Manu (2) mid

Jana Househ

N	Normal force, N also, angular speed, rpm
N_f	parts produced per face
N_i	parts produced per insert
r	cutting ratio
R	resultant force, N also, tool radius, m
R_t	peak-to-valley roughness, m
t	time or tool life, s
t_c	time to change an insert, s also, chip thickness, m
t_i	time to index an insert, s
t_l	part loading and unloading time, s
t_m	machining time, s
t_o	optimum tool life, s also, depth of cut, m
t_p	time to produce one part, s also, tool life for maximum production, s
T	temperature, °C
u_f	specific frictional energy, W-s/m^3
u_t	energy dissipated per volume, W-s/m^3
v	workpiece velocity, m/s
V	cutting speed, m/s
V_c	chip velocity, m/s
V_o	optimum cutting speed, m/s
V_s	velocity of shear in shear plane, m/s
w	width, m
α	rake angle, deg
α_c	chip flow angle, deg
α_e	effective rake angle, deg also, edge cutting angle, deg
α_n	normal rake angle, deg
α_s	side cutting angle, deg
β	friction angle, deg
ϵ	true strain
ϕ	shear angle, deg
γ	shear strain, m/m
$\dot{\gamma}$	shear strain rate, s^{-1}
κ	thermal diffusivity, m^2/s
μ	coefficient of friction
ρ	density, kg/m
σ	normal stress
σ_f	flow stress, N
τ	shear stress,

Subscripts

avg	average
o	original, optimum

8.6 Calculation of Material-Removal Rate, Power Required, and Cutting Time in Face Milling 544
8.7 Machining Outer Bearing Races on a Turning Center 558

CASE STUDY:

8.1 Ping Golf Putters 569

8.1 Introduction

Machining is the general term used to describe material removal processes and are usually divided into the following broad categories:

- **Cutting**, which generally involves single-point or multipoint cutting tools and processes, such as turning, boring, drilling, tapping, milling, broaching, and sawing. Cutting is the focus of this chapter.
- **Abrasive processes**, such as grinding, honing, lapping, and ultrasonic machining (Sections 9.6 through 9.9).
- **Advanced machining processes**, sometimes referred to as *non-traditional machining processes*, that use electrical, chemical, thermal, hydrodynamic, and optical sources of energy, as well as combinations of these sources, to remove material from the workpiece (Sections 9.10 through 9.15).

As described throughout this chapter, machining processes are preferable or even necessary for the following reasons:

1. Closer **dimensional accuracy** may be required than can be achieved by metalworking or casting processes alone. For example, in a crankshaft, the bearing surfaces cannot be produced with good dimensional accuracy and smooth enough surface finish through forging or sand casting alone.
2. Parts may require external and/or internal **geometric features**, such as sharp corners and internal threads, that cannot be produced by other processes.
3. Some parts are heat treated for improved hardness and wear resistance, but because heat-treated parts may undergo distortion and surface discoloration, they may require additional **finishing operations**.
4. Special **surface characteristics** or **textures** may be required on surfaces of the part that cannot be produced by other means. As an example, copper mirrors with very high reflectivity are typically made by machining with a diamond cutting tool.
5. It may be more **economical** to machine the part than to make it by other processes, particularly if the number of parts required is relatively small. Recall that metalworking processes typically require expensive dies and tooling; the cost of these can only be justified if the number of parts made is sufficiently high.

Against these major advantages, machining has certain limitations:

1. Machining processes inevitably **waste material** and generally require more energy and labor than other metalworking operations.
2. Removing a volume of material from a workpiece generally takes **more time** than other processes.
3. Material-removal processes can have **adverse effects** on the surface integrity of the product, including its fatigue life.

In spite of these limitations, machining operations continue to be indispensable in manufacturing.

As in all manufacturing operations, machining should be viewed as a **system**, consisting of the *workpiece, cutting tool, tool holder, workholding devices, machine tool, and operating personnel*. Machining operations cannot be carried out efficiently and economically without a fundamental knowledge of the often complex interactions among these critical factors, as will be evident throughout this chapter.

8.2 Mechanics of Chip Formation

Machining processes remove material from the surface of a workpiece by producing chips, as shown in Fig. 8.1. The basic mechanics of chip formation are represented by the model shown in Fig. 8.2. A cutting tool moves along the workpiece at a certain velocity (**cutting speed**), V, and a **depth of**



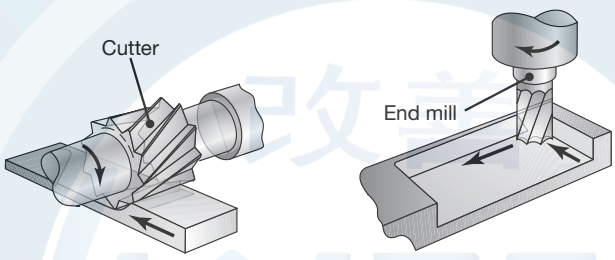


FIGURE 8.1 Some examples of common machining operations.

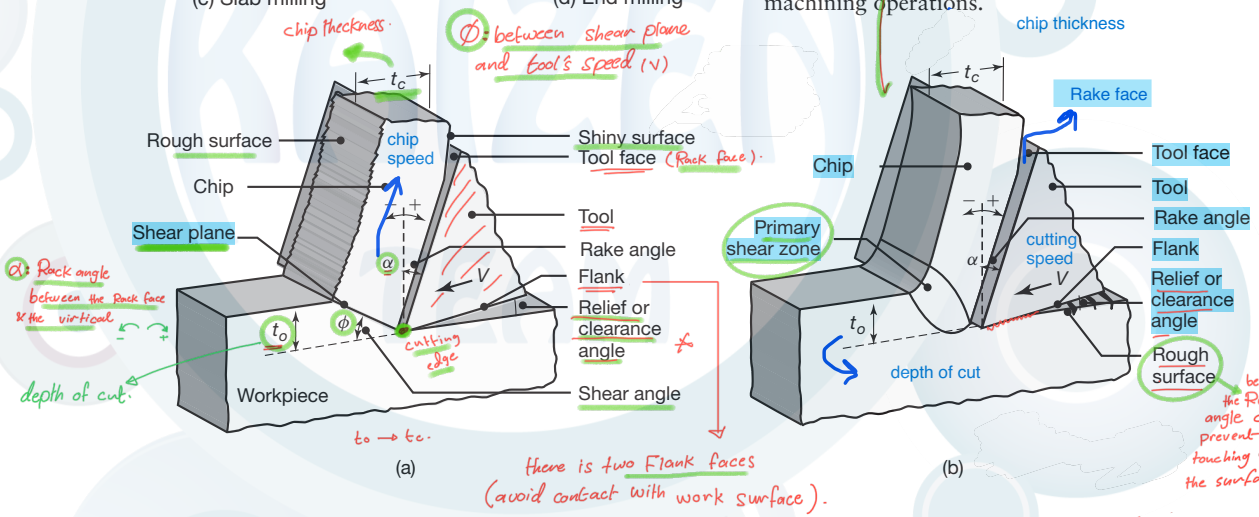


FIGURE 8.2 Schematic illustration of a two-dimensional cutting process, or orthogonal cutting. (a) Orthogonal cutting with a well-defined shear plane, also known as the Merchant model; and (b) Orthogonal cutting without a well-defined shear plane.

cut, t_o. A **chip** is produced just ahead of the tool by *shearing* the material continuously along the **shear plane**.

In this process, the major *independent* *variables* are:

- Type of cutting tool and its properties; material
- The shape of the tool, its surface finish and sharpness; geometry
- Workpiece material, its properties, and the temperature at which it is machined;
- Cutting conditions, such as speed, feed, and depth of cut;

- Type of cutting fluid, if used;
- Characteristics of the machine tool, particularly its stiffness and damping; and
- Tool holder and workholding devices.

The *dependent variables* are:

- Type of chip produced;
- Force required and energy dissipated in the cutting process;
- Temperature rise in the workpiece, the chip, and the cutting tool;
- Wear, chipping, and failure of the tool; and
- Surface finish and integrity of the workpiece after it is machined.

In order to appreciate the importance of the complex interrelationships among these variables, consider the following commonly encountered situations:

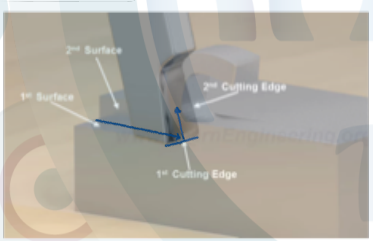
1. If the surface finish of the machined workpiece is unacceptable, which of the independent variables should be modified first?
2. If the workpiece becomes too hot, thus possibly affecting its properties and dimensional accuracy, what modifications should be made to the process parameters?
3. If the cutting tool wears rapidly and becomes dull, what should be changed: the cutting speed, the depth of cut, the tool material, or some other variable?
4. If the dimensional tolerance of the machined part is over the specified limits, what modification should be made?
5. If the cutting tool begins to vibrate and chatter, what should be changed to eliminate or reduce this problem?

Although almost all machining operations are three dimensional in nature, the two-dimensional model shown in Fig. 8.2 is appropriate and useful in studying the basic mechanics of the metal cutting process. This model is known as **orthogonal cutting**, meaning that the cutting edge of the tool is perpendicular (orthogonal) to the cutting direction. The tool has a **rake angle**, α, (positive as shown in the figure) and a **relief**, or **clearance, angle**. Note that the sum of the rake, the relief, and the included angles of the tool is 90°.

Microscopic examinations reveal that metal chips are produced by a **shearing** mechanism, shown in Fig. 8.3a. Shearing takes place along the **shear plane**, which makes an angle ϕ with the workpiece surface, called the *shear angle*. Below the shear plane, the workpiece is deformed elastically, and above the shear plane, the chip is already formed and is moving up the face of the tool as cutting progresses. Because of the relative movement, there is friction involved between the chip and the rake face of the tool.

Note that the thickness of the chip, t_c, can be determined if t_o, α, and ϕ are known. The ratio of t_o to t_c is known as the **cutting ratio**, r, which can be expressed as

$$r = \frac{t_o}{t_c} = \frac{\sin \phi}{\cos(\phi - \alpha)}. \tag{8.1}$$



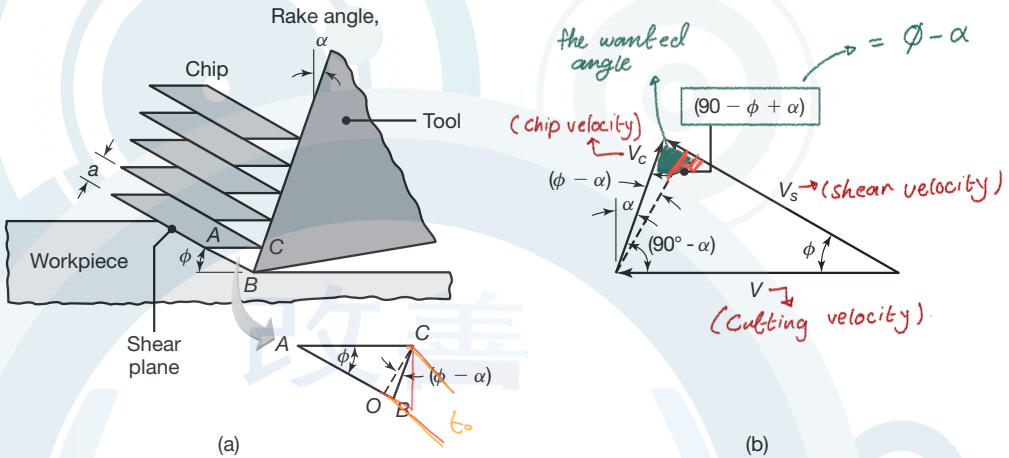


FIGURE 8.3 (a) Schematic illustration of the basic mechanism of chip formation in cutting. (b) Velocity diagram in the cutting zone.

Cutting ratio less than one always ($t_c > t_o$)

Note that the chip thickness is always greater than the depth of cut (also known as the **undeformed chip thickness**), so that r is always less than unity. The reciprocal of r is known as the **chip compression ratio**, and is a measure of how thick the chip has become compared with the depth of cut; thus the chip compression ratio is always greater than unity.

chip compression ratio $= \frac{t_c}{t_o} = \frac{1}{r}$

On the basis of Fig. 8.3a, the **shear strain**, γ, that the material undergoes during cutting can be expressed as

$$\gamma = \frac{AB}{OC} = \frac{AO}{OC} + \frac{OB}{OC}, \tag{8.2}$$

or

$$\gamma = \cot\phi + \tan(\phi - \alpha). \tag{8.3}$$

Note from this equation that high shear strains are associated with low shear angles and low or negative rake angles. Shear strains of 5 or higher have been observed in actual cutting operations. Thus, the chip undergoes greater deformation during cutting than it does in other operations such as forging and shaping operations (Chapter 6), as can also be seen in Table 2.3.

From Fig. 8.2, it can be noted that the undeformed chip thickness and the depth of cut are the same parameter, t_o, in orthogonal cutting. Because the chip thickness, t_c, is greater than the undeformed chip thickness, t_o, the *velocity of the chip*, V_c, must be lower than the cutting speed, V. Since mass continuity has to be maintained,

$$Vt_o = V_c t_c \quad \text{or} \quad V_c = Vr, \tag{8.4}$$

(V_c (cutting velocity) $= V$ (cutting) $\times r$ (cutting ratio))

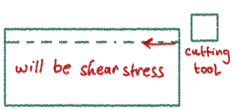
and therefore,

Same ratios as the dimensions.

$$V_c = V\frac{\sin\phi}{\cos(\phi - \alpha)}. \tag{8.5}$$

(Known that (r) always less than one ... so chip velocity < cutting velocity.)

* there is only one case where ($V_s = V$) ⟹ macro shear. there is no cutting.
* in the normal case of cutting (ϕ) always greater than zero
* in macro shear ... to make ($V_s = V$) the two vectors should be in the same direction. so (ϕ) should be zero. ⟹ I can't call it cutting.



A velocity diagram can be constructed, such as that shown in Fig. 8.3b. From trigonometric relationships, the following equations can be written:

$$\frac{V}{\cos(\phi - \alpha)} = \frac{V_s}{\cos\alpha} = \frac{V_c}{\sin\alpha}, \qquad (8.6)$$

where V_s is the velocity at which shearing takes place in the shear plane. The **shear-strain rate** is the ratio of V_s to the thickness, a, of the *shear zone* (Fig. 8.3a), or

$$\dot{\gamma} = \frac{V_s}{a}. \qquad (8.7)$$

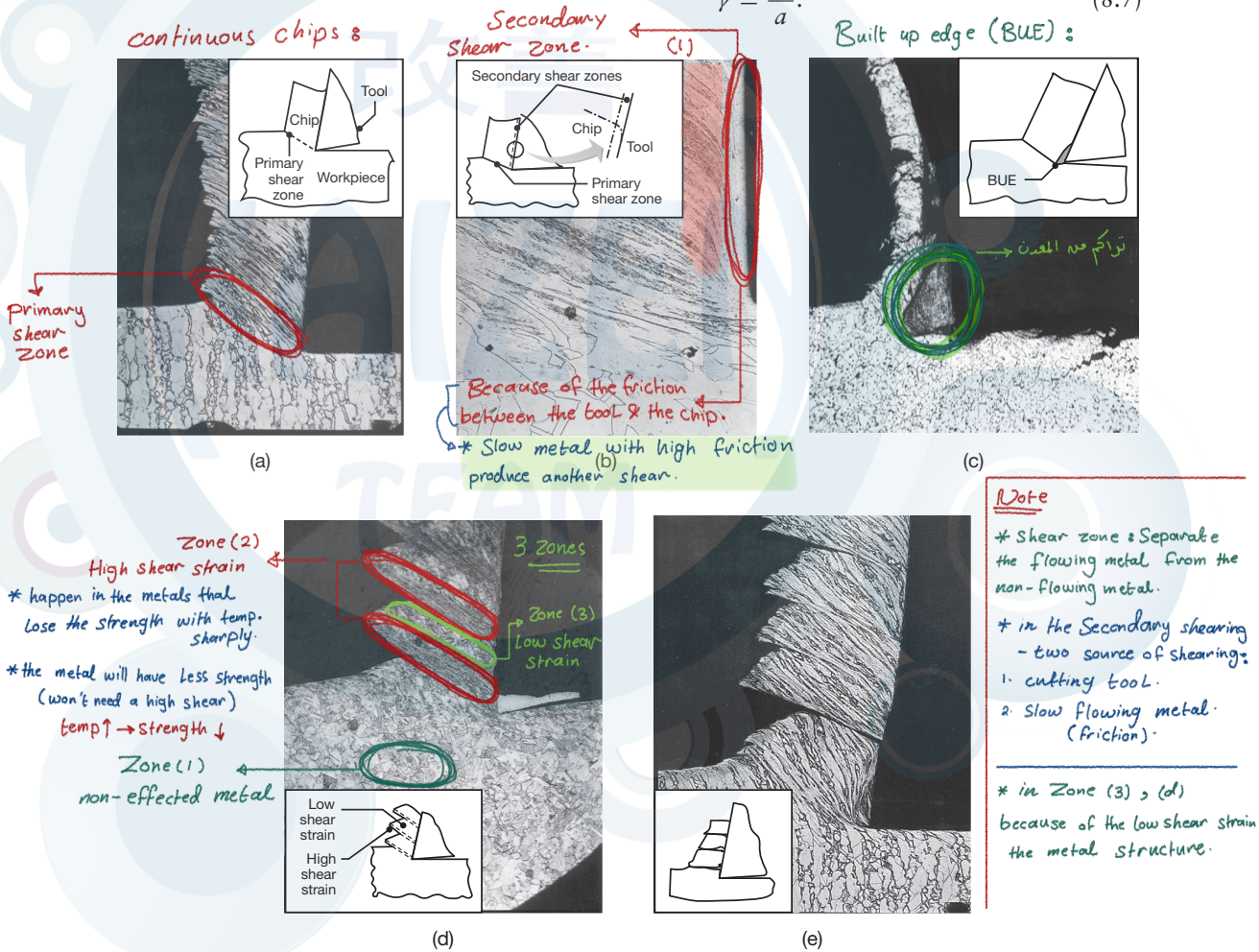


FIGURE 8.4 Basic types of chips produced in metal cutting and their micrographs: (a) continuous chip with narrow, straight primary shear zone; (b) secondary shear zone at the tool-chip interface; (c) continuous chip with built-up edge; (d) segmented or nonhomogeneous chip; and (e) discontinuous chip. *Source:* After M.C. Shaw, P.K. Wright, and S. Kalpakjian.

Experimental evidence indicates that a is typically on the order of 10^{-2} mm to 10^{-3} mm. This range indicates that, even at low cutting speeds, the shear-strain rate is very high, on the order of 10^3/s to 10^6/s. The shear-strain rate is important because of its effects on the strength and ductility of the material (see Section 2.2.7 and Table 2.3), as well as the type of the chip produced.

→ one of the dependant variable – type of chips produced.

8.2.1 Chip Morphology

The type of chips produced (*chip morphology*) significantly influences surface finish and integrity and the overall machining operation. When metal chips, produced under different cutting conditions, are observed under a microscope, it will be found that there are significant deviations from the ideal model shown in Figs. 8.2 and 8.3a. Major types of metal chips commonly observed in practice are shown in Fig. 8.4.

Note that a chip has two surfaces: One surface has been in contact with the rake face of the tool, and the other surface is the newly-generated surface of the workpiece. The tool side of the chip surface is shiny or *burnished* (Fig. 8.5), which is caused by rubbing of the chip as it climbs up the tool face of the tool. The other surface of the chip has a jagged, step-like appearance (as can be seen in Fig. 8.4a), which is due to the shearing mechanism of chip formation (See also Figs. 3.5 and 3.7). Note that this surface has not come in contact with any solid body.

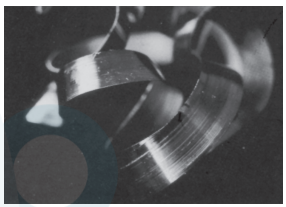


FIGURE 8.5 Shiny (burnished) surface on the tool side of a continuous chip produced in turning.

The basic types of metal chips produced in machining are described as follows:

primary shear zone is in the continuous ⇒ Extremely thin shear zone.

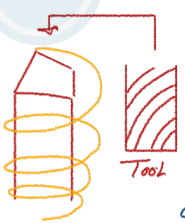
1. **Continuous chips**. *Continuous chips* are typically formed at high cutting speeds and/or high rake angles (Fig. 8.4a). The deformation of the metal takes place along a very narrow shear zone, called the **primary shear zone**. These type of chips also may develop a **secondary shear zone** at the tool-chip interface (Fig. 8.4b), caused by friction; as expected, the secondary zone becomes thicker as the tool-chip friction increases.

   Deformation of continuous chips may also take place along a wide primary-shear zone, with *curved boundaries*, as shown in Fig. 8.2b. Note that the lower boundary of this zone is *below* the machined surface, and thus it has subjected the machined surface to distortion, possible surface damage and induced surface residual stresses. This situation occurs particularly in machining soft metals at low cutting speeds and low rake angles. *

   Although they generally produce good surface finish, continuous chips are not always desirable, particularly in computer-controlled machine tools (see Section 8.11), because the chips tend to become tangled around the tool. This situation can be avoided with *chip breaker* features on cutting tools (see below).

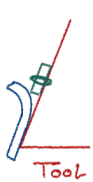
   * chip breaker

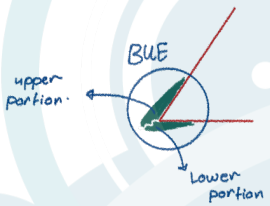
   – Tangled around
   less surface finish, less dimension accuracy, could break the tool.
   ∴ we will use chip breaker.

   As a result of strain hardening (caused by the shear strain to which it is subjected), a chip generally becomes harder, stronger, and less ductile than the original workpiece material. As the rake angle decreases, the shear strain increases, as can be seen from Eq. (8.3).

   With chip breaker:
   – Less bending radius with the same ductility & thickness
   ∴ it will break.

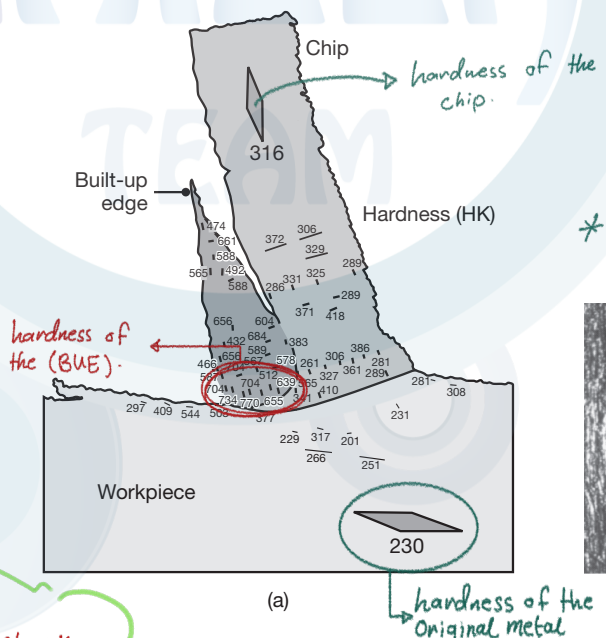
   



worst type of surface finish.

2. **Built-up-edge chips**. A *built-up edge* (BUE) may form at the tip of the tool during cutting (Fig. 8.4c); it consists of thin layers of metal from the workpiece that are gradually deposited on the tool (hence the term *built-up*). As it grows larger, the BUE becomes unstable and eventually breaks up; the upper portion of the BUE is carried away on the tool side of the chip and the lower portion is deposited randomly on the machined surface. The process of BUE formation and breakup is repeated continuously during the cutting operation.

The built-up edge is commonly observed in practice and is one of the significant factors that adversely affects surface finish and integrity in machining, as can be seen in Figs. 8.4 and 8.6. A built-up edge, in effect, changes the geometry of cutting. Note, for example, the large tip radius of the BUE and the rough surface finish it has produced. Because of work hardening and deposition of successive layers of material, BUE hardness increases significantly (Fig. 8.6a). Although BUE is generally undesirable, a thin but stable BUE is generally regarded as desirable, because it protects the tool surface.



hardness of the chip.

hardness of the (BUE).

hardness of the original metal

* (BUE) & the bad effect in the surface finish.

* (BUE) always has a higher material strength
* (BUE) worst type of surface finish.
* Best type is the continuous, with the chip breaker.

FIGURE 8.6 (a) Hardness distribution in the cutting zone for 3115 steel. Note that some regions in the built-up edge are as much as three times harder than the bulk workpiece. (b) Surface finish in turning 5130 steel with a built-up edge. *Source:* Courtesy of Metcut Research Associates, Inc.

Affinity: القدرة على تشكيل الروابط بشكل سريع

higher chemical affinity, will make higher ability to produce (BUE)

higher strain-hardening, will make higher ability to produce (BUE).

Defind by chemical affinity.

* * *

BUE formation is affected by (a) adhesion of the workpiece material to the rake face of the tool and the strength of the interfacial bond (see also Section 4.4). Ceramic cutting tools (see Section 8.6), for example, have much lower affinity to form BUE than do tool steels; (b) growth of the successive layers of adhered metal on the tool; (c) tendency of the workpiece material for strain hardening; the higher the strain-hardening exponent, n, the higher the probability for BUE formation.

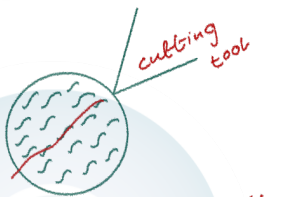
Generally, the built-up edge decreases or is eliminated (a) as the cutting speed, V, increases; (b) as depth of cut, t_o, decreases; (c) as rake angle, α, increases; (d) as tip radius of the tool decreases; and (e) by using an effective cutting fluid (Section 8.7).

① to decreases the amount of the shear strain will be less ⇒ strain hardening ↓ ⇒ BUE ↓

② Rack angle (α) increases ↑ : the tool will have less friction with the chip ⇒ velocity ↑ & BUE ↓

③ tip radius decreases ↓: tip radius will be extremely sharp the tool will cut the (BUE) when it start forming.

3. **Serrated chips**. *Serrated chips*, also called **segmented** or **nonhomogeneous** chips, are semi-continuous, with zones of low shear and high shear strain (Fig. 8.4d); the chips have the appearance of saw teeth, hence the term serrated. Metals with low thermal conductivity and strength that decreases sharply with temperature, such as titanium, exhibit this behavior.
4. **Discontinuous chips**. *Discontinuous chips* consist of segments that may be either firmly or loosely attached to each other (Fig. 8.4e). These chips usually develop under the following conditions:
   a. The workpiece material is brittle, and cannot undergo the high shear strains involved in cutting.
   b. The workpiece material contains hard inclusions and impurities (see Figs. 3.24 and 3.25) or has a structure such as that of graphite flakes in gray cast iron (Fig. 5.13a). Impurities and hard particles act as sites for internal cracks, thereby producing discontinuous chips. As the depth of cut increases, the probability of such defects being present in the cutting zone increases.
   c. The cutting speed is very low or very high.
   d. The depth of cut (undeformed chip thickness) is large or the rake angle is low.
   e. The machine tool has low stiffness and poor damping.
   f. Lack of an effective cutting fluid.



will have easier cutting both.

dependent on the temp.

relative to the high speed, so the cutting fluid will reduce the temp. & friction.

An additional factor in the formation of discontinuous chips is the magnitude of the compressive stresses on the shear plane [see also Eq. (8.17)]. Recall from Section 2.2.8 that the maximum shear strain at fracture increases with increasing compressive stress; thus, if the normal stress is not sufficiently high, the material will be unable to undergo the large shear strain necessary to form a continuous chip.

Because of the discontinuous nature of chip formation, cutting forces continually vary during machining. Consequently, the stiffness of the cutting-tool holder, the workpiece holding devices, and the machine tool are important factors in cutting with discontinuous or serrated chips. If not sufficiently stiff, the machine tool may begin to vibrate and chatter (see Section 8.12). Such vibration adversely

affects the surface finish and dimensional accuracy of the machined component, and may even cause damage or excessive wear of the cutting tool and the machine tool itself.

Chip formation in machining nonmetallic materials. Much of the discussion thus far for metals also is generally applicable to nonmetallic materials. A variety of chips can develop in cutting thermoplastics, depending on the type of polymer (see Chapter 10) and the process parameters, such as depth of cut, cutting speed, and tool geometry. Thermosetting plastics and ceramics tend to produce discontinuous chips, because they generally are brittle (see also *ductile-regime cutting* in Section 8.9.2).

Chip curl. *Chip curl* (Figs. 8.5 and 8.7a) is commonly observed in all machining operations with metals and nonmetallic materials, such as thermoplastics and wood. Factors contributing to chip curl are: (a) the distribution of stresses in the primary and secondary shear zones; (b) thermal gradients in the cutting zone; (c) work-hardening characteristics of the workpiece material; and (d) the shape of the rake face of the tool. Process variables also affect chip curl; generally, the radius of curvature decreases (the chip becomes curlier) with decreasing depth of cut, increasing rake angle, and decreasing friction at the tool-chip interface. The use of cutting fluids and various additives in the workpiece material also influence chip curl.

Chip breakers. Long continuous chips are generally undesirable, because they tend to become entangled and interfere with the machining operation and can become a safety hazard to the operator; this situation is especially troublesome in high-speed automated machinery. The common procedure

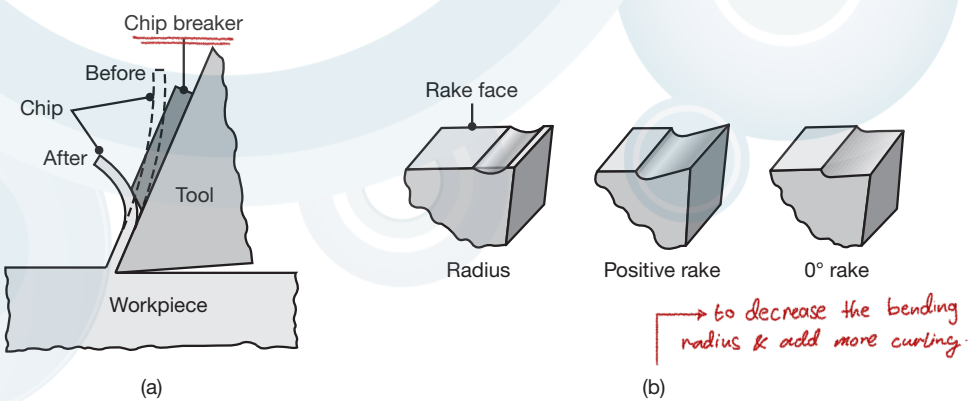


FIGURE 8.7 (a) Schematic illustration of the action of a chip breaker. Note that the chip breaker decreases the radius of curvature of the chip. (b) Grooves on the rake face of cutting tools, acting as chip breakers. Cutting tools inserts generally incorporate built-in chip-breaker features.

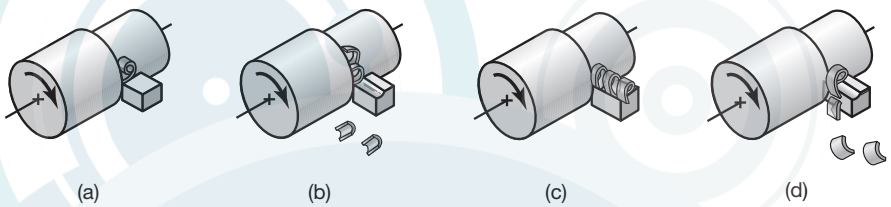


FIGURE 8.8 Various chips produced in turning: (a) tightly curled chip; (b) chip hits workpiece and breaks; (c) continuous chip moving radially outward from workpiece; and (d) chip hits tool shank and breaks off.

to avoid the formation of continuous chips is to break the chip intermittently with a *chip breaker*. Chip breakers are now an integral part of the cutting tool itself (Fig. 8.7). Chips can also be broken by modifying the tool geometry, thus controlling chip flow, as in the turning operations illustrated in Fig. 8.8.

15 · Oct

8.2.2 Mechanics of Oblique Cutting

the cutting edge has an angle.

i: the inclination angle ⇒ produce more chip curling.

no elongation

Unlike the two-dimensional cutting described thus far, the majority of machining operations involve tool shapes that are three-dimensional (oblique). The basic difference between two-dimensional and oblique cutting are illustrated in Fig. 8.9a. Recall that in orthogonal cutting, the tool cutting edge is perpendicular to the movement of the tool, and that the chip slides straight up the rake face of the tool. In oblique cutting, the cutting edge is at an angle i, called the **inclination angle** (Fig. 8.9b). The chip in Fig. 8.9a flows up the rake face of the tool at an angle α_c (the **chip flow angle**), measured in the plane of the tool face. The angle α_n is the **normal**

third dimension.

inclination angle
i = chipflow angle

curls form in two directions:
1) along the rake face.
2) away from the rake face.
For orthogonal:
i=0 curls form only along the rake face due the rake angle an.
for oblique:
i=!0 helical curls form on two directions along and away increasing i increases ac thus more away rather along more elongation less radius (tighter)
application: drilling

α_c: not tangential in the actual chip, only in the begining

α_n: normal rack angle.

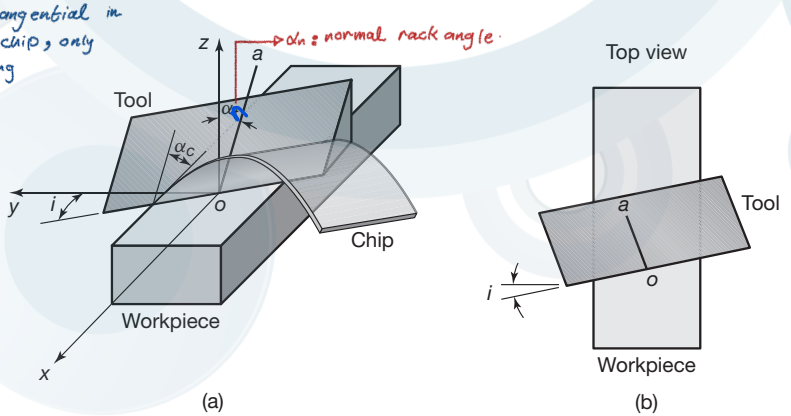
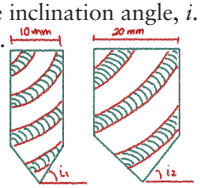


FIGURE 8.9 (a) Schematic illustration of cutting with an oblique tool. (b) Top view, showing the inclination angle, i. (c) Types of chips produced with different inclination angles.



* Greater diameter ⇒ bigger paths for the chip so the curling will has less strength,
* Dia. ↑ of the tool, the dia. wher the chips take a path ↑ So i will need less curling,
Dia ↑ ⇒ width ↑ ⇒ (i) ↓

Less Dia. ⇒ the width of the flow ↓ ⇒ more curling

Dia ↓ ⟶ width ↓ ⟶ (i) ↑ so the amount of curling ↑.

rake angle, which is the angle between the normal oz to the workpiece surface and the line oa on the tool face.

As the workpiece material approaches the tool at a velocity V, it leaves the workpiece surface as a chip with a velocity V_c. The effective rake angle, α_e, measured in the plane of these two velocities, can then be calculated as follows: Assuming that the chip flow angle, α_c, is equal to the inclination angle, i (which has been experimentally verified), the effective rake angle, α_e, is

$$\alpha_e = \sin^{-1}\left(\sin^2 i + \cos^2 i \sin\alpha_n\right). \tag{8.8}$$

Since both i and α_n can be measured directly, this equation can be used to calculate the magnitude of the effective rake angle. Note that as i increases, the effective rake angle increases, and thus the chip becomes thinner and longer. The effect of the inclination angle on chip shape is illustrated in Fig. 8.9c.

Figure 8.10 shows a typical single-point turning tool; note the various angles, each of which must be selected properly for efficient machining. Various three-dimensional cutting tools are described in greater detail in Sections 8.8 and 8.9, including those for such operations as drilling, tapping, milling, planing, shaping, broaching, sawing, and filing.

* Single point cutting tool.
* Insert : used to install the cutting tool with 8 cutting edges.
  → installed by clamps, made from cheaper material.
* every surface has two angles.

Shaving and skiving. Thin layers of material can be removed from straight or curved surfaces by a process similar to using a *plane* to shave wood. *Shaving* is particularly useful in improving the surface finish and dimensional accuracy of punched slugs or holes (See Fig. 7.10). Parts that are long or have a combination of angles and shapes are shaved by *skiving*, using a specially shaped cutting tool.

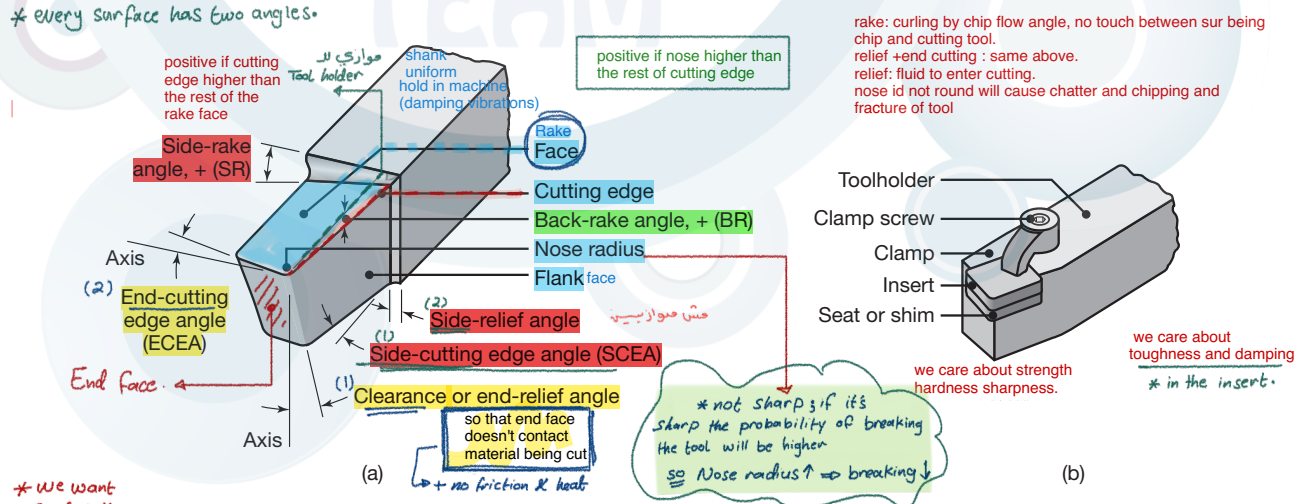


FIGURE 8.10 (a) Schematic illustration of a right-hand cutting tool for turning. Although these tools have traditionally been produced from solid tool-steel bars, they are now replaced by inserts of carbide or other tool materials of various shapes and sizes, as shown in (b).

* We want
  - Good Cutting.
  - Good chip flow.
  - Good surface finish & integrity.
* angles: to prevent the contact between the workpiece & the tool face
* No contact with the machine surface only in the Sigle edge.

if left mirror image

advantages:
1) economical as the tool holder is made of any steel having toughness and only the insert is expensive.
2) when failure dull we only rotate insert so we don't have to change it nor throw the whole tool.

The cutting edge is orthogonal to the cutting tool.

8.2.3 Forces in Orthogonal Cutting

Determining cutting forces and power requirements in machining operations is essential for the following reasons:

1. **Power requirements** must be known so that a machine tool of suitable capacity can be selected for a particular application;
2. Data on cutting forces are necessary for the proper **design of machine tools** so that they have certain specific characteristics, including stiffness, in order to maintain the desired dimensional accuracy; and
3. The workpiece must be able to withstand the cutting forces without excessive **distortion**.

elastic strain resistance

The factors that significantly influence the forces and power in orthogonal cutting are:

1. **Cutting forces.** The forces acting on the tool in orthogonal cutting are shown in Fig. 8.11. The **cutting force**, F_c, acts in the direction of the cutting speed, V, and supplies the energy required for the machining operation. The **thrust force**, F_t, acts in the direction normal to the cutting velocity, that is, perpendicular to the workpiece. These two forces produce the **resultant force**, R, which can then be resolved into two components on the tool face: a **friction force**, F, along the tool-chip interface and a **normal force**, N, perpendicular to the interface. From Fig. 8.11, it can be shown that the friction force is

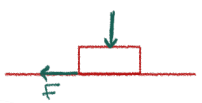
$$F = R \sin \beta, \tag{8.9}$$

and the normal force is

$$N = R \cos \beta. \tag{8.10}$$

* Cutting force (F_c) ⇒ most important
  ↳ source of power & Energy.
  – Same direction as speed (cutting tool)
* Thrust Force (F_t) ⇒ normal to the cutting velocity & (F_c).

to keep in space



* $F = N \cdot M$
M = coef. of friction.

* (R) in the rake face

Rack face

$M = \frac{F}{N} = \tan\beta$

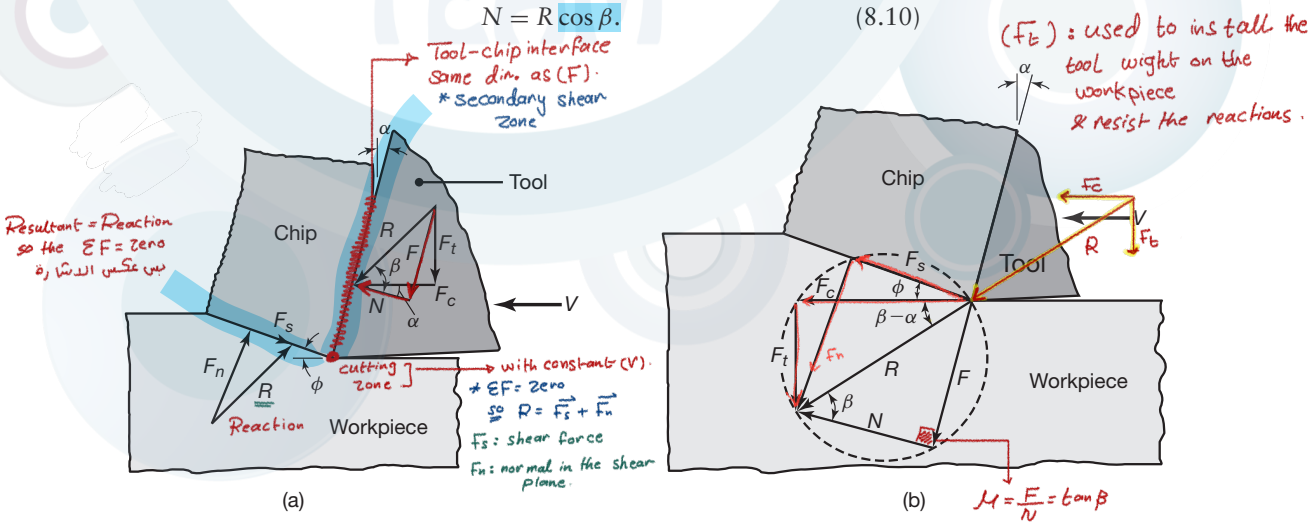


FIGURE 8.11 (a) Forces acting on a cutting tool in two-dimensional cutting. Note that the resultant forces, R, must be collinear to balance the forces. (b) Force circle to determine various forces acting in the cutting zone.

β: between (R) & the normal force.

Note also that the resultant force is balanced by an equal and opposite force on the shear plane, and is resolved into a **shear force**, F_s, and a **normal force**, F_n. From Fig. 8.11, the cutting force can be shown to be

$$F_c = R\cos(\beta - \alpha) = \frac{wt_o\tau\cos(\beta - \alpha)}{\sin\phi\cos(\phi + \beta - \alpha)}, \tag{8.11}$$

where τ is the *average shear stress* along the shear plane.

The ratio of F to N is the **coefficient of friction**, μ, at the tool-chip interface (see also Section 4.4.1), and the angle β is known as the **friction angle**. The coefficient of friction can be expressed as

$$\mu = \tan\beta = \frac{F_t + F_c\tan\alpha}{F_c - F_t\tan\alpha}. \tag{8.12}$$

In cutting metals, μ generally ranges from about 0.5 to 2, indicating that the chip encounters considerable frictional resistance in climbing up the rake face of the tool.

The forces in machining operations are generally found to be on the order of a few hundred or thousand newtons. However, the local stresses in the cutting zone and the normal stresses on the rake face of the tool are very high, because the contact areas are very small. The tool-chip contact length (Fig. 8.2), for example, is typically on the order of 1 mm, so that the tool is subjected to very high local stresses.

2. **Thrust force and its direction.** Although the thrust force does not contribute to the energy required in cutting, its magnitude is important because the tool holder, the workholding devices, and the machine tool must be sufficiently stiff to minimize deflections caused by this force. For example, if the thrust force (See Fig. 8.11) is too high and the machine tool is not sufficiently stiff, the tool will be pushed away from the workpiece surface. This deflection will, in turn, reduce the actual depth of cut, leading to loss of dimensional accuracy of the machined part and possibly to vibration and chatter (see Section 8.12).

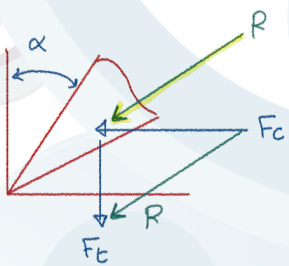
Note from Fig. 8.11 that the direction of the thrust force is *downward*. It can be shown, however, that this force can also be upward (negative), by first observing that

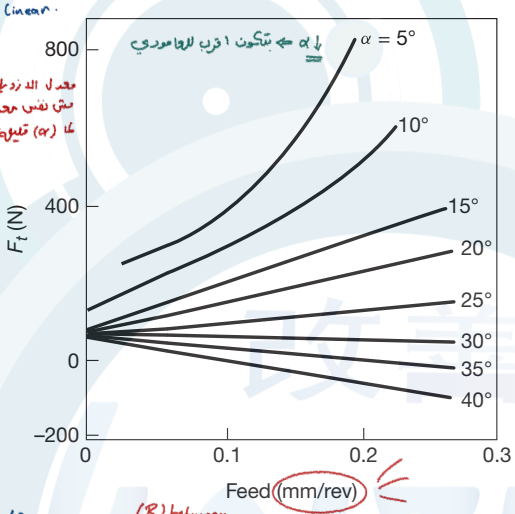
$$F_t = R\sin(\beta - \alpha) \tag{8.13}$$

or

$$F_t = F_c\tan(\beta - \alpha). \tag{8.14}$$

The sign of F_c is always positive (as shown in Fig. 8.11), but the sign of F_t can be either positive or negative. Thus, when $\beta > \alpha$, F_t is positive (downward), and for $\beta < \alpha$, it is negative (upward). It is therefore possible to have an upward thrust force when friction at the tool-chip interface is low and/or when the rake angle is high.





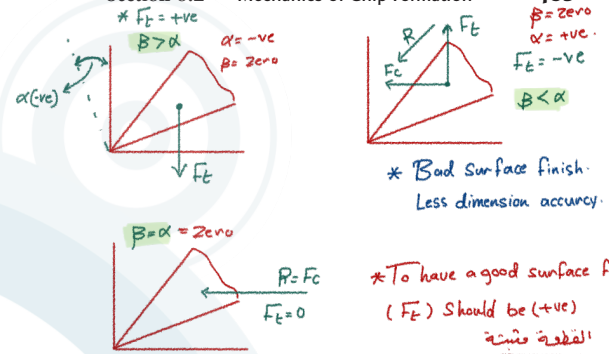


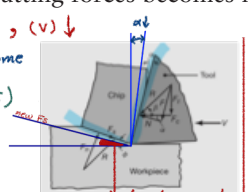
FIGURE 8.12 Thrust force as a function of rake angle and feed in orthogonal cutting of AISI 1112 cold-rolled steel. Note that at high rake angles, the thrust force is negative. A negative thrust force has important implications in the design of machine tools and in controlling the stability of the cutting process.

This situation can be seen in Fig. 8.11 and noting that when $\mu = 0$, $\beta = 0$, so that the resultant force, R, coincides with the normal force, N; thus, F_t will have a thrust-force component that is upward. Also note that for the condition of $\alpha = 0$ and $\beta = 0$, the thrust force will be zero. These observations have been verified experimentally (See Fig. 8.12).

The depth of cut has an important influence; as t_o increases, R must also increase and thus, F_c will increase as well. Note also that additional energy is required in order to remove the extra material associated with the increased depth of cut. The change in the direction and magnitude of the thrust force can play a significant role. It can, for example, lead to *instability* in machining operations, particularly if the machine tool is not sufficiently stiff.

3. **Observations on cutting forces.** In addition to being a function of the strength of the workpiece material, cutting forces are influenced by other variables. Data such as those given in Tables 8.1 and 8.2 indicate that the cutting force increases with increasing depth of cut, decreasing rake angle, and decreasing cutting speed. By reviewing the data given in Table 8.2, the effect of cutting speed can be attributed to the fact that as speed decreases, the shear angle decreases, and the coefficient of friction increases.

The tip radius of the tool also is an important factor: the larger the radius (hence the duller the tool), the higher the cutting force. Experimental evidence has indicated that, for depths of cut on the order of five times the tip radius or higher, the effect of tool dullness on the cutting forces becomes negligible (see also Section 4.4).



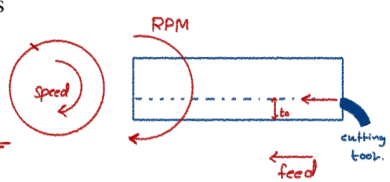


TABLE 8.1 Data on orthogonal cutting of 4130 steel.

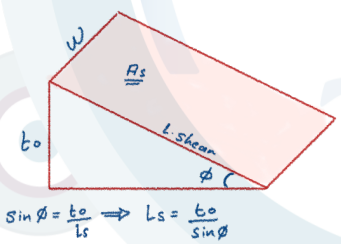
α	ϕ	γ	μ	β	F_c (N)	F_t (N)	u_t (MN-m/m^3)	u_s	u_f	u_f/u_t (%)
25°	20.9°	2.55	1.46	56°	1690	996	2206	1441	765	35
35	31.6	1.56	1.53	57°	1130	454	1475	772	703	48
40	35.7	1.32	1.54	57°	1030	316	1344	650	696	52
45	41.9	1.06	1.83	62°	1030	302	1344	517	827	62

$t_o = 0.0625$ mm; $w = 12$ mm; $V = 0.457$ m/s; tool: high-speed steel. *Source:* After E.G. Thomsen.

TABLE 8.2 Data on orthogonal cutting of 9445 steel.

α	V (m/s)	ϕ	γ	μ	β	F_c (N)	F_t (N)	u_t (MN-m/m^3)	u_s	u_f	u_f/u_t (%)
+10°	1.0	17°	3.4	1.05	46°	1646	1214	2758	2013	745	27
	2.0	19°	3.1	1.11	48°	1600	1260	2690	1834	856	32
	3.25	21.5°	2.7	0.95	44°	1463	965	2455	1717	738	30
	6.0	25°	2.4	0.81	39°	1348	747	2260	1551	709	31
−10°	2.0	16.5°	3.9	0.64	33°	1850	1712	3100	2358	742	24
	3.25	19°	3.5	0.58	30°	1708	1450	2861	2150	711	25
	5.9	22°	3.1	0.51	27°	1583	1170	2655	1993	662	25

$t_o = 0.94$ mm; $w = 6.35$ mm; tool: cemented carbide. *Source:* After M.E. Merchant.



$\sin\phi = \frac{t_o}{l_s} \Rightarrow l_s = \frac{t_o}{\sin\phi}$

$\left(A_s = w \cdot \frac{t_o}{\sin\phi}\right)$

4. **Shear and normal stresses in the cutting zone.** The stresses along the shear plane and at the tool-chip interface can be analyzed by first assuming that they are uniformly distributed. The forces in the shear plane can then be resolved into shear and normal forces and stresses. Note that the area, A_s, of the shear plane is

$$A_s = \frac{wt_o}{\sin\phi}, \tag{8.15}$$

and therefore, the *average shear stress* in the shear plane is

$$\tau = \frac{F_s}{A_s} = \frac{F_s \sin\phi}{wt_o}, \tag{8.16}$$

and the *average normal stress* is

$$\sigma = \frac{F_n}{A_s} = \frac{F_n \sin\phi}{wt_o}. \tag{8.17}$$

Some data on average stresses are given in Fig. 8.13, where the following conclusions can be drawn:

a. The shear stress along the shear plane is independent of the rake angle.

b. The normal stress on the shear plane decreases with increasing rake angle.

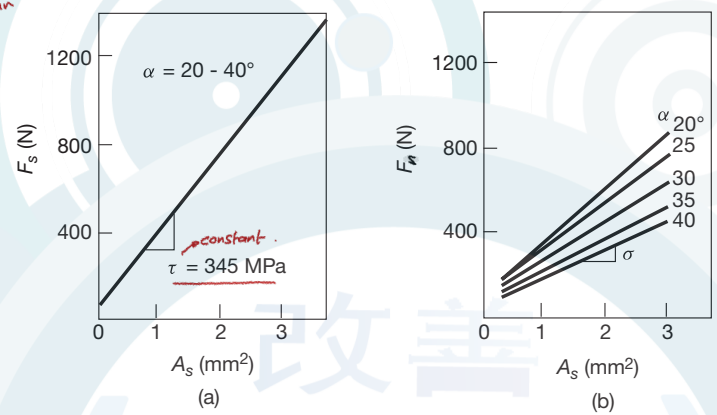


FIGURE 8.13 (a) Shear force and (b) normal force as a function of the area of the shear plane and the rake angle for 85–15 brass. Note that the shear stress in the shear plane is constant, regardless of the magnitude of the normal stress, indicating that the normal stress has no effect on the shear flow stress of the material. *Source:* After S. Kobayashi and E.G. Thomsen.

c. The normal stress in the shear plane has no effect on the magnitude of the shear stress. However, normal stress strongly influences the allowable shear strain in the shear zone prior to fracture. Recall from Section 2.2.8 that the maximum shear strain to fracture increases with the normal compressive stress. For this reason, small or negative rake angles will often be used in machining less ductile materials, in order to promote shearing without fracture.

Determining the stresses on the rake face of the tool presents several difficulties: (a) Accurately determining the length of contact at the tool-chip interface is challenging (Fig. 8.2); the length has been found to increase with decreasing shear angle, indicating that the contact length is a function of rake angle, cutting speed, and friction at the tool-chip interface. (b) The stresses are not uniformly distributed along the rake face; *photoelastic studies* have shown that the actual stress distribution is as shown in Fig. 8.14. Note that the normal stress on the rake face is a maximum at the tool tip, and it decreases rapidly toward the end of the contact length. The shear stress indicates a similar trend, except that it levels off about half-way along the tool-chip contact length. This behavior indicates that *sticking* is taking place (see Section 4.4.1), whereby the shear stress has reached the shear-yield strength of the workpiece material.

* σ, τ for the rake face not the same as in the shear plan.
* rake face ⇒ has secondary shear zone] between chip & rake face (tool)

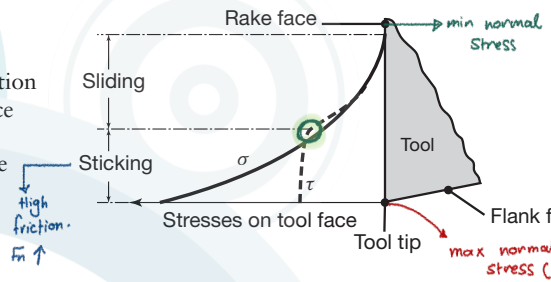


FIGURE 8.14 Schematic illustration of the distribution of normal and shear stresses at the tool-chip interface (rake face). Note that, whereas the normal stress increases continuously toward the tip of the tool, the shear stress reaches a maximum and remains at that value (a phenomenon known as *sticking*; see Section 4.4.1).

5. **Measuring cutting forces.** Cutting forces are typically measured by (a) using force transducers, such as piezoelectric crystals; (b) using force dynamometers; (c) with resistance-wire strain gages mounted on the tool holder or the workholding device on the machine tool; and (d) calculating it from the power measured during machining, provided that the mechanical efficiency of the machine tool can be determined.

8.2.4 Shear-Angle Relationships

The shear angle and the shape of the shear zone influence the mechanics of cutting; consequently, much effort has been expended in correlating the shear angle to material properties and process variables. One approach is based on the assumption that (a) the shear angle adjusts itself so that the cutting force is a minimum or (b) that the maximum shear stress occurs in the shear plane. From the force diagram given in Fig. 8.11, the shear stress in the shear plane can be expressed as

$$\tau = \frac{F_s}{A_s} = \frac{F_c \sec(\beta - \alpha)\cos(\phi + \beta - \alpha)\sin\phi}{wt_o}. \tag{8.18}$$

Assuming that β is independent of ϕ, the shear angle corresponding to the maximum shear stress can be determined by differentiating Eq. (8.18) with respect to ϕ and equating it to zero. Thus,

$$\frac{d\tau}{d\phi} = \cos(\phi + \beta - \alpha)\cos\phi - \sin(\phi + \beta - \alpha)\sin\phi = 0, \tag{8.19}$$

and

$$\tan(\phi + \beta - \alpha) = \cot\phi = \tan(90^\circ - \phi),$$

or

$$\phi = 45^\circ + \frac{\alpha}{2} - \frac{\beta}{2}. \tag{8.20}$$

Note from Eq. (8.20) that as the rake angle decreases and/or as the friction at the tool-chip interface increases, the shear angle decreases, and the chip becomes thicker. This is to be expected, because decreasing α and/or increasing β tend to cause greater resistance to the chip as it moves up the rake face of the tool. This makes the chip thicker, indicating that the shear angle is decreasing.

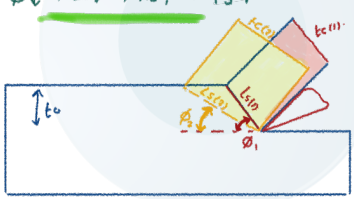
* Shear force depends on the value of the shear angle.
↓ changes (A_s)

*) Cutting force is min.
↳ when the max. shear stress is on the shear plane
* to use the min. amount of energy.

*) $\tau_c = \frac{F_s}{A_s}$ ⇒ constant, equivalent to the UTS in the max. shear stress
* (τ) is variable until reaching the max. value.
⇒ we are looking for value of (τ) to start the shearing
* keep increasing the force & shear stress until it become bigger than the frictional force ⇒ become constant



∅↓ ⇒ Ls↑ ⇒ As↑ ⇒ Fs↑



∅↑ ⇒ Shear plane ↓
* Shear plan increase till the min(F).

(β) is related to the friction
α↓ + friction ↑ (↳ β↑) (μ = tan β) = ∅↓ + tc ↑ + Length of the shear plane ↑ (Ls) + Fs ↑

Fs = τ * As
Ls↑

* (α) & (β) Both effects the (F_t).
↳ F_t : will change the resultant.

Another method of determining ϕ is based on a slip-line analysis, which gives an expression for the shear angle as

$$\phi = 45^\circ + \alpha - \beta. \tag{8.21}$$

Note that this expression is similar to Eq. (8.20) and indicates the same trends. In another study the following simple relationship has been given:

$$\phi = \alpha \quad \text{for} \quad \alpha > 15^\circ, \tag{8.22}$$

$$\phi = 15^\circ \quad \text{for} \quad \alpha < 15^\circ. \tag{8.23}$$

Several other expressions, based on various models and with different assumptions, have been developed over the years. Equations (8.21) through (8.23) do not agree well with experimental data over a wide range of conditions (Fig. 8.15a). However, the shear angle always decreases with increasing $\beta - \alpha$, as shown in Fig. 8.15a.

8.2.5 Specific Energy

From Fig. 8.11 it can be seen that the **total power** in cutting is

$$\text{Power} = F_c V.$$

The **specific energy**, or *total energy per unit volume of material removed*, u_t, is then

$$u_t = \frac{F_c V}{w t_o V} = \frac{F_c}{w t_o}, \tag{8.24}$$

where w is the width of the cut. Note that u_t is the ratio of the cutting force to the projected area of the cut. From Figs. 8.3 and 8.11 it can be seen that

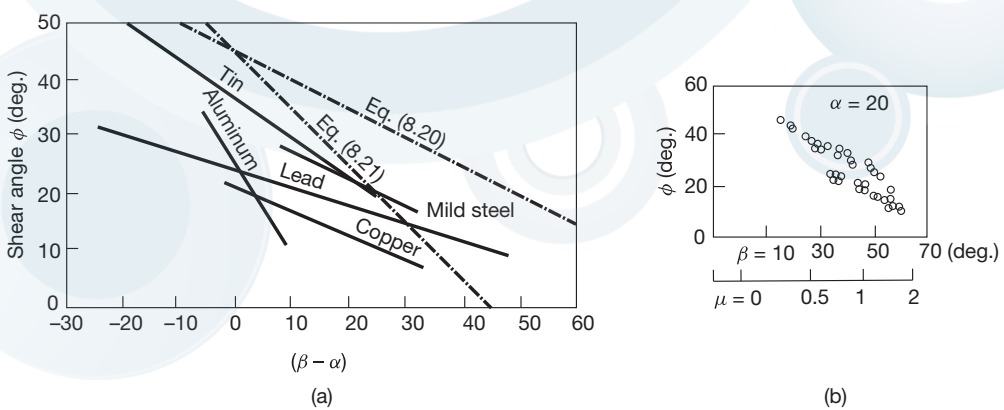


FIGURE 8.15 (a) Comparison of experimental and theoretical shear angle relationships. (b) Relation between the shear angle and the friction angle for various alloys and cutting speeds. *Source:* After S. Kobayashi.

the power required to overcome friction at the tool-chip interface is the product of F and V_c, or, in terms of specific energy for friction, u_f, as

$$u_f = \frac{FV_c}{wt_oV} = \frac{Fr}{wt_o} = \frac{(F_c \sin\alpha + F_t \cos\alpha)\, r}{wt_o}. \tag{8.25}$$

Likewise, the power dissipated along the shear plane is the product of F_s and V_s. Thus, the specific energy for shearing, u_s, is

$$u_s = \frac{F_s V_s}{wt_o V}. \tag{8.26}$$

The total specific energy, u_t, is the sum of the two energies

$$u_t = u_f + u_s. \tag{8.27}$$

Tables 8.1 and 8.2 give some experimental data on specific energies, where it can be noted that as the rake angle increases, the frictional specific energy remains relatively constant, whereas the shear specific energy rapidly decreases. Thus, the ratio u_f/u_t increases significantly as α increases. This trend also can be predicted by developing an expression for the energy ratio, as follows:

$$\frac{u_f}{u_t} = \frac{FV_c}{F_cV} = \frac{R\sin\beta}{R\cos(\beta-\alpha)} \cdot \frac{Vr}{V} = \frac{\sin\beta}{\cos(\beta-\alpha)} \cdot \frac{\sin\phi}{\cos(\phi-\alpha)}. \tag{8.28}$$

Experimental observations have indicated that as α increases, both β and ϕ increase, and inspection of Eq. (8.28) indicates that the ratio u_f/u_t should increase with α.

EXAMPLE 8.1 Relative Energies in Cutting

Given: An orthogonal cutting operation is being carried out in which $t_o = 0.1$ mm, $V = 2$ m/s, $\alpha = 10°$, and the width of cut $= 5$ mm. It is observed that $t_c = 0.25$ mm, $F_c = 500$ N, and $F_t = 200$ N.

Find: Calculate the percentage of the total energy that is dissipated in friction at the tool-chip interface.

Solution: The percentage of energy can be expressed as

$$\frac{\text{Friction energy}}{\text{Total energy}} = \frac{FV_c}{F_cV} = \frac{Fr}{F_c},$$

where

$$r = \frac{t_o}{t_c} = \frac{0.1}{0.25} = 0.40,$$

$$F = R\sin\beta$$

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

and

$$R = \sqrt{F_t^2 + F_c^2} = \sqrt{200^2 + 500^2} = 538 \text{ N}.$$

Thus,

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

from which we find that

$$\beta = 31.7^\circ \quad \text{and} \quad F = 538 \sin 31.7^\circ = 283 \text{ N}.$$

Therefore, the percentage of friction energy is calculated as

$$\text{Percentage} = \frac{(283)(0.40)}{500} = 0.22 = 22\%$$

and similarly, the percentage of shear energy is calculated as 78%.

سؤال مهم: always energy in machining higher.

EXAMPLE 8.2 Comparison of Forming and Machining Energies

Given: Two cylinders (rods) of annealed 304 stainless-steel, each with a diameter of 10 mm and a length of 150 mm, are to have their diameters reduced to 9 mm (a) for one piece by *pulling* it in tension and (b) for the other by *machining* it on a lathe (See Fig. 8.8) in one pass.

Find: Calculate the respective amounts of work involved, and explain the reasons for the difference in the energies dissipated.

* plastic deformation without friction.
$W = u * \text{volume}$.
but: plastic deformation.
(V): volume for all the workpiece in machining:
(V): volume of the chip.

Solution:

a. The work done in pulling the rod is (see Section 2.12):
(plastic deformation).

$$W_{\text{tension}} = (u)(\text{Volume}),$$

where, from Eq. (2.56),

$$u = \int_0^{\epsilon_1} \sigma \, d\epsilon.$$

The true strain is found from Eq. (2.10) as

$$\epsilon_1 = \ln\left(\frac{D_o}{D}\right)^2 = \ln\left(\frac{10}{9}\right)^2 = 0.105.$$

* very small strain

$\epsilon_1 = \ln\left(\frac{D_o}{D}\right)^2$ --- ①

$u = \frac{K \epsilon^{n+1}}{n+1}$ --- ②

From Table 2.2, the following values for K and n are obtained for this material:

$$K = 1275 \text{ MPa} \quad \text{and} \quad n = 0.45.$$

Volume $= \pi (r^2) * h$ --- ③

$W = u * (V)$ --- ④

Thus,

$$u = \frac{K\epsilon_1^{n+1}}{n+1} = \frac{(1275)(0.105)^{1.45}}{1.45} = 33.5 \times 10^6 \text{ Nm/m}^3.$$

and

$$W_{\text{tension}} = \left(33.5 \times 10^6\right)(\pi)(0.010)^2(0.15) = 1580 \text{ Nm}.$$

b. From Table 8.3, an average value for the specific energy in machining stainless steels is taken as 4.1 W-s/mm^3. The volume of material machined is

$$\text{Volume} = \frac{\pi}{4}\left[(10)^2 - (9)^2\right](150) = 2240 \text{ mm}^3.$$

Hence, the work done in machining is

$$W_{\text{mach}} = (4.1)(2240) = 9180 \text{ Nm}.$$

It will be noted that the work done in machining is over 5 times higher than that for tension. The reasons for the large difference between the two energies are that (a) tension involves very little strain (hence very little work of deformation) and (b) there is no friction. On the other hand, machining involves significant friction, and the material removed (even though relatively small in volume) has undergone much higher strains than it does in the bulk material undergoing tension. Assuming, from Tables 8.1 and 8.2, an average shear strain of 3 [equivalent to an effective strain of 1.7; see Eq. (2.55)], the material removed in machining is subjected to a strain of 1.7/0.105 = 16 times higher than that in tension for this case.

These differences explain why machining consumes much more energy than bulk deformation. However, it can be shown that as the diameter of the rod decreases and assuming that the same depth of material is involved, the difference between the two energies becomes *smaller*. This result can be explained by noting the changes in the relative volumes involved in machining vs. tension as the diameter of the rod decreases.

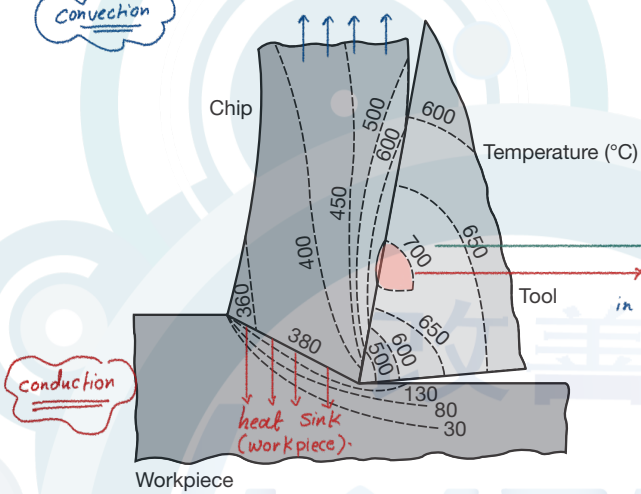
TABLE 8.3 Approximate specific energy requirements in machining operations.

Material	Specific energy* W-s/mm^3
Aluminum alloys	0.4–1.1
Cast irons	1.6–5.5
Copper alloys	1.4–3.3
High-temperature alloys	3.3–8.5
Magnesium alloys	0.4–0.6
Nickel alloys	4.9–6.8
Refractory alloys	3.8–9.6
Stainless steels	3.0–5.2
Steels	2.7–9.3
Titanium alloys	3.0–4.1

*At drive motor, corrected for 80% efficiency; multiply the energy by 1.25 for dull tools.

heat lost by the convection – in contact with the atmosphere.

convection



conduction

heat sink (workpiece).

* The highest temp. is not in the tool tip
– Highest temp. on the Secondary shear zone.

* With the high friction → high temp.
but: hard to get rid of the heat;
– surrounded by high temp. points
– Less heat diffusion.
* first point to be weared.

Highest temp. in the middle between chip-tool interface (High friction).

FIGURE 8.16 Typical temperature distribution in the cutting zone. Note the severe temperature gradients within the tool and the chip, and that the workpiece is relatively cool. *Source:* After G. Vieregge.

8.2.6 Temperature

Energy → heat.

As in all metalworking operations, the energy dissipated in machining operations is converted into heat, which causes a temperature rise in the cutting zone (Fig. 8.16). The rise in temperature is important because:

- High temperatures can adversely affect the strength, hardness, and wear resistance of the cutting tool;
- Control of tolerances can be made difficult by dimensional changes in the workpiece; and
- The machined surface can encounter thermal damage, adversely affecting its properties and service life.

Because of the work done in shearing and in overcoming friction on the rake face of the tool, the principal sources of heat generation are the (a) primary shear zone and (b) friction at the tool-chip interface. Moreover, if the tool is worn, heat is also generated by the dull tool tip rubbing against the machined surface.

→ Secondary shear zone.

→ increase of friction.

Variables affecting temperature. An approximate but simple expression for the *mean temperature* for orthogonal cutting is

$$T = \frac{0.000665\sigma_f}{\rho c}\sqrt[3]{\frac{Vt_o}{\kappa}}, \tag{8.29}$$

σ_f = flow stress: strength level of the material.
* $\sigma_f \uparrow$ → hard machinability → force required ↑
→ Energy consumption ↑
then Energy to heat ↑

where T is the *mean temperature* of the tool-chip interface in K; σ_f is the *flow stress* of the workpiece material (in MPa); V is the *cutting speed* (m/s); t_o is the *depth of cut* (m); ρc is the *volumetric specific heat* of the workpiece (in kJ/m^{3}K); and κ is the *thermal diffusivity* (ratio of thermal conductivity to volumetric specific heat) of the workpiece material (m^2/s). Note that because the material parameters in Eq. (8.29) themselves depend on

(k) Thermal diffusivity: The ability of the material to get red of the heat.
$K \uparrow$ → temp ↓

*(ρc): The amount of Energy required to increse the temp. of ($1\ m^3$) of the material by (1 K).
$\rho c \uparrow$ → energy required ↑ → temp ↓

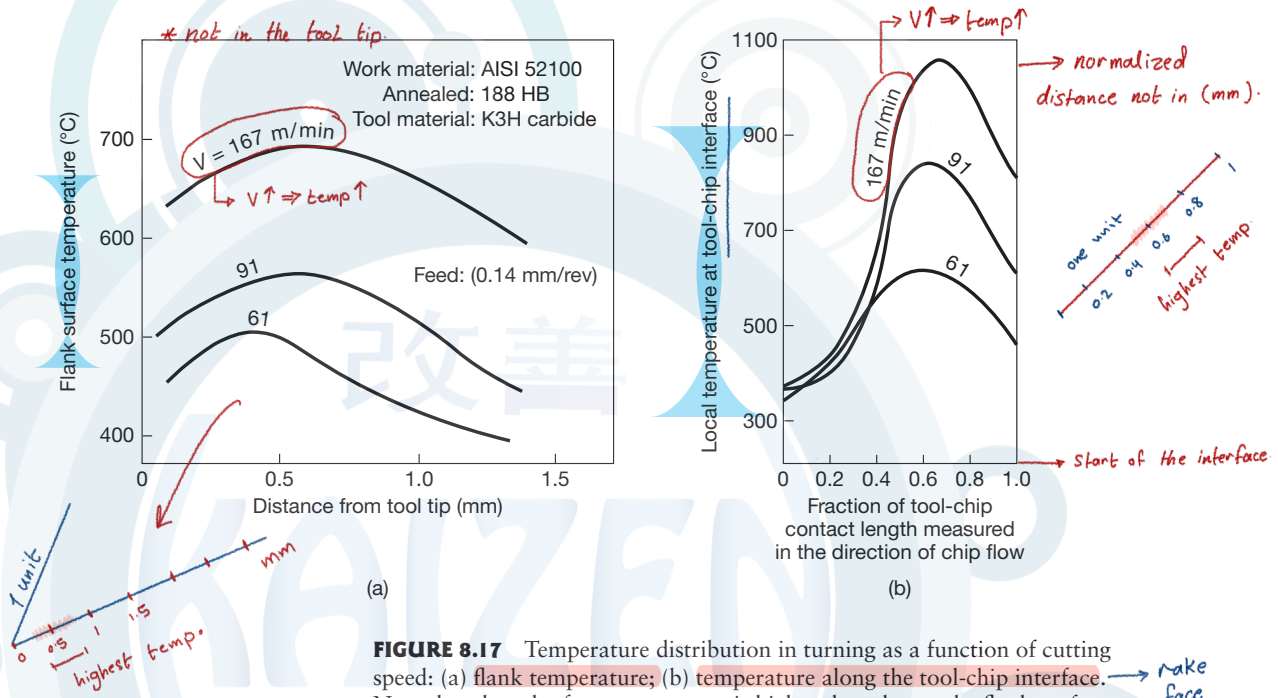


FIGURE 8.17 Temperature distribution in turning as a function of cutting speed: (a) flank temperature; (b) temperature along the tool-chip interface. Note that the rake-face temperature is higher than that at the flank surface. *Source:* After B.T. Chao and K.J. Trigger.

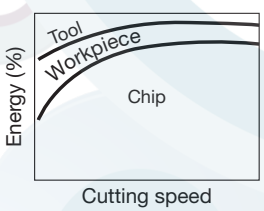


FIGURE 8.18 Proportion of the heat generated in cutting transferred to the tool, workpiece, and chip as a function of the cutting speed. Note that most of the cutting energy is carried away by the chip (in the form of heat), particularly as speed increases.

temperature, it is important to substitute appropriate values that are compatible with the *predicted* temperature range. The properties in Eq. (8.29) all pertain to the workpiece. It has been shown that thermal properties of the tool material (see Section 8.6) are relatively unimportant as compared with those of the workpiece material.

The temperature generated in the shear plane is a function of the specific energy for shear, u_s, and the specific heat of the workpiece material. As Eq. (8.29) indicates, temperature rise is highest in machining materials with high strength and low specific heat. The temperature rise at the tool-chip interface is also a function of the coefficient of friction. Moreover, flank wear (see Section 8.3.1) is an additional source of heat, caused by rubbing of the tool on the machined surface.

Figure 8.17 shows results from experimental measurements of temperature in a turning operation. Note that (a) the maximum temperature is at a location away from the tool tip and (b) the temperature increases with cutting speed. As the speed increases, there is less time for the heat to be conducted through the workpiece and tool, and hence temperature rises. Also, as speed increases, a larger proportion of the heat generated is carried away by the chip (convective heat transfer), as can be seen in Fig. 8.18. The chip is thus an effective heat sink, in that it carries away most of the heat generated at higher cutting speeds.

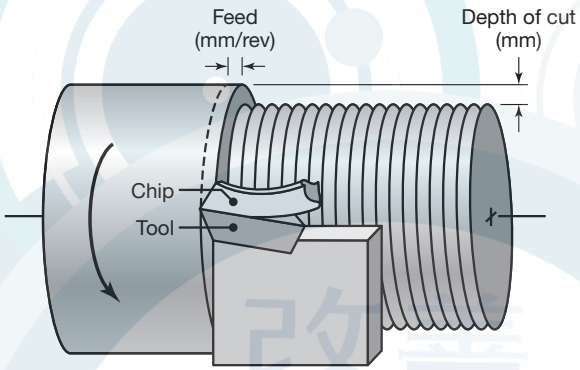


FIGURE 8.19 Terminology used in a turning operation on a lathe, where f is the feed (in mm/rev) and d is the depth of cut. Note that feed in turning is equivalent to the depth of cut in orthogonal cutting (See Fig. 8.2), and the depth of cut in turning is equivalent to the width of cut in orthogonal cutting (See also Fig. 8.39).

Equation (8.29) also indicates that the mean temperature increases with (a) the strength of the workpiece material, because of the higher energy required; and (b) the depth of cut, because of the decreasing ratio of surface area to chip thickness. Note also that a thin chip cools faster than a thick chip; however, the depth of cut has been found to have negligible influence on the mean temperature for depths exceeding twice the tool tip radius (See also Fig. 8.26).

Based on Eq. (8.29), another expression has been developed for the mean temperature in turning (See Fig. 8.39), as given by

$$T \propto V^a f^b, \tag{8.30}$$

→ depends on the velocity (V) & feed rate (f) & the type of material.

where a and b are constants, V is the cutting speed, and f is the feed (as shown in Fig. 8.19). For a carbide tool, a is approximately 0.2 and b is 0.125; for a high-speed steel tool, a is around 0.5 and b is 0.375.

Techniques for measuring temperature. Temperature and its distribution in the cutting zone may be determined by several techniques: (a) Using thermocouples, embedded in small holes in the tool or in the workpiece; this technique involves considerable effort. (b) Measuring thermal emf (electromotive force) at the tool-chip interface, which acts as a hot junction between two different materials (the tool and the chip). (c) Using a *radiation pyrometer*, monitoring the infrared radiation from the cutting zone; however, this technique indicates only surface temperatures and the accuracy of the results depends on the *emissivity* of the surfaces, which can be difficult to determine accurately.

→ Temp > 0° K will be radiation.

8.3 Tool Wear and Failure

Recall that cutting tools are subjected to high stresses, elevated temperatures, and sliding over the machined surface; these conditions all induce wear (see Section 4.4.2). Because of its effects on the quality of the machined surface and the economics of machining, *tool wear* is one of the most important aspects of machining operations. A variety of factors affect tool wear, such as cutting tool and workpiece materials and their physical, mechanical, and chemical properties; tool geometry; cutting fluids (if used); and processing parameters, such as cutting speed, feed, and depth of cut.

In typical wear patterns in cutting tools, regions of wear are identified as *flank wear*, *crater wear*, *nose wear*, and *chipping* of the cutting edge. Whereas wear is generally a gradual process, chipping of the tool, especially *gross chipping*, is regarded as *catastrophic failure*. In addition to wear, *plastic deformation* of the tool itself also may take place, especially with tool materials that begin to lose their strength and hardness at elevated temperatures (see Section 8.6).

8.3.1 Flank Wear

Flank wear is generally attributed to

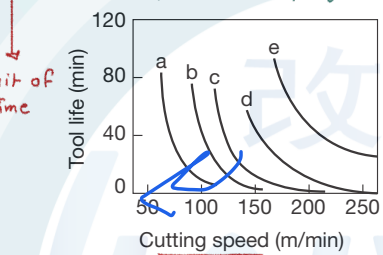
1. Sliding of the tool along the machined surface, causing adhesive and/or abrasive wear of the tool; and
2. Temperature rise, because of its adverse effects on the mechanical properties of the tool material.

Following an extensive study, a tool-wear relationship was established for machining a variety of steels, as

$$Vt^n = C, \tag{8.31}$$

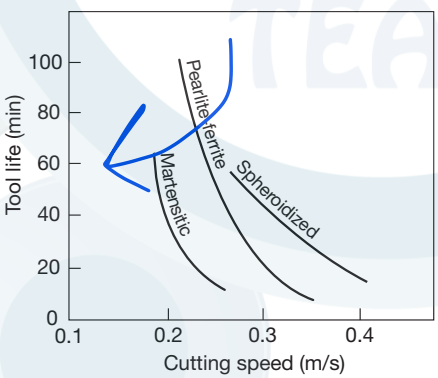
where V is the cutting speed, t is the time that it takes to develop a flank wear land or objectionable surface finish, n is an exponent that depends on workpiece and tool material as well as cutting conditions, and C is a constant. Equation (8.31) is known as the *Taylor tool life equation*, after its developer, F.W. Taylor.

Tool-life curves. *Tool-life curves* are plots of experimental data obtained in machining tests (Fig. 8.20), typically for turning operations. Note that (a) tool life decreases rapidly as cutting speed increases; (b) the condition of the workpiece material has a strong influence on tool life; and (c)



	Hardness (HB)	Ferrite	Pearlite
a. As cast	265	20%	80%
b. As cast	215	40	60
c. As cast	207	60	40
d. Annealed	183	97	3
e. Annealed	170	100	–

(a)



(b)

FIGURE 8.20 Effect of workpiece microstructure on tool life in turning. Tool-Life is hyphenated, is given in terms of the time (in minutes) required to reach a flank wear land of a specified dimension. (a) Ductile cast iron; and (b) steels, with identical hardness. Note in both figures the rapid decrease in tool life as the cutting speed increases.

there is a large difference in tool life for different microstructures of the workpiece. Heat treatment of the workpiece material is important largely because of the increase in hardness. For example, ferrite has a hardness of about 100 HB, pearlite 200 HB, and martensite 300 HB to 500 HB (see Section 5.11). Impurities and hard constituents in the workpiece material also are important, because they reduce tool life due to their abrasive action on the tool (see also Section 4.4.2).

The exponent n is determined from the tool life curves, with a range of typical values given in Table 8.4. It has been observed that although tool-life curves are usually linear over a specific range of cutting speeds, they are rarely so over a wide range. Moreover, the exponent n can become negative at low cutting speeds, indicating that tool-life curves may actually reach a maximum and then curve downward as cutting speed increases. Consequently, caution should be exercised when using tool-life equations beyond the range of cutting speeds at which they were developed.

Because of the major influence of temperature on the physical and mechanical properties of materials (see Section 2.2.6), it would be expected that wear is strongly influenced by temperature. Experimental investigations have shown that there is indeed a direct relationship between flank wear and the temperature generated during machining (Fig. 8.21b). Although cutting speed has been found to be the most significant process

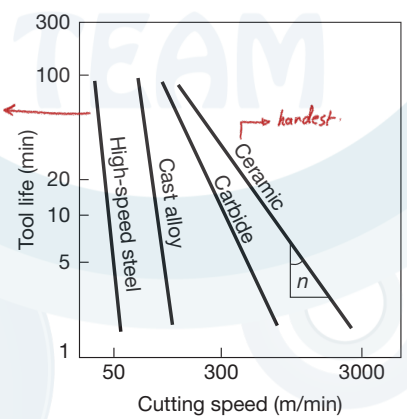
TABLE 8.4 Range of n values for various cutting tools.

Tool material	n
High-speed steels	0.08–0.2
Cast alloys	0.1–0.15
Carbides	0.2–0.5
Ceramics	0.5–0.7

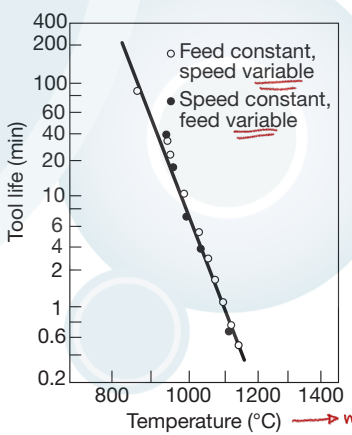
dependent in tool-material.

Tools soft relatively to the then cutting tools

soft cutting tool = Less tool-life.



(a)



(b)

FIGURE 8.21 (a) Tool-life curves for a variety of cutting-tool materials. The negative inverse of the slope of these curves is the exponent n in tool-life equations. (b) Relationship between measured temperature during cutting and tool life (flank wear). Note that high cutting temperatures severely reduce tool life. See also Eq. (8.30). *Source:* After H. Takeyama and Y. Murata.

TABLE 8.5 Allowable average wear land for cutting tools for various operations.

Operation	Allowable wear land (mm)	
	High-speed steels	Carbides
Turning	1.5	0.4
Face milling	1.5	0.4
End milling	0.3	0.3
Drilling	0.4	0.4
Reaming	0.15	0.15

High precision machining ←

variable in tool life, depth of cut and feed rate also are important; thus, Eq. (8.31) can be modified as

$$Vt^n d^x f^y = C, \tag{8.32}$$

where d is the depth of cut and f is the feed rate (in mm/rev) in turning. The exponents x and y must be determined experimentally for each cutting condition. Taking $n = 0.15$, $x = 0.15$, and $y = 0.6$ as typical values encountered in practice, it can be seen that cutting speed, feed rate, and depth of cut are of decreasing order of importance.

Equation (8.32) can be rewritten as

$$t = C^{1/n} V^{-1/n} d^{-x/n} f^{-y/n}, \tag{8.33}$$

or

$$t \simeq C^7 V^{-7} d^{-1} f^{-4}. \tag{8.34}$$

Thus, for a constant tool life, the following observations can be made from Eq. (8.34):

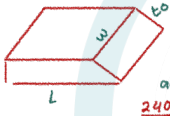
1. If the feed or the depth of cut is increased, the cutting speed must be decreased, and vice versa; and
2. A reduction in the cutting speed will allow an increase in feed and/or depth of cut. Depending on the magnitude of the exponents, this can then result in an increase in the volume of the material removed.

Allowable wear land. Although somewhat arbitrary, typical values of *allowable wear land* for various processing conditions are given in Table 8.5. For improved dimensional accuracy and surface finish, the allowable wear land may be specified at a smaller value than those given in the table. In practice, the recommended cutting speed for a high-speed steel tool is generally the one that gives a tool life of 60–120 min.; for carbide tools, it is 30–60 min (See Table 8.9).

Optimum cutting speed. Recall that as the cutting speed decreases, tool life increases. However, a lower cutting speed means that the rate at which material is being removed will be low; thus, there is an *optimum* cutting speed.

Speed that you can define the criteria for it ↔ Productivity / Cost / Time

Speed = 1 m/s → Speed = 2 m/s
T. life = 40 min. T. life = 5 min
distance = 2400 m distance = 600 m.



at constant (w) & (t_0)
L: will determine the amount of material removed.
$\frac{2400}{600} = \frac{L_1}{L_2} \Rightarrow L_1 = 4L_2$.
L↓ when the Speed ↑
* Material removing rate = $\frac{L}{Time}$, case (1) = $\frac{2400}{40} = 60$
case (2) = $\frac{600}{5} = 120$

The effect of cutting speed on the volume of metal removed between tool indexing (rotating in its holder) or replacement can be appreciated by analyzing Fig. 8.20a. Assume that the material being machined is in the condition represented by curve "a". If the cutting speed is 1 m/s, the tool life will be about 40 min. Thus, the tool travels a distance of (1 m/s)(60 s/min)(40 min) = 2400 m before it reaches its life. If the cutting speed is increased to 2 m/s, the tool life will be about 5 min, and the tool travels a distance of (2)(60)(5) = 600 m. Because the volume of material removed is directly proportional to the distance the tool has traveled, it can be seen that by *decreasing* the cutting speed, *more* material will be removed between tool indexing or changes. Note, however, that the lower the cutting speed, the longer it will take to machine the part, thus reducing productivity (see Section 8.15).

EXAMPLE 8.3 Increasing Tool Life by Reducing the Cutting Speed

Given: A tool and material combination has $n = 0.5$ and $C = 400$.

Find: Calculate the percentage increase in tool life when the cutting speed is reduced by 50% using the Taylor equation [Eq. (8.31)].

Solution: Since $n = 0.5$, the Taylor equation can be rewritten as $V\sqrt{t} = 400$. Letting V_1 be the initial speed and V_2 the reduced speed, it can be noted that, for this problem, $V_2 = 0.5V_1$. Because C is a constant,

$V_2 t^n$

$$(0.5V_1\sqrt{t_2}) = V_1\sqrt{t_1}.$$

$Vt^n = C$
$V(t)^{0.5} = 400$

Simplifying this expression,

$$\frac{t_2}{t_1} = \frac{1}{0.25} = 4.0.$$

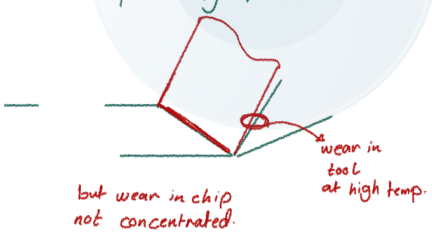
This relation indicates that the tool-life change is

$$\frac{t_2 - t_1}{t_1} = \left(\frac{t_2}{t_1}\right) - 1 = 4 - 1 = 3,$$

300% increasing.

or that it is increased by 300%. Note that the reduction in cutting speed has resulted in a major increase in tool life.

* Chemical affinity = probability of diffusion.



8.3.2 Crater Wear

→ happen in the tool-chip interface. (Secondary shear zone).
in a very high temp. & high friction.

Although the factors affecting flank wear also influence *crater wear*, the most significant factors in crater wear are temperature and the level of chemical affinity between the tool and the workpiece materials. Recall that the rake face of the tool is subjected to high localized stress and temperature, as well as sliding of the chip up the rake face at relatively high speeds (See Fig. 8.3b). As shown in Fig. 8.17b, peak temperatures in the cutting zone can be on the order of 1100°C. Note that the location of *maximum depth* of crater wear generally coincides with the location of maximum temperature at the tool-chip interface. *

--- 1
--- 2
--- 3

Crater wear increase rapidly with increase the temp.

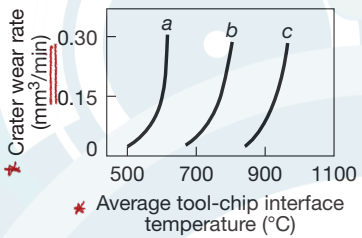
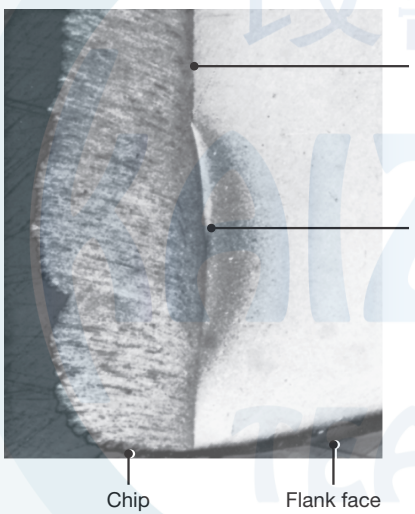


FIGURE 8.22 Relationship between crater-wear rate and average tool-chip interface temperature in turning: (a) high-speed steel tool; (b) C1 carbide; and (c) C5 carbide. Note that crater wear increases rapidly within a narrow range of temperature. *Source:* After K.J. Trigger and B.T. Chao.



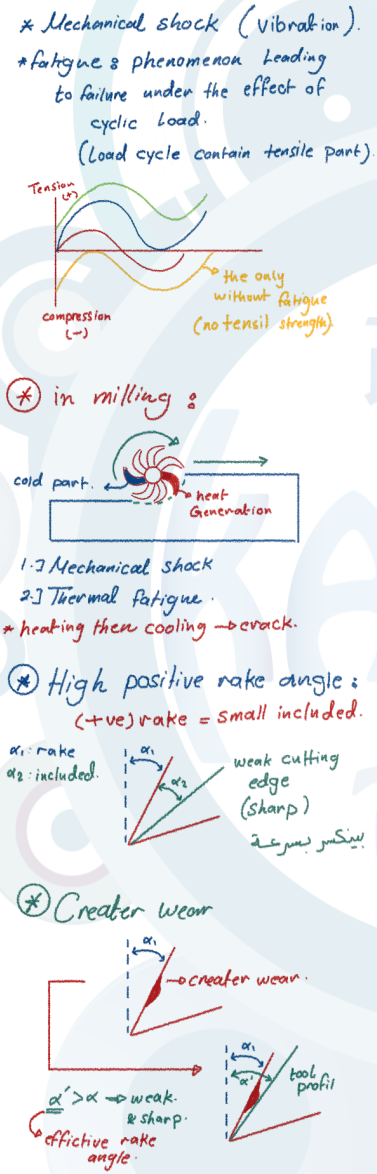
+ discoloration (Change in tool material because of the high temp.)

FIGURE 8.23 Interface of chip (left) and rake face of cutting tool (right) and crater wear in cutting AISI 1004 steel at 3 m/s. Discoloration of the tool indicates the presence of high temperature (loss of temper). Note how the crater-wear pattern coincides with the discoloration pattern. Compare this pattern with the temperature distribution shown in Fig. 8.16. *Source:* Courtesy of P.K. Wright.

Experimental evidence has indicated that a direct relationship exists between crater-wear rate and tool-chip interface temperature (Fig. 8.22). Note, for example, the sharp increase in crater wear after a certain temperature range has been reached. Figure 8.23 shows the cross section of the tool-chip interface in cutting steel at high speeds. Note (a) the location of the crater-wear pattern and the *discoloration* of the tool (called *loss of temper*) as a result of high temperatures to which the tool has been subjected; and (b) the similarity of the discoloration profile to the temperature profile shown in Fig. 8.16.

chemical affinity.

The effect of temperature on crater wear has been described in terms of a **diffusion** mechanism (the movement of atoms across the tool-chip interface). Diffusion depends on the tool-workpiece material combination and on temperature, pressure, and time; as these quantities increase, the diffusion rate increases. An example of diffusion-induced crater wear can be observed when a diamond cutting tool is used to machine steel. The high solubility of carbon in steel leads to rapid crater wear, and eventually to tool failure.



8.3.3 Chipping

The term *chipping* in machining describes the sudden breaking away of a piece from the cutting edge of the tool. The pieces may be very small (*microchipping* or *macrochipping*), or they may consist of relatively large fragments (*gross chipping* or *fracture*). Two main causes of chipping are **mechanical shock** and **thermal fatigue**, such as seen in interrupted cutting operations as in milling, described in Section 8.10.

Chipping by mechanical shock may occur in a region of a cutting tool where a small crack or defect already exists. High positive rake angles also can contribute to chipping, because of the small included angle of the tool tip (See Fig. 8.31); this is a phenomenon similar to chipping of the tip of a very sharp pencil. Crater wear also may contribute to chipping, because wear progresses toward the tool tip and weakens it. Thermal cracks, which are generally perpendicular to the cutting edge, typically are caused by the thermal cycling of the tool in interrupted cutting.

8.3.4 General Observations on Tool Wear

In addition to wear and chipping, other phenomena also occur in tools. The wear **groove** or **notch** has been attributed to the fact that this narrow region is the boundary (the **depth-of-cut line**, DOC) where the chip is no longer in contact with the tool. This boundary oscillates because of inherent variations in the cutting operation, thus accelerating the wear process. Moreover, note that this region on the tool is in contact with the machined surface from the previous cut (See, for example, Fig. 8.19), that may have developed a thin work-hardened layer (depending on tool sharpness and its shape); and this contact would then contribute to the formation of the wear groove.

Because they are hard and abrasive, scale and oxide layers on the surface of a workpiece also increase wear, in which case the depth of cut (See Fig. 8.19) should be greater than the thickness of the oxide film or the work-hardened layer. In other words, light cuts should not be taken on rusted or corroded workpieces, as otherwise the tool will travel through this thin, hard, and abrasive layer.

8.3.5 Tool-Condition Monitoring

With the extensive use of computer-controlled machine tools and implementation of highly automated manufacturing systems, the reliable and repeatable performance of cutting tools is a major consideration. Once programmed properly, machine tools now operate with little direct supervision by an operator; consequently, the failure of a cutting tool will have serious detrimental effects. It is therefore essential to continuously monitor the condition of the cutting tool, such as for wear, chipping, or gross failure.

Techniques for tool-condition monitoring typically fall into two general categories: direct and indirect. The **direct method** involves *optical measurement* of wear, by periodically observing changes in the profile of the tool.

Indirect methods of measuring wear involve correlating the tool condition with variables such as force, power, temperature rise, surface finish, and vibration and chatter. The **acoustic emission** technique utilizes a piezoelectric transducer, attached to a tool holder, which picks up acoustic-emission signals (typically above 100 kHz) that result from the stress waves generated during machining. By analyzing the signals, tool wear and chipping can be monitored. This technique is particularly effective in precision machining operations where, because of the very small amounts of material removed, cutting forces are low.

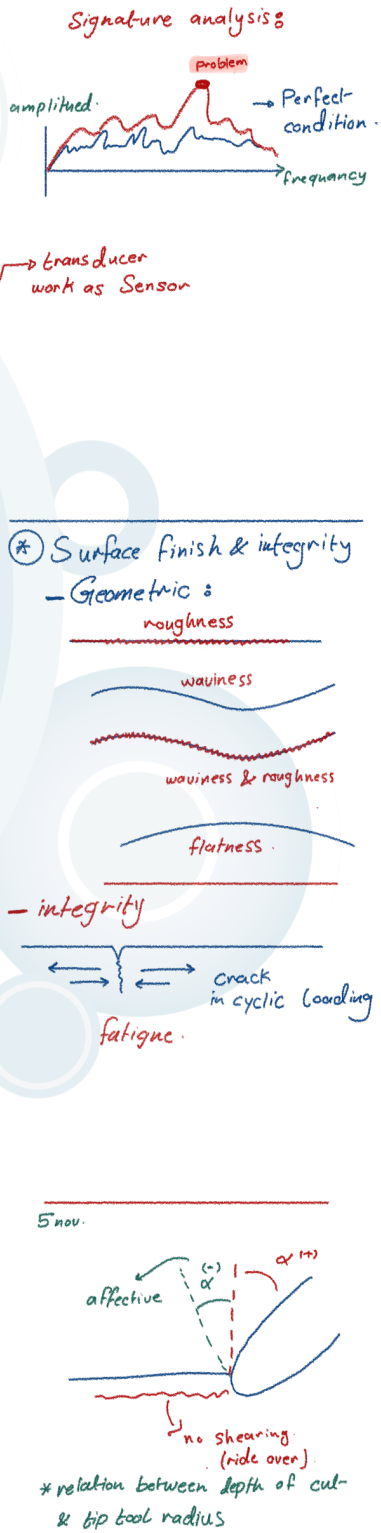
A similar indirect tool-condition monitoring system consists of **transducers** (installed in an original machine tool or retrofitted on an existing machine) that continually monitor such parameters as spindle *torque* and cutting-tool *forces*. A microprocessor analyzes the signals (which are preamplified) and interprets them. This system is capable of differentiating the signals from tool breakage, tool wear, a missing tool, overloading of the machine, or collision of machine components. It can also automatically compensate for tool wear, so that dimensional accuracy of the part is maintained.

The design of the transducers must be such that they are (a) nonintrusive to the particular machining operation; (b) accurate and repeatable in signal detection; (c) rugged enough for a typical shop-floor environment; and (d) cost effective. *Sensors* (see Section 14.8), including *infrared* and *fiber optic* techniques for temperature measurement, are now being used extensively in a variety of machining operations.

8.4 Surface Finish and Surface Integrity

Surface finish describes the *geometric* features of surfaces, whereas **surface integrity** pertains to *properties* that are strongly influenced by the type of surface produced (see also Section 4.3). The ranges of surface roughness in machining and other processes are given in Fig. 8.24. As can be seen, the processes are generally organized in order of increasing surface quality, which also correspond to increasing cost and machining time (See also Fig. 16.5).

Built-up edge and depth of cut can adversely affect surface finish and integrity. Figure 8.25 shows surfaces obtained in two different machining operations; note the damage to the surfaces from BUE. A shallow depth of cut (or dull tool) can also compromise surface finish. A dull cutting tool has a larger radius along its edges, just as a dull pencil or knife does. Figure 8.26 illustrates the relationship between the radius of the cutting edge and depth of cut in orthogonal cutting. Note that at small depths of cut, the rake angle of an otherwise positive-rake tool can effectively become *negative*; the tool may simply ride over the workpiece surface and not remove any material. If the radius is large in relation to the depth of cut, the tool will rub over the machined surface, generating frictional heat, inducing surface residual stresses, and causing surface damage, such as tearing and cracking. In practice, the depth of cut should generally be greater than the radius on the cutting edge.



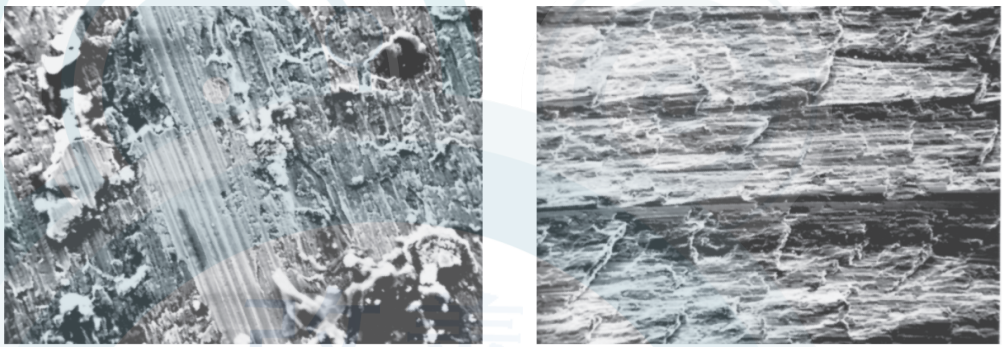


FIGURE 8.25 Surfaces produced on steel in machining, as observed with a scanning electron microscope: (a) turned surface, and (b) surface produced by shaping. *Source:* JT. Black and S. Ramalingam.

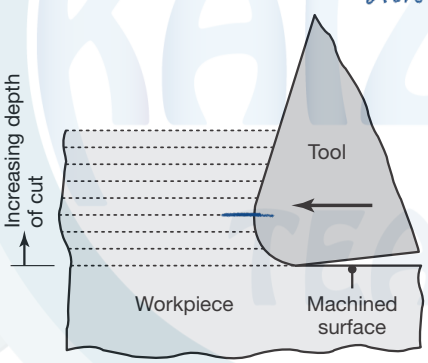


FIGURE 8.26 Schematic illustration of a dull tool in orthogonal cutting (exaggerated). Note that at small depths of cut, the rake angle can effectively become negative. In such cases, the tool may simply ride over the workpiece surface, burnishing it, instead of cutting.

Feed marks. In turning, as in some other machining operations, the cutting tool leaves a spiral profile (*feed marks*) on the machined surface as it moves across the workpiece (See Fig. 8.19). As expected, the higher the feed, f, and the smaller the radius, R, the more prominent are these marks. Although not significant in rough machining operations, feed marks are important in finish machining (see Section 8.9).

The peak-to-valley roughness, R_t, in turning can be expressed as

$$R_t = \frac{f^2}{8R}, \tag{8.35}$$

where f is the feed and R is the nose radius of the tool. For the condition where R is much smaller than f, the roughness is given by the expression

$$R_t = \frac{f}{\tan\alpha_s + \cot\alpha_e}, \tag{8.36}$$

where α_s and α_e are the side and edge cutting angles, respectively (See Fig. 8.38). For face milling (See Fig. 8.54), the roughness is given by

$$R_t = \frac{f^2}{16\left[D \pm (2fn/\pi)\right]}, \tag{8.37}$$

where D is the cutter diameter, f is the feed per tooth, and n is the number of inserts on the cutter. Equations (8.35) to (8.37) are derived considering only geometry; they do not account for such phenomena as cracking of the workpiece surface, thermal distortion, and chatter marks.



(a)

8.5 Machinability

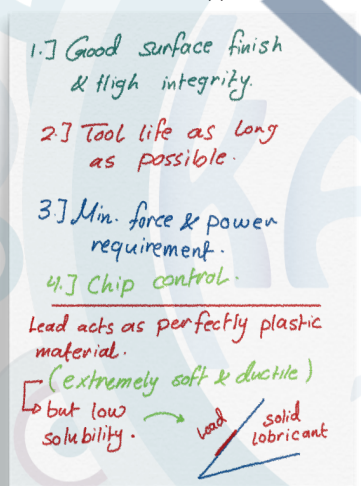
The *machinability of a material* is generally defined in terms of the following four factors: (a) surface finish and integrity of the machined part; (b) tool life; (c) force and power requirements; and (d) chip control. Thus, good machinability indicates *good surface finish and integrity, long tool life, low force and power requirements,* and type of *chip* produced are easily collected and do not interfere with the machining operation (see Section 8.2.1).

8.5.1 Machinability of Steels

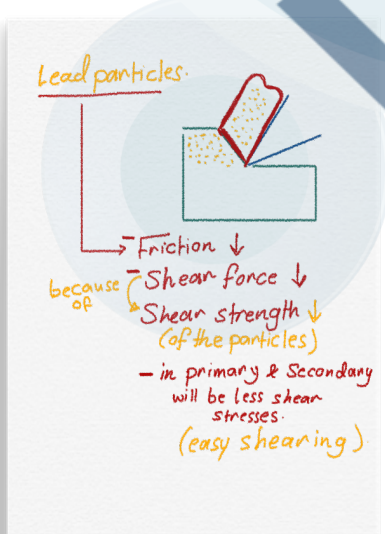
Steels are among the most important and commonly used engineering materials. Their machinability has been studied extensively and has been greatly improved by adding *lead* and *sulfur*, called **free-machining steels**.

Leaded steels. Lead is added to molten steel and takes the form of dispersed fine lead particles (See Fig. 5.2a). During machining, the lead particles are sheared and smeared over the tool-chip interface; because of their low shear strength, the lead particles act as a solid lubricant (see Section 4.4.4). This behavior can be verified from the presence of high concentrations of lead on the tool-side face of the chips when machining leaded steels. In addition, lead lowers the shear stress in the primary shear zone, thus reducing cutting forces and power consumption. Leaded steels are identified by the letter L between the second and third numerals, such as 10L45. Because of its toxicity and environmental concerns, the trend has been toward eliminating the use of lead in favor of such elements as bismuth and tin (*lead-free steels*).

Resulfurized and rephosphorized steels. *Sulfur* in steels forms *manganese-sulfide inclusions* (second-phase particles; see Fig. 8.27). These particles act as stress raisers in the primary shear zone; as a result, the chips produced are small and they break up easily, thus improving machinability. *Phosphorus* in steels improves machinability by virtue of strengthening the ferrite, thereby increasing the hardness of steels and producing less continuous chips.



(c)



in the production of the steel &
* we add (O_2) to produce → then deoxidization.
high temp.

Calcium-deoxidized steels. In these steels, oxide flakes of *calcium aluminosilicate* (CaO, SiO_2, and Al_2O_3) are formed. These flakes, in turn, lower the strength of the secondary shear zone, thus reducing tool-chip interface friction and wear, and hence lowering the temperature. As a result, these steels develop less crater wear of the tool, especially at high cutting speeds when temperatures are higher.

Effects of other elements on the machinability of steels. (a) The presence of *aluminum* and *silicon* in steels is always harmful, because these elements combine with oxygen to form aluminum oxide and silicates, which are hard and abrasive. (b) *Carbon* and *manganese* have various effects on the machinability of steels, depending on their composition. As the carbon content increases, machinability decreases, although plain low-carbon steels (less than 0.15% C) can produce poor surface finish due to forming a built-up edge. Alloying elements, such as nickel, chromium, molybdenum, and vanadium (which improve the properties of steels) generally reduce machinability. (c) Cast steels have a machinability similar to that of wrought steels. (d) Tool and die steels are very difficult to machine, usually requiring annealing prior to machining them.

* Machinability of most steels is generally improved by cold working, which reduces the tendency for built-up edge formation. Austenitic

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* (Al) & silicon harmful (used alone)
but increse the machinability when they are used with calcium
* Aluminum oxide & Silicate (react with O_2).
hard materials

① Carbon content increases ⇒ machinability decreases.
↳ because hardness increases.
C ↑ → hardness ↑ → machinability ↓
+ (more power requirement.)
C > 0.15% (midium to High C).

② Carbon Level Less than 0.15% (C < 0.15%).
machinability ↑ by avoiding deformation of (BUE), Extremely soft steel ⇒ high chance of BUE
we will increase the carbon to get rid of BUE by decrease the ductility.

plain carbon steel: (Fe+C+Mn)
sulfur is an unwanted impurity.
S+F = FeS iron sulfides
free-machining steel, high machinability (low force & power requirement, not continuous chip).
– Brittle & weak
stress concentration ← sharp-edged
– low bonding with the matrix
when it's tensil stresses not compression.
* we use it with compressive force.

we added Mn
react with sulfur
MnS.
Manganese sulfides.
– Strong & ductile.
less stress cons. ← – Round-edged
– good bonding with the matrix.

The softer the steel.
The more ability to produce (BUE)

0.15%
C > 0.15 reduce chance of BUE
C < 0.15 less power requirement.

turning and milling operations. The process of heating to and maintaining a uniform temperature distribution within the workpiece may be difficult to control, whereby the original microstructure of the workpiece may be altered, adversely affecting the properties of the machined part. Some success has been obtained in laser-assisted machining of silicon-nitride ceramics and *Stellite* (see Section 8.6.3).

8.6 Cutting-Tool Materials

The selection of appropriate cutting-tool materials for a specific application is among the more important considerations in machining operations, as is the selection of mold and die materials for forming and shaping processes. Recall that in machining, the tool is subjected to high localized temperatures, high contact stresses, rubbing on the workpiece surface, and the chip climbing up the rake face of the tool (see Section 8.2). Consequently, a cutting tool must possess the following characteristics:

- **Hardness**, particularly at elevated temperatures (**hot hardness**), so that the strength of the tool is maintained at the temperatures encountered in machining operations (Fig. 8.28);
- **Toughness**, so that impact forces on the tool in interrupted cutting operations, such as milling or turning a splined shaft, do not chip or fracture the tool;
- **Wear resistance**, so that the tool has an acceptable tool life before it is **indexed** or replaced; and

/small included angle/ machine tool with low stiffness

Resharpened/rotate

hot hardness : the cutting tool should keep its hardness at a high temp.

Toughness : represent shock absorption.

indexed : when there is an inserts more than one cutting edge. Change the cutting edge when there is dull tool tip.

Replacment : one-piece-tool, & the cutting edge have a wear or dull tip.

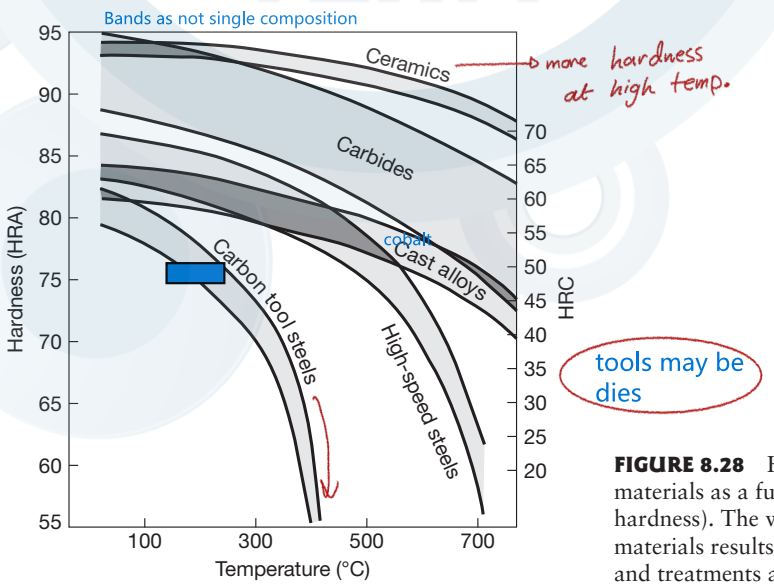


FIGURE 8.28 Hardness of various cutting-tool materials as a function of temperature (hot hardness). The wide range in each group of tool materials results from the variety of compositions and treatments available for that group.

- **Chemical stability** or **inertness** with respect to the workpiece material, so that any adverse reactions that may contribute to tool wear are minimized or avoided.

Several cutting-tool materials with a wide range of these characteristics are available (See Table 8.6). Tool materials are generally divided into the following categories, listed in the approximate chronological order in which they were developed and implemented. Note that many of these materials are also used for dies and molds, as described throughout Chapters 5, 6, 7, 10, and 11.

1. **Carbon and medium-alloy steels;**
2. **High-speed steels;**
3. **Cast-cobalt alloys;**
4. **Carbides;**
5. **Coated tools;**
6. **Alumina-base ceramics;**
7. **Cubic boron nitride;**
8. **Silicon-nitride-base ceramics;**
9. **Diamond;** and
10. **Whisker-reinforced and nanomaterials.**

This section describes the characteristics, applications, and limitations of tool materials. Their characteristics include hot hardness, toughness, impact strength, wear resistance, resistance to thermal shock, costs, and the range of cutting speeds and depth of cut for optimum performance in machining.

8.6.1 Carbon and Medium-Alloy Steels

Carbon steels are the oldest of tool materials, and have been used widely for drills, taps, broaches, and reamers since the 1880s. Low-alloy and medium-alloy steels were developed later for similar applications, but with longer tool life. Although inexpensive and easily shaped and sharpened, these steels do not have sufficient hot hardness and wear resistance for machining at high cutting speeds, where temperature rise is significant. Note in Fig. 8.28, for example, how rapidly the hardness of carbon steels decreases as the temperature increases. The use of these steels is thus limited to very low-speed machining operations or woodworking.

8.6.2 High-Speed Steels

High-speed steel (HSS) tools are so named because they were developed to machine at speeds higher than previously possible. First produced in the early 1900s, high-speed steels are the most highly alloyed of tool steels (see also Section 3.10.4). They can be hardened to various depths, have good wear resistance, and are relatively inexpensive. Because of their high toughness and resistance to chipping and fracture, high-speed steels are especially suitable for (a) high positive-rake-angle tools (that is, small included angle; see Fig. 8.2); (b) interrupted cuts; and (c) use on machine

tools that, because of their low stiffness, are subject to vibration and chatter. High-speed steels are the most commonly used tool materials, followed closely by various die steels and carbides. They are especially used in machining operations that require complex tool shapes, such as drills, reamers, taps, and gear cutters.

There are two basic types of high-speed steels: **molybdenum** (*M* series) and **tungsten** (*T* series). The *M* series contains up to about 10% molybdenum, with chromium, vanadium, tungsten, and cobalt as alloying elements. The *T* series contains 12 to 18% tungsten, with chromium, vanadium, and cobalt as alloying elements. The *M* series generally has higher abrasion resistance than the *T* series, undergoes less distortion during heat treating, and is less expensive.

High-speed steel tools are available in wrought, cast, and sintered (see *powder-metallurgy*, Chapter 11) conditions. They can be **coated** for improved performance (see Section 8.6.5), and may also be subjected to surface treatments, such as case hardening (Section 4.5.1), for improved hardness and wear resistance.

8.6.3 Cast-Cobalt Alloys

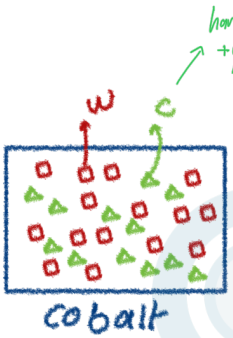
Cast-cobalt alloys have high hardness, typically 58 to 64 HRC, good wear resistance, and maintain their hardness at elevated temperatures. Their composition ranges from 38 to 53% cobalt, 30 to 33% chromium, and 10 to 20% tungsten. Commonly known as *Stellite* tools, these alloys are cast and ground into relatively simple tool shapes. Because they are not as tough as high-speed steels, and are sensitive to impact forces, they less suitable than high-speed steels for interrupted cutting operations.

8.6.4 Carbides

The tool materials described thus far possess sufficient toughness, impact strength, and thermal shock resistance for numerous applications; however, they have significant limitations regarding such important characteristics as strength and hardness, particularly hot hardness. Consequently, they cannot be used as effectively where high cutting speeds, and hence high temperatures, are involved, and their tool life can be relatively short. *Carbides*, also known as **cemented or sintered carbides**, were introduced in the 1930s to meet the challenge of higher machining speeds for higher productivity.

Because of their high hardness over a wide range of temperatures (as can be seen in Fig. 8.28), high elastic modulus, high thermal conductivity, and low thermal expansion, carbides are among the most important, versatile, and cost-effective tool and die materials for a wide range of applications. The two basic categories of carbides are *tungsten carbide* and *titanium carbide*. In order to differentiate them from coated tools (see Section 8.6.5), plain carbide tools are usually referred to as **uncoated carbides**.

1. **Tungsten carbide.** *Tungsten carbide* (WC) is a *composite material*, consisting of tungsten-carbide particles bonded together in a *cobalt*



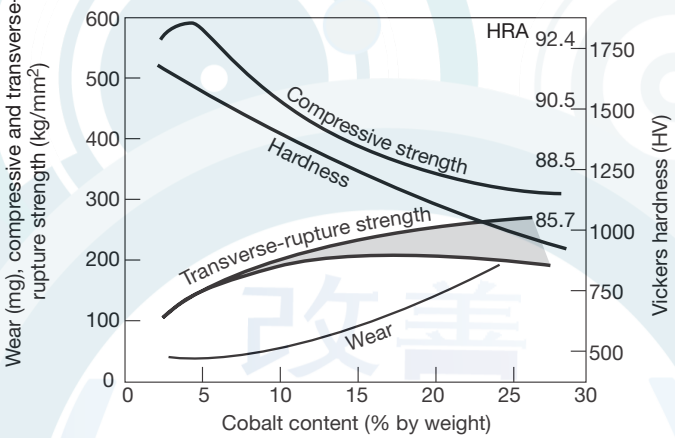


FIGURE 8.29 Effect of cobalt content in tungsten-carbide tools on mechanical properties.

matrix. Tungsten carbide is often compounded with carbides of titanium and niobium to impart special properties to carbide tools and dies. The amount of cobalt significantly affects the properties of carbide tools; as the cobalt content increases, strength, hardness, and wear resistance decrease, while toughness increases (Fig. 8.29). Tungsten-carbide tools are generally used for machining steels, cast irons, and abrasive nonferrous materials. The tools are manufactured by powder-metallurgy techniques.

2. **Titanium carbide.** *Titanium carbide* (TiC) has higher wear resistance than tungsten carbide, but it is not as tough. With a *nickel-molybdenum* alloy as the matrix, TiC is suitable for machining hard materials, mainly steels and cast irons, and for machining at speeds higher than those for tungsten carbide.

Inserts. High-speed steel and carbon-steel cutting tools can be produced in various geometries (See Fig. 8.10), including drills and milling cutters. However, after the cutting edges wear and become dull, the tool has to be removed from its holder and reground, a time-consuming process. The need for a more efficient method led to the development of *inserts*, that are individual cutting tools with a number of cutting edges in various shapes (Fig. 8.30). A square insert, for example, has eight cutting edges, and a triangular insert has six. Inserts also are available with a wide variety of **chip-breaker** features (see Section 8.2.1) for controlling chip flow, reducing vibration, and reducing the heat generated.

Inserts are usually clamped on the tool *shank*, using various locking mechanisms (Figs. 8.30a and b); less frequently, inserts may also be *brazed* (see Section 12.14.1) to the tool shank (See Fig. 8.36). However, because of the difference in thermal expansion between the insert and the tool-shank materials, brazing must be done properly in order to avoid cracking or warping. Clamping is the preferred method because after a cutting edge is worn, it is *indexed* so that a new edge can be used. In addition to those shown in Fig. 8.30, a wide variety of other toolholders also is available

included angle ↑
chipping ↓

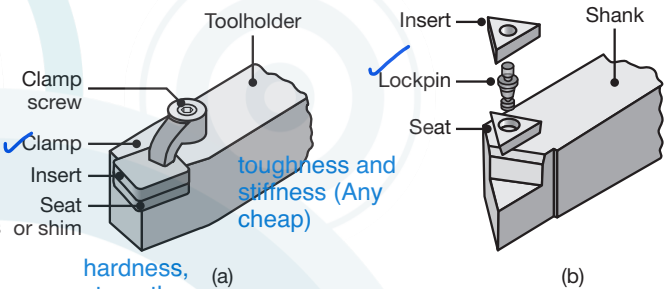


FIGURE 8.30 Methods of mounting inserts on toolholders: (a) clamping, and (b) wing lockpins. *Source:* Courtesy of Valenite.

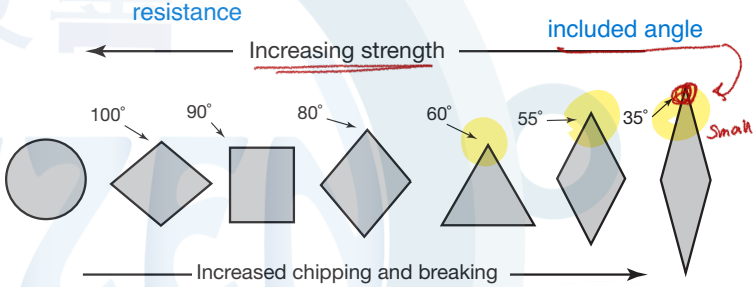


FIGURE 8.31 Relative edge strength and tendency for chipping and breaking of inserts with various shapes. Strength refers to that of the cutting edge shown by the included angles. *Source:* Courtesy of Kennametal, Inc.

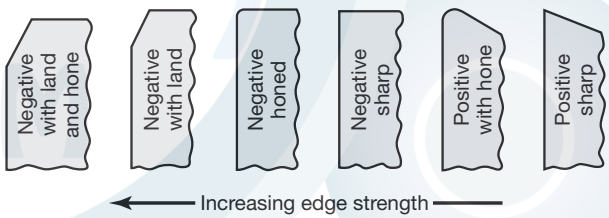


FIGURE 8.32 Edge preparations for inserts to improve edge strength. *Source:* Courtesy of Kennametal, Inc.

for specific applications, including toolholders with quick insertion and removal features, for more efficient operations.

The strength of the cutting edge of an insert depends on its shape; the smaller the included angle of the edge (Fig. 8.31), the lower its strength. In order to further improve edge strength and prevent chipping, insert edges are usually honed, chamfered, or they are made with a negative land (Fig. 8.32). Most inserts are honed to a radius of about 0.025 mm.

8.6.5 Coated Tools

A variety of materials are available as coatings, typically over high-speed steel and carbide tools. Because of their unique properties, **coated tools** can be used at high cutting speeds, thus reducing the machining time, and hence costs. It has been shown that coated tools can improve tool life by an order of magnitude over uncoated tools; note in Fig. 8.33, for example,

x10
two order x100

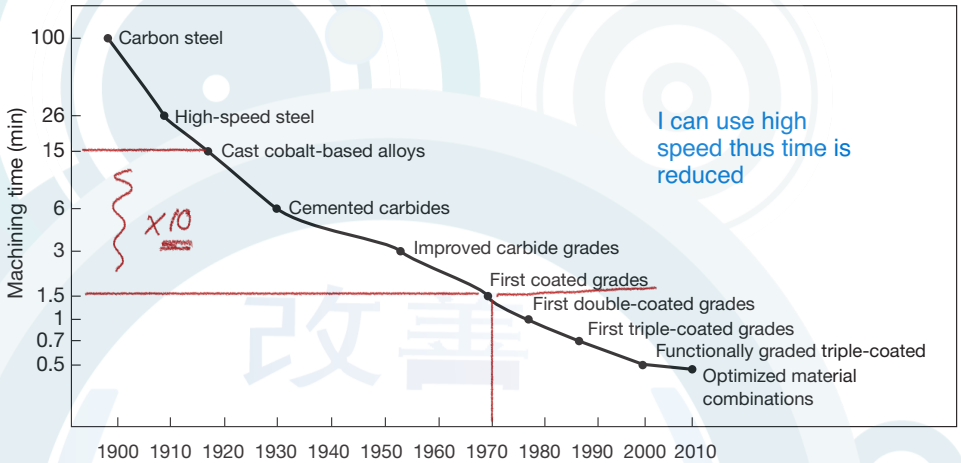
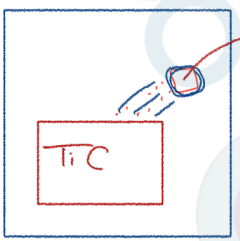


FIGURE 8.33 Relative time required to machine with various cutting-tool materials, with indication of the year the tool materials were introduced. Note that, within one century, machining time has been reduced by two orders of magnitude. *Source:* After Sandvik Coromant.

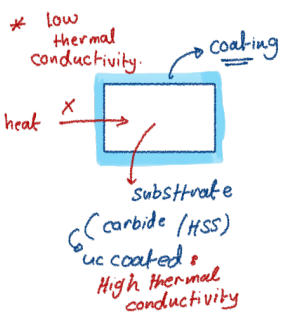


that the machining time has been reduced by a factor of more than 100 since 1900.

Commonly used *coating materials* include titanium nitride, titanium carbide, titanium carbonitride, and aluminum oxide (Al_2O_3), as described below. Generally in the thickness range of 2–10 μm, coatings are applied by **chemical vapor deposition** (CVD) and **physical-vapor deposition** (PVD) techniques, described in Section 4.5. The CVD process is the most common method for carbide tools with multiphase and ceramic coatings. The PVD-coated carbides with TiN coatings, on the other hand, have higher cutting-edge strength, lower friction, lower tendency to form a built-up edge, and are smoother and more uniform in thickness, which is generally in the range of 2–4 μm. **Medium-temperature chemical-vapor deposition** (MTCVD) provides higher resistance to crack propagation than do CVD coatings.

Coatings must have the following general characteristics:

- High hardness at elevated temperatures;
- Chemical stability and inertness to the workpiece material;
- Low thermal conductivity;
- Good bonding to the substrate; and
- Little or no porosity.



The effectiveness of coatings is enhanced by hardness, toughness, and high thermal conductivity of the substrate, which may be carbide or high-speed steel. Honing (see Section 9.7) of the cutting edges is an important procedure to maintain the strength of the coating and to prevent chipping at sharp edges and corners.

Various coatings are described below.

1. **Titanium nitride.** *Titanium nitride* (TiN) coatings have low coefficient of friction, high hardness, good high temperature properties, and good adhesion to the substrate. These properties greatly improve the life of high-speed steel tools and of carbide tools, drills, and cutters. Titanium-nitride coated tools (gold in color) perform well at higher cutting speeds and feeds; they do not perform as well as uncoated tools at low speeds, because the coating is susceptible to chip adhesion. Using appropriate cutting fluids to discourage chip-tool adhesion is therefore important. Flank wear is significantly lower than for uncoated tools (Fig. 8.34), and flank surfaces can be reground after use without removing the coating on the rake face of the tool.
2. **Titanium carbide.** *Titanium carbide* (TiC) coatings (silver-gray in color) over tungsten-carbide inserts have high resistance to flank wear, especially in machining abrasive materials.
3. **Titanium carbonitride.** *Titanium carbonitride* (TiCN), violet to mauve red in color (depending on carbon content), is deposited by physical-vapor deposition techniques, and is harder and tougher than TiN. It can be used over carbide and high-speed steel tools, and is particularly effective in cutting stainless steels.
4. **Ceramic coatings.** Because of their high-temperature performance, chemical inertness, low thermal conductivity, and resistance to flank and crater wear, ceramics are attractive coating materials. The most commonly used ceramic coating is *aluminum oxide* (Al_2O_3). However, because ceramic coatings are not chemically reactive, oxide coatings generally bond weakly to the substrate and thus they may have a tendency to peel off the tool.
5. **Multiphase coatings.** The desirable properties of various coatings can be combined and optimized by using *multiphase coatings* (Fig. 8.35). Coated carbide tools are available with two or three layers of such coatings, and are particularly effective in machining cast irons and steels.

In the example shown in Fig. 8.36, the first layer over the tungsten-carbide substrate is TiC, followed by Al_2O_3, and then TiN. It is important for (a) the first layer to bond well to the substrate; (b) the outer layer to resist wear and have low thermal conductivity; and

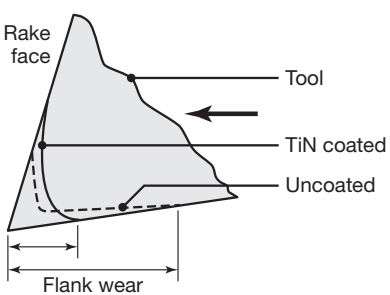


FIGURE 8.34 Wear patterns on high-speed steel uncoated and titanium-nitride-coated cutting tools. Note that flank wear is lower for the coated tool.

(c) the intermediate layer to bond well and be compatible with both layers.

Typical applications of multiple-coated tools are:

a. High-speed, continuous cutting: TiC/Al_2O_3;
b. Heavy-duty, continuous cutting: $TiC/Al_2O_3/TiN$; and
c. Light, interrupted cutting: TiC/TiC + TiN/TiN.

Coatings consisting of **alternating multiphase layers**, with layers that are thinner than in typical multiphase coatings. The thickness of these layers is in the range of 2–10 μm. The reason for using thinner coatings is that coating hardness increases with decreasing grain size, a phenomenon that is similar to the Hall-Petch effect (see Section 3.4.1).

like powder

6. **Diamond coatings.** Polycrystalline diamond is used as a thin coating, particularly over tungsten-carbide and silicon-nitride inserts. The films are deposited on substrates by PVD and CVD techniques, whereas thick films are produced by growing a large sheet of pure diamond, which is then laser cut to shape and brazed to a carbide shank. Diamond-coated tools are particularly effective in machining abrasive materials, such as aluminum-silicon alloys, graphite, and fiber-reinforced and metal-matrix composite materials (see Section 11.14). Improvements in tool life of as much as tenfold have been obtained over other coated tools.

like welding melting temp of connection is low

7. **Other coating materials.** Advances are continually being made in developing and testing new coating materials. **Titanium aluminum nitride** (TiAlN) is effective in machining aerospace alloys. Chromium-based coatings, such as **chromium carbide** (CrC), have been found to be effective in machining softer metals that tend to adhere to the cutting tool, such as aluminum, copper, and titanium. Other coating materials include **zirconium nitride** (ZrN) and **hafnium nitride** (HfN), **nanocoatings** with carbide, boride, nitride, oxide, or some combination, and **composite coatings**, using a variety of materials.

8.6.6 Alumina-Base Ceramics

Ceramic tool materials, introduced in the early 1950s, consist primarily of fine-grained, high-purity aluminum oxide. They are pressed into inserts, under high pressure and at room temperature, then sintered (see Section 11.4); they are called white, or cold-pressed, ceramics (see also Section 11.9.3). Titanium carbide and zirconium oxide can be added to improve such properties as toughness and resistance to thermal shock.

Alumina-base ceramic tools have very high abrasion resistance and hot hardness (Fig. 8.35). Chemically, they are more stable than high-speed steels and carbides, thus they have lower tendency to adhere to metals during machining and hence lower tendency to form a built-up edge. Consequently, good surface finish is obtained, particularly in machining cast irons and steels. However, ceramics lack toughness, which can result in premature tool failure by chipping or fracture. The shape and setup of ceramic tools also are important; negative rake angles, hence large included angles, are generally preferred in order to avoid chipping. Tool failure can be reduced by increasing the stiffness and damping capacity of machine tools and workholding devices, thus reducing vibration and chatter (see Section 8.12).

Cermets. *Cermets* (from the words *ceramic* and *metal*), also called black or hot-pressed ceramics (carboxides), typically contain 70% aluminum oxide and 30% titanium carbide. Other cermets may contain molybdenum carbide, niobium carbide, or tantalum carbide. The performance of cermets is between that of ceramics and carbides (See Fig. 8.35).

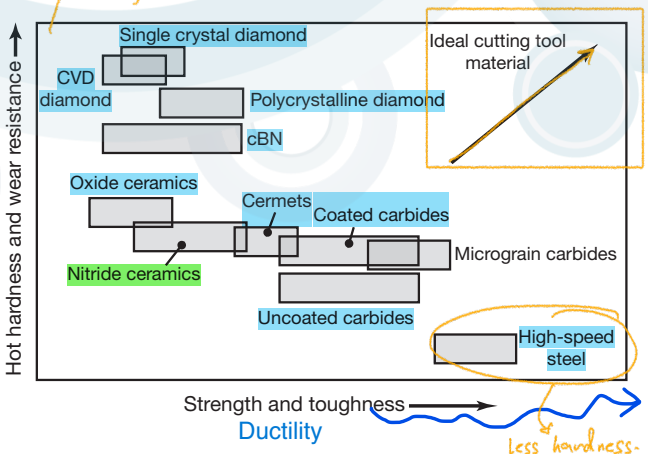


FIGURE 8.35 Ranges of properties for various groups of cutting-tool materials. (See also Tables 8.1 through 8.5.)

lattice
Cubic structure

8.6.7 Cubic Boron Nitride

Next to diamond, *cubic boron nitride* (cBN) is the hardest material presently available. The cutting tools are made by bonding a 0.5 to 1 mm layer of *polycrystalline cubic boron nitride* to a carbide substrate, by sintering under pressure (Fig. 8.36). While the carbide provides toughness, the cBN layer provides very high wear resistance and cutting-edge strength. Cubic-boron-nitride tools are also made in small sizes without a substrate. At elevated temperatures, cBN is chemically inert to iron and nickel and its resistance to oxidation is high; it is therefore particularly suitable for machining hardened ferrous and high-temperature alloys (see also *hard turning*, in Section 8.9.2). Because cBN tools are brittle, stiffness and damping capacity of the machine tool and fixturing devices is important in order to avoid vibration and chatter. Cubic boron nitride is also used as an abrasive, as described in Section 9.2.

by the matrix (Co)

8.6.8 Silicon-Nitride-Base Ceramics

Silicon-nitride-base ceramic (SiN) tool materials consist of silicon nitride with additions of aluminum oxide, yttrium oxide, and titanium carbide. These tools have high toughness, hot hardness, and good thermal-shock resistance. A common example is **sialon**, after the elements *si*licon, *al*uminum, *o*xygen, and *n*itrogen in its composition. It has higher resistance to thermal shock than silicon nitride and is recommended for machining cast irons and nickel-base superalloys, at intermediate cutting speeds. However, because of their chemical affinity to steels, SiN-base tools are not suitable for machining steels.

interrupted cutting and hard mat

BUE Crater wear

8.6.9 Diamond

The hardest substance of all known materials is *diamond*, a crystalline form of carbon (see also Section 11.13). As a cutting tool, it has low tool-chip friction, high wear resistance, and thus the ability to maintain a sharp cutting edge. Diamond is used where very fine surface finish and dimensional accuracy are required, particularly in machining abrasive nonmetallic materials and soft nonferrous alloys. *Single-crystal diamond* is used for special applications, such as machining copper-front high-precision optical mirrors. Diamond is brittle, and tool shape and sharpness are thus important; low rake angles and large included angles are normally used for a strong-cutting edge. Wear of diamond tools may occur by microchipping (caused by thermal stresses and oxidation) and transformation to carbon (caused by the high temperatures generated during machining).

Abrasive: harder than them

Soft: BUE wont form since stable.

Nonferrous: due to the chemical affinity of carbon to steel leading to the diffusion of carbon attoms into steel and thus crater wear.

If soft fer 100% BUE

very smooth

CO and carried away

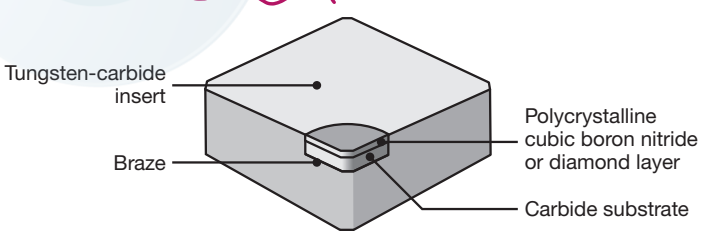


FIGURE 8.36 Construction of polycrystalline cubic-boron-nitride or diamond layer on a tungsten-carbide insert.

Single-crystal single-point diamond tools have been largely replaced by polycrystalline diamond tools (called *compacts*), that are also used as wire-drawing dies for fine wire (see Section 6.5). Compacts consist of very small synthetic crystals, fused to a thickness of about 0.5–1 mm, by a high-pressure, high-temperature process, and bonded to a carbide substrate, similar to cBN tools (See Fig. 8.36). The random orientation of the diamond crystals prevents the propagation of cracks through the compact, significantly improving its toughness.

Diamond tools can be used satisfactorily at almost any speed but are suitable mostly for light and uninterrupted finishing cuts. In order to minimize tool fracture, a single-crystal diamond tool must be resharpened as soon as it becomes dull. Because of its strong chemical affinity, diamond is not recommended for machining plain-carbon steels (as is the case with sialon tools) and titanium, nickel, and cobalt-base alloys. Diamond is also used as an abrasive in grinding and polishing operations (Chapter 9), and as a wear-resistant coating (see Section 4.5).

8.6.10 Whisker-Reinforced and Nanocrystalline Tool Materials

In order to further improve the performance and wear resistance of cutting tools, particularly in machining abrasive and hard workpieces, new tool materials are continually being developed with enhanced properties, such as (a) high fracture toughness, (b) resistance to thermal shock, (c) cutting-edge strength, and (d) hot hardness.

Whiskers. *Whiskers* are used as reinforcing fibers in composite tool materials. Examples of **whisker-reinforced** materials include silicon-nitride-base tools reinforced with silicon-carbide (SiC) whiskers, and aluminum-oxide-base tools reinforced with silicon-carbide whiskers, sometimes with the addition of *zirconium oxide* (ZrO_2).

Micrograin carbides. Progress in nanomaterials (Section 3.11.9) has led to the development of cutting tools that are made of very fine-grained (*micrograin*, with grain size in the range of 0.2 to 0.8 μm) carbides of tungsten, titanium, and tantalum. These materials are stronger, harder, and more wear resistant than traditional carbides. In one application, for example, drills with diameters on the order of 100 μm are made from these materials and used in the fabrication of microelectronic circuit boards (see Chapter 13).

Functionally-graded carbides. In these tools, the composition of the carbide in the insert varies through its near-surface depth, instead of being uniform as in carbide inserts. Materials with graded mechanical properties eliminate stress concentrations and promote better tool life and performance; however, they are more expensive, and may not be justified for all applications.

8.6.11 Cryogenic Treatment of Cutting Tools

The beneficial effect of cryogenic treatment of tools and other metals on their performance in machining operations (see Section 5.11.6 for details) continues to be of some interest. In this application, the tool is cooled very

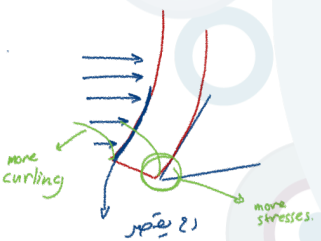
slowly to temperatures of about −180°C and slowly returned to room temperature; it is then tempered. Depending on the combinations of tool and workpiece materials involved, tool-life increases of up to 300% can be achieved with this procedure.

8.7 Cutting Fluids

Cutting fluids are used extensively in machining operations to:

- Cool the cutting zone, thus reducing workpiece temperature and distortion, and improving tool life;
- Reduce friction and wear, thus improving tool life and surface finish;
- Reduce forces and energy consumption;
- Wash away chips; and
- Protect the newly machined surfaces from environmental attack.

A cutting fluid predominantly serves as a **coolant** and/or as a **lubricant** (see Section 4.4.4). Its effectiveness in machining operations depends on several factors, such as the method of application, temperature, cutting speed, and type of machining operation. There are situations, however, in which the use of cutting fluids can be detrimental. For example, in interrupted cutting operations, such as milling (Section 8.10), the cooling action of the cutting fluid increases the extent of alternate heating and cooling (*thermal cycling*) to which the cutter teeth are subjected, a condition that can lead to the development of thermal cracks (*thermal fatigue* or *thermal shock*). Moreover, cutting fluids may also cause the chip to become more curled (i.e., smaller radius of curvature), concentrating the stresses on the tool closer to its tip, thus concentrating the heat closer to the tool tip and reduce tool life.



Cutting fluids can present **biological and environmental hazards** (see also Section 4.4.4), requiring proper recycling and disposal, and adding to cost. For these reasons, **dry cutting, or dry machining**, has become an increasingly important approach, in which no coolant or lubricant is used in the machining operation (see Section 8.7.2). Even though this approach would suggest that higher temperatures and thus more rapid tool wear would occur, some tool materials and coatings maintain an acceptable tool life. Dry cutting has been associated with high-speed machining, because higher cutting speeds transfer a greater amount of heat to the chip (See Fig. 8.18), which is an incentive for reducing the need for a coolant. See also Section 3.9.7 on possible detrimental effects of cutting fluids on some cutting tools, called *selective leaching*, such as in carbide tools with cobalt binders.

8.7.1 Types of Cutting Fluids and Methods of Application

There are four basic types of cutting fluids commonly used in machining operations: **oils, emulsions**, **semisynthetics**, and **synthetics** (see Section 4.4.4). Cutting-fluid recommendations for specific machining operations are given throughout the rest of this chapter. In selecting an appropriate