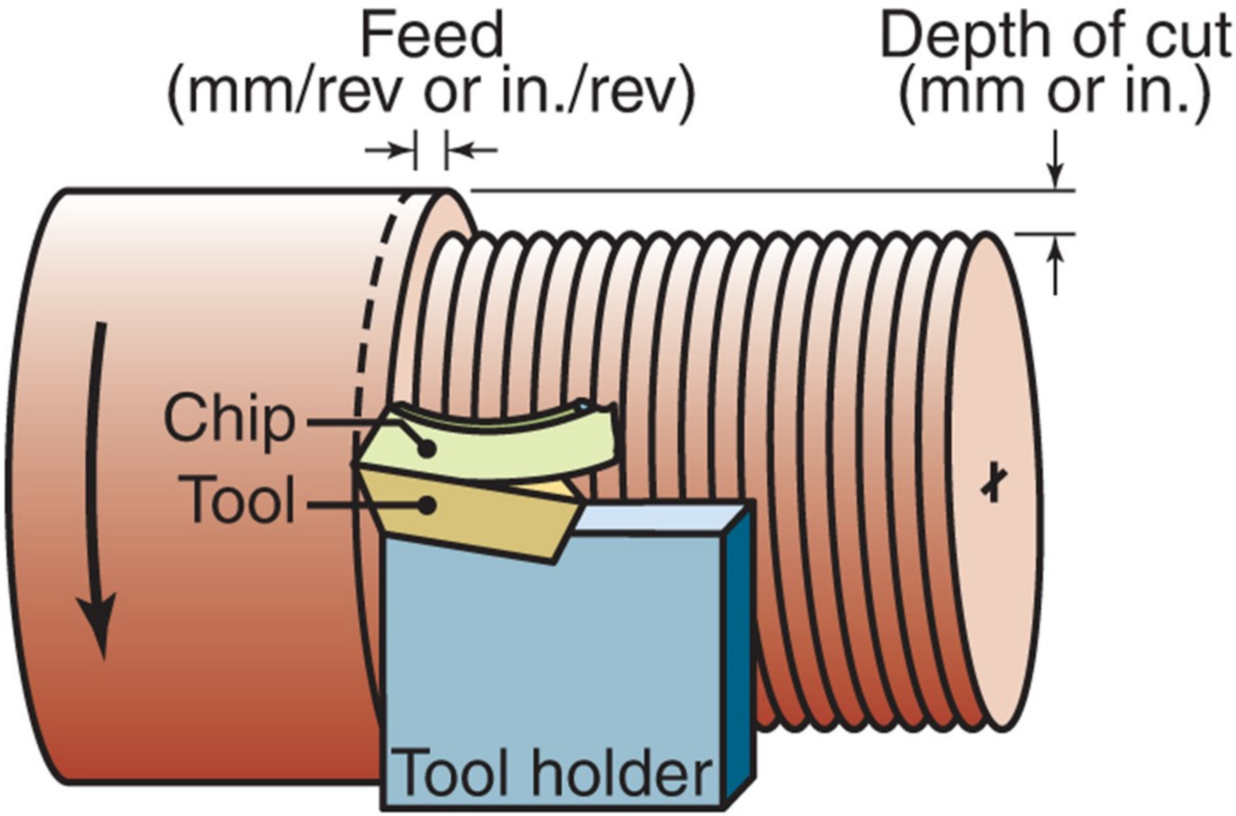


Figure 20.5: ***Cutting speed***, ***feed,*** **and** ***depth of cut*** **for a turning operation.**

Unit 2.3 CUTTING CONDITIONS



Schematic illustration of the turning operation, showing various features.

Unit 2.4 MACHINE TOOLS

- **A machine tool is used to hold the work part, position the tool relative to the work, and provide power for the machining process at the speed, feed, and depth that have been set.**

- **By controlling the tool, work, and cutting conditions, machine tools permit parts to be made with great accuracy and repeatability, to tolerances of 0.025 mm (0.001 in) and better.**

- **The term machine tool applies to *any power-driven machine that performs a machining operation, including grinding.***

Unit 2.4 MACHINE TOOLS

- **The term is also applied to machines that perform metal forming and press working operations .**
- **The *traditional machine tools* used to perform turning, drilling, and milling are lathes, drill presses, and milling machines, respectively.**
- ***Conventional machine tools* are usually tended by a human operator, who loads and unloads the work parts, changes cutting tools, and sets the cutting conditions.**
- **Many modern machine tools are designed to accomplish their operations with a form of automation called *computer numerical control(CNC)*.**

Unit 3.THEORY OF CHIP FORMATION IN METAL MACHINING

- **The geometry of most practical machining operations is somewhat complex.**
- **A simplified model of machining is available that neglects many of the geometric complexities, yet describes the mechanics of the process quite well.**
- **It is called the *orthogonal cutting model*, Figure 20.6.**
- **Although an actual machining process is three-dimensional, the *orthogonal model has only two dimensions* that play active roles in the analysis.**

Unit 3.THEORY OF CHIP FORMATION IN METAL MACHINING(continued)

- By definition, ***orthogonal cutting*** **uses a wedge-shaped tool in which the cutting edge is perpendicular to the direction of cutting speed.**
- **As the tool is forced into the material, the** ***chip is formed by shear deformation*** **along a plane called the** ***shear plane*****, which is oriented at an angle ϕ with the surface of the work.**
- **Only at the sharp cutting edge of the tool does failure of the material occur, resulting in separation of the chip from the parent material.**
- **Along the shear plane, where the bulk of the mechanical energy is consumed in machining, the material is plastically deformed.**

Unit 3.THEORY OF CHIP FORMATION IN METAL MACHINING(continued)

- **The tool in orthogonal cutting has only two elements of geometry: (1) *rake angle* and (2) *clearance angle.***
- **As indicated previously, the rake angle α determines the direction that the *chip flows* as it is formed from the work part; and the *clearance angle* provides a small clearance between the tool flank and the newly generated work surface.**
- **During cutting, the cutting edge of the tool is positioned a certain distance below the original work surface.**
- **This corresponds to the *thickness* of the chip prior to chip formation, t_0.**
- **As the chip is formed along the shear plane, its thickness increases to t_c. The ratio of t_0 to t_c is called the chip thickness ratio (or simply the chip ratio) r:**
- $$r = \frac{t_0}{t_c}$$

Unit 3.THEORY OF CHIP FORMATION IN METAL MACHINING

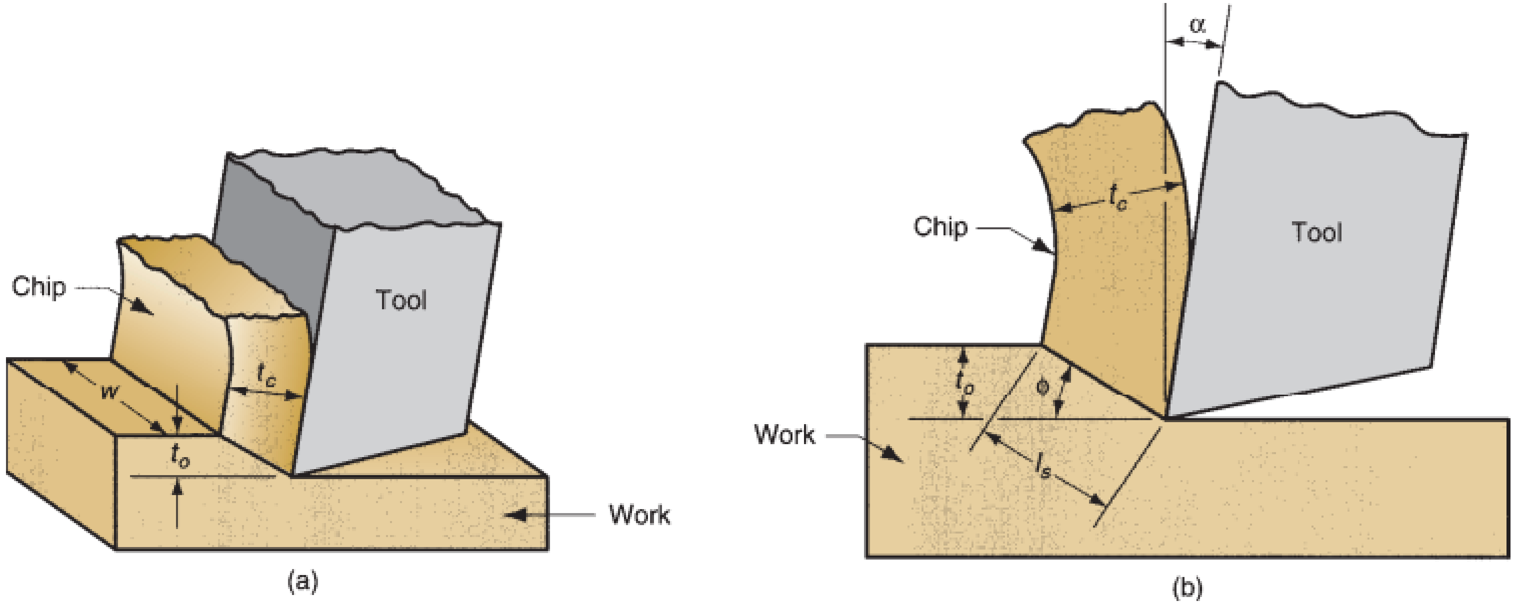
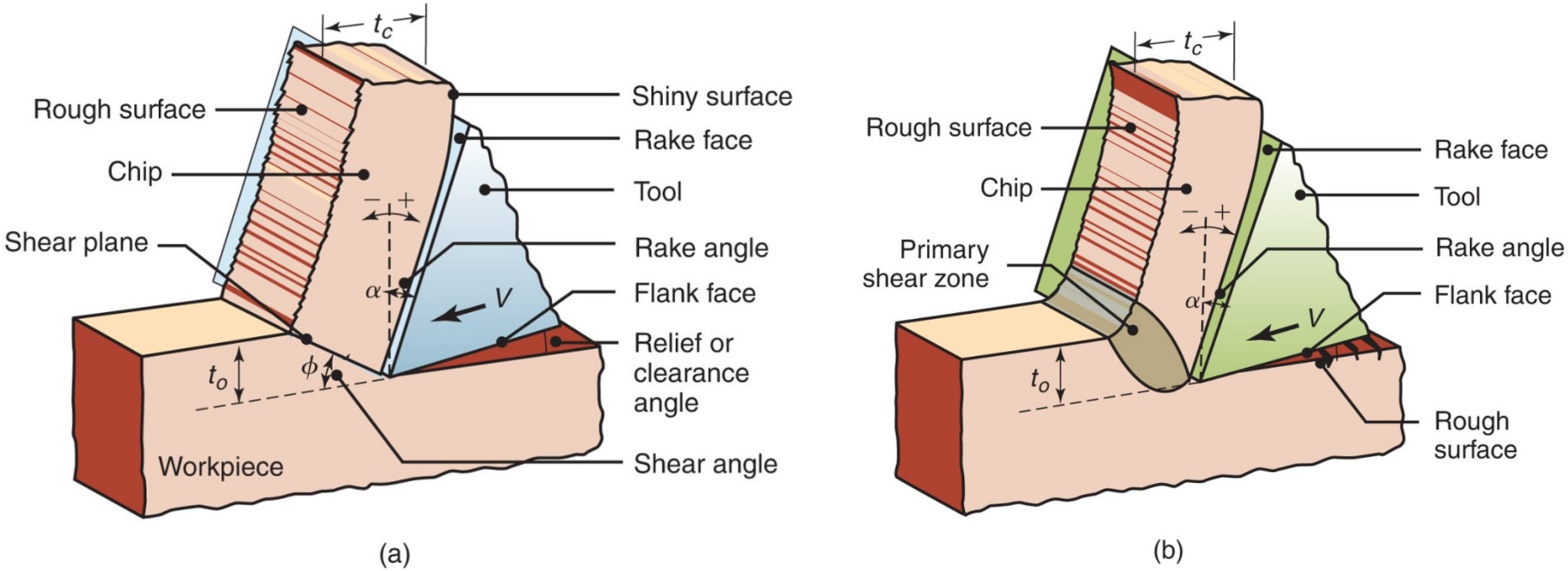


Figure 20.6: Orthogonal cutting: (a) as a three-dimensional process and (b) how it reduces to two dimensions in the side view.

NB: Since the chip thickness after cutting is *always* greater than the corresponding thickness before cutting, the chip ratio will always be less than 1.0.

Unit 3.THEORY OF CHIP FORMATION IN METAL MACHINING



- **Schematic illustration of a two-dimensional cutting process, also called orthogonal cutting: (a) Orthogonal cutting with a well-defined shear plane, also known as the M.E. Merchant model. Note that the tool shape, the depth of cut, t_0, and the cutting speed, V , are all independent variables.**
- **Schematic illustration of a two-dimensional cutting process, also called orthogonal cutting: (b) Orthogonal cutting without a well-defined shear plane**.

Unit 3. THEORY OF CHIP FORMATION IN METAL MACHINING(continued)

- **In addition to t_0 , the orthogonal cut has a width dimension w, as shown in Figure 20.6(a), even though this dimension does not contribute much to the analysis in orthogonal cutting.**
- **The geometry of the orthogonal cutting model allows an important relationship to be defined between the chip thickness ratio, the rake angle, and the shear plane angle.**
- **Let l_s be the length of the shear plane. The following substitutions can be made: $t_0 = l_s \sin \phi$, and $t_c = l_s \cos (\phi - \alpha)$. Thus,**

Unit 3.THEORY OF CHIP FORMATION IN METAL MACHINING(continued)

$$r = \frac{l_s \sin\phi}{l_s \cos(\phi - \alpha)} = \frac{\sin\phi}{\cos(\phi - \alpha)}$$

- This can be rearranged to determine ϕ as follows:

$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha} \qquad (20.3)$$

- **The shear strain that occurs along the shear plane can be estimated by examining Figure 20.7. Part (a) shows shear deformation approximated by a series of parallel plates sliding against one another to form the chip.**

- **Consistent with the definition of shear strain, each plate experiences the shear strain shown in Figure 20.7(b).**
- Referring to part (c), this can be expressed as

$$\gamma = \frac{AC}{BD} = \frac{AD+DC}{BD}$$

which can be reduced to the following definition of shear strain in metal cutting:

$$\gamma = tan(\phi - \alpha) + cot\phi$$

Unit 3.THEORY OF CHIP FORMATION IN METAL MACHINING(continued)

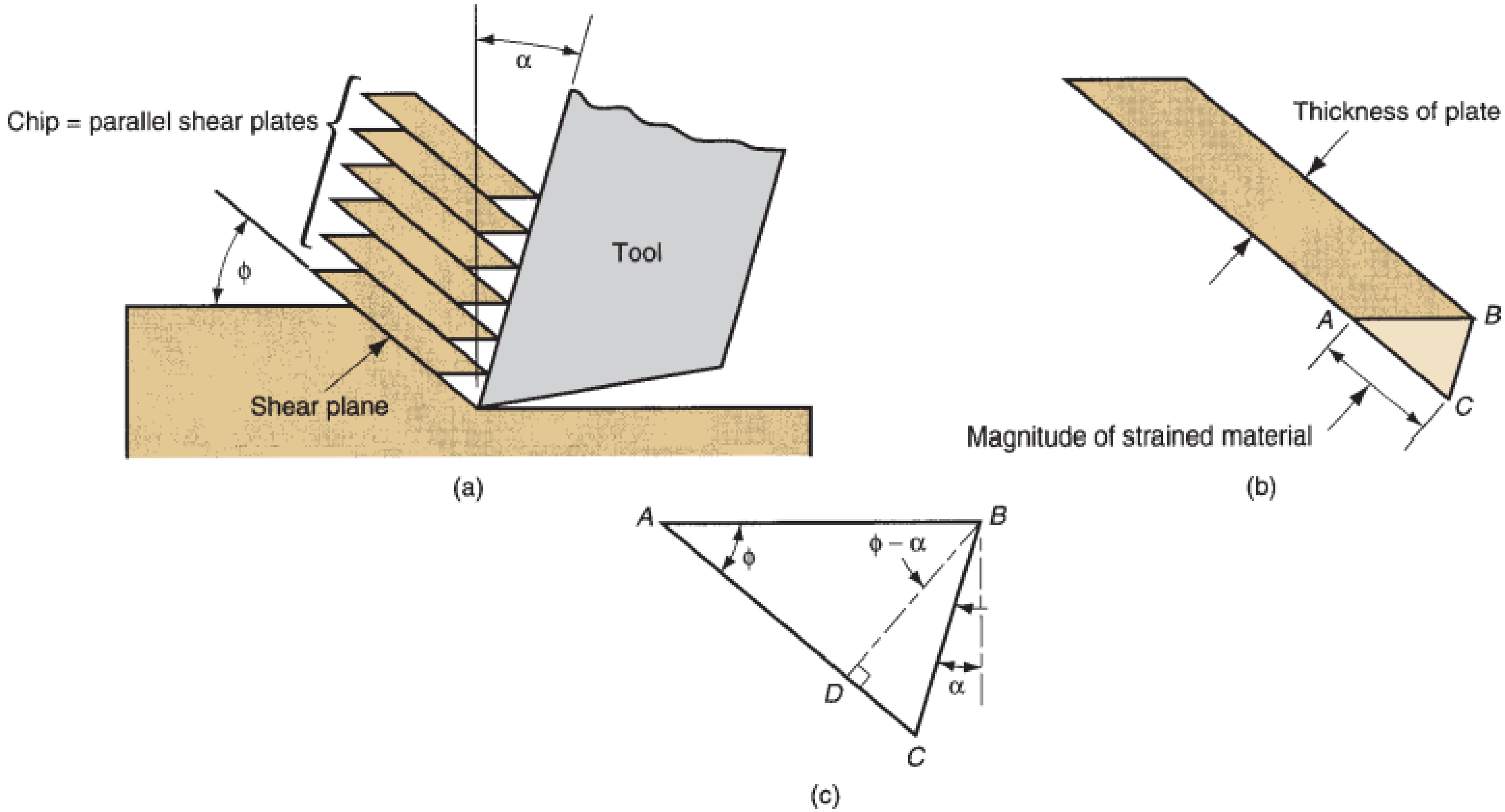


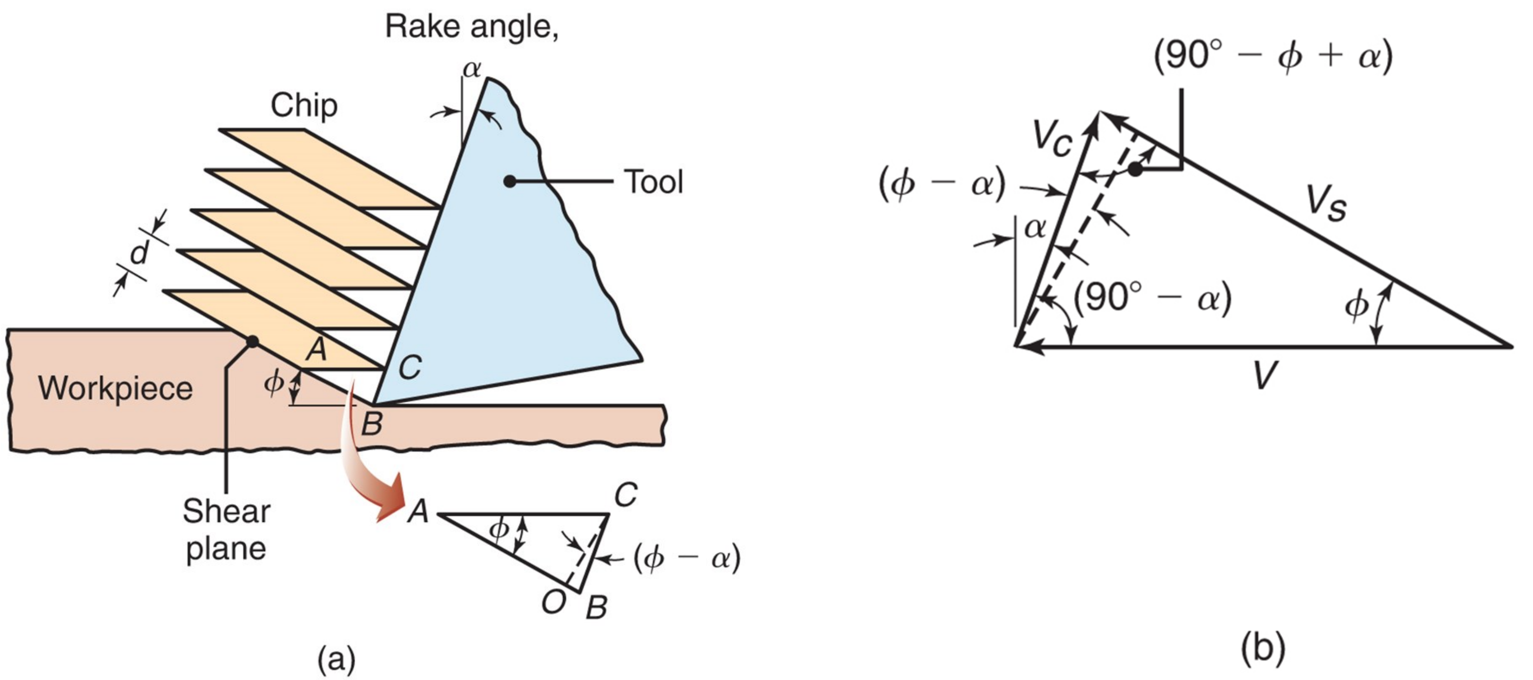
Figure 20.7 Shear strain during chip formation:

(a) chip formation depicted as a series of parallel plates sliding relative to each other,

(b) one of the plates isolated to illustrate the definition of shear strain based on this parallel plate model, and

(c) shear strain triangle used to derive Equation (20.4).

Unit 3.THEORY OF CHIP FORMATION IN METAL MACHINING(continued)



(a) Schematic illustration of the basic mechanism of chip formation by shearing.

(b) Velocity diagram showing angular relationships among the three speeds in the cutting zone.

Example 20.1: Orthogonal cutting

In a machining operation that approximates orthogonal cutting, the cutting tool has a rake angle = 10°. The chip thickness before the cut t_0 = 0.50 mm and the chip thickness after the cut t_c = 1.125 mm. Calculate the shear plane angle and the shear strain in the operation.

Unit 3.THEORY OF CHIP FORMATION IN METAL MACHINING(continued)

Solution: Orthogonal cutting

The chip thickness ratio can be determined from Equation (20.2):

$$r = \frac{t_0}{t_c} = \frac{0.50}{1.125} = 0.444$$

The shear plane angle is given by Equation (20.3):

$$\tan\phi = \frac{0.444 \cos 10}{1 - 0.444 \sin 10} = 0.4738$$

$$\phi = 25.4°$$

Finally, the shear strain is calculated from Equation (20.4):

$$\gamma = \tan(\phi - \alpha) + \cot\phi$$

$$\gamma = \tan(25.4 - 10) + \cot 25.4$$

$$\gamma = 0.275 + 2.111 = 2.386$$

Unit 4. ACTUAL CHIP FORMATION

- **It should be noted that there are differences between the orthogonal model and an actual machining process. First, the shear deformation process does not occur along a plane, but within a zone.**

- **If shearing were to take place across a plane of zero thickness, it would imply that the shearing action must occur instantaneously as it passes through the plane, rather than over some finite (although brief) time period.**

- **For the material to behave in a realistic way, the shear deformation must occur within a thin shear zone.**

- **This more realistic model of the shear deformation process in machining is illustrated in Figure 20.8.**

Unit 4. ACTUAL CHIP FORMATION

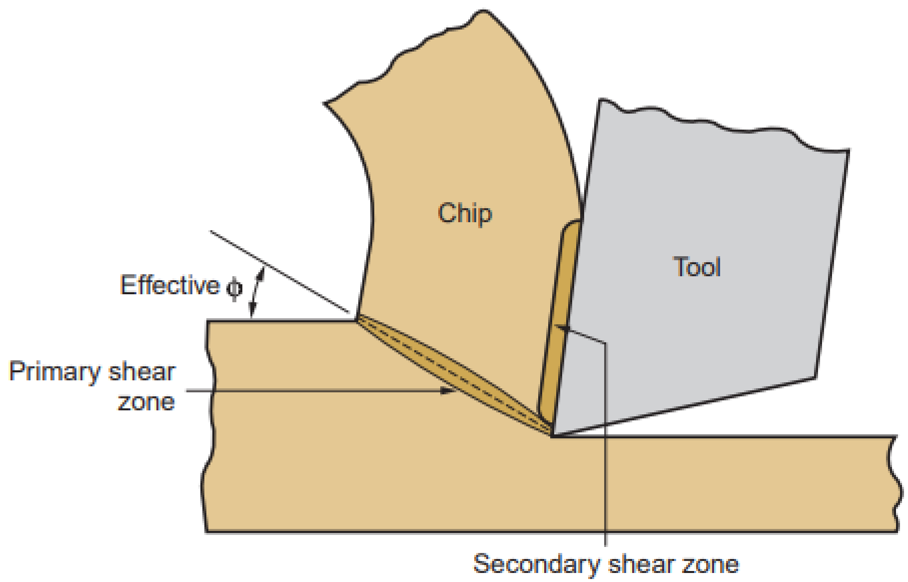


Figure 20.8: More realistic view of chip formation, showing shear zone rather than shear plane. Also shown is the secondary shear zone resulting from tool–chip friction.

Unit 4. ACTUAL CHIP FORMATION

- **Third, chip formation depends on the type of material being machined and the cutting conditions of the operation.**

Four basic types of chip can be distinguished as shown in Figure 20.9:

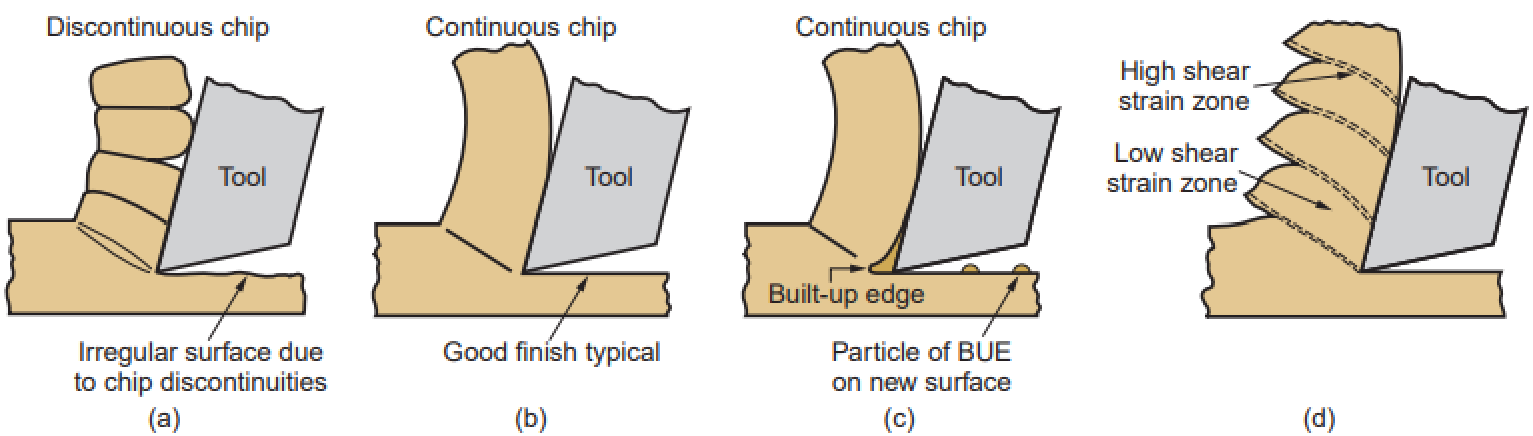


FIGURE 20.9: Four types of chip formation in metal cutting: (a) discontinuous, (b) continuous, (c) continuous with built-up edge, (d) serrated.

Unit 4. ACTUAL CHIP FORMATION

❑ *Discontinuous chip*.

When relatively *brittle materials* (e.g., cast irons) are machined at low cutting speeds, the chips tend to form into separate segments (they are sometimes loosely attached). This tends to impart an irregular texture to the machined surface. High tool–chip friction and large feed and depth of cut promote the formation of this chip type.

❑ *Continuous chip*.

When ***ductile work materials*** are cut at high speeds and small feeds and depths, long continuous chips are formed. A good surface finish typically results when this chip type is formed. ***A sharp cutting edge on the tool and low tool–chip friction encourage the formation of continuous chips.*** Long, continuous chips (as in turning) can cause problems with regard to chip disposal and/or tangling about the tool. ***To solve these problems, turning tools are often equipped with chip breakers.***

Unit 4. ACTUAL CHIP FORMATION

- ***Continuous chip with built-up edge.***

When machining ductile materials at *low-to-medium* cutting speeds, *friction* between tool and chip tends to cause portions of the work material to *adhere* to the rake face of the tool near the cutting edge. *This formation is called a built-up edge (BUE).*

- **The formation of a BUE is cyclical; it forms and grows, then becomes unstable and breaks off . Much of the detached BUE is carried away with the chip, sometimes taking portions of the tool rake face with it, which reduces the life of the cutting tool.**
- **Portions of the detached BUE that are not carried off with the chip become imbedded in the newly created work surface, causing the surface to become rough.**

Unit 4. ACTUAL CHIP FORMATION

❑ *Serrated chip (also called shear-localized chip).*

These chips are ***semi-continuous*** in the sense that they ***possess a saw-tooth appearance*** that is produced by a cyclical chip formation of alternating high shear strain followed by low shear strain.

- **This fourth type of chip is most closely associated with certain *difficult-to-machine metals such as titanium alloys*, *nickel-base super alloys*, and *austenitic stainless steels* when they are machined at higher cutting speeds.**
- **However, the phenomenon is also found with more common work metals (e.g., steels) when they are cut at high speeds.**

Unit 5. FORCE RELATIONSHIPS AND THE MERCHANT EQUATION

5.1 FORCES IN METAL CUTTING

- **Consider the forces acting on the chip during orthogonal cutting in Figure 20.10(a).**
- **The forces applied against the chip by the tool can be separated into two mutually perpendicular components: *friction force F*, which is the frictional force resisting the flow of the chip along the rake face of the tool, and *normal force to friction N*, which is perpendicular to the friction force.**
- **These two components define the coefficient of friction between the tool and the chip:**

$$\mu = \frac{F}{N} \qquad \textbf{(20.5)}$$

Unit 5. FORCE RELATIONSHIPS AND THE MERCHANT EQUATION

5.1 FORCES IN METAL CUTTING

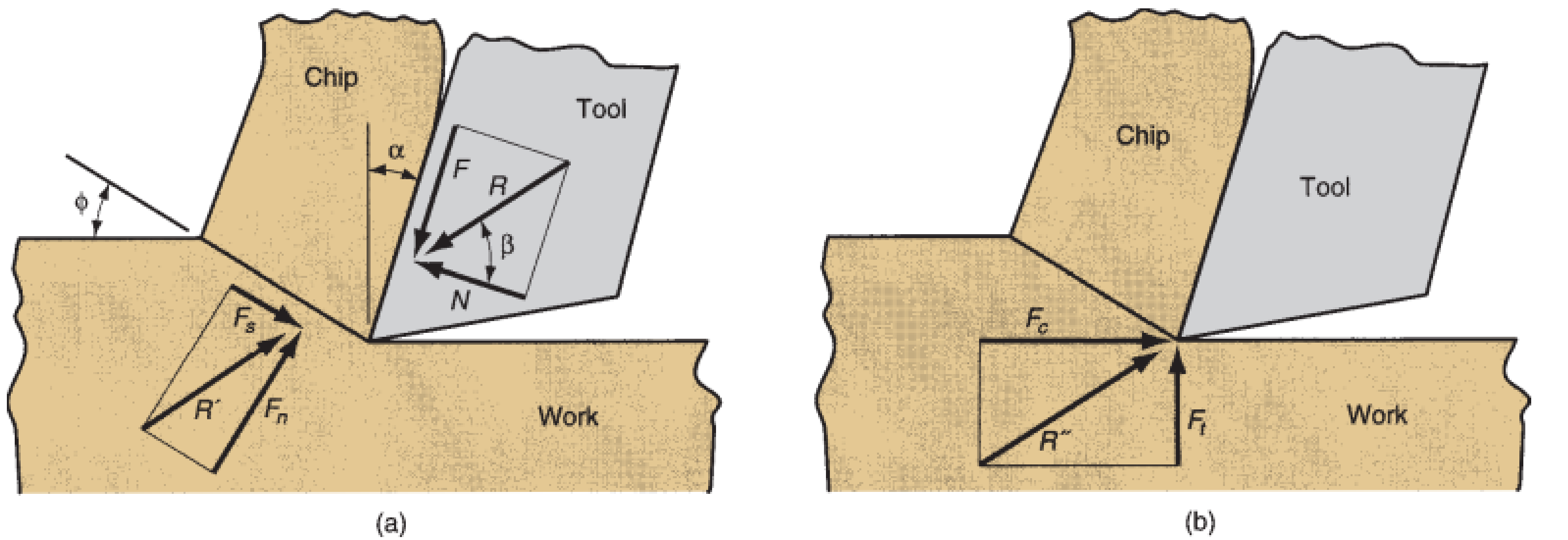


Figure 20.10: Forces in metal cutting: (a) forces acting on the chip in orthogonal cutting and (b) forces acting on the tool that can be measured.

Unit 5. FORCE RELATIONSHIPS AND THE MERCHANT EQUATION

5.1 FORCES IN METAL CUTTING

- **The friction force and its normal force can be added vectorially to form a *resultant force R,* which is oriented at an angle *β*, called the *friction angle.* The friction angle is related to the coefficient of friction as**

$$\mu = \tan\beta \qquad \textbf{(20.6)}$$

- **In addition to the tool forces acting on the chip, there are two force components applied by the workpiece on the chip: *shear force* F_s , which is the force that causes shear deformation to occur in the shear plane, and *normal force to shear* F_n , which is perpendicular to the shear force.**

- **The shear stress that acts along the shear plane between the work and the chip is defined as**

$$\tau = \frac{F_s}{A_s} \qquad \textbf{(20.7)}$$

5.1 FORCES IN METAL CUTTING

- where A_s = area of the shear plane, which is calculated as follows:

$$A_s = \frac{t_0 w}{\sin\phi} \tag{20.8}$$

- **The shear stress in Equation (20.7) represents the level of stress required to perform the machining operation. Therefore, this stress is equal to the shear strength of the work material ($\tau = S$) under the conditions at which cutting occurs.**
- **Vector addition of the two force components F_s and F_n yields the resultant force R'. In order for the forces acting on the chip to balance, this resultant R' must be equal in magnitude, opposite in direction, and collinear with the resultant R.**

Unit 5. FORCE RELATIONSHIPS AND THE MERCHANT EQUATION

5.1 FORCES IN METAL CUTTING (continued)

- **None of the four force components F, N, F_s , and F_n can be easily measured in a machining operation, because the directions in which they are applied vary with different tool geometries and cutting conditions.**

- **However, it is possible for the cutting tool to be instrumented using a *force measuring device* called a *dynamometer*,** so that two additional force components acting against the tool can be directly measured:
  - ***cutting force* F_c , which is in the direction of cutting, the same direction as the *cutting speed* v, and *thrust force* F_t , which is perpendicular to the cutting force and is associated with the chip thickness before the cut t_0.**

Unit 5. FORCE RELATIONSHIPS AND THE MERCHANT EQUATION

5.1 FORCES IN METAL CUTTING (continued)

- **The cutting force and thrust force are shown in Figure 20.10(b) together with their resultant force *R″*. The respective directions of these forces are known, so the *force transducers* in the dynamometer can be aligned accordingly.**
- **Equations can be derived to relate the four force components that cannot be measured to the two forces that can be measured. Using the force diagram in Figure 20.11, the following trigonometric relationships can be derived:**

5.1 FORCES IN METAL CUTTING (continued)

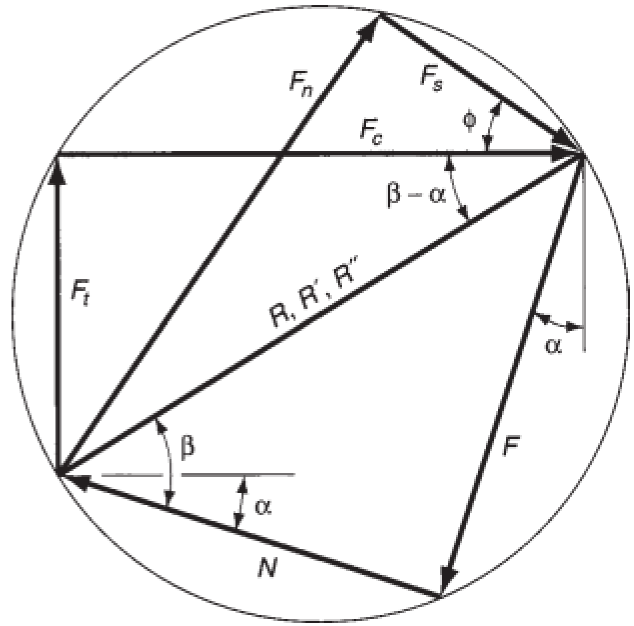


FIGURE 20.11 Force diagram showing geometric relationships among *F*, *N*, $\boldsymbol{F_s}$, $\boldsymbol{F_n}$, $\boldsymbol{F_c}$ *and* $\boldsymbol{F_t}$.

Unit 5. FORCE RELATIONSHIPS AND THE MERCHANT EQUATION

5.1 FORCES IN METAL CUTTING (continued)

$$F = F_c \sin\alpha + F_t \cos\alpha \qquad (20.9)$$

$$N = F_c \cos\alpha - F_t \sin\alpha \qquad (20.10)$$

$$F_s = F_c \cos\phi - F_t \sin\phi \qquad (20.11)$$

$$F_n = F_c \sin\phi + F_t \cos\phi \qquad (20.12)$$

- **If cutting force and thrust force are known, these four equations can be used to calculate estimates of shear force, friction force, and normal force to friction.**
- **Based on these force estimates, shear stress and coefficient of friction can be determined.**

5.1 FORCES IN METAL CUTTING (continued)

- **Note that in the special case of orthogonal cutting when the rake angle $\alpha = 0$, Equations (20.9) and (20.10) reduce to $F = F_t$ *and* $N = F_c$, respectively.**
- **Thus, in this special case, friction force and its normal force could be directly measured by the dynamometer.**

5.1 FORCES IN METAL CUTTING (continued)

EXAMPLE 20.2 SHEAR STRESS IN MACHINING

Suppose in Example 20.1 that cutting force and thrust force are measured during an orthogonal cutting operation:

$\boldsymbol{F_c} = 1559$ N and $\boldsymbol{F_t} = 1271$ N.

The width of the orthogonal cutting operation $w =$ 3.0 mm. Based on these data, determine the shear strength of the work material.

5.1 FORCES IN METAL CUTTING (continued)

Solution:

From Example 20.1, rake angle $\alpha = 10°$, and shear plane angle $\phi = 25.4°$. Shear force can be computed from Equation (20.11):

$$F_s = F_c \cos\phi - F_t \sin\phi \qquad \textbf{(20.11)}$$

$$F_s = 1559 \cos 25.4 - 1271 \sin 25.4 = 863\ N$$

The shear plane area is given by Equation (20.8):

$$A_s = \frac{t_0 w}{\sin\phi} = \frac{(0.5)(3.0)}{\sin 25.4} = 3.497\ mm^2$$

Thus the shear stress, which equals the shear strength of the work material, is

$$\tau = S = \frac{F_s}{A_s} = \frac{863}{3.497} = N/mm^2 = 247\ MPa$$

Solution (Continued):

- **This example demonstrates that *cutting force* and *thrust force* are related to the *shear strength* of the work material.**
- **The relationships can be established in a more direct way. Recalling from Equation (20.7) that the shear force $F_s = SA_s$, the force diagram of Figure 20.11 can be used to derive the following equations:**

$$F_c = \frac{St_0 w\cos(\beta - \alpha)}{\sin\phi\cos(\phi + \beta - \alpha)} = \frac{F_s\cos(\beta - \alpha)}{\cos(\phi + \beta - \alpha)} \qquad \textbf{(20.13)}$$

Solution (Continued):

$$F_t = \frac{St_0 w\sin(\beta-\alpha)}{\sin\phi\cos(\phi+\beta-\alpha)} = \frac{F_s \sin(\beta-\alpha)}{\cos(\phi+\beta-\alpha)} \quad (20.14)$$

- **These equations allow one to estimate *cutting force* and *thrust force* in an *orthogonal cutting operation* if the *shear strength of the work material is known.***

5.2 THE MERCHANT EQUATION

- **One of the important relationships in metal cutting was derived by *Eugene Merchant.***
- **Its derivation was based on the assumption of orthogonal cutting, but its general validity extends to three-dimensional machining operations.**
- **Merchant started with the definition of shear stress expressed in the form of the following relationship derived by combining Equations (20.7), (20.8), and (20.11):**

$$\tau = \frac{F_c \cos\phi - F_t \sin\phi}{(t_0 w / \sin\phi)} \qquad (20.15)$$

Unit 5. FORCE RELATIONSHIPS AND THE MERCHANT EQUATION

5.2 THE MERCHANT EQUATION

- **Merchant reasoned that, out of all the possible angles emanating from the cutting edge of the tool at which shear deformation could occur, there is one angle ϕ that predominates.**
- **This is the angle at which shear stress is just equal to the shear strength of the work material, and so shear deformation occurs at this angle.**
- **For all other possible shear angles, the shear stress is less than the shear strength, so chip formation cannot occur at these other angles.**

5.2 THE MERCHANT EQUATION

- **In effect, the work material will select a shear plane angle that minimizes energy.**
- **This angle can be determined by taking the derivative of the shear stress τ in Equation (20.15) with respect to ϕ and setting the derivative to zero.**
- **Solving for ϕ, the relationship named after Merchant is obtained:**

$$\phi = 45 + \frac{\alpha}{2} - \frac{\beta}{2} \qquad (20.16)$$

5.2 THE MERCHANT EQUATION

- **Among the *assumptions in the Merchant equation is that shear strength of the work material is a constant,* unaffected by *strain rate, temperature, and other factors.***

- **Because this assumption is violated in practical machining operations, *Equation (20.16) must be considered an approximate relationship rather than an accurate mathematical equation.***

- **Nevertheless, consider its application in the following example.**

Example 20.3 Estimating friction angle

Using the data and results from the previous examples, determine (a) the friction angle and (b) the coefficient of friction.

Solution:

(a) From Example 20.1, $\alpha = 10°$, **and** $\boldsymbol{\phi}$

Rearranging Equation (20.16), the friction angle can be estimated:

$$\boldsymbol{\beta = 2(45) + 10 - 2(25.4) = 49.2°}$$

(b) The coefficient of friction is given by Equation (20.6):

$$\boldsymbol{\mu = tan\,49.2 = 1.16}$$

5.2 THE MERCHANT EQUATION(Lessons Based on the Merchant Equation)

- **The real value of the Merchant equation is that it defines the general relationship between *rake angle, tool–chip friction, and shear plane angle.***
- **The shear plane angle can be increased by (1) increasing the rake angle and (2) decreasing the friction angle (and coefficient of friction) between the tool and the chip.**
- **Rake angle can be increased by proper tool design, and friction angle can be reduced by using a lubricant cutting fluid.**

Unit 5. FORCE RELATIONSHIPS AND THE MERCHANT EQUATION

5.2 THE MERCHANT EQUATION(Lessons Based on the Merchant Equation)

- **The importance of increasing the shear plane angle can be seen in Figure 20.12. If all other factors remain the same, a higher shear plane angle results in a smaller shear plane area.**
- **Since the shear strength is applied across this area, the shear force required to form the chip will decrease when the shear plane area is reduced.**
- **A greater shear plane angle results in *lower cutting energy, lower power requirements,* and *lower cutting temperature. These are good reasons to try to make the shear plane angle as large as possible during machining.***

5.2 THE MERCHANT EQUATION (Approximation of Turning by Orthogonal Cutting)

- The orthogonal model can be used to approximate turning and certain other single-point machining operations so long as the feed in these operations is small relative to depth of cut.
- Thus, most of the cutting will take place in the direction of the feed, and cutting on the point of the tool will be negligible.
- Figure 20.13 indicates the conversion from one cutting situation to the other.

5.2 THE MERCHANT EQUATION (Approximation of Turning by Orthogonal Cutting)

- **The interpretation of cutting conditions is different in the two cases.**
  - **The chip thickness before the cut t_0 in orthogonal cutting corresponds to the feed f in turning, and**
  - **The width of cut w in orthogonal cutting corresponds to the depth of cut d in turning.**
- **In addition, the thrust force F_t in the orthogonal model corresponds to the feed force F_f in turning.**
- **Cutting speed and cutting force have the same meanings in the two cases. Table 20.1 summarizes the conversions.**

5.2 THE MERCHANT EQUATION (Approximation of Turning by Orthogonal Cutting)

TABLE 20.1 CONVERSION KEY: TURNING OPERATION VS. ORTHOGONAL CUTTING.

Turning Operation	Orthogonal Cutting Model
Feed f =	Chip thickness before cut t_0
Depth d =	Width of cut w
Cutting speed v =	Cutting speed v
Cutting force F_c =	Cutting force F_c
Feed force F_f =	Thrust force F_t

Unit 5. FORCE RELATIONSHIPS AND THE MERCHANT EQUATION

5.2 THE MERCHANT EQUATION (*The importance of increasing the shear plane angle can be seen*)

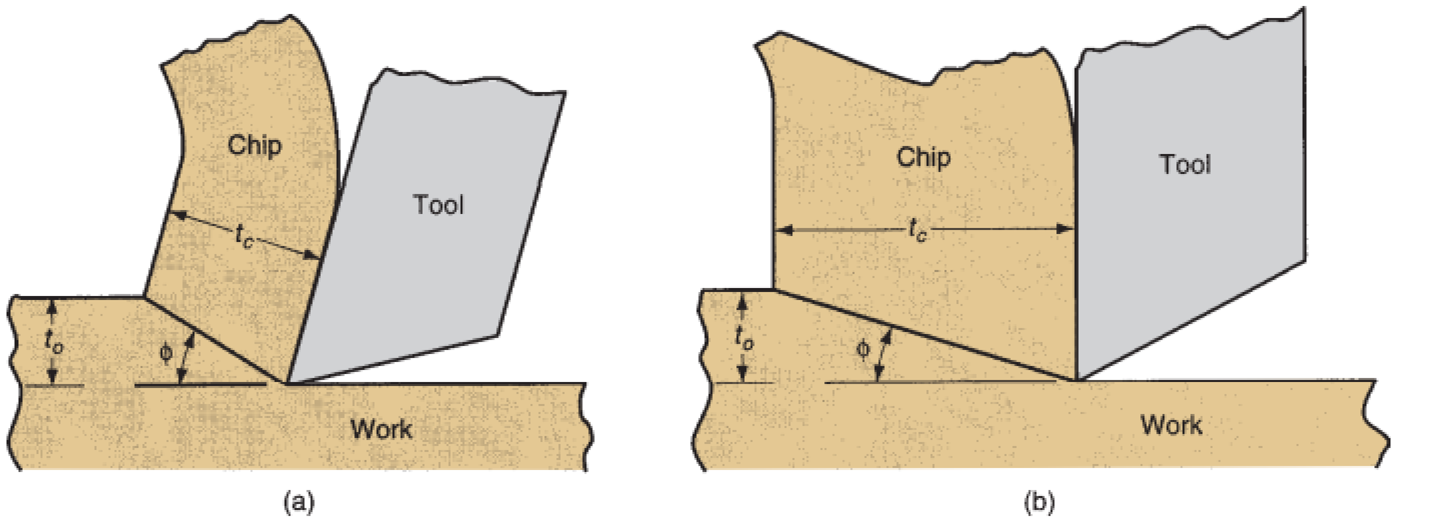


FIGURE 20.12 Effect of shear plane angle ϕ: (a) higher ϕ with a resulting lower shear plane area; (b) smaller ϕ with a corresponding larger shear plane area. Note that the rake angle is larger in (a), which tends to increase shear angle according to the Merchant equation.

Unit 5. FORCE RELATIONSHIPS AND THE MERCHANT EQUATION

5.2 THE MERCHANT EQUATION *(Approximation of Turning by Orthogonal Cutting)*

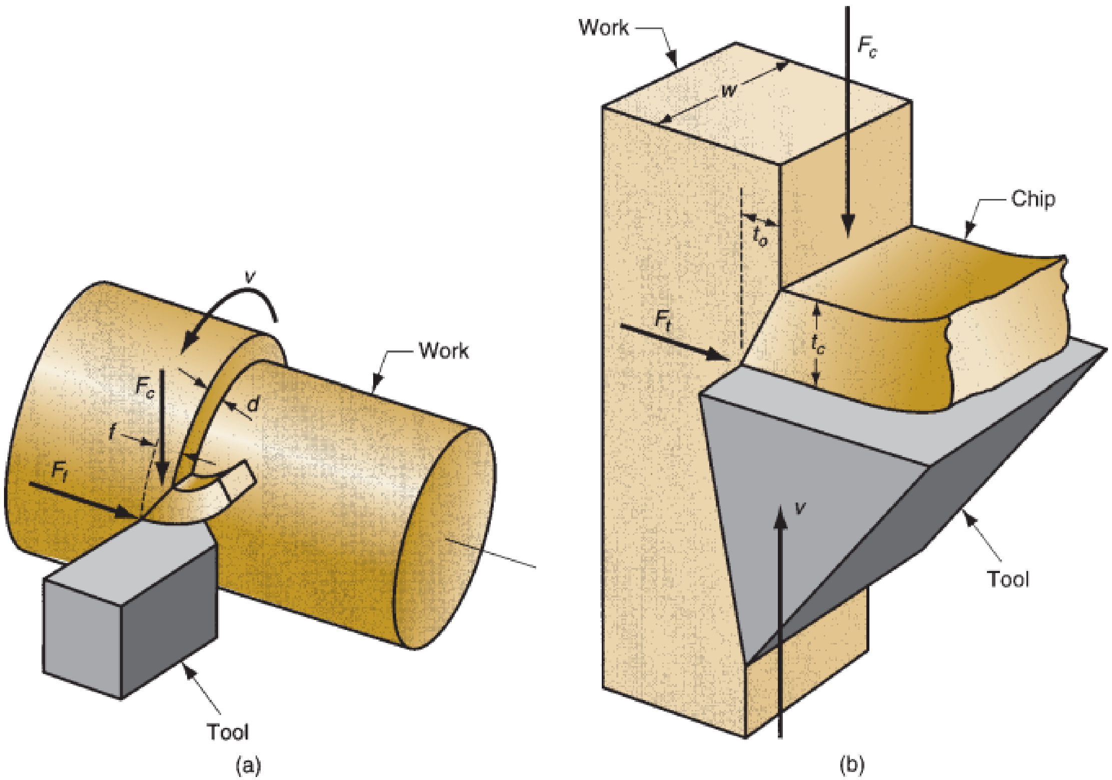


FIGURE 20.13 Approximation of turning by the orthogonal model: (a) turning; and (b) the corresponding orthogonal cutting.

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

- **A machining operation requires power. The cutting force in a production machining operation might exceed 1000 N (several hundred pounds), as suggested by Example 20.2.**
- **Typical cutting speeds are several hundred m/min. The product of cutting force and speed gives the power (energy per unit time) required to perform a machining operation:**

$$P_c = F_c v \qquad (20.17)$$

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

- **Typical cutting speeds are several hundred m/min. The product of cutting force and speed gives the power (energy per unit time) required to perform a machining operation:**

$$P_c = F_c v \qquad \textbf{(20.17)}$$

Where P_c = cutting power, N– m/s or W (ft– lb/min); $\boldsymbol{F_c}$ = cutting force, N (lb); and v = cutting speed, m/s (ft/min). In U.S. customary units, power is traditionally expressed as horsepower by dividing ft-lb/min by 33,000. Hence,

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

- Hence,

$$HP_c = \frac{F_c v}{33{,}000} \qquad \textbf{(20.18)}$$

where $HP_c =$ cutting horsepower, *hp*. The gross power required to operate the machine tool is greater than the power delivered to the cutting process because of mechanical losses in the motor and drive train in the machine.

These losses can be accounted for by the mechanical efficiency of the machine tool:

$$P_g = \frac{P_c}{E} \ \text{or}\ HP_g = \frac{HP_c}{E} \qquad \textbf{(20.19)}$$

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

- where P_g = gross power of the machine tool motor, W; HP_g = gross horsepower; and $\boldsymbol{E}$ = mechanical efficiency of the machine tool. Typical values of $\boldsymbol{E}$ for machine tools are around 90%.
- It is often useful to convert power into power per unit volume rate of metal cut. This is called the unit power, P_u (or ***unit horsepower,***HP_u), defined:

$$P_u = \frac{P_c}{R_{MR}} \qquad \text{or} \quad HP_u = \frac{HP_c}{R_{MR}} \qquad (20.20)$$

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

- where R_{MR} = material removal rate, mm^3/s (in^3/min). The material removal rate can be calculated as the product of vt_0w. This is ***Equation (20.1)*** using the conversions from **Table 20.1**.

- Unit power is also known as the ***specific energy U.***

- $$U = P_u = \frac{P_c}{R_{MR}} = \frac{F_c v}{v t_0 w} = \frac{F_c}{t_0 w} \qquad \textbf{(20.21)}$$

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

- **The units for specific energy are typically N-m/mm^3 (in-lb/in^3). However, the last expression in Equation (20.21) suggests that the units might be reduced to N/mm^2 (lb/in^2).**
- **It is more meaningful to retain the units as N-m/mm^3 or J/mm^3 (in-lb/ in^3).**

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

Example 20.4 Power relationships in machining

Continuing with the previous examples, determine cutting power and specific energy in the machining operation if the cutting speed =100 m/min. Summarizing the data and results from previous examples, $t_0 = 0.50$ mm, $w = 3.0\ mm$, F_c =1557 N.

Solution: From Equation (20.17), power in the operation is

$$P_c = F_c v = (1557\text{ N})\ (100\ m/\text{min}) = 155,700\ \text{N}\text{–}m/min$$

$$= 155,\ 700\ J/\text{min}) = 2595\ \text{J/s} = 2595\ W$$

Specific energy is calculated from Equation (20.21):

$$U = \frac{F_c v}{\mathrm{v} t_0 w} = \frac{155,700}{100(\ 10^3)(3.0)(0.5)} = \frac{155,700}{150,000} = 1.038\ N\text{–}m/mm^3$$

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Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

TABLE 20.2 VAUES OF UNIT HORSEPOWER AND SPECIFIC ENERGY FOR SELECTED WORK MATERIALS USING SHARP CUTTING TOOLS AND CHIP THICKNESS BEFORE THE CUT $t_0 = 0.25\,mm(0.010\,in)$

		Specific Energy U or Unit Power P_u		
Material	**Brinell Hardness**	$N\text{-}m/mm^2$	$in\text{-}lb/in^2$	**Unit Horsepower** $HP_u(in^3/min)$
Carbon steel	150-200	1.6	240,000	0.6
	201-250	2.2	320,000	0.8
	251-300	2.8	400,000	1.0
Alloy steels	200-250	2.2	320,000	0.8
	251-300	2.8	400,000	1.0
	301-350	3.6	520,000	1.3
	351-400	4.4	640,000	1.6
Cast irons	125-175	1.1	160,000	0.4
	175-250	1.6	240,000	0.6
Stainless steel	150-250	2.8	400,000	1.0
Aluminium	50-100	0.7	100,000	0.25
Aluminium alloys	100-150	0.8	120,000	0.3
Brass	100-150	2.2	320,000	0.8
Bronze	100-150	2.2	320,000	0.8
Magnesium alloys	50-100	0.4	60,000	0.15

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

- ***Unit power*** **and** ***specific energy*** **provide a useful measure of how much power (or energy) is required to remove a unit volume of metal during machining. Using this measure, different work materials can be compared in terms of their power and energy requirements. Table 20.2 presents a listing of unit horsepower and specific energy values for selected work materials.**
- **The values in Table 20.2 are based on two assumptions: (1) the cutting tool is sharp, and (2) the chip thickness before the cut t_0 = 0.25 mm (0.010 in).**
- **If these assumptions are not met, some adjustments must be made. For worn tools, the power required to perform the cut is greater, and this is reflected in higher specific energy and unit horsepower values.**
- **As an approximate guide, the values in the table should be multiplied by a factor between 1.00 and 1.25 depending on the degree of dullness of the tool.**
- **For sharp tools, the factor is 1.00. For tools in a finishing operation that are nearly worn out, the factor is around 1.10, and for tools in a roughing operation that are nearly worn out, the factor is 1.25.**

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

- **Chip thickness before the cut to also affects the specific energy and unit horsepower values. As t_0 is reduced, unit power requirements increase.**

- **This relationship is referred to as the *size effect*. For example, grinding, in which the chips are extremely small by comparison to most other machining operations, requires very high specific energy values.**

- **The U and HP_u values in Table 20.2 can still be used to estimate horsepower and energy for situations in which t_0 is not equal to 0.25 mm (0.010 in) by applying a correction factor to account for any difference in chip thickness before the cut.**

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

- **Figure 20.14 provides values of this correction factor as a function of t_0. The unit horsepower and specific energy values in Table 20.2 should be multiplied by the appropriate correction factor when t_0 differs from 0.25 mm (0.010 in).**

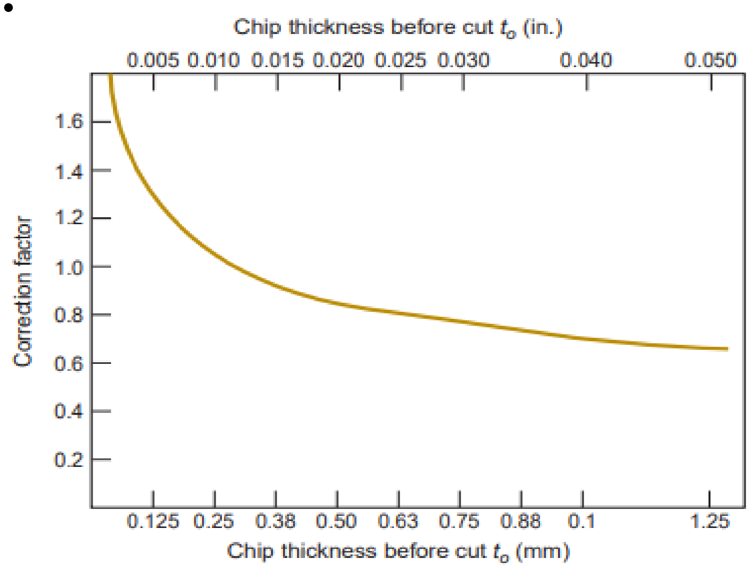

FIGURE 20.14 Correction factor for unit horsepower and specific energy when values of chip thickness before the cut to are different from 0.25 mm (0.010 in).

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

Table 20.3: TROUBLESHOOTING GUIDE FOR POWER PROBLEMS	
PROBLEM	**POSSIBLE SOLUTION**
Cutting power requirements too high from machine tool	Reduce cutting speed
	Reduce depth of cut and/or feed
	Use a more machinable work material
	Use a machine tool with more power
	Use a cutting fluid
	Use a cutting tool with higher rake angle

Unit 6. POWER AND ENERGY RELATIONSHIPS IN MACHINING

- **In addition to tool sharpness and size effect, other factors also influence the values of specific energy and unit horsepower for a given operation.**

- **These other factors include rake angle, cutting speed, and cutting fluid.**

- **As rake angle or cutting speed are increased, or when cutting fluid is added, the U and HP_u values are reduced slightly.**

-

Unit 7. CUTTING TEMPERATURE

Of the total energy consumed in machining, nearly all of it (~ 98%) is converted into heat. This heat can cause temperatures to be very high at the tool–chip interface— over 600°C (1100°F) is not unusual. The remaining energy (~2%) is retained as elastic energy in the chip.

- **Cutting temperatures are important because high temperatures**

  (1) reduce tool life;

  (2) produce hot chips that pose safety hazards to the machine operator, and

  (3) can cause inaccuracies in work part dimensions due to thermal expansion of the work material. This section discusses the calculation and measurement of temperatures in machining.

Unit 7.1 ANALYTICAL METHODS TO COMPUTE CUTTING TEMPERATURES

- There are several analytical methods to calculate estimates of cutting temperature. References [3], [5], [9], and [15] present some of these approaches.
- The method by Cook [5] was derived using experimental data for a variety of work materials to establish parameter values for the resulting equation.
- The equation can be used to predict the increase in temperature at the tool–chip interface during machining:

$$\Delta T = \frac{0.4U}{\rho C}\left(\frac{vt_0}{K}\right)^{0.333} \qquad \textbf{(20.22)}$$

Unit 7.1 ANALYTICAL METHODS TO COMPUTE CUTTING TEMPERATURES

- **Where** $\Delta T =$ **mean temperature rise at the tool chip interface,**℃ **(F°)**;
- **U** $=$ **specific energy in the operation,** N$-m/mm^3$ **or** J/mm^3**(in**$-/in^3$);
- $v =$ **cutting speed,** $m/s($ in/sec**)**;$t_0 =$ **chip thickness before the cut, m (in);**
- ρC = volumetric specific heat of the work material,J/mm^3–C (in-lb/in^3– F); K

Unit 7.1 ANALYTICAL METHODS TO COMPUTE CUTTING TEMPERATURES

Example 20.5 Cutting temperature

- **For the specific energy obtained in Example 20.4, calculate the increase in temperature above ambient temperature of 20°C. Use the given data from the previous examples in this lecture: v =100 m/min, t_0 = 0.50 mm.**
- **In addition, the volumetric specific heat for the work material = 3.0 (10^{-3}) J/mm^3 -C, and thermal diffusivity = 50 (10^{-6}) m^2 /s (or 50 mm^2/s).**

Unit 7.1 ANALYTICAL METHODS TO COMPUTE CUTTING TEMPERATURES

Example 20.5 Cutting temperature

Solution: Cutting speed must be converted to mm/s: $\upsilon = (100$ m/min) $(10^3$ mm/m)/ (60 s/min) = 1667 mm/s. Equation (20.22) can now be used to compute the mean temperature rise:

$$\Delta T = \frac{0.4U}{\rho C}\left(\frac{vt_0}{K}\right)^{0.333} = \frac{0.4(1.038)}{3.0(10^3)}℃\left(\frac{1667(0.5)}{50}\right)^{0.333} = (138.4)(2.552)$$

$$= \mathbf{353℃}$$

20.5.2 MEASUREMENT OF CUTTING TEMPERATURE

- Experimental methods have been developed to measure temperatures in machining. The most frequently used measuring technique is the tool–chip thermocouple.

- This thermocouple consists of the tool and the chip as the two dissimilar metals forming the thermocouple junction.

- By properly connecting electrical leads to the tool and work part (which is connected to the chip), the voltage generated at the tool–chip interface during cutting can be monitored using a recording potentiometer or other appropriate data-collection device.

20.5.2 MEASUREMENT OF CUTTING TEMPERATURE

- The voltage output of the tool–chip thermocouple (measured in mV) can be converted into the corresponding temperature value by means of calibration equations for the particular tool–work combination.
- The tool–chip thermocouple has been utilized by researchers to investigate the relationship between temperature and cutting conditions such as speed and feed.

Unit 7.1 ANALYTICAL METHODS TO COMPUTE CUTTING TEMPERATURES

20.5.2 MEASUREMENT OF CUTTING TEMPERATURE

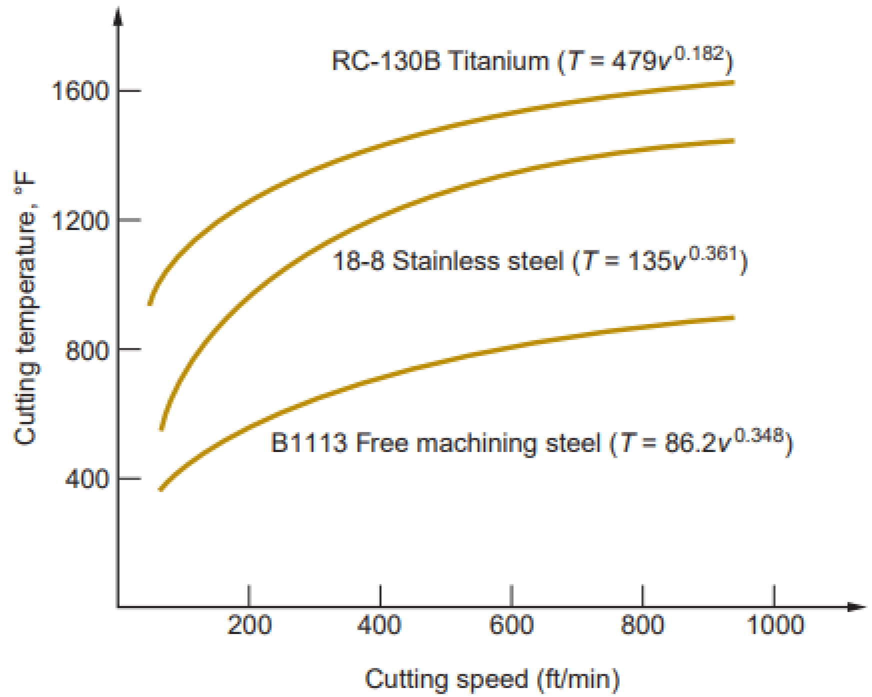

FIGURE 20.15 Experimentally measured cutting temperatures plotted against speed for three work materials, indicating general agreement with Equation (20.23).Based on data [1].

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Unit 7.1 ANALYTICAL METHODS TO COMPUTE CUTTING TEMPERATURES

20.5.2 MEASUREMENT OF CUTTING TEMPERATURE

- Trigger [2] determined the speed–temperature relationship to be of the following general form:
- $$T = Kv^m \quad \textbf{(2023)}$$
- where T = measured tool–chip interface temperature and v = cutting speed. The parameters K and m depend on cutting conditions (other than v) and work material.
- Figure 20.15 plots temperature versus cutting speed for several work materials, with equations of the form of Equation (20.23) determined for each material.

Unit 7.1 ANALYTICAL METHODS TO COMPUTE CUTTING TEMPERATURES

20.5.2 MEASUREMENT OF CUTTING TEMPERATURE

- A similar relationship exists between cutting temperature and feed; however, the effect of feed on temperature is not as strong as cutting speed.
- These empirical results tend to support the general validity of the Cook equation: Equation (20.22).

REFERENCE:

[1] Loewen, E. G., and Shaw, M. C. "On the Analysis of Cutting Tool Temperatures," ASME Transactions. Vol. 76, No. 2, February 1954, pp. 217–225

[2] Trigger, K. J. "Progress Report No. 2 on Tool–Chip Interface Temperatures." ASME Transactions. Vol. 71, No. 2, February 1949, pp. 163–174

REVIEW QUESTIONS

1 What are the three basic categories of material removal processes?

2 What distinguishes machining from other manufacturing processes?

3 Identify some of the reasons why machining is commercially and technologically important.

4 Name the three most common machining processes.

5 What are the two basic categories of cutting tools in machining? Give two examples of machining operations that use each of the tooling types.

6 What are the parameters of a machining operation that are included within the scope of cutting conditions?

7 Explain the difference between roughing and finishing operations in machining.

8 What is a machine tool?

9 What is an orthogonal cutting operation?

REVIEW QUESTIONS

10 Why is the orthogonal cutting model useful in the analysis of metal machining?

11 Name and briefly describe the four types of chips that occur in metal cutting.

12 Identify the four forces that act upon the chip in the orthogonal metal cutting model but cannot be measured directly in an operation.

13 Identify the two forces that can be measured in the orthogonal metal cutting model.

14 What is the relationship between the coefficient of friction and the friction angle in the Orthogonal cutting model?

15 Describe in words what the Merchant equation tells us.

16 How is the power required in a cutting operation related to the cutting force?

17 What is the specific energy in metal machining?

18 What does the term size effect mean in metal cutting?

19 What is a tool-chip thermocouple?