



Manufacturing Engineering Technology in SI Units, 6th Edition

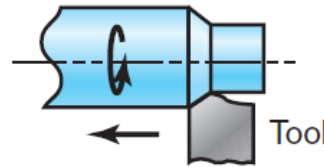
Chapter 21: Fundamental of Machining

Chapter Outline

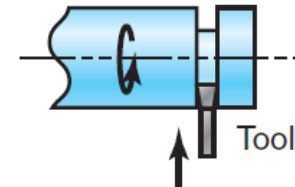
1. Introduction
2. Mechanics of Cutting
3. Cutting Forces and Power
4. Temperatures in Cutting
5. Tool Life: Wear and Failure
6. Surface Finish and Integrity
7. Machinability

Introduction

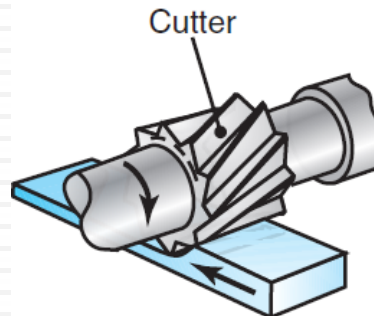
- Cutting processes remove material from the surface of a workpiece by producing **chips**
- Common cutting processes:
 1. **Turning**
 2. **Cutting off**
 3. **Slab milling**
 4. **End milling**



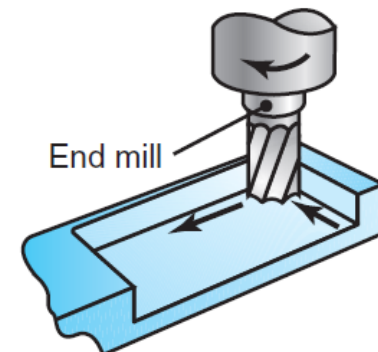
(a) Straight turning



(b) Cutting off



(c) Slab milling

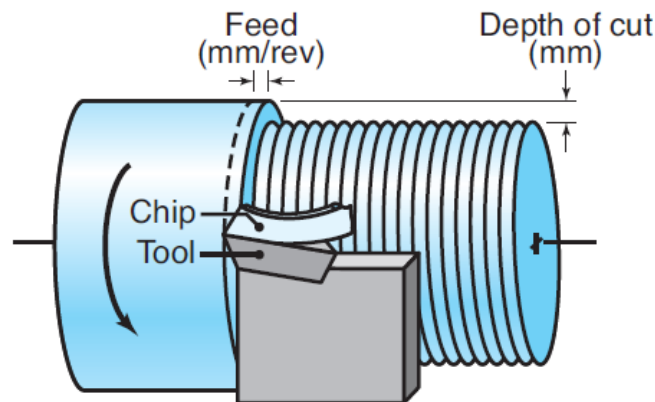


(d) End milling



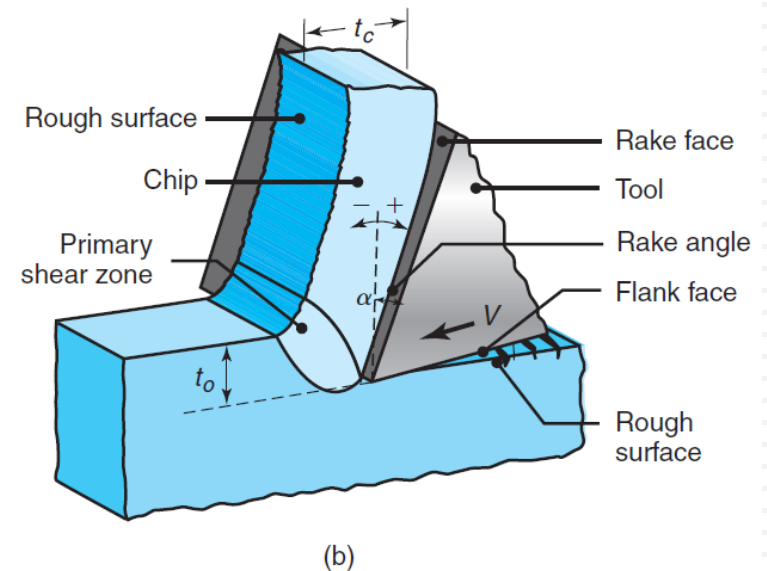
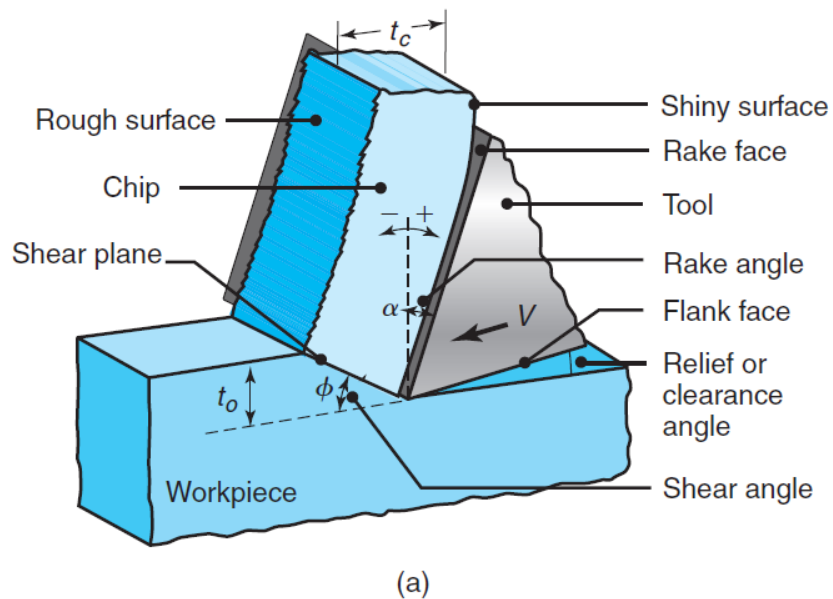
Introduction

- In the turning process, the cutting tool is set at a certain *depth of cut* (mm) and travels to the left as the workpiece rotates
- *Feed*, or *feed rate*, is the distance the tool travels horizontally per unit revolution of the workpiece (mm/rev)



Introduction

- In idealized model, a cutting tool moves to the left along the workpiece at a constant velocity and a depth of cut



Mechanics of Cutting

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



Mechanics of Cutting

- Major *independent variables* in the cutting process:
 1. Tool material and coatings
 2. Tool shape, surface finish, and sharpness
 3. Workpiece material and condition
 4. Cutting speed, feed, and depth of cut
 5. Cutting fluids
 6. Characteristics of the machine tool
 7. Work holding and fixturing

Mechanics of Cutting

- *Dependent variables* in cutting are:
 1. Type of chip produced
 2. Force and energy dissipated during cutting
 3. Temperature rise in the workpiece, the tool and the chip
 4. Tool wear and failure
 5. Surface finish and surface integrity of the work piece

Mechanics of Cutting

Cutting Ratio

- The ratio is related to the two angles by

$$\tan \phi = \frac{r \cos \alpha}{1 - r \sin \alpha} \Rightarrow r = \frac{t_0}{t_c} = \frac{\sin \phi}{\cos(\phi - \alpha)}$$

- As the chip thickness is always greater than the depth of cut, the value of r is always less than unity
- Reciprocal of r is known as the *chip-compression ratio* or *chip-compression factor*
- A measure of how thick the chip has become

Mechanics of Cutting

Velocities in the Cutting Zone

- Since mass continuity is maintained,

$$Vt_0 = V_c t_c \text{ or } V_c = Vr \Rightarrow V_c = \frac{V \sin \phi}{\cos(\phi - \alpha)}$$

- From *Velocity diagram*, we can obtained equations from trigonometric relationships,

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

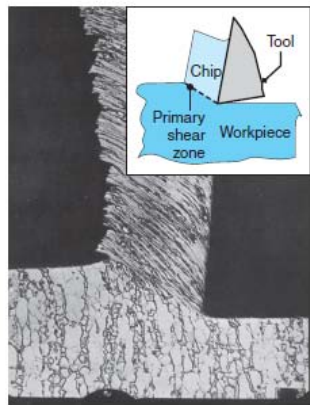
- Note also that

$$r = \frac{t_0}{t_c} = \frac{V_c}{V}$$

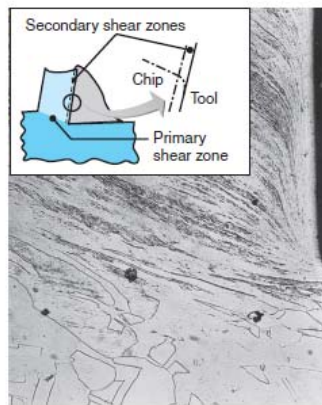
Mechanics of Cutting:

Types of Chips Produced in Metal Cutting

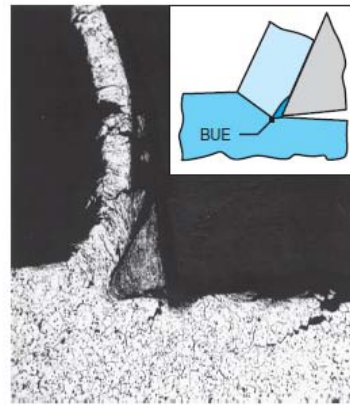
- Types of metal chips are commonly observed in practice
- There are 4 main types:



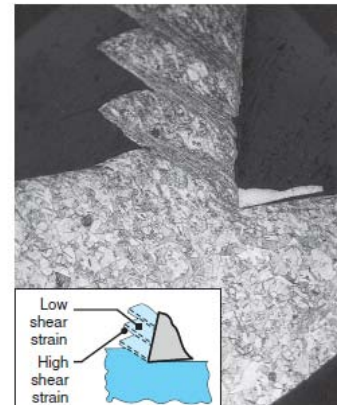
(a)



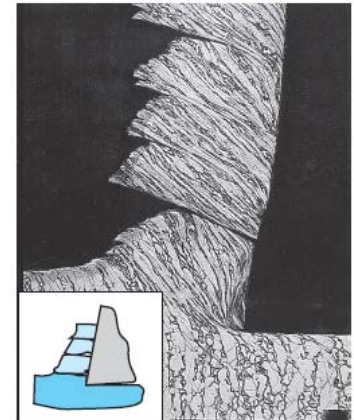
(b)



(c)



(d)



(e)

- a) Continuous
- b) Built-up edge
- c) Serrated or segmented
- d) Discontinuous

Mechanics of Cutting:

Types of Chips Produced in Metal Cutting

Continuous Chips

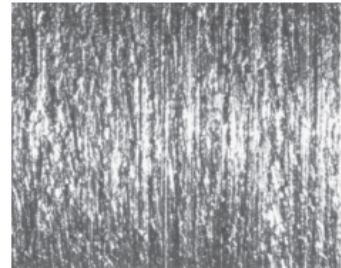
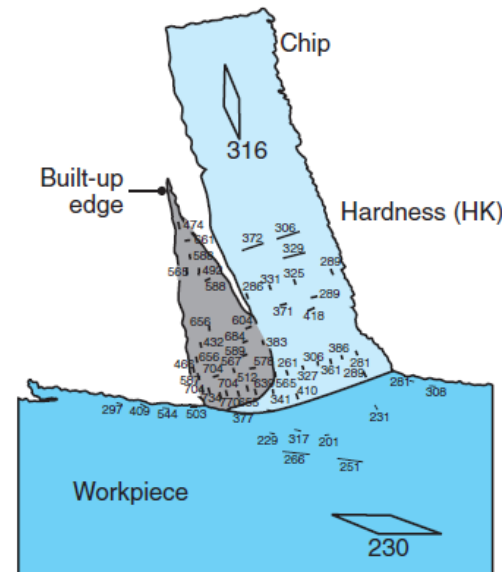
- Formed with ductile materials machined at high cutting speeds and/or high rake angles
- Deformation takes place along a narrow shear zone called the (*primary shear zone*)
- Continuous chips may develop a *secondary shear zone* due to high friction at the tool–chip interface

Mechanics of Cutting:

Types of Chips Produced in Metal Cutting

Built-up Edge (BUE) Chips

- ❑ Consists of layers of material from the workpiece that are deposited on the tool tip
 - ❑ As it grows larger, the BUE becomes unstable and eventually breaks apart
 - ❑ BUE can be reduced by:
 1. Increase the cutting speeds
 2. Decrease the depth of cut
 3. Increase the rake angle
 4. Use a sharp tool
 5. Use an effective cutting fluid
 6. Use a cutting tool that has lower chemical affinity for the workpiece material
- The image contains a central diagram and two micrographs. The diagram shows a cross-section of a cutting process. A light blue area at the top is labeled 'Chip'. Below it, a grey, irregularly shaped region is labeled 'Built-up edge'. The area below the built-up edge is labeled 'Workpiece'. The diagram is overlaid with a grid of hardness values (HK). The chip area has values like 316, 372, 306, 329, 289, 331, 325, 289, 371, 418. The built-up edge area has values like 1474, 1581, 1588, 1490, 588, 656, 604, 432, 684, 383, 468, 656, 589, 574, 261, 309, 366, 251, 589, 704, 513, 337, 565, 341, 410, 281, 308. The workpiece area has values like 297, 409, 644, 603, 377, 229, 317, 201, 231, 266, 251, 230. To the right of the diagram, there are two micrographs. The top one shows a surface with a built-up edge. The bottom one shows a surface with a regular, stepped pattern.



Mechanics of Cutting:

Types of Chips Produced in Metal Cutting

Serrated Chips

- Also called *segmented* or *nonhomogeneous* chips
- They are semicontinuous chips with large zones of low shear strain and small zones of high shear strain (*shear localization*)
- Chips have a sawtooth-like appearance

Mechanics of Cutting:

Types of Chips Produced in Metal Cutting

Discontinuous Chips

- Consist of segments that attached firmly or loosely to each other
- Form under the following conditions:
 1. Brittle workpiece materials
 2. Materials with hard inclusions and impurities
 3. Very low or very high cutting speeds
 4. Large depths of cut
 5. Low rake angles
 6. Lack of an effective cutting fluid
 7. Low stiffness of the machine tool

Mechanics of Cutting:

Types of Chips Produced in Metal Cutting

Chip Curl

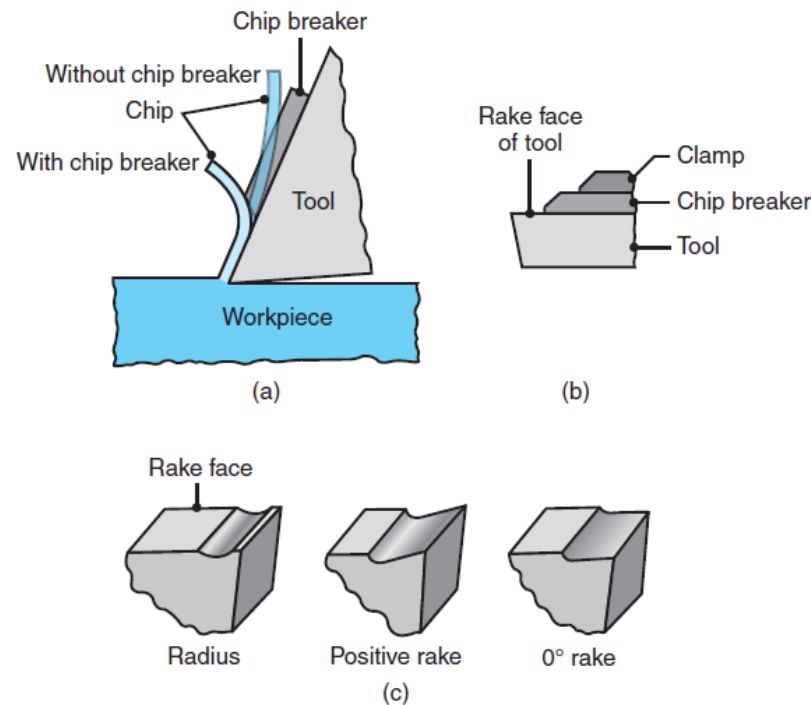
- Chips will develop a curvature (*chip curl*) as they leave the workpiece surface
- Factors affecting the chip curl conditions are:
 1. Distribution of stresses in the primary and secondary shear zones.
 2. Thermal effects.
 3. Work-hardening characteristics of the workpiece material
 4. Geometry of the cutting tool
 5. Cutting fluids

Mechanics of Cutting:

Types of Chips Produced in Metal Cutting

Chip Breakers

- A situation that break the chip intermittenly with cutting tools have *chip-breaker* features

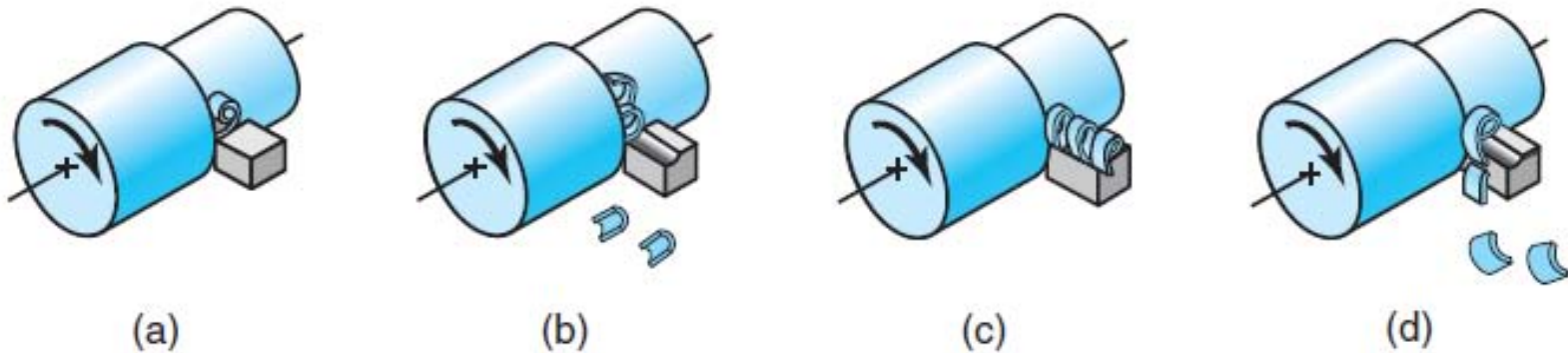


Mechanics of Cutting:

Types of Chips Produced in Metal Cutting

Chip Breakers

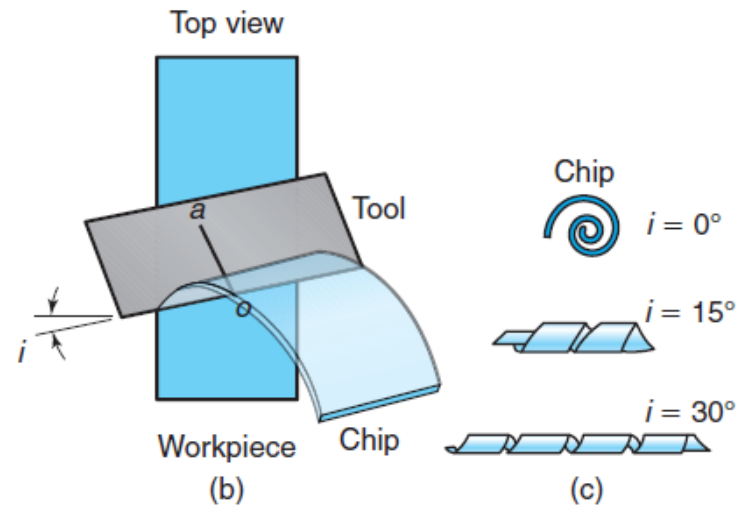
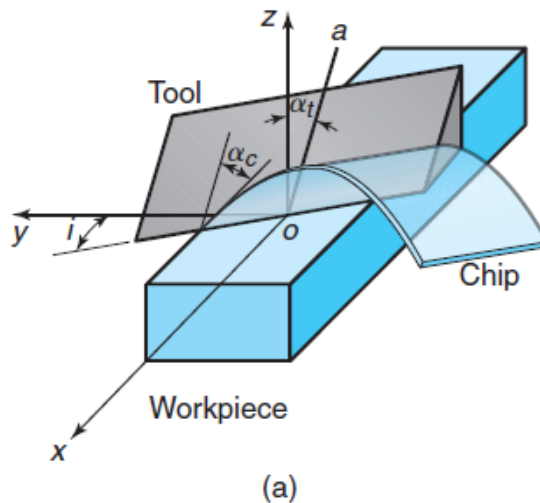
- Chips can also be broken by changing the tool geometry to control chip flow



Mechanics of Cutting:

Oblique Cutting

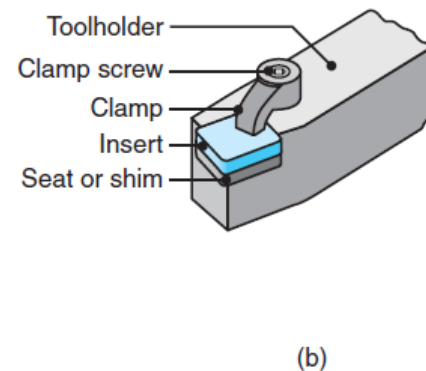
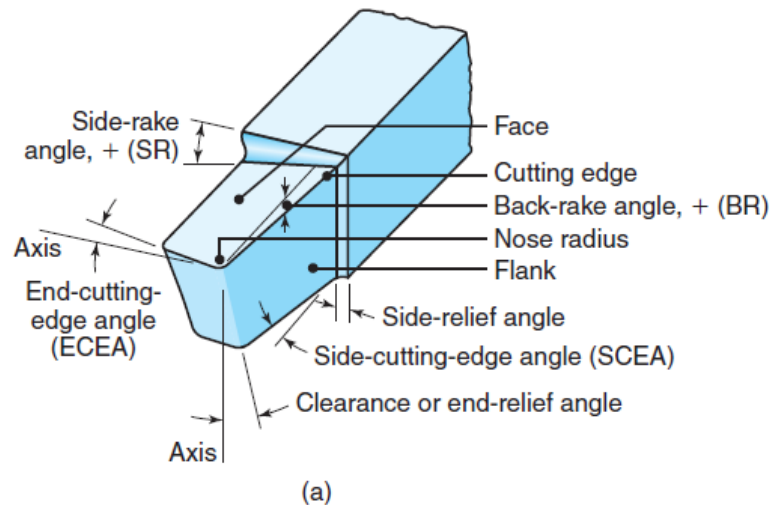
- Majority of machining operations involve tool shapes that are three dimensional where the cutting is said to be *oblique*
- There is a difference between oblique and orthogonal cutting



Mechanics of Cutting:

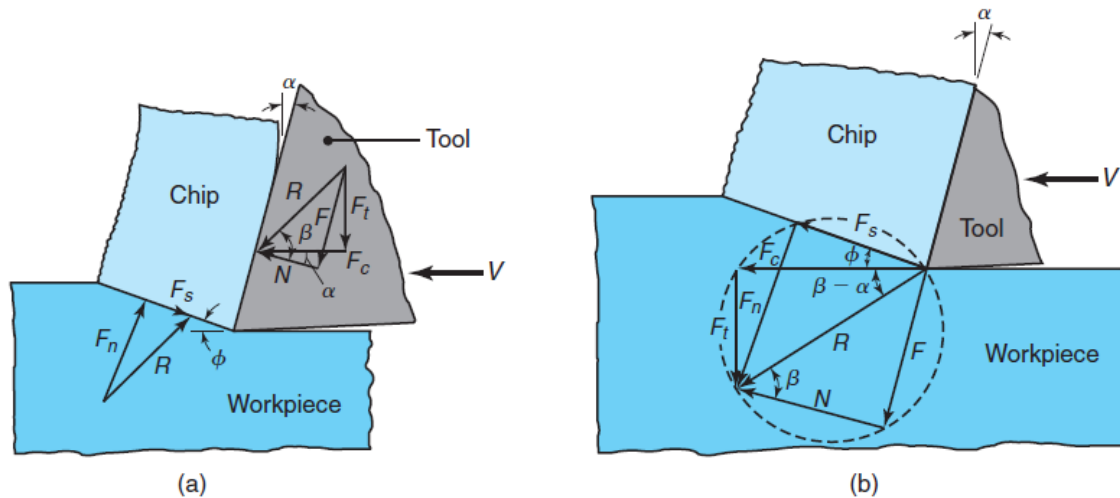
Oblique Cutting

- Orthogonal cutting the chip slides directly up the face of the tool
- In oblique cutting, the chip is *helical* and at an **inclination angle**



Cutting Forces and Power

- Knowledge of the *cutting forces* and *power* involved:
 1. Data on cutting forces
 2. Power requirements
- **Cutting force** acts in the direction of the cutting speed, and supplies the energy required for cutting



Cutting Forces and Power

- It can also be shown that

$$F = R \sin \beta \Rightarrow N = R \cos \beta$$

- Resultant force is balanced by an equal and opposite force along the shear plane
- It is resolved into a **shear force** and a **normal force**

- Thus,
$$F_s = F_c \cos \phi - F_t \sin \phi$$

$$F_n = F_c \sin \phi + F_t \cos \phi$$

- The magnitude of **coefficient of friction** is

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

Cutting Forces and Power

Thrust Force

- The toolholder, work-holding devices, and machine tool must be stiff to support thrust force with minimal deflections
- The effect of rake angle and friction angle on the direction of thrust force is

$$F_t = R \sin(\beta - \alpha) \text{ or } F_t = F_c \tan(\beta - \alpha)$$

- Magnitude of the cutting force is always positive as the force that supplies the work is required in cutting

Cutting Forces and Power

Power

- The power input in cutting is

$$Power = F_c V$$

- The power dissipated in the shear plane is

$$Power \text{ for shearing} = F_s V_s$$

- Denoting the width of cut as w , the **specific energy for shearing**, is

$$\mu_s = \frac{F_s V_s}{wt_0 V}$$

Cutting Forces and Power

Power

- The power dissipated in friction is

$$\text{Power for friction} = FV_c$$

- The **specific energy for friction** is

$$\mu_f = \frac{FV_c}{wt_0V} = \frac{Fr}{wt_0}$$

- **Total specific energy** is

$$\mu_t = \mu_s + \mu_f$$

- Sharpness of the tool tip also influences forces and power

Cutting Forces and Power

Power

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

Material	<u>Specific energy</u> $\text{W} \cdot \text{s}/\text{mm}^3$
Aluminum alloys	0.4–1
Cast irons	1.1–5.4
Copper alloys	1.4–3.2
High-temperature alloys	3.2–8
Magnesium alloys	0.3–0.6
Nickel alloys	4.8–6.7
Refractory alloys	3–9
Stainless steels	2–5
Steels	2–9
Titanium alloys	2–5

Cutting Forces and Power

Measuring Cutting Forces and Power

- Cutting forces can be measured using a **force transducer**, a **dynamometer** or a **load cell** mounted on the cutting-tool holder
- It is also possible to calculate the cutting force from the **power consumption** during cutting
- The *specific energy* in cutting can be used to calculate cutting forces

Cutting Forces and Power

EXAMPLE 21.1

Relative Energies in Cutting

In an orthogonal cutting operation, $t_o=0.13$ mm, $V=120$ m/min, $\alpha=10^\circ$ and the width of cut 6 mm. It is observed that $t_c=0.23$ mm, $F_c=500$ N and $F_t=200$ N. Calculate the percentage of the total energy that goes into overcoming friction at the tool–chip interface.

Cutting Forces and Power

Solution

Relative Energies in Cutting

The percentage of the energy can be expressed as

$$\frac{\text{Friction Energy}}{\text{Total Energy}} = \frac{FV_c}{F_c V} = \frac{Fr}{F_c}$$

where

$$r = \frac{t_0}{t_c} = \frac{0.13}{0.23} = 0.565$$

We have

$$F = R \sin \beta, \quad F = R \cos(\beta - \alpha) \quad \text{and}$$

$$R = \sqrt{(F_t^2 + F_c^2)} = \sqrt{200^2 + 500^2} = 539 \text{ N}$$

Cutting Forces and Power

Solution

Relative Energies in Cutting

Thus,

$$500 = 539 \cos(\beta - 10) \Rightarrow \beta = 32^\circ$$

$$F = 539 \sin 32^\circ = 286 \text{ N}$$

Hence

$$\text{Percentage} = \frac{(286)(0.565)}{500} = 0.32 \text{ or } 32\%$$

Temperatures in Cutting

- *Temperature rise* - its major adverse effects:
 1. Lowers the strength, hardness, stiffness and wear resistance of the cutting tool
 2. Causes uneven dimensional changes
 3. Induce thermal damage and metallurgical changes in the machined surface
- Expression for *mean temperature* is

$$T = \frac{0.000665Y_f}{\rho c} \sqrt[3]{\frac{Vt_0}{K}}$$

- *Mean temperature in turning* on a lathe is given by

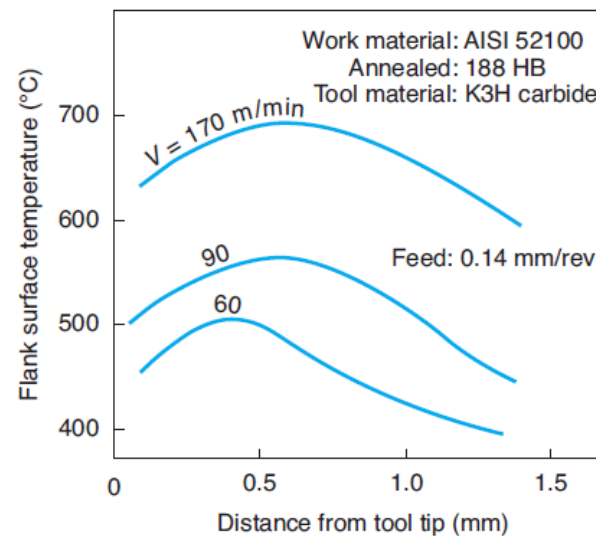
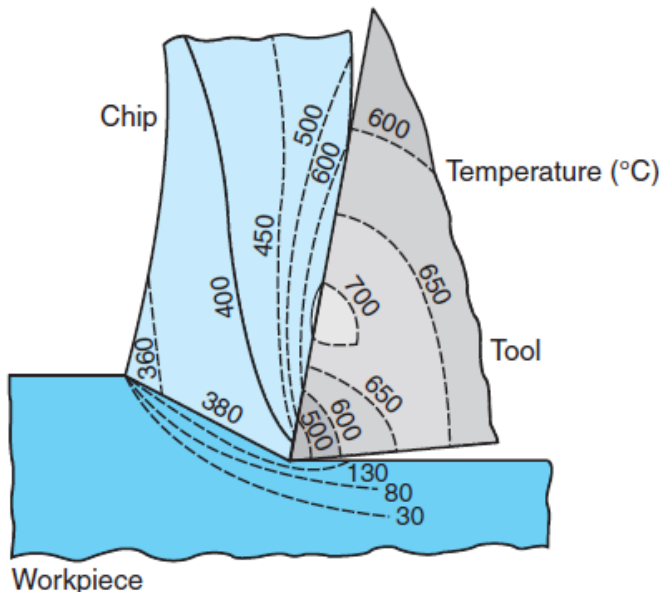
$$T_{mean} \propto V^a f^b$$



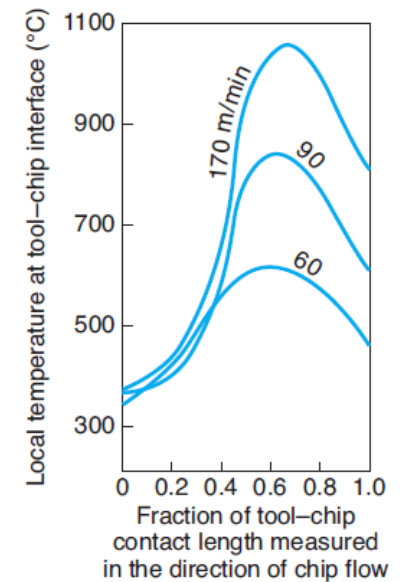
Temperatures in Cutting

Temperature Distribution

- The sources of heat generation are concentrated in the primary shear zone and at the tool–chip interface
- There are temperature gradients in the cutting zone



(a)



(b)

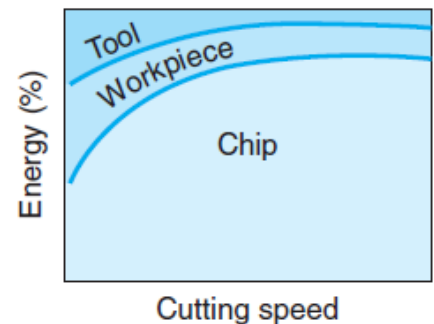
Temperatures in Cutting

Temperature Distribution

- The temperature increases with cutting speed
- Chips can become red hot and create a safety hazard for the operator
- The chip carries away most of the heat generated

Techniques for Measuring Temperature

- Temperatures and their distribution can be determined from **thermocouples**



Tool Life: Wear and Failure

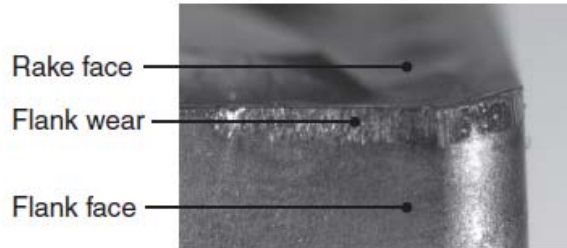
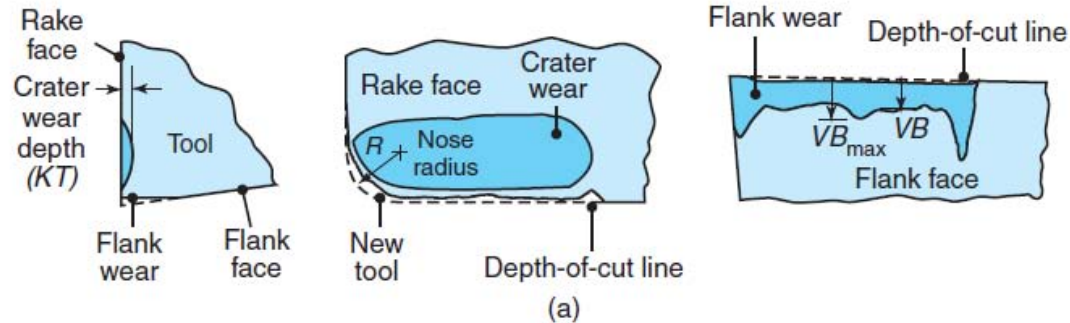
- Cutting tools are subjected to:
 1. High localized stresses at the tip of the tool
 2. High temperatures
 3. Sliding of the chip along the rake face
 4. Sliding of the tool along the newly cut workpiece surface
- Wear is a gradual process
- The rate of tool wear depends on tool and workpiece materials, tool geometry, process parameters, cutting fluids and the characteristics of the machine tool



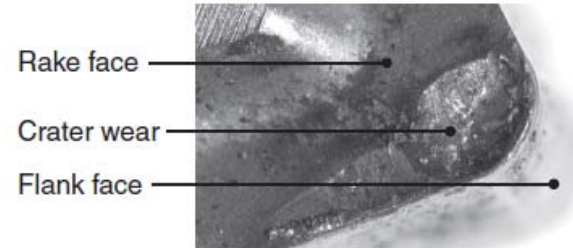
Tool Life: Wear and Failure

- Tool wear and the changes in tool geometry and they are classified as:
 - a) *Flank wear*
 - b) *Crater wear*
 - c) *Nose wear*
 - d) *Notching plastic deformation of the tool tip*
 - e) *Chipping*
 - f) *Gross fracture*

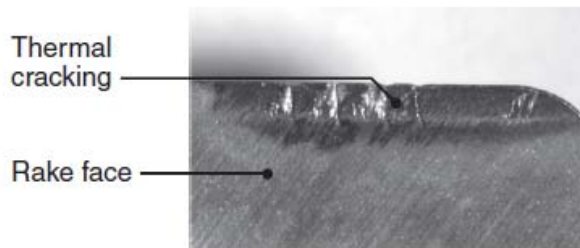
Tool Life: Wear and Failure



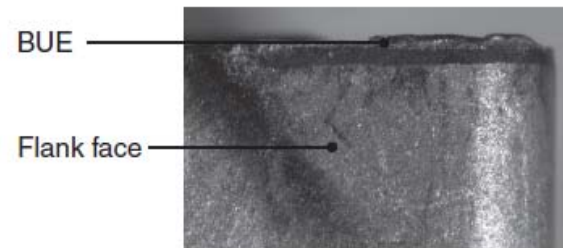
(b)



(c)



(d)



(e)

Tool Life: Wear and Failure:

Flank Wear

- Occurs on the relief (flank) face of the tool
- It is due to (a) rubbing of the tool along the machined surface and (b) high temperatures
- *Taylor tool life equation* states that

$$VT^n = C$$

V = cutting speed

T = time taken to develop a certain flank **wear land**

n = an exponent that depend on tool and workpiece materials and cutting conditions

C = constant

- To appreciate the importance of the exponent,

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

Tool Life: Wear and Failure:

Flank Wear

- For turning, it can be modified to

$$VT^n d^x f^y = C$$

- Since x and y must be determined experimentally for each cutting condition, we have

$$T = C^{1/n} V^{-1/n} d^{x/n} f^{y/n}$$

Ranges of n Values for the Taylor Equation (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

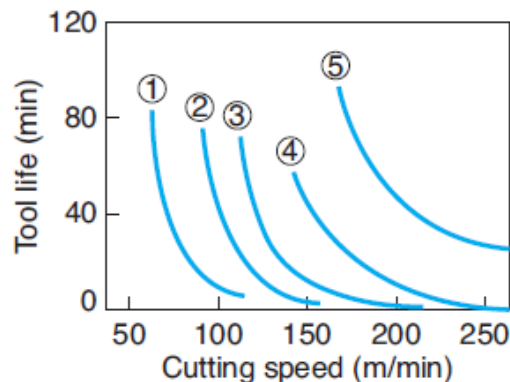
- To obtain a constant tool life:
 1. The cutting speed must be decreased
 2. Depending on the exponents

Tool Life: Wear and Failure:

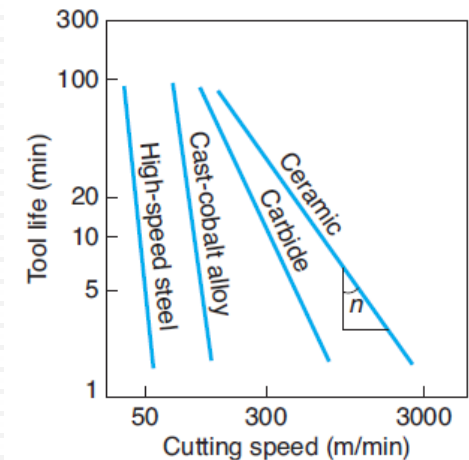
Flank Wear

Tool-life Curves

- *Tool-life curves* are plots of experimental data from performed cutting tests on various materials under different cutting conditions
- The exponent n can be determined from tool-life curves



		Hardness (HB)	Ferrite	Pearlite
①	As cast	265	20%	80%
②	As cast	215	40	60
③	As cast	207	60	40
④	Annealed	183	97	3
⑤	Annealed	170	100	—



- As temperature increases, flank wear rapidly increases

Tool Life: Wear and Failure:

Flank Wear

Allowable Wear Land

- Cutting tools need to be replaced when:
 1. Surface finish of the machined workpiece begins to deteriorate
 2. Cutting forces increase significantly
 3. Temperature rises significantly

Allowable Average Wear Land (see VB in Fig. 21.15a) for Cutting Tools in Various Machining Operations

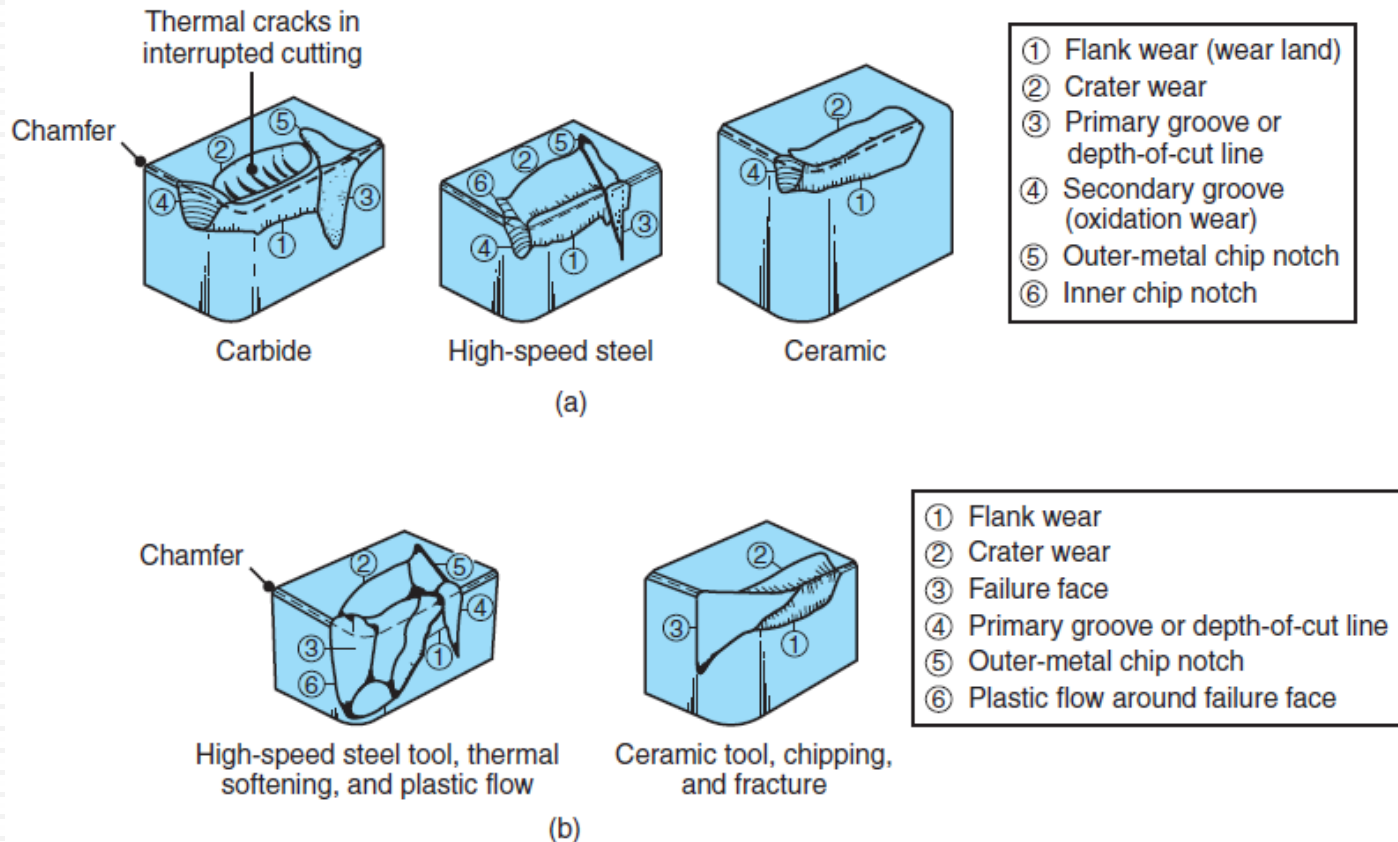
Operation	Allowable wear land (mm)	
	High-speed steel tools	Carbide tools
Turning	1.5	0.4
Face milling	1.5	0.4
End milling	0.3	0.3
Drilling	0.4	0.4
Reaming	0.15	0.15

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

Tool Life: Wear and Failure:

Crater Wear

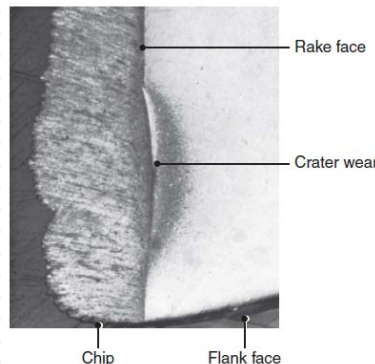
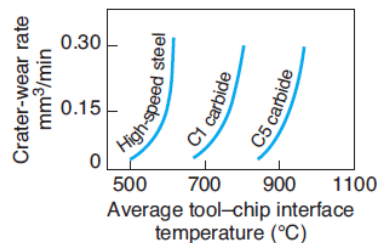
- *Crater wear* occurs on the rake face of the tool



Tool Life: Wear and Failure:

Crater Wear

- Factors influencing crater wear are
 1. The temperature at the tool–chip interface
 2. The chemical affinity between the tool and workpiece materials
- Diffusion rate increases with increasing temperature, crater wear increases as temperature increases
- Location of the max depth of crater wear, KT , coincides with the location of the *max temperature* at the tool–chip interface



Tool Life: Wear and Failure:

Other Types of Wear, Chipping, and Fracture

- *Nose wear* is the rounding of a sharp tool due to mechanical and thermal effects
- It dulls the tool, affects chip formation and causes rubbing of the tool over the workpiece
- Tools also may undergo *plastic deformation* because of temperature rises in the cutting zone
- Tools may undergo *chipping*, where small fragment from the cutting edge of the tool breaks away
- Chipping may occur in a region of the tool where a small crack already exists
- Two main causes of chipping: **Mechanical shock & Thermal fatigue**

Tool Life: Wear and Failure:

Tool-condition Monitoring

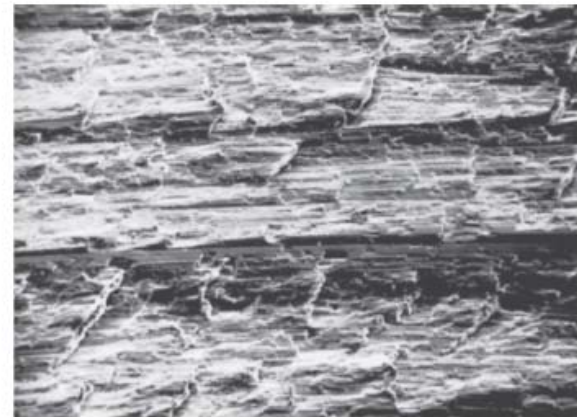
- Tool-condition monitoring systems are integrated into computer numerical control and programmable logic controllers
- Classified into 2 categories:
 1. **Direct method** is observing the condition of a cutting tool involves optical measurements of wear
 2. **Indirect methods** is observing tool conditions involve the correlation of the tool condition with parameters
- Another similar system consists of transducers, which continually monitor torque and forces during cutting

Surface Finish and Integrity

- Surface finish influences the dimensional accuracy of machined parts, properties and performance in service
- *Surface finish* describes the geometric features of a surface while *surface integrity* pertains to material properties
- The *built-up edge* has the greatest influence on surface finish



(a)

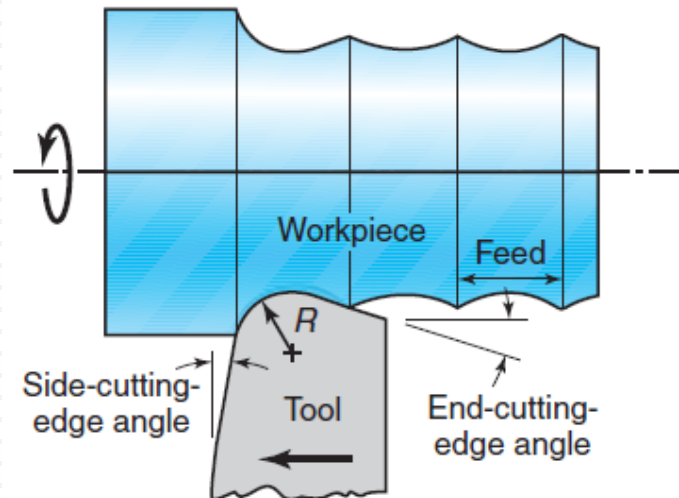
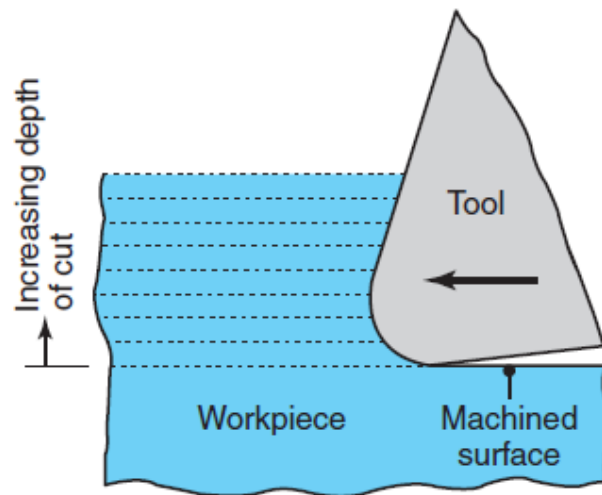


(b)



Surface Finish and Integrity

- A *dull* tool has a large radius along its edges
- In a turning operation, the tool leaves a spiral profile (**feed marks**) on the machined surface as it moves across the workpiece
- Typical surface roughness is expressed as $R_t = \frac{f^2}{8R}$



Surface Finish and Integrity

- Factors influencing *surface integrity* are:
 1. Temperatures generated
 2. Surface residual stresses
 3. Plastic deformation and strain hardening of the machined surfaces, tearing and cracking
- Finish machining is considering the surface finish to be produced
- Rough machining is to remove a large amount of material at a high rate

Machinability

- *Machinability* is defined in terms of:
 1. Surface finish and surface integrity
 2. Tool life
 3. Force and power required
 4. The level of difficulty in chip control
- Good machinability indicates good surface finish and surface integrity, a long tool life, and low force and power requirements
- **Machinability ratings (indexes)** are available for each type of material and its condition



Machinability:

Machinability of Ferrous Metals

Steels

- If a carbon steel is too ductile, chip formation can produce built-up edge, leading to poor surface finish
- If too hard, it can cause abrasive wear of the tool because of the presence of carbides in the steel
- In **lead steels**, a high percentage of lead solidifies at the tips of manganese sulfide inclusions
- **Calcium-deoxidized steels** contain oxide flakes of calcium silicates (CaSiO_3) that reduce the strength of the secondary shear zone and decrease tool–chip interface friction and wear

Machinability:

Machinability of Ferrous Metals

Effects of Various Elements in Steels

- Presence of *aluminum* and *silicon* is harmful, as it combine with oxygen to form aluminum oxide and silicates, which are hard and abrasive
- Thus tool wear increases and machinability reduce

Stainless Steels

- Austenitic (300 series) steels are difficult to machine
- Ferritic stainless steels (also 300 series) have good machinability
- Martensitic (400 series) steels are abrasive

Machinability:

Machinability of Nonferrous Metals

- **Aluminum** is very easy to machine
- **Beryllium** requires machining in a controlled environment
- **Cobalt-based alloys** require sharp, abrasion-resistant tool materials and low feeds and speeds
- **Copper** can be difficult to machine because of builtup edge formation
- **Magnesium** is very easy to machine, with good surface finish and prolonged tool life
- **Titanium** and its alloys have very poor thermal conductivity
- **Tungsten** is brittle, strong, and very abrasive

Machinability:

Machinability of Miscellaneous Materials

- Machining **thermoplastics** requires sharp tools with positive rake angles, large relief angles, small depths of cut and feed and high speeds
- **Polymer-matrix composites** are difficult to machine
- **Metal-matrix and ceramic-matrix composites** can be difficult to machine, depending on the properties of the matrix material and the reinforcing fibers
- The type of chips and the surfaces produced also vary significantly, depending on the type of **wood** and its condition

Machinability:

Thermally Assisted Machining

- In *thermally assisted machining* (**hot machining**), a source of heat is focused onto an area just ahead of the cutting tool
- Advantages of hot machining are:
 1. Reduced cutting forces
 2. Increased tool life
 3. Higher material-removal rates
 4. Reduced tendency for vibration and chatter