

Chapter 21.

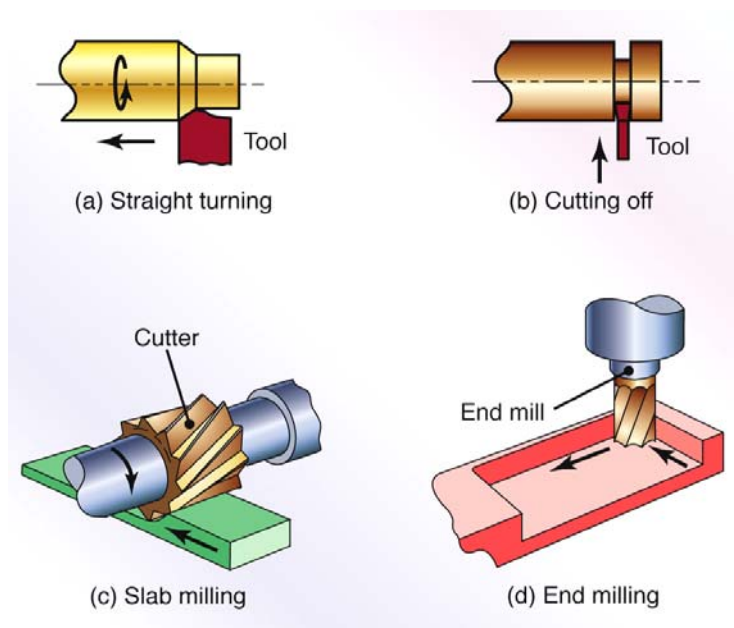
Fundamentals of Machining

21.1 Introduction

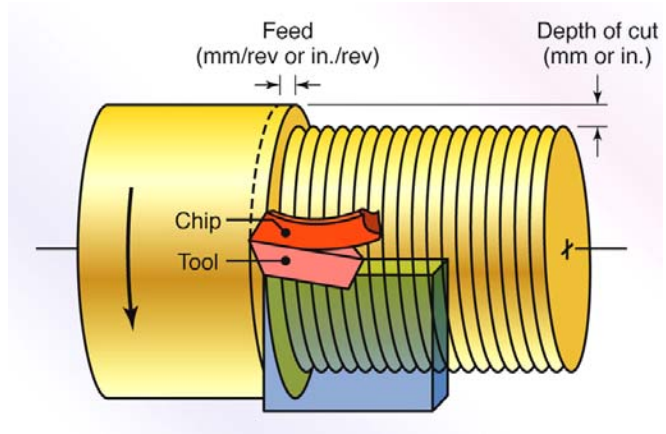
- ❖ Parts manufactured by casting, forming, and shaping processes often require further operations before the product is ready to use.
- ❖ **Features** such as smooth shiny surfaces, small-diameter deep holes in a part, threaded section, and threaded holes all require further manufacturing operations.
- ❖ **Machining** is a general term describing a group of processes that consist of the **removal** of material and modification of the surfaces of a workpiece after it has been produced.
- ❖ **Machining** involves operations such as turning, boring, drilling, milling, planing, shaping, broaching, and grinding, ultrasonic machining; chemical, electrical, electrochemical machining; and high-energy-beam machining. Thus, machining involves secondary and finishing operations.
- ❖ Another **classification** of machining processes: cutting, abrasive processes, and advance machining processes.
- ❖ Machining operations is viewed as a system consisting of:
 - ✓ Workpiece,
 - ✓ Cutting tool,
 - ✓ Machine tool, and
 - ✓ Production personnel.

- ❖ **Cutting processes** remove material from the surface of workpiece by producing chips. Some of the more common cutting processes are illustrated in the Figure:

- **Turning**, in which the workpiece is rotated and a cutting tool removes a layer of material as it moves to the left.
- **Cutting-off** operation, where the cutting tool moves radially inward and separates the right piece from the bulk of blank.
- **Slab-milling** operation, in which a rotating cutting tool removes a layer of material from the surface of workpiece.
- **End-milling** operation, in which a rotating cutter travels along a certain depth in the workpiece and produces a cavity.



- ❖ The turning process is shown with greater detail. The cutting tool is set at a certain **depth of cut** (mm or in.) and travels to left with a certain velocity as the workpiece rotates.
- ❖ The feed or **feed rate** is the distance the tool travels horizontally per unit revolution of the workpiece (**mm/rev** or **in./rev**). This movement of the tool produces a chip which moves up the face of the tool.



- ❖ To analyze this process in detail, a 2-D model of it is represented in Fig. 21.3a.
 - ✓ In this idealized model, a cutting tool moves to the left along the workpiece at a constant **velocity** V , and a **depth of cut** t_o .
 - ✓ A **chip** is produced a head of the tool by plastically deforming and shearing the material continuously along the shear plane. (butter stick—chocolate shavings).

- ❖ Comparing Figs. 21.2 and 21.3, note that the feed in turning is equivalent to t_o and the depth of the cut in turning is equivalent to the width of the cut (dimension perpendicular to the page) in the idealized model. These relationships can be visualized by rotating Fig. 21.3 clockwise by 90° .

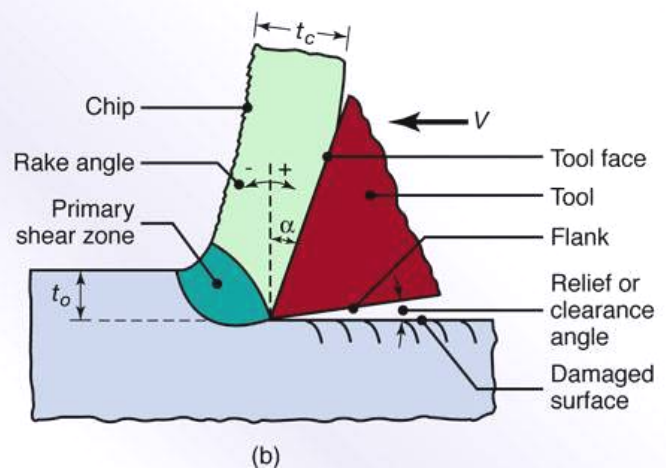
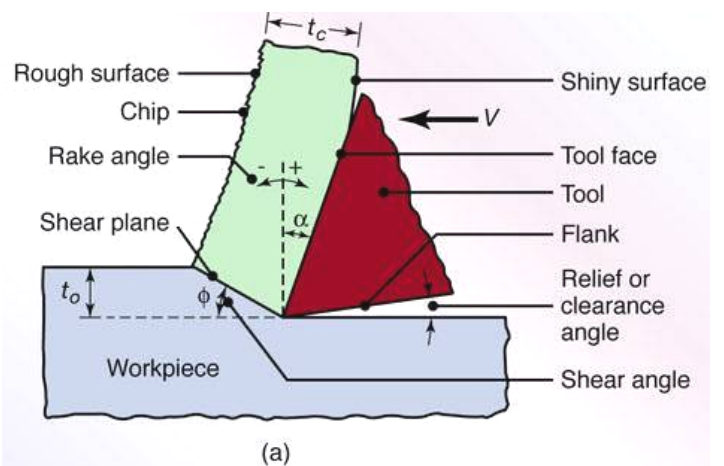


Figure 21.3 Schematic illustration of a two-dimensional cutting process, also called orthogonal cutting: (a) Orthogonal cutting with a well-defined shear plane, also known as the Merchant Model. Note that the tool shape, depth of cut, t_o , and the cutting speed, V , are all independent variables, (b) Orthogonal cutting without a well-defined shear plane.

21.2 Mechanics of Cutting

- ❖ The factors that influence the cutting process are outlined in Table 21.1.

TABLE 21.1

Factors Influencing Machining Operations

Parameter	Influence and interrelationship
Cutting speed, depth of cut, feed, cutting fluids	Forces, power, temperature rise, tool life, type of chip, surface finish and integrity
Tool angles	As above; influence on chip flow direction; resistance to tool wear and chipping
Continuous chip	Good surface finish; steady cutting forces; undesirable, especially in automated machinery
Built-up edge chip	Poor surface finish and integrity; if thin and stable, edge can protect tool surfaces
Discontinuous chip	Desirable for ease of chip disposal; fluctuating cutting forces; can affect surface finish and cause vibration and chatter
Temperature rise	Influences tool life, particularly crater wear and dimensional accuracy of workpiece; may cause thermal damage to workpiece surface
Tool wear	Influences surface finish and integrity, dimensional accuracy, temperature rise, forces and power
Machinability	Related to tool life, surface finish, forces and power, and type of chip

- ❖ To understand this table, let us identify the **major independent variables** in the cutting process:
 - Tool material and coatings;
 - Tool shape, surface finish, and sharpness;
 - Workpiece material and condition;
 - Cutting speed, feed, and depth of cut;
 - Cutting fluids;
 - Characteristics of the machine tool (such as its stiffness and damping); and
 - Workholding and fixturing.
- ❖ **Dependent variables** in cutting are those that are influenced by changes in the independent variables listed above, and include:
 - Type of chip produced,
 - Force and energy dissipated during cutting,
 - Temperature rise in the workpiece, the tool, and chip,
 - Tool wear and failure, and
 - Surface finish of the workpiece after machining.
- ❖ When machining operations yield unacceptable results, a typical question posed is *which of the independent variables should be changed first and to what extent*, if:
 - The surface finish of the workpiece being cut is poor and unacceptable,
 - The cutting tool wears rapidly and becomes dull,
 - The workpiece becomes very hot, and
 - The tool begins to vibrate and chatter.

❖ **The Mechanics of Chip Formation:**

- ✓ To answer the above questions, we need to study the mechanics of chip formation. A subject that has been studied since early 1940's where several models have been proposed.
- ✓ Fig. 21.3a shows the simple model (referred as the M.E. Merchant model) is sufficient for our purpose. It is called **orthogonal cutting** (forces involved are perpendicular to each other).

❖ **Orthogonal cutting:**

- ✓ The cutting tool has a **rake angle** of α , and a **relief (clearance) angle**.
- ✓ Microscopic examination of chips obtained in actual machining operations has revealed that they are produced by shearing (see Fig. 21.4a) – similar to the movement in a deck of cards sliding against each other.
- ✓ Shearing takes place along a well-defined plane called shear plane at an angle ϕ called the **shear angle**.
- ✓ The dimension d in the figure is highly exaggerated to show the mechanism involved. This dimension is only on the order of 10^{-2} to 10^{-3} mm.
- ✓ Some materials (cast irons at low speeds) do not shear along a well-defined plane but instead in a zone as shown in Fig. 21.3b.

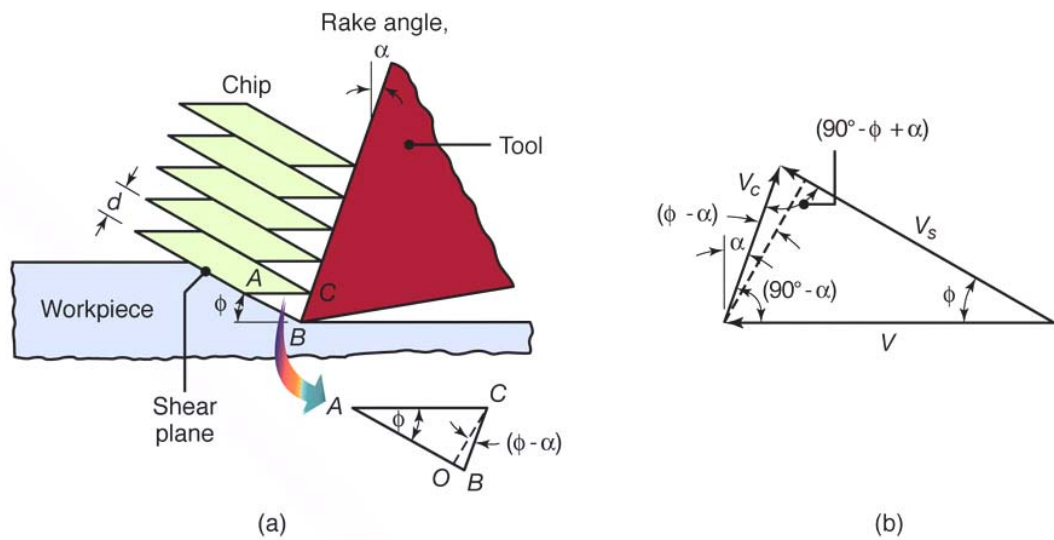


Figure 21.4 (a) Schematic illustration of the basic mechanism of chip formation by shearing. (b) Velocity diagram showing angular relationships among the three speeds in the cutting zone.

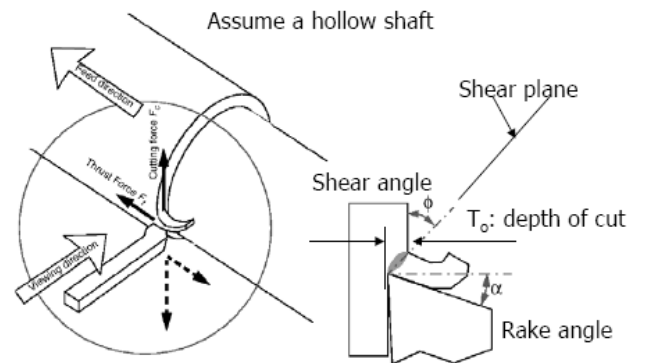
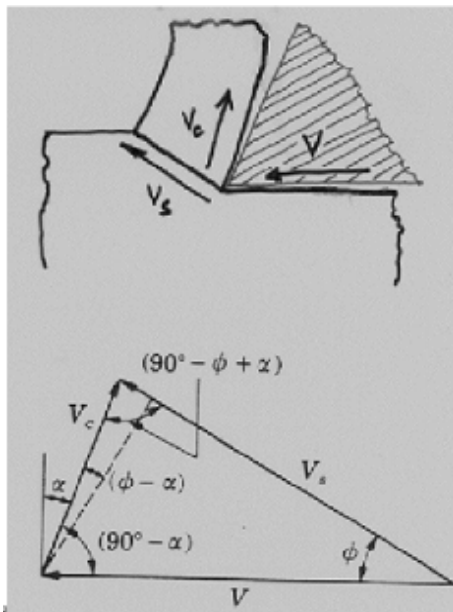
- ✓ **Cutting ratio.** The chip thickness t_c can be determined by knowing the depth of the cut t_o , and α and ϕ . The ratio of t_o/t_c is known as the **cutting ratio, r**, related to the two angles by:

$$\tan \phi = \frac{r \cos \alpha}{1 - r \sin \alpha} \quad (21.1a)$$

and

$$r = \frac{t_o}{t_c} = \frac{\sin \phi}{\cos(\phi - \alpha)} \quad (21.1b)$$

- ✓ The chip thickness is always greater than the depth of cut; therefore, the *value of r is always less than 1*.
- ✓ The *reciprocal of r* is known as the **chip compression ratio** and is a measure of how thick the chip has become compared to the depth of cut. Thus the chip compression ratio is always greater than 1.
- ✓ The depth of the cut (feed) is referred to as undeformed chip thickness.
- ✓ To visualize this situation, assume that the workpiece is a *thin-walled* tube the width of the cut is the same as the thickness of the tube. See Figure.



- ✓ **Shear strain.** Referring to Fig. 21.4a, we can express the shear strain, γ , that the material undergoes as:

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

$$\gamma = \cot \phi + \tan(\phi - \alpha) \quad (21.2)$$

- ✓ Note that large shear strains are associated with low shear angles or low or negative rake angles.
- ✓ Shear strains of 5 or higher have been observed in actual cutting operations.
- ✓ Deformation in cutting generally takes place within a very narrow deformation zone; that is, the dimension $d = OC$ in Fig. 4.21a is very small; therefore, the rate at which shearing takes place is high.
- ✓ The shear angle has great significance in the mechanics of cutting operations. It influences: **force and power requirements, chip thickness, and temperature.**
- ✓ Consequently, much attention has been focused on determining the relationships between the shear angle and workpiece material properties and cutting process variables.

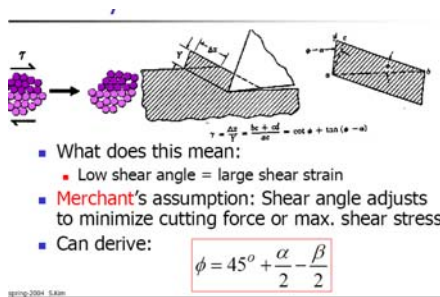
- ✓ One of the earliest analyses was based on the *assumption that the shear angle adjusts itself to minimize the cutting force*, or that the shear plane is a plane of *maximum shear stress*. The analysis yielded the expression

$$\phi = 45^\circ + \frac{\alpha}{2} - \frac{\beta}{2} \quad (21.3)$$

Where β is the *friction angle* and is related to the *coefficient of friction, μ , at the tool – chip interface* (rake face) by the expression:

$$\mu = \tan \beta \quad (21.3a)$$

- ✓ Equation (21.3) indicates that: (a) as the rake angle decreases and / or the friction at the tool – chip interface increases, the shear angle decreases and the chip becomes thicker; (b) thicker chips mean more energy dissipation because the shear strain is higher [see Eq. (21.2)]; and (c) because work done during cutting is converted into heat, temperature rise is also higher.



- ✓ **Velocities in the cutting zone.** From Fig. 21.3, note that (since chip thickness is greater than the depth of cut) the velocity of the chip, V_c , has to be lower than the cutting speed, V .
- ✓ Since mass continuity has to be maintained, we have Hence,

$$V t_o = V_c t_c \quad \text{or} \quad V_c = V r$$

Hence,
$$V_c = \frac{V \sin \phi}{\cos(\phi - \alpha)} \quad (21.5)$$

- ✓ A velocity diagram constructed (Fig. 21.4b), from trigonometry (law of sines) we obtain the equation:

$$\frac{V}{\cos(\phi - \alpha)} = \frac{V_s}{\cos \alpha} = \frac{V_c}{\sin \phi} \quad (21.6a)$$

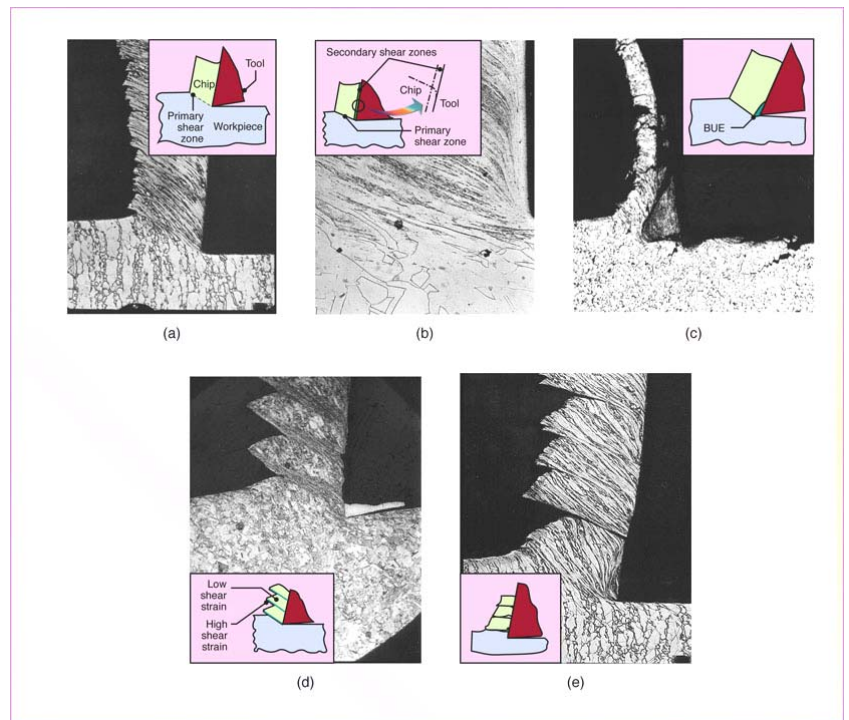
where V_s is the velocity at which shearing takes place in the shear plane. Note also that:

$$r = \frac{t_o}{t_c} = \frac{V_c}{V} \quad (21.6b)$$

21.2.1 Types of chips produced in metal cutting

- ❖ **Types of metal chips** are commonly observed in practice and their photomicrographs shown in Fig. 21.5. The four main types are:
 - a) Continuous,
 - b) Built-up edge,
 - c) Serrated or segmented, and
 - d) Discontinuous.
- ❖ A chip has two surfaces: one that is in contact with the rake face of the tool and has shiny and burnished appearance caused by rubbing as the chip moves up the tool face. The other surface is from the original surface of the workpiece, it has a jagged, rough appearance (Fig. 20.3), which is caused by the shearing mechanism shown in fig. 21.4a.
- ❖ **A. Continuous Chips.**
 - ✓ Formed with ductile materials at high cutting speeds and/or high rake angles (Fig. 21.5a). The deformation of the material takes place along a narrow shear zone, the primary shear zone.
 - ✓ Continuous chips may develop a secondary shear zone (Fig. 21.5b) because of high friction at tool-chip interface, this zone becomes thicker as tool –chip friction increases.
 - ✓ In continuous chips, deformation may also take place along a wide primary shear zone with curved boundaries (see Fig. 21.3) unlike that shown in Fig. 21.5a.
 - ✓ Note that the lower boundary is below the machined surface, subjecting the machined surface to distortion, as depicted by the distorted vertical lines in the machines subsurfaces. This situation occurs particularly in machining soft metals at low speeds and low rake angles. It can produce poor surface finish and induce residual surface stresses.
 - ✓ Although they generally produce good surface finish, continuous chips are not always desirable, particularly with the computer-controlled machine tools widely used today, as they tend to be tangled around the tool holder, the fixturing, the workpiece, as well as the chip-disposal system. This problem can be eliminated by chip breakers, or by changing parameters such as cutting speed or depth of cut.

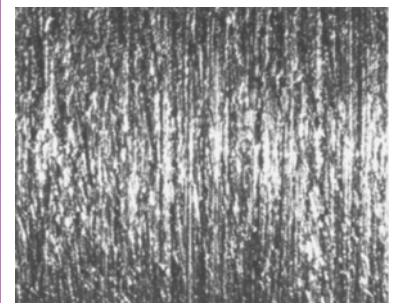
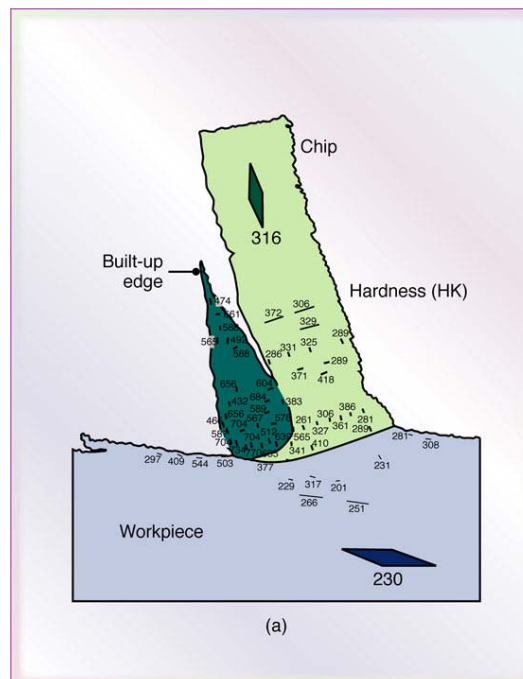
Figure 21.5 Basic types of chips produced in orthogonal metal cutting, their schematic representation, and photomicrographs of the cutting zone: (a) continuous chip with narrow, straight, and primary shear zone; (b) continuous chip with secondary shear zone at the chip-tool interface; (c) built-up edge; (d) segmented or nonhomogeneous chip; and (e) discontinuous chip.



❖ B. Built-up edge Chips

- ✓ A built-up edge (BUE) consists of layers of material from the workpiece that are gradually deposited on the tool tip, Fig. 21.5c).
- ✓ As it becomes larger, the BUE becomes unstable and eventually breaks apart.
- ✓ Part of the BUE material is carried away by the tool-side of the chip; the rest is deposited randomly on the workpiece surface.
- ✓ The process of BUE formation and destruction is repeated continuously during the cutting operation, unless measures are taken to eliminate it. In fact, build-up edge changes the geometry of the cutting edge and dulls it (Fig.21.6a).
- ✓ Although BUE adversely affects the surface finish (Fig. 21.5c and 21.6b and c), a thin, stable BUE is usually regarded as desirable because it reduces tool wear by protecting its rake face.
- ✓ Cold-worked metals generally have less tendency to form BUE than in their annealed conditions.
- ✓ Because of work hardening and deposition of successive layers of material, the BUE hardness increases significantly (Fig. 21.6a).
- ✓ As the cutting speed increases the size of the BUE decreases, in fact it may not form at all.
- ✓ The tendency for a BUE to form is also reduced by any of the following practices:
 - Increase the cutting speeds,
 - Decrease the depth of cut,
 - Increase the rake angle,
 - Use a sharp tool,
 - Using an effective cutting fluid, and
 - Use a cutting tool that has lower chemical affinity (tendency to form bond) for the workpiece material.

Figure 21.6 (a) Hardness distribution with a built-up edge in the cutting zone (material, 3115 steel). Note that some regions in the built-up edge are as much as three times harder than the bulk metal of the workpiece. (b) Surface finish produced in turning 5130 steel with a built-up edge. (c) Surface finish on 1018 steel in face milling. Magnifications: 15x

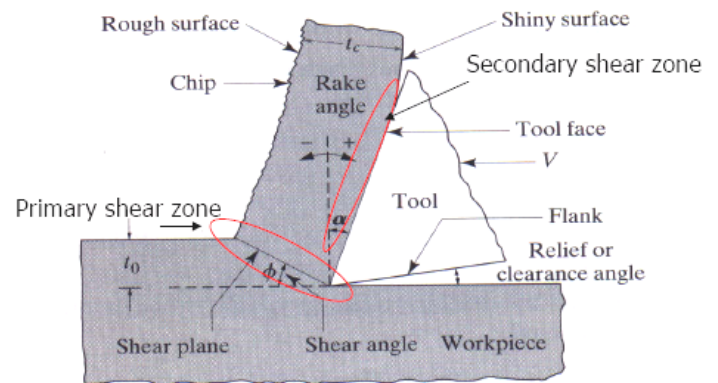


❖ C. Serrated Chips

- ✓ Serrated chips (also called segmented or nonhomogeneous chips) are semicontinuous chips with large zones of low shear strain and small zones with high shear strain (Fig. 21.5d).
- ✓ Metals with low thermal conductivity and strength that decreases sharply with temperature (thermal softness) exhibit this behavior such as titanium.
- ✓ The chips have a sawtooth-like appearance.

❖ D. Discontinuous Chips

- ✓ Discontinuous chips consist of segments that may be firmly or loosely attached to each other (Fig. 21.5e).
- ✓ Discontinuous chips usually form under the following conditions:
 - Brittle workpiece materials.
 - Workpiece materials that contain hard inclusions and impurities, or have structures such as the graphite flakes in gray cast iron.
 - Very low or very high cutting speeds.
 - Large depths of cut.
 - Low rake angles.
 - Lack of an effective cutting fluid.
 - Low stiffness of the tool holder or the machine tool, thus allowing vibration and chatter to occur.
- ✓ Because of the discontinuous nature of chip formation, forces continually vary during cutting.
- ✓ Consequently, the stiffness or rigidity of the cutting-tool holder, the workholding devices, and the machine tool are important in cutting with both discontinuous chips and serrated chips.



❖ Chip Curl.

- ✓ In all cutting operations performed on metals, as well as nonmetallic materials such as plastic and wood, chips develop a curvature (chip curl) as they leave the workpiece surface (Fig. 21,5).
- ✓ Some factors that affect the chip curl are:
 - The distribution of stresses in the primary and secondary shear zones.
 - Thermal effects.
 - Work-hardening characteristics of the workpiece material.
 - The geometry of the cutting tool.
 - Cutting fluids.
- ✓ Process variables also affect chip curl. Generally, as the depth of cut decreases, the radius of curvature decreases; that is, the chip becomes curlier.
- ✓ Also, cutting fluids can make chips become more curly, thus reducing the tool-chip contact area and concentrating the heat closer to the tip of the tool. As a result, tool wear increases.

❖ **Chips Breakers.**

- ✓ As mentioned earlier, continuous and long chips are undesirable as they tend to become entangled and severely interfere with machining operations and also become a potential safety hazard.
- ✓ If all of the process variables are under control the usual procedure to avoid this situation is to use cutting tools with that have **chip breaker** features (Fig. 22.2).
- ✓ Chip breakers have traditionally been a piece of metal clamped to the tool's rake face, which bend and break the chip.
- ✓ However, most modern cutting tools and inserts now have built-in chip-breaker features (see Fig. 21.8).
- ✓ Chips breakers increase the effective rake angle of the tool and, consequently, increase the shear angle.
- ✓ Chips can also be broken by changing the tool geometry to control chip flow, as in the turning operations shown in Fig. 21.8.
- ✓ Experience has indicated that the ideal chip size to be broken is in the shape of the letter C or the number 9 and fits within a 25 mm (1 in.) square space.
- ✓ With soft workpiece materials such as pure aluminum or copper, chip breaking by such means is generally not effective.
- ✓ Common techniques used with such materials, include machining at small increments (pausing so that a chip is not generated) or reversing the feed by small increments.
- ✓ In interrupted-cutting operations, such as milling, chip breakers are generally not necessary, since the chips already have finite lengths.

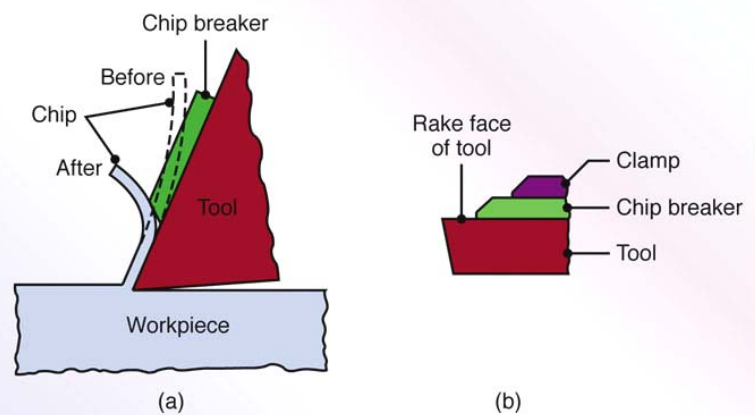
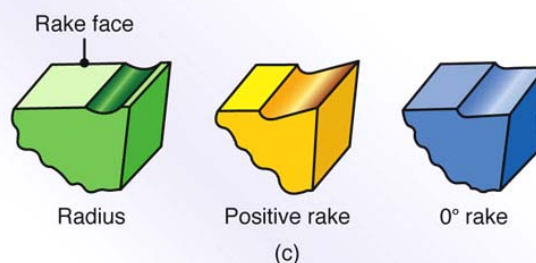


Figure 21.7 (a) Schematic illustration of the action of a chip breaker. Note that the chip breaker decreases the radius of curvature of the chip and eventually breaks it. (b) Chip breaker clamped on the rake face of a cutting tool. (c) Grooves in cutting tools acting as chip breakers. Most cutting tool used now are *inserts* with built-in chip breaker features.



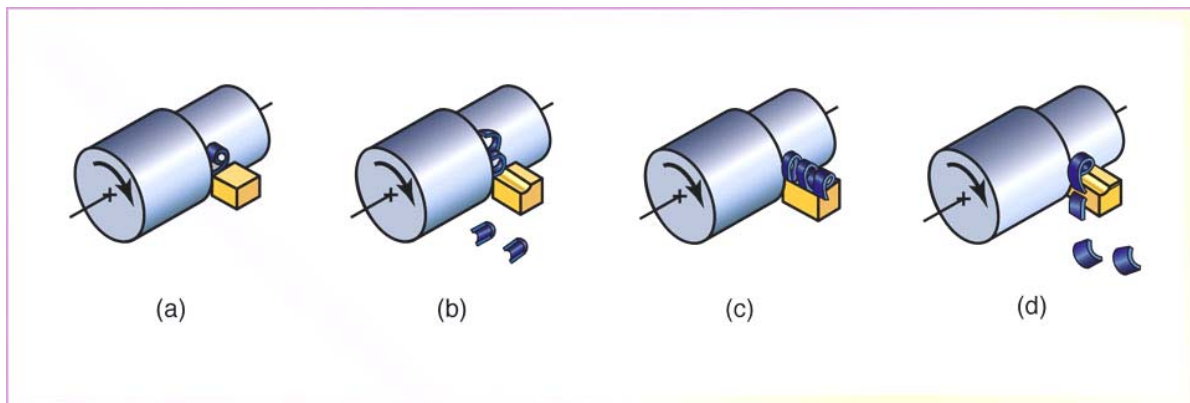


Figure 21.8 Chips produced in turning: (a) tightly curled chip; (b) chip hits workpiece and breaks; (c) continuous chip moving radially away from workpiece; and (d) chip hits tool shank and breaks off.

❖ **Controlled Contact on Tools.**

- ✓ Cutting tools can be designed so that the tool-chip contact length is reduced by recessing the rake face of the tool some distance away from its tip.
- ✓ This reduction in contact length affects chip-formation mechanics. Primarily, it reduces the cutting forces and, thus, the energy and temperature.
- ✓ Determination of an optimum length is important as too small a contact length would concentrate the heat at the tool tip, thus increasing wear.

❖ **Chip Formation in Nonmetallic Materials.**

- ✓ A variety of chips are encountered in cutting thermoplastics, depending of the polymer and process parameters, such as depth of cut, tool geometry, and cutting speed. Many of the discussions concerning metals also are applicable generally to polymers.
- ✓ Because they are brittle, thermosetting plastics and ceramics generally produce discontinuous chips. See section 21.7.3 for other machined materials such as wood, ceramics, and composite materials.

21.2.2 The Mechanics of Oblique Cutting

- ❖ Majority of machining operations involves tool shapes that are 3-D, thus the cutting is oblique.
- ❖ Figure 21.9a shows the basic difference between oblique and orthogonal cutting.
- ❖ Whereas in orthogonal cutting, the chip slide directly up the face of the tool, in oblique cutting, the chip is helical and at an angle I , called the inclination angle (Fig. 21.9b).
- ❖ The chip in Fig. 20.9a flows up the rake face of the tool at angle α_c (chip flow angle), which is measured in the plane of the tool face.
- ❖ Angle α_n , the **normal** rake angle, is a basic geometric property of the tool. This is the angle between the normal oz to the workpiece surface and the line oa on the tool face.

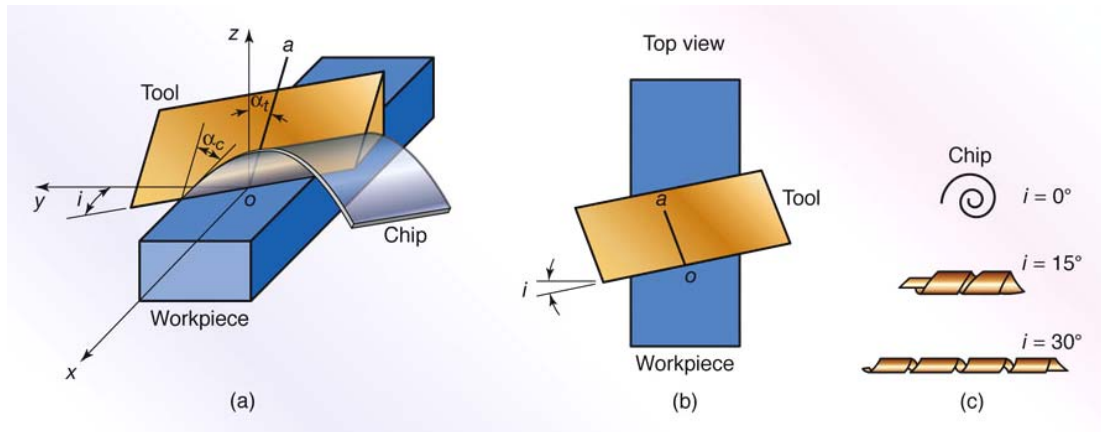


Figure 21.9 (a) Schematic illustration of cutting with an oblique tool. Note the direction of chip movement. (b) Top view, showing the inclination angle, i , (c) Types of chips produced with tools at increasing inclination angles.

- ❖ The workpiece material approaches the tool at a velocity V and leaves the surface (as a chip) with a velocity V_c .
- ❖ The effective rake angle α_e is calculated in the plane of these two velocities.
- ❖ Assuming that the chip flow angle α_c is equal to the inclination angle i , the effective rake angle α_e is

$$\alpha_e = \sin^{-1}(\sin^2 i + \cos^2 i * \sin \alpha_n) \quad (21.7)$$

- ❖ As i increases, the effective rake angle increases and the chip becomes thinner and longer, and hence the cutting force decrease. The influence of the inclination angle on chip shape is shown in Fig. 21.9c.

- ❖ A typical single-point turning tool used on a lathe is shown in Fig. 21.10a. The majority of cutting tools are now available in inserts (see Fig. 21.10b).

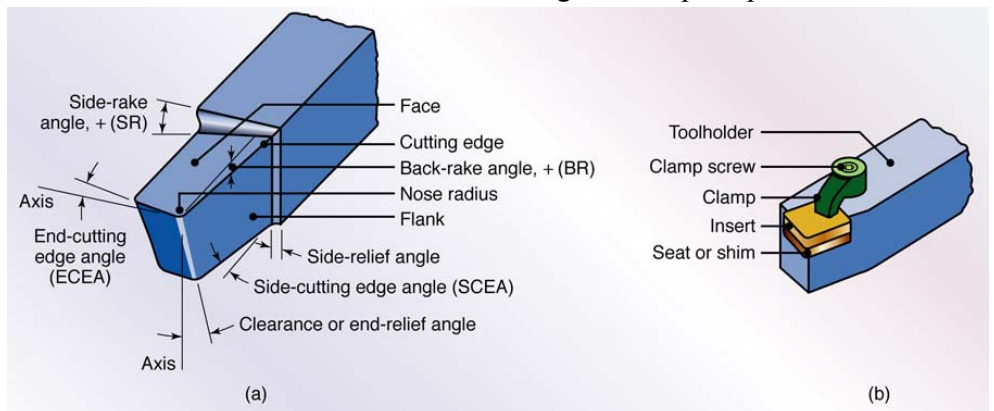


Figure 21.10 (a) Schematic illustration of right-hand cutting tool. The various angles on these tools and their effects on machining are described in Section 23.3.1 Although these tools traditionally have been produced from solid tool-steel bars, they have been replaced largely with (b) inserts made of carbides and other materials of various shapes and sizes.

21.3 Cutting Forces and Power

- ❖ Knowledge of cutting forces and power involved in machining is important for the following reasons:
 - ✓ Data on cutting forces is essential so that (a) machine *tools can be properly designed* to minimize distortion of the machine components, maintain dimensional accuracy of the part, and help select appropriate toolholders and workholding devices, and (b) the workpiece is capable of withstanding these forces without excessive distortion.
 - ✓ Power requirement must be known in order to enable the selection of a machine tool with *adequate electric power*.
- ❖ The *cutting force*, F_c , acts in the direction of the cutting speed, V , and supplies the energy required for cutting.
- ❖ The *thrust force*, F_t , acts in a direction normal to the cutting velocity, that is, perpendicular to the workpiece.
- ❖ These two forces produce the *resultant force*, R . See Figure below.
- ❖ The resultant force can 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 it.

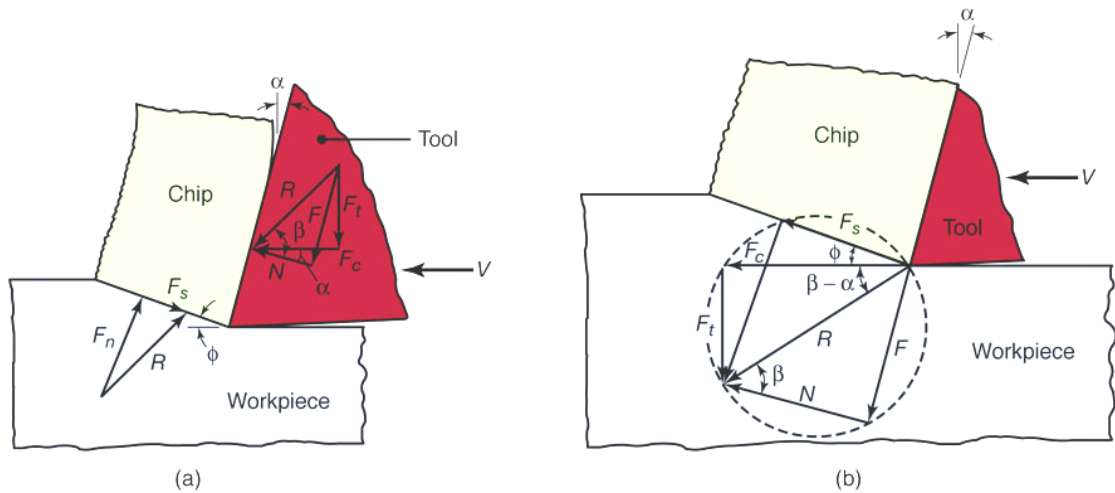


Figure 21.11 (a) Forces acting on a cutting tool during two-dimensional cutting. Note that the resultant force, R , must be collinear to balance the forces. (b) Force circle to determine various forces acting in the cutting zone.

- ❖ Using Fig. 21.11, we may write

$$F = R \sin \beta \quad (20.8a)$$

$$N = R \cos \beta \quad (20.8b)$$

- ❖ The resultant force, also, is balanced by an equal and opposite force *along the shear plane* and is resolved into a shear force, F_s , and a normal force, F_n .
- ❖ It can be shown that these forces can be expressed as follows:

$$F_s = F_c \cos \phi - F_t \sin \phi \quad (21.9)$$

and

$$F_n = F_c \sin \phi + F_t \cos \phi \quad (21.10)$$

- ❖ Because we can calculate the area of the shear plane by knowing the shear angle and the depth of cut, we can determine the shear and normal stresses in the shear plane.
- ❖ The ratio of F to N is the *coefficient of friction*, μ , at the tool-chip interface, and the angle β is the friction angle (as in Eq. 21.3a), see figure above. We can express μ , as

$$\mu = \frac{F}{N} = \frac{F_t + F_c \tan \alpha}{F_c - F_t \tan \alpha} \quad (21.11)$$

- ❖ The coefficient of friction in metal cutting generally ranges from *about 0.5 to 2*.

A. Thrust Force:

- ❖ If the thrust force is too high or if the machine tool is not sufficiently stiff, the tool will be pushed *away from the surface being machined*.
- ❖ This movement will, in turn, *reduce the depth of cut*, resulting in *lack of dimensional accuracy* in the machined part.
- ❖ Also, we can show the effect of rake angle and friction angle on the direction of the thrust force by noting from Fig. 21.11b that:

$$F_t = R \sin(\beta - \alpha) \quad (21.12a)$$

Or
$$F_t = F_c \tan(\beta - \alpha) \quad (21.12b)$$

- ❖ As the rake angle increases and/or friction at the rake face decreases, this force can act upward. When $\beta > \alpha$, the sign of F_t is positive (downward), and when $\beta < \alpha$, the sign is negative (force is upward).
- ❖ Therefore, it is possible to have an upward thrust force under the conditions of (a) high rake angles, (b) low friction at the tool-chip interface, or (c) both.
- ❖ This situation can be visualized by noting that when $\mu = 0$ (that is, $\beta = 0$), the resultant force, R , coincides with the normal force, N . In this case, R will have a thrust-force component that is upward.

B. Power:

- ❖ Power is defined as the product of force and velocity.
- ❖ The power input in cutting is

$$\text{Power input in cutting} = F_c V \quad (21.13)$$

This power is dissipated mainly in the shear zone *need energy to shear the material and on the rake face (due to tool-chip interface friction).

- ❖ From Figs. 21.4b and 21.11, the power dissipated in the shear plane is

$$\text{Power for shearing} = F_s V_s \quad (21.14)$$

- ❖ If we let w be the *width of cut*, then the *specific energy for shearing*, u_s , is given by

$$u_s = \frac{F_s V_s}{w t_o V} \quad (21.15)$$

- ❖ Similarly, the power dissipated in friction is:

$$\text{Power for friction} = F V_c \quad (21.16)$$

and the *specific energy for friction*, u_f , is

$$u_f = \frac{F V_c}{\omega t_o V} = \frac{F r}{\omega t_o} \quad (21.17)$$

❖ The *total specific energy*, u_t , thus is

$$u_t = u_s + u_f \quad (21.18)$$

- ❖ Because of many factors involved, reliable prediction of cutting forces and power still is *based largely on experimental data*, such as those given in Table 21.2.
- ❖ The sharpness of the tool tip also influences forces and power. *Duller tools require higher forces and power.*

C. Measuring cutting forces and power:

- ❖ Cutting forces can be measured using a force transducer (typically *with quartz piezoelectric sensors*), a *dynamometer or a load cell* mounted on the cutting-tool holder. Also force can be calculated from the power consumption during cutting.
- ❖ The power can be measured easily by a power monitor, such as wattmeter.

See Example 21.1 Relative energies in cutting.

TABLE 21.2

Approximate Range of Energy Requirements in Cutting Operations at the Drive Motor of the Machine Tool (For Dull Tools, Multiply by 1.25)

Material	Specific energy	
	W-s/mm ³	hp-min/in ³
Aluminum alloys	0.4-1	0.15-0.4
Cast irons	1.1-5.4	0.4-2
Copper alloys	1.4-3.2	0.5-1.2
High-temperature alloys	3.2-8	1.2-3
Magnesium alloys	0.3-0.6	0.1-0.2
Nickel alloys	4.8-6.7	1.8-2.5
Refractory alloys	3-9	1.1-3.5
Stainless steels	2-5	0.8-1.9
Steels	2-9	0.7-3.4
Titanium alloys	2-5	0.7-2

21.4 Temperatures in Cutting

- ❖ Whenever plastic energy involved, the *energy dissipated in cutting is converted into heat*, which, in turn, raises the temperature in the cutting zone.
- ❖ Temperature rise is a very important factor in machining because of its major *adverse effects* such as:
 - ✓ *Excessive temperature lowers* the strength, hardness, stiffness, and wears resistance of the cutting tool. Tools also may soften and undergo plastic deformation; thus tool shape is altered.
 - ✓ *Increased heat causes uneven dimensional changes* in part being machined; so *hard to control dimensional accuracy and tolerance.*
 - ✓ Excessive temperature rise can induce *thermal damage and metallurgical changes* in the machined surface, adversely affecting its properties.
- ❖ The main *sources of heat* in machining are
 - a) the work done in shearing *in the primary shear zone*,
 - b) energy dissipated as friction *at the tool-chip interface*, and
 - c) heat generated as the *tool rubs against the machine surface*, especially for dull or worn tools.
- ❖ Efforts have been expended to establish relationships among temperature and various material and process variables in cutting. A comprehensive expression for the mean temperature, T_{mean} , in orthogonal cutting is:

$$T_{mean} = \frac{1.2 Y_f}{\rho c [V t_o / K]^{1/3}} \quad (21.19a)$$

Where the mean temperature $^{\circ}\mathbf{F}$, Y_f is the flow stress in psi, ρc is the volumetric specific heat in in.-lb/in³- $^{\circ}\mathbf{F}$, and K is thermal diffusivity (thermal conductivity/volumetric specific heat) in in²/s.

- ❖ We can see that the **mean cutting temperature increases** with workpiece strength, cutting speed, and depth of cut; and it decreases with increasing specific heat and thermal conductivity of the workpiece material.
- ❖ An expression for the mean temperature in turning on a lathe is found to be proportional to the cutting speed, V , and feed of the tool, f : (see Figure 21.2)

$$T_{mean} \propto V^a f^b \quad (21.19b)$$

Where ***a and b are constants*** that depend on the tool and workpiece materials. Approximate values for the exponents a and b are:

Tool material	a	b
Carbide	0.2	0.125
High-speed steel	0.5	0.375

A. Temperature Distribution:

- ❖ Because the sources of heat generation in machining are concentrated in the primary shear zone and the tool-chip interface, it is to be expected that there will be severe temperature gradients in the cutting zone.
- ❖ A typical temperature distribution is shown in Fig. 21.12.
- ❖ The **maximum temperature is about halfway up the tool-chip interface**.

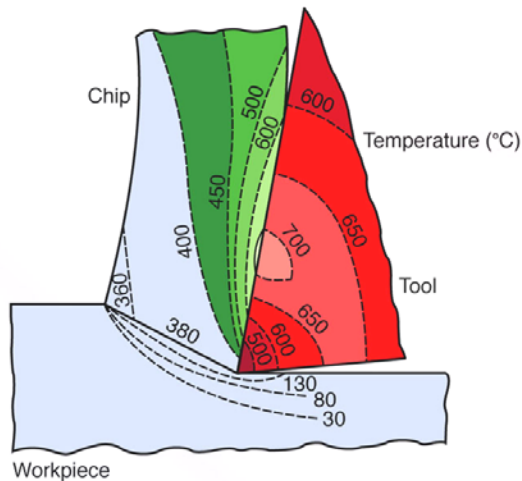


Figure 21.12 Typical temperature distribution in the cutting zone. Note the severe temperature gradients within the tool and the chip, and that the workpiece is relatively cool.

- ❖ The temperatures developed in a turning operation on 52100 steel are shown in Fig. 21.13.
- ❖ Note that *the temperature increases with cutting speed* and that the highest temperature is almost 1100°C (2000°F).
- ❖ The presence of such high temperatures in machining can be verified by simply observing the *dark-bluish color* of the chips (caused by oxidation) produced at high cutting speeds. Chips can become red hot and create a safety hazard for the operator.
- ❖ As speed increases, the time for heat dissipation decreases and hence temperature rises (eventually becoming an almost adiabatic process). Try rubbing your hands together faster and faster.

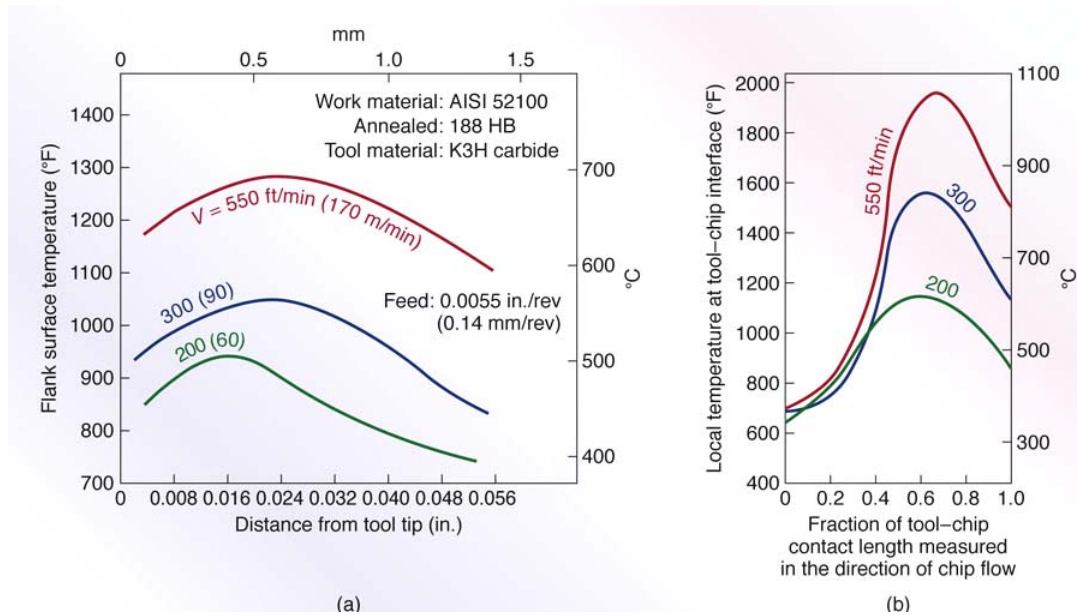
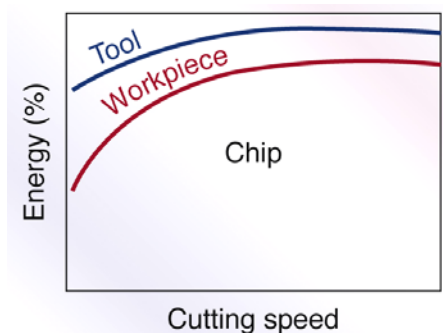


Figure 21.13 Temperatures developed in turning 52100 steel: (a) *flank temperature* distribution and (b) *tool-chip interface* temperature distribution.

- ❖ The *chip carries away most of the heat generated*. It has been estimated that *90% of the energy* is dissipated in the chip during a typical machining operation, with rest in the tool and the workpiece.

Figure 21.14 Proportion of the heat generated in cutting transferred into the tool, workpiece, and chip as a function of the cutting speed. Note that the chip removes most of the heat.



B. Techniques for measuring temperature:

- ❖ *Thermocouples embedded in the tool and/or the workpiece* are may be used to determine the temperatures and their distribution in the cutting zone.
- ❖ *Infrared radiation* from the cutting zone may be monitored with a radiation *pyrometer*. This technique indicates the only surface temperatures.

21.5 Tool Life: Wear and Failure

❖ Conditions that would cause *tool wear* are:

- High localized stresses at the tip* of the tool,
- High temperature*, specially along the *rake face*,
- Sliding of the chip* along the *rack face*, and
- Sliding of the tool* along the newly cut *workpiece surface*.

❖ *Wear is a gradual process* (like a tip of a pencil). The *rate of wear depends* on:

- Tool and workpiece materials,
- Tool geometry,
- Cutting fluids,
- Process parameters, and
- Machine tool characteristics

❖ Tool wear can be one (or a combination) of the following (see Fig. 21.15):

Flank wear, crater wear, nose wear, notching, plastic deformation of the tool tip, chipping, and gross fracture.

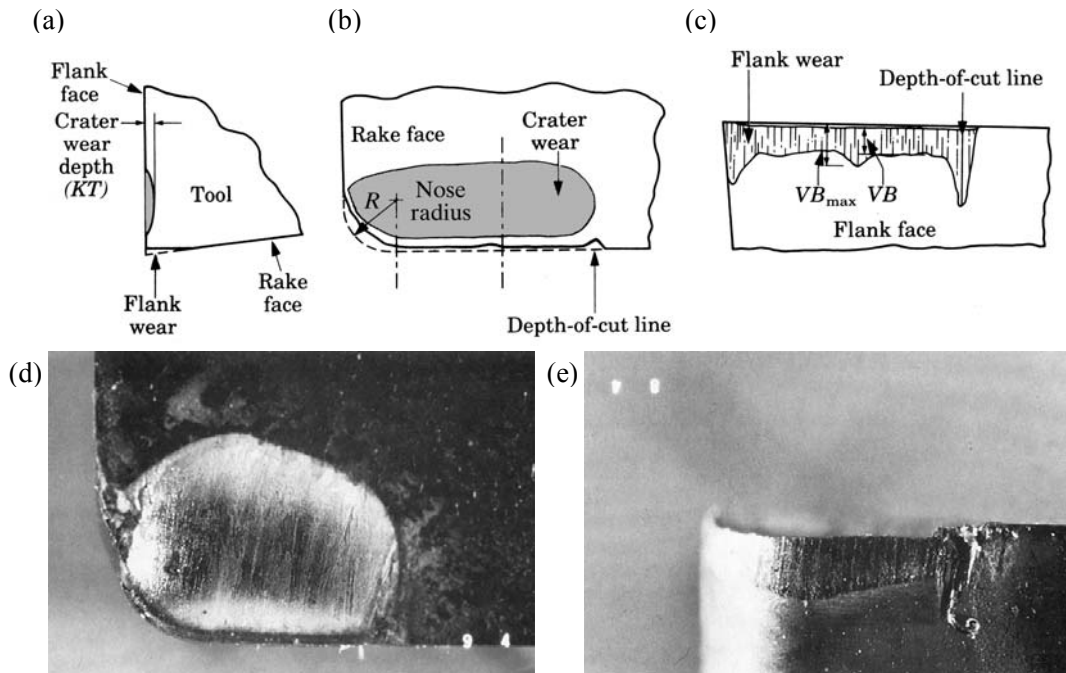


Figure 21.15 (a) Flank and crater wear in a cutting tool. Tool moves to the left. (b) View of the rake face of a turning tool, showing nose radius R and crater wear pattern on the rake face of the tool. (c) View of the flank face of a turning tool, showing the average flank wear land VB and the depth-of-cut line (wear notch). See also Fig. 20.18. (d) Crater and (e) flank wear on a carbide tool. *Source: J.C. Keefe, Lehigh University.*

21.5.1 Flank wear

- ❖ Occurs on the relief face (Figs. 21.15a, c, and d). It is caused by:
 - rubbing the tool along machined surface, and
 - high temperatures.
- ❖ Taylor equation:

$$VT^n = C \quad (21.20a)$$

Where T = time (in minutes) required to develop certain flank wear land (Fig 21.15c)
 n = exponent that depends on tool and workpiece materials and cutting conditions.
 C = constant.

C and n are unique and determined experimentally. Generally, however, n depends on the tool material (see Table 21.3), and C on the workpiece material. Note that C equals the cutting speed when $T = 1$ min.

TABLE 21.3

Ranges of n Values for the Taylor Eq. (21.20a) for Various Tool Materials

High-speed steels	0.08-0.2
Cast alloys	0.1-0.15
Carbides	0.2-0.5
Coated carbides	0.4-0.6
Ceramics	0.5-0.7

- ❖ To appreciate the importance of the exponent n , Eq. (21.20a) can be rewritten as:

$$T = \left(\frac{C}{V} \right)^{\frac{1}{n}} \quad (21.20b)$$

The smaller the value of n , the lower the tool life.

- ❖ **Cutting speed is the most important process variable** associated with tool life, followed by depth of cut and feed, f . Equation (21.20) can be modified as:

$$V T^n d^x f^y = C \quad (21.21)$$

Where d = depth of cut
 f = feed in mm/rev
 x & y = exponents and determined experimentally for each cutting condition.

- ❖ Equation (21.21) can be rewritten as:

$$T = C^{1/n} V^{-1/n} d^{-x/n} f^{-y/n} \quad (21.22)$$

- ❖ Taking $n = 0.15$, $x = 0.15$, $y = 0.6$ as typical values encountered in machining practice:

$$T \approx C^7 V^{-7} d^{-1} f^{-4} \quad (21.23)$$

So, from Eq. (21.23), **to obtain the same tool life**: (a) if the feed or depth of cut is increased, the cutting speed must be decreased (and vice versa), and (b) depending on the exponents, a reduction in speed can result in an increase in the volume of the material removed because of the increased feed and/or depth of cut.

A. Tool-life curves:

- ❖ Tool-life curves are *plots of experimental data obtained by performing cutting tests on various materials under different conditions and with varying process parameters*, such as cutting speed, feed, depth of cut, tool material and geometry, and cutting fluids.

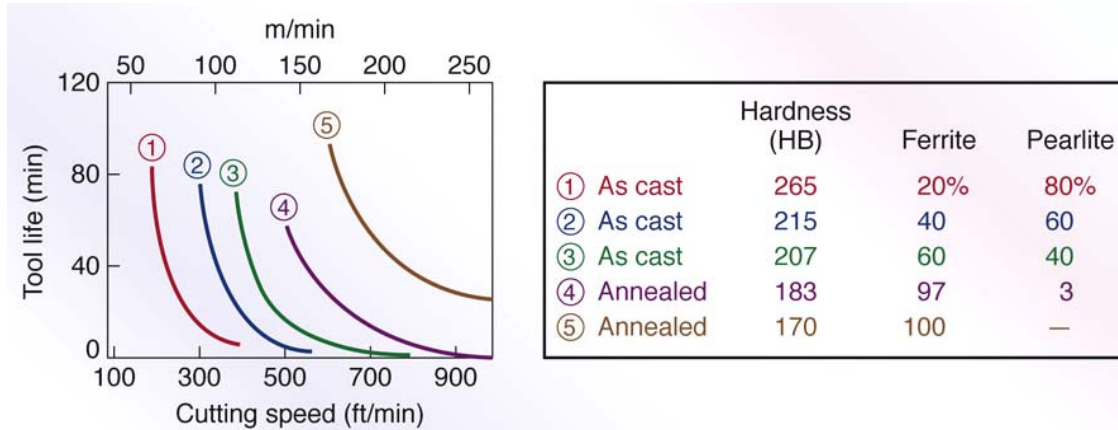
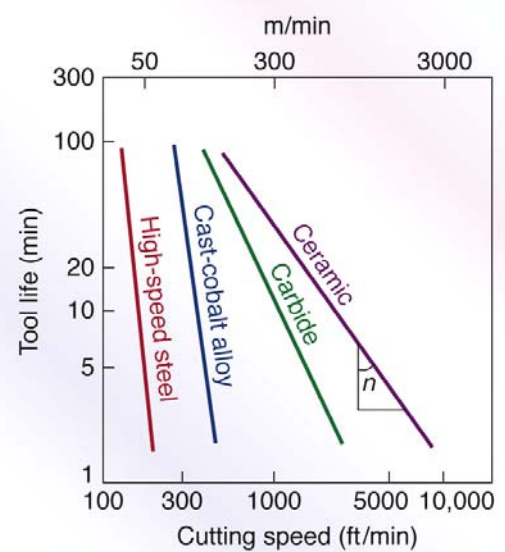


Figure 21.16 Effect of workpiece hardness and microstructure on tool life in turning ductile cast iron. Note the rapid decrease in tool life (approaching zero) as the cutting speed increases. Tool materials have been developed that resist high temperatures, such as carbides, ceramics, and cubic boron nitride, as will be described in Chapter 22

- ❖ 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) there is a large difference in tool life for different workpiece-material microstructures.
- ❖ Also, heat treatment of the workpiece is important, largely due to increasing workpiece hardness. For example, ferrite has a hardness of 100 HB, pearlite 200 HB, and martensite 300 to 500 HB.
- ❖ *Tool-life curves*, from which the exponent n can be determined (see Fig. 21.17), are generally plotted on *log-log paper*.
- ❖ Note that the *smaller the n value*, the steeper the curve, and thus the faster *the tool life decreases with increasing cutting speed*.
- ❖ The curves shown are generally linear over a limited range of cutting speeds.
- ❖ The exponent n can become $-ve$ at low cutting speeds, thus tool-life curves may reach a max. and then curve downward.
- ❖ As temperature increases, flank wear rapidly increases.

Figure 21.17 Tool-life curves for a variety of cutting-tool materials. The negative inverse of the slope of these curves is the exponent n in the Taylor tool-life equation and C is the cutting speed at $T = 1$ min, ranging from about 200 to 10,000 ft./min in this figure.



See Example 21.2 and 21.3

B. Allowable wear land

- ❖ Cutting tools need to be *replaced (or resharpened)* when (a) the surface finish of the machined workpiece begins to deteriorate, (b) cutting forces increases significantly, or (c) temperature rises significantly.
- ❖ The allowable wear land (VB in Fig 21.15c) for various machining conditions is given in Table 21.4. For improved dimensional accuracy, tolerance, and surface finish, the allowable wear land may be smaller than the values given in the table.
- ❖ The recommended cutting speed for a high-speed steel tool is the one that yields a tool life of 60 to 120 min, and for a carbide tool is 30 – 60 min.

TABLE 21.4

Allowable Average Wear Land (see VB in Fig. 21.15c) for Cutting Tools in Various Machining Operations		
Operation	Allowable wear land (mm)	
	High-speed-steel tools	Carbide tools
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

Note: Allowable wear for ceramic tools is about 50% higher. Allowable notch wear, VB_{max} , is about twice that for VB .

C. Optimum cutting speed

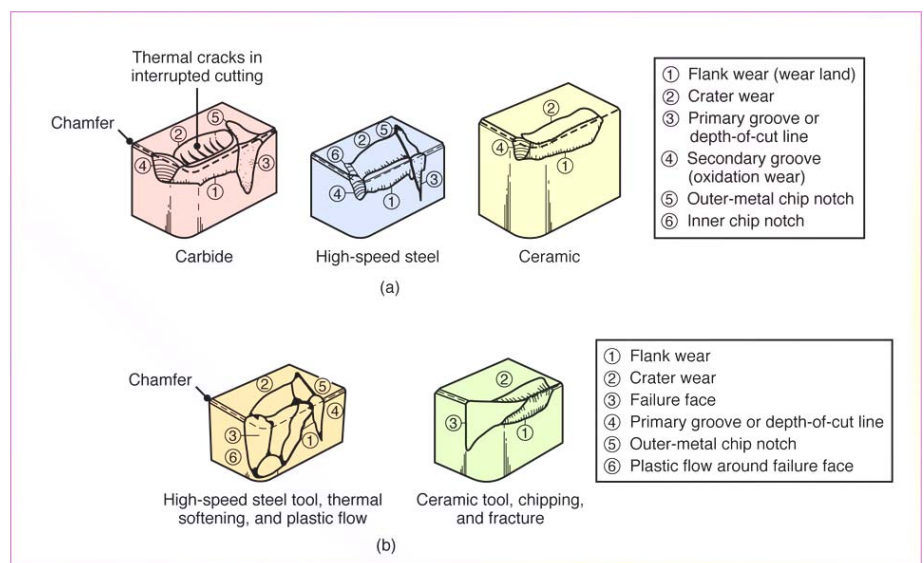
- ❖ So far, we noticed that as cutting speed increases, tool life is reduced rapidly.
- ❖ On the other hand, if the cutting speed is low, tool life is long, but the rate at which material is removed is also low.
- ❖ Thus, there is an optimum cutting speed, see section 25.8.

See Example 21.4

21.5.2 Crater wear

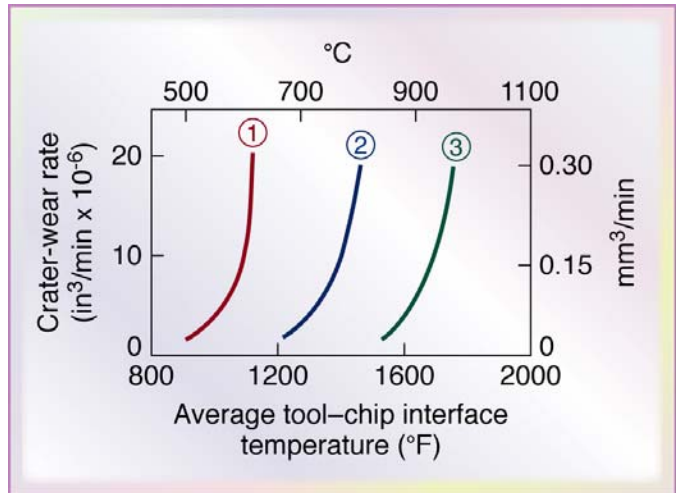
- ❖ *Crater wear occurs on the rake face* of the tool (Fig 21.15a, b, and d and Fig 21.18).
- ❖ Factors influencing crater wear:
 1. temperature at tool-chip interface, and
 2. the Chemical affinity between the tool and workpiece materials.
 3. Additionally the factors influencing flank wear also may influence crater wear.

Figure 21.18 (a) Schematic illustration of types of wear observed on various cutting tools. (b) Schematic illustrations of catastrophic tool failures. A wide range of parameters influence these wear and failure patterns.



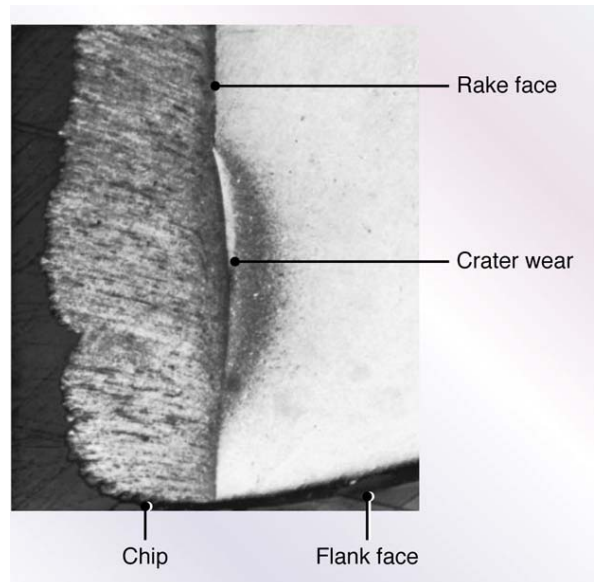
- ❖ Crater wear generally is **attributed to a diffusion mechanism**, that is the movement of atoms across tool-chip interface,
- ❖ Since diffusion rate increases with increasing temperature, *crater wear increases as temperature increases* (See Fig. 21.19)

Figure 21.19 Relationship between crater-wear rate and average tool-chip interface temperature: 1) High-speed steel, 2) C-1 carbide, and 3) C-5 carbide (see Table 22.4).



- ❖ **Coating tools** is an effective means of *slowing* the diffusion process and thus reducing crater wear. Typical coatings are titanium nitride, titanium carbide, titanium carbonitride, and aluminum oxides (section 22.6).
- ❖ Upon comparing Figs. 21.12 and 21.15a, it can be seen that the location of the maximum depth of crater wear (KT) coincides with the location of maximum temperature at the tool-chip interface.
- ❖ An actual cross-section of this interface, when cutting steel at high speeds, is shown in Fig. 21.20.

Figure 21.20 Interface of a cutting tool (right) and chip (left) in machining plain-carbon steel. The discoloration of the tool indicates the presence of high temperatures. Compare this figure with the temperature profiles shown in Fig. 21.12.



21.5.3 Other types of wear, chipping, and fracture

- ❖ **Nose wear** (Fig. 21.15b) is the rounding of sharp tool, due to mechanical and thermal effects. It dulls the tool, affects chip formation, and causes rubbing of the tool over the workpiece, raising its temperature and possibly inducing residual stresses on the machined surface.
- ❖ The **notch or groove** (see Fig. 21.15b and c and 21.18) is observed on cutting tools. It is the boundary where the chip is no longer in contact with the tool. Known as **depth-of-cut line (DOC)** with a depth VN , this boundary oscillates because of inherent variations in the cutting operation. If sufficiently deep, the notch can lead to gross chipping of the tool tip.
- ❖ **Chipping:**
 - ✓ In addition to wear, tools also may undergo **chipping** in which a **small fragment from the cutting edge of the tool breaks away**. Typically occurs in brittle tool materials such as ceramics (tip of a pencil is too sharp).
 - ✓ Unlike wear, which is a gradual process, chipping is a **sudden loss** of tool material, and hence a change in its shape.
 - ✓ The chipped fragments may be very small (microchipping or macrochipping), or they may be relatively large, variously called **gross chipping, gross fracture, and catastrophic failure** (see Fig. 21.15d and 12.18).
 - ✓ Two main causes of chipping are:
 1. Mechanical shock (impact due to interrupted cutting).
 2. Thermal fatigue (cyclic variations in temperature of the tool in interrupted cutting).
 - ✓ Thermal cracks normal to the cutting edge of the tool (Fig. 2.15d and Fig 21.18a).
 - ✓ Chipping may occur in a region in the tool where a small crack or defect already exists.
 - ✓ High, positive rake angles can contribute to chipping.
 - ✓ It's possible for crater wear region to progress toward the tool tip, weakening the tip and causing chipping.

21.5.4 Tool-condition monitoring

- ❖ It is essential to continuously and indirectly monitor the condition of the cutting tool so as to note, for example: wear, chipping, or gross failure.
- ❖ In modern machine tools, tool-condition monitoring systems are integrated into computer numerical control and **programmable logic controllers (PLC)**.
- ❖ Techniques for tool-monitoring typically fall into two general categories: direct and indirect.
 - ✓ The **direct methods**:
 1. One direct method involves **optical measurement** of wear. It is done using a microscope (toolmakers' microscope). Need to stop cutting operation.
 2. Another direct method involves programming the tool to contact a **sensor** after every machining cycle. Usually the sensor is depressed by the tool tip.
 - ✓ The **indirect methods**: involve the correlation of the tool condition with parameters such as cutting forces, power, temperature rise, workpiece surface finish, vibration, and chatter:
 1. **Acoustic emission technique** (AE), which utilizes a piezo-electric transducer attached to a tool holder. The transducer picks up acoustic emissions (above 100 kHz) that result from the stress waves generated during cutting. By analyzing the signals, tool wear and chipping can be monitored.
 2. **Transducers** that are installed in original machine tools. They continually monitor torque and forces during cutting. The signals are pre-amplified, and a microprocessor analyzes and interprets their content. The system is capable of differentiating the signals that come from tool breakage, tool wear, a missing tool, overloading of the machine, or colliding machine components. The system also auto compensate for tool wear and thus improve dimensional accuracy.

21.6 Surface Finish and Integrity

- ❖ Surface finish describes the geometric features of a surface.
- ❖ Surface integrity refers to material properties such as fatigue life and corrosion resistance.
- ❖ The **build-up edge has the greatest influence on surface finish**. Figure 21.21 shows the surfaces obtained in two different cutting operations. Note the considerable damage to the surfaces from BUE; its damage is manifested in the scuffing marks, which deviate from the straight grooves that would result from normal machining.

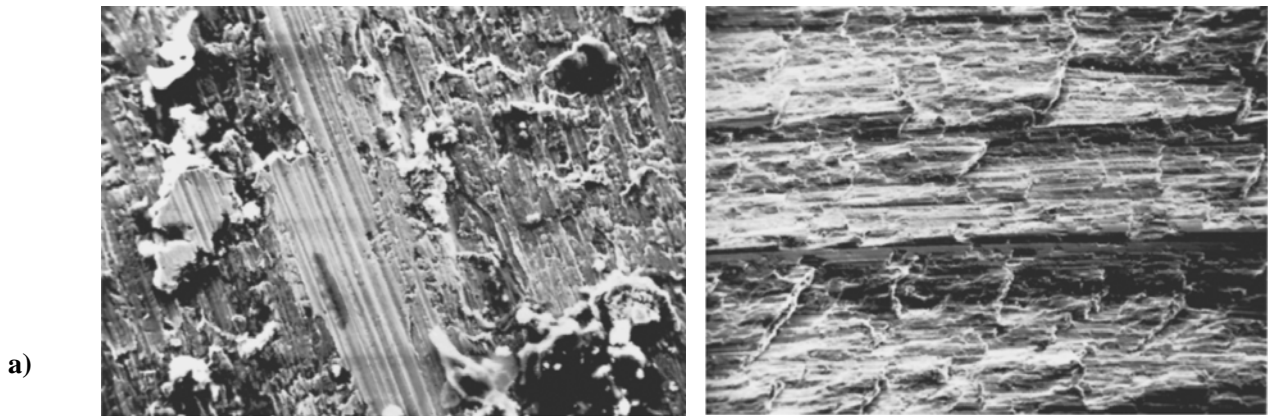
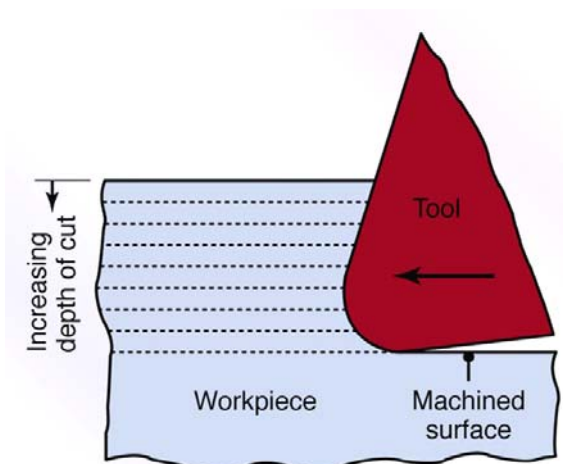


Figure 21.21 Machined surfaces produced on steel (highly magnified), as observed with a scanning electron microscope: (a) turned surface and (b) surface produced by shaping.

- ❖ **Ceramic and diamond tools** generally produce better surface finish than other tools, largely because there is less tendency to form BUE.
- ❖ A dull tool has a large radius along its edges, just as the tip of a dull pencil or the cutting edge of a knife. Figure 21.22 illustrates the relationship between the radius of the cutting edge and the depth of the cut in orthogonal cutting.
- ❖ **Note that the tool has a positive rake angle, but as the depth of cut decreases, the rake angle effectively can become negative. The tool then simply rides over the workpiece (without cutting) and burnishes its surface; this action raises the workpiece temperature and causes surface residual stresses.**
- ❖ If the tip radius of the tool is large in relation to the depth of cut, the tool simply will rub over the machined surface. This generates heat and induces residual surface stresses, which in turn may cause surface damages, such as tearing and cracking.
- ❖ Thus, the depth of cut should be greater than the radius on the cutting edge.

Figure 21.22 Schematic illustration of a dull tool with respect to the depth of cut in orthogonal machining (exaggerated).

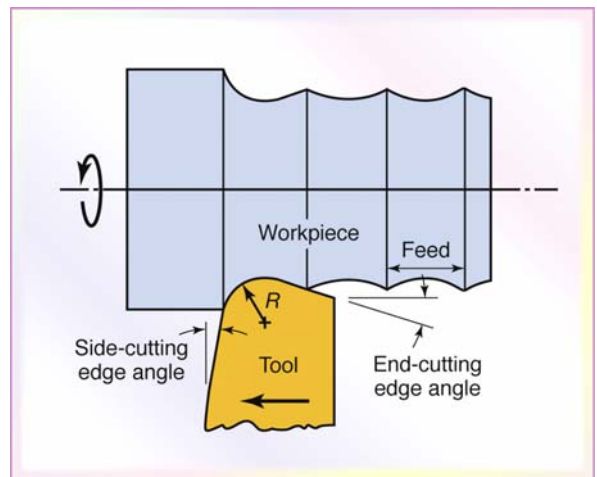


- ❖ In a turning operation, as in other cutting processes, the tool leaves a spiral profile (feed marks) on the machined surface as it moves across the workpiece; see Figs. 21.2 and 21.23.
- ❖ The higher the feed, f , and the smaller the **tool-nose radius, R** , the more prominent these marks will be. It can be shown that **the surface roughness** for such a case is given by:

$$R_a = \frac{f^2}{8R} \quad (21.24)$$

where R_a is the arithmetic mean value (section 33.3)

Figure 21.23 Schematic illustration of feed marks on a surface being turned (exaggerated).



- ❖ If the tool vibrates or chatters during cutting, it will affect the workpiece surface finish adversely. Vibrating tool periodically changes the dimensions of the cut. Also, excessive chatter can cause chipping and premature failure of the most brittle cutting tools, such as ceramic and diamond.

- ❖ Factors influencing **surface integrity**:

1. Temperatures generated.
2. Surface residual stresses.
3. Metallurgical transformations.
4. surface plastic deformation and strain hardening of machined surface, tearing and cracking

21.7 Machinability

- ❖ Machinability of a material is usually defined in terms of 4 factors:

1. Surface finish and surface integrity of the machined part.
2. Tool life.
3. Force and power required.
4. The level of difficulty in chip control

- ❖ It is difficult to establish relationships that quantitatively define the machinability of a particular material.

- ❖ In practice, tool life and surface roughness are considered to be the most important factors in machinability.

21.7.1 Machinability of ferrous metals

A. Machinability of steels

- ❖ **Carbon steels** have a wide range of machinability:

- ✓ If too ductile, chip formation can produce BUE, leading to poor surface finish;
- ✓ If the steel too hard, it can cause abrasive wear of the tool because of the presence of the carbides in the steel

- ✓ Cold-worked carbon steels are desirable from a machinability standpoint.
- ❖ **Free-machining steels**, containing sulfur and phosphorus (resulfurized & rephosphorized steels):
 - ✓ Sulfur forms manganese sulfide inclusions (2nd phase particles), which act as stress raisers in the primary shear zone. So, chips break up easily and are small, thus improving machinability.
 - ✓ Phosphorus in steels has 2 major effects:
 1. It strengthens the ferrite, causing increased hardness, resulting in better chip formation and surface finish.
 2. It increase hardness causes the formation of short chips instead of continuous stringy ones, thereby improving machinability.
- ❖ **Leaded steels**:
 - ✓ A high % of lead in steels solidifies at the tip of manganese sulfide inclusions.
 - ✓ In non-resulfurized steels, lead takes the form of dispersed fine particles.
 - ✓ Lead acts as solid lubricant because of low shear strength.
 - ✓ When temp. is high, such as high cutting speeds and feeds, the lead melts in front of the tool, acting as a liquid lubricant. In addition to this effect, lead lowers the shear stress in the primary shear zone, thus reducing cutting forces and power consumption.
 - ✓ Bismuth and tin are possible substitutes for lead in steels, although their performance is not as high.
- ❖ **Calcium-Deoxidized steels**
 - ✓ Contain oxide flakes of calcium silicates (CaSO) formed as flakes which, in turn, reduce the strength of the secondary shear zone and decrease tool-chip interface friction and wear.
 - ✓ Temp rise also is reduced, and hence steels produce less crater wear, especially at high cutting speed.
- ❖ **Alloy steels**
 - ✓ Contain oxide flakes of calcium silicates (CaSO) formed as flakes which, in turn, reduce the strength of the secondary shear zone and decrease tool-chip interface friction and wear.
- ❖ **Stainless steels**
 - ✓ Austenitic steels are generally difficult to machine
 - ✓ Chatter can be a problem, need machine tools with high stiffness
 - ✓ Ferrite steels have good machinability
 - ✓ Martensitic steels are abrasive, tend to form BUE, and require tool material with high hot hardness and crater wear resistance.
 - ✓ Precipitation-hardening steels are strong and abrasive, require hard and abrasion resistance tool material
- ❖ **Effects of other elements in steel on mach**
 - ✓ Al and Si is always harmful because they combine with O to form aluminium oxide and silicates, which are hard and abrasive
 - ✓ C and Mn have various effects on mach, depending on their comp
 - ✓ Plain low carbon steels (< 0.15% C) can produce poor SF by forming BUE
 - ✓ Tool and die steels are very diff to machine and usually req annealing prior to mach
 - ✓ Mach of most steel is improved by cold working, which hardens the mat and reduces the tendency to form BUE.
 - ✓ Ni, Cr, Molybdenum, Vn generally reduce mach

21.7.2 Machinability of nonferrous metals (not covered)

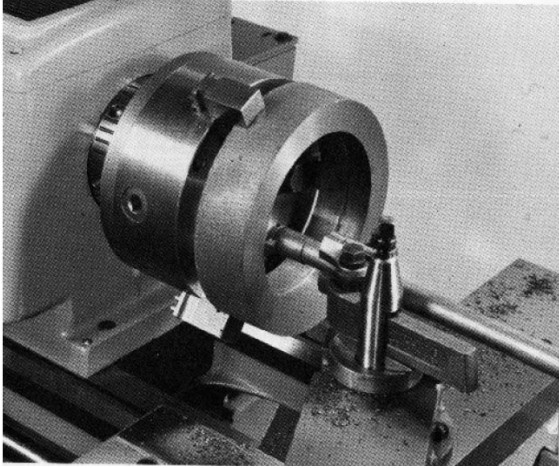
21.7.3 Machinability of miscellaneous materials (not covered)

21.7.4 Thermally assisted machining

- ❖ Source of heat is focused to an area just ahead of the cutting tool
- ❖ Advantages are:
 1. lower cutting forces
 2. increased tool life
 3. use of inexpensive cutting tool material
 4. higher material removal rates
 5. reduced tendency for vibration and chatter

Some Photos

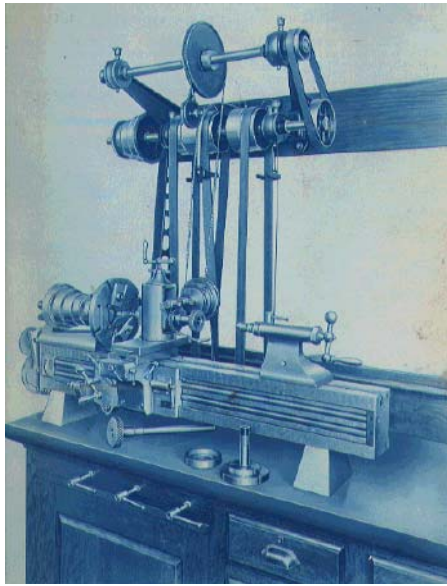
Lathe machine



Boring operation



Threader and cutter



Desktop unit \$2500





CNC Lathe



Milling



CNC Mill