Machining

(Reading: Chap 8 in Kalpakjian and Schmid)

Outline

- Chip formation during machining
- Force and power requirement
- Mechanisms of tool wear and fatigue
- Types and properties of cutting-tool materials
- Characteristics of machine tools
- Vibration and chatter
- Design and economics of machining

Machining

- Machining: Material removal processes
- Categories of machining
  - Cutting – involve single or multipoint cutting tools and processes

    Turning, boring, drilling, tapping, milling, sawing, and broaching
  - Abrasive processes

    Grinding, honing, lapping, ultrasonic machining
  - Advanced machining (Non- traditional machining processs)

    Involving electrical, chemical, thermal, hydrostatic and optical sources of energy

Pros and Cons of Machining

- Pros
  - Closer dimensional accuracy
  - Sharp or internal features
  - Better surface finish or surface characteristics
  - More economic for small number of products
- Cons
  - Waste material
  - More time consuming
  - May adversely affect surface integrity of the product

Common Machining Processes

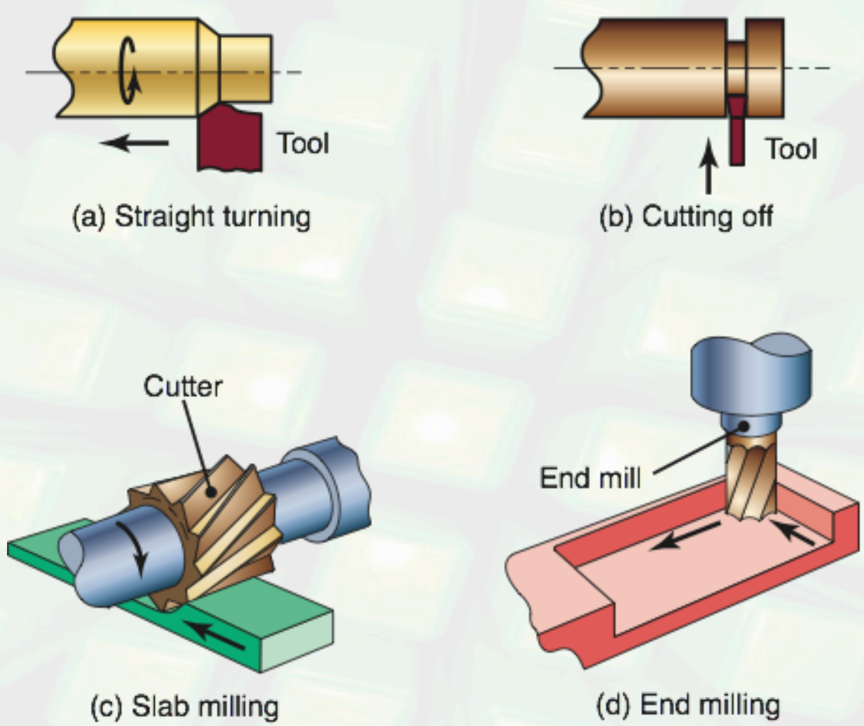


FIGURE 8.1 Some examples of common machining processes.

Orthogonal Cutting

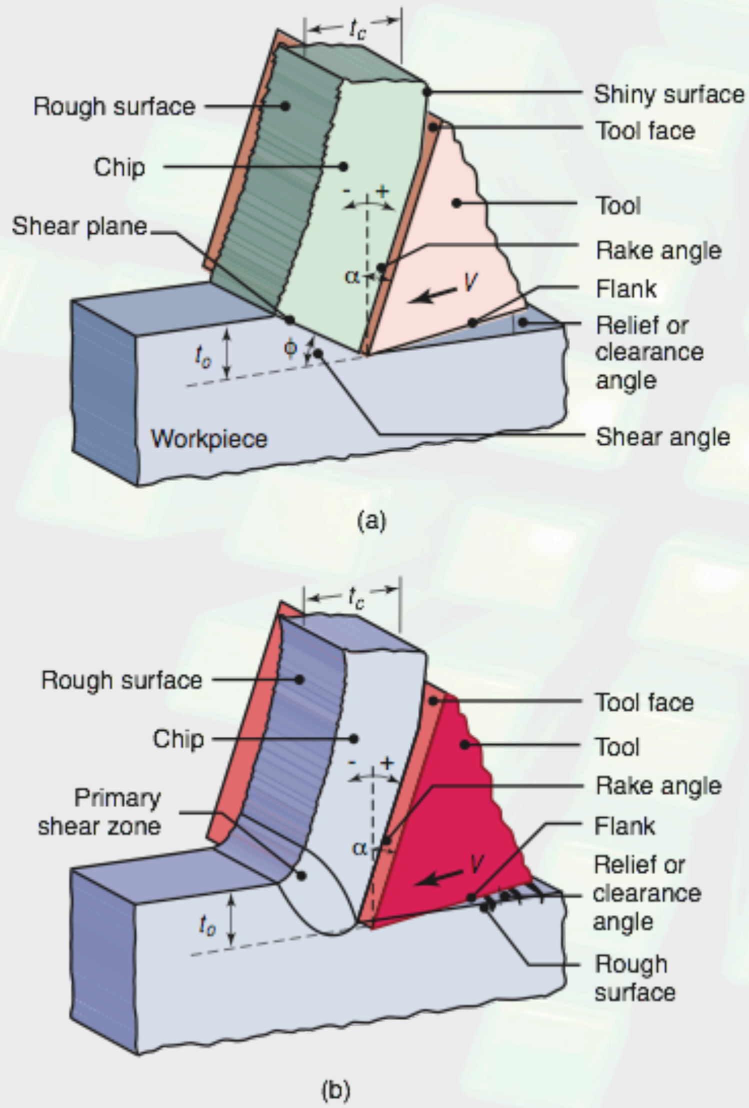


FIGURE 8.2 Schematic illustration of a two-dimensional cutting process, or orthogonal cutting. (a) Orthogonal cutting with a well-defined shear plane, also known as the **Merchant** model; (b) Orthogonal cutting without a well-defined shear plane.

Chip Formation Mechanism

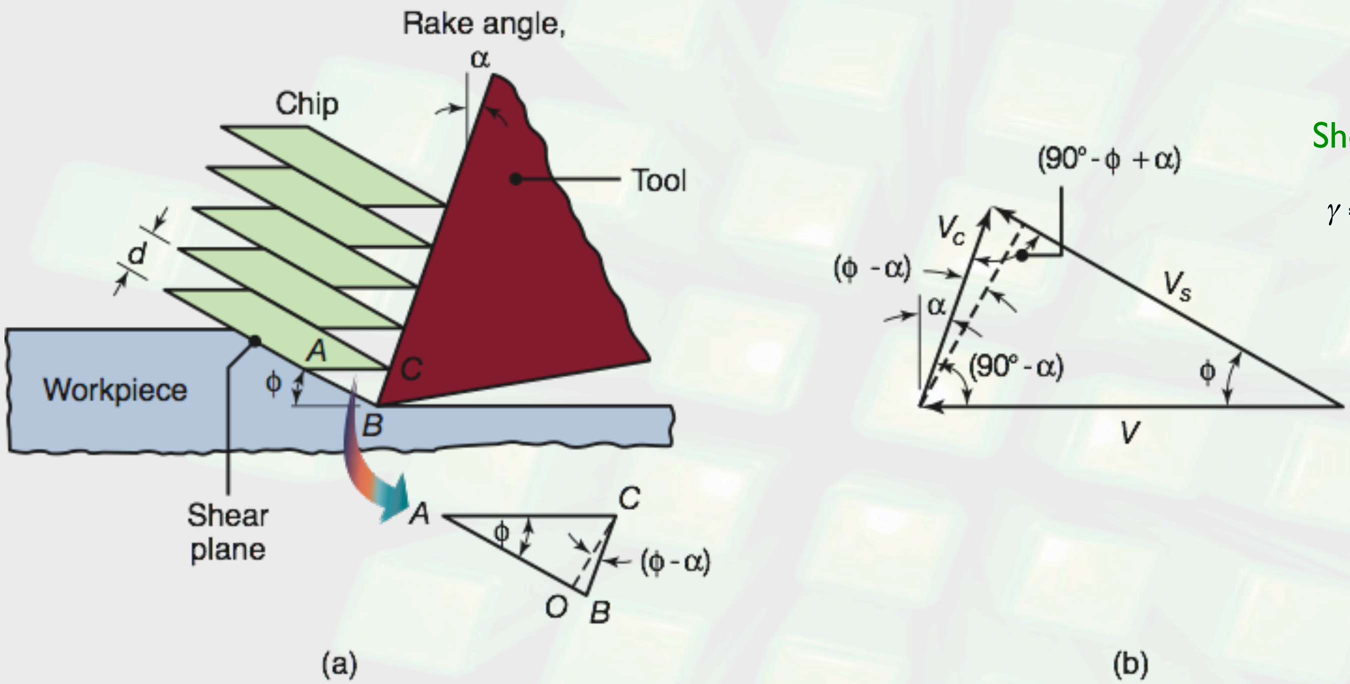


FIGURE 8.3 (a) Schematic illustration of the basic mechanism of chip formation in cutting. (b) Velocity diagram in the cutting zone.

Cutting ratio

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

Shear strain

$$\gamma = \frac{AB}{OC} = \frac{AO}{OC} + \frac{OB}{OC} = \cot\phi + \tan(\phi-\alpha)$$

Chip velocity

$$Vt_0 = V_c t_c$$

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

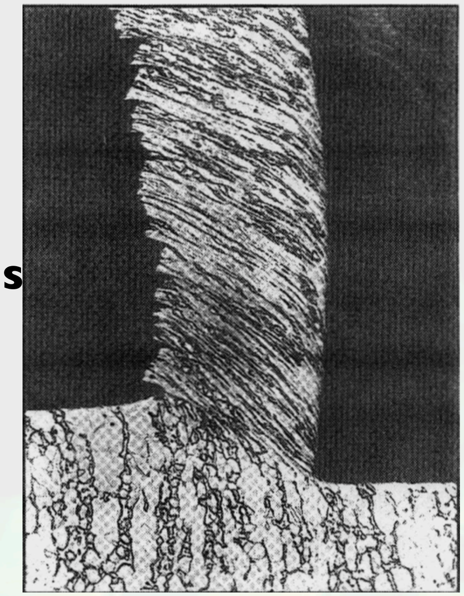
$$\frac{V}{\cos(\phi-\alpha)} = \frac{V_s}{\cos\alpha} = \frac{V_c}{\sin\alpha}$$

Shear strain rate

$$\dot{\gamma} = \frac{V_s}{d}$$

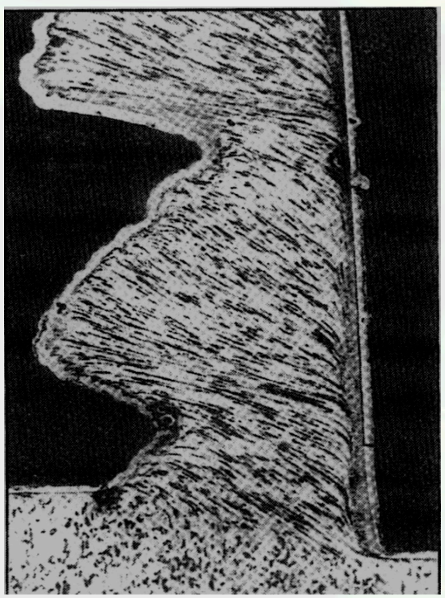
Types of Chips

Continuous Chips

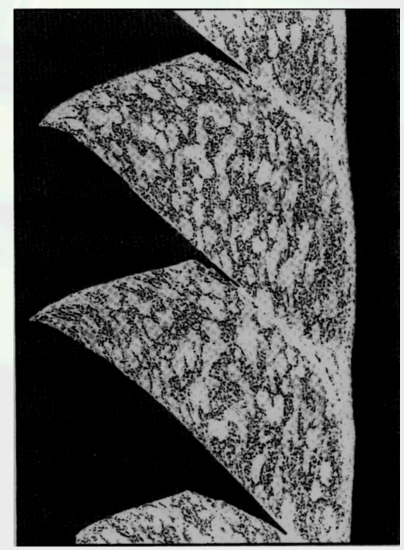


Continuous Chips with Built Up Edge (BUE)

Serrated Chips



Discontinuous Chips



Chip Formation

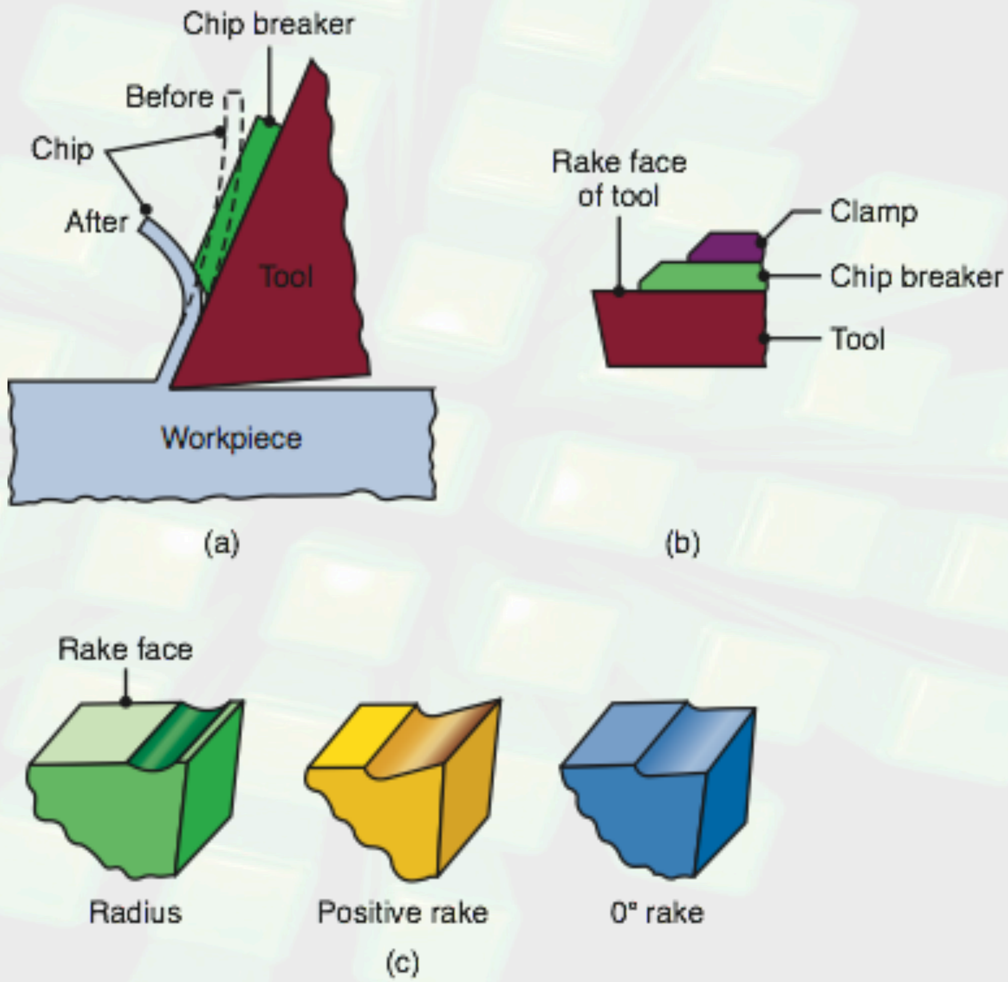
- Continuous chips
  - Ductile Materials
  - High tool rake angles
  - High cutting speeds
  - Can clog machines
    - Use of chip breakers to minimize bad effects
  - Good Surface Finish

- Continuous Chips with Built Up Edge (BUE)
  - Adhesion and friction dominated
  - Rough surface finish
  - Ductile materials
  - Low Cutting Speed
  - Can protect tool if stable
  - Low rake angles
  - High depth of cut

- Serrated Chips
  - Low thermal conductivity
  - Brittle materials
  - Ti, Cast Iron…

- Discontinuous Chips
  - Serrated to the point of chip failure
  - Brittle materials
  - Materials with inclusion/impurities
  - Very low or very high cutting speed
  - High cut depth or low rake angle
  - Low stiffness machine tool and poor damping
  - Ineffective cutting fluid

Chip Breaker



Oblique Cutting

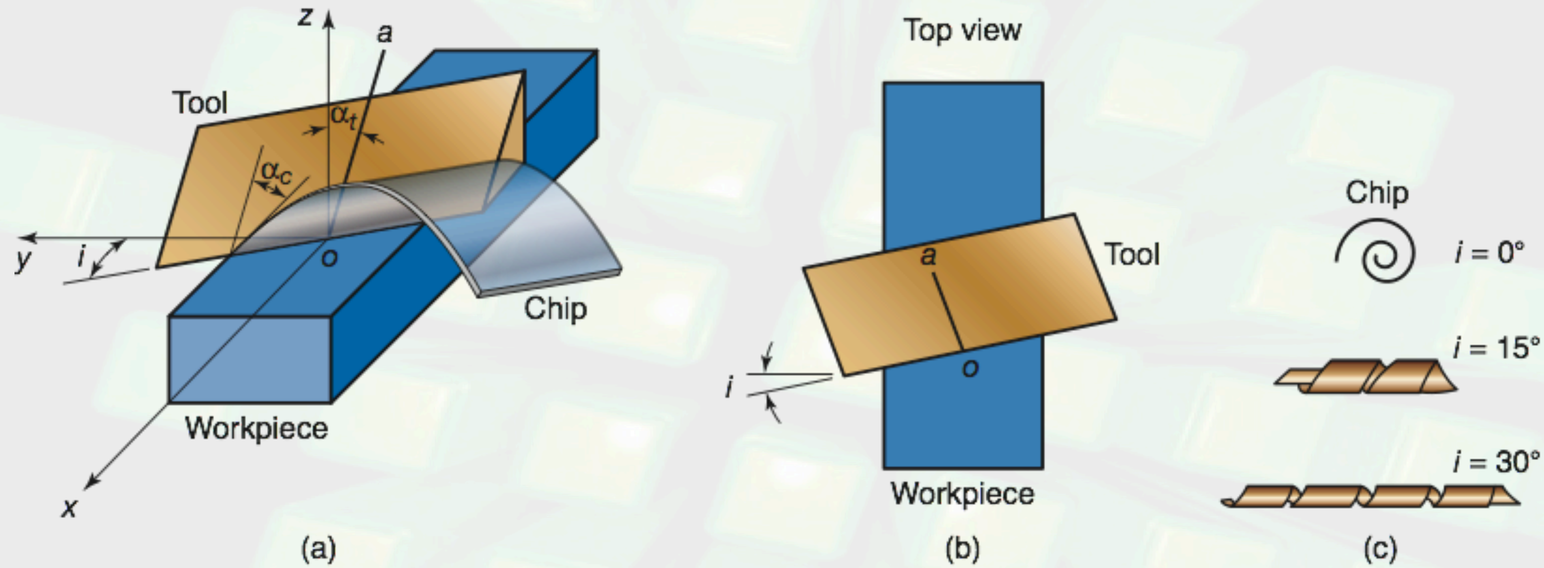


FIGURE 8.9 (a) Schematic illustration of cutting with an oblique tool. (b) Top view, showing the inclination angle, *i*. (c) Types of chips produced with different inclination angles.

Forces in Orthogonal Cutting

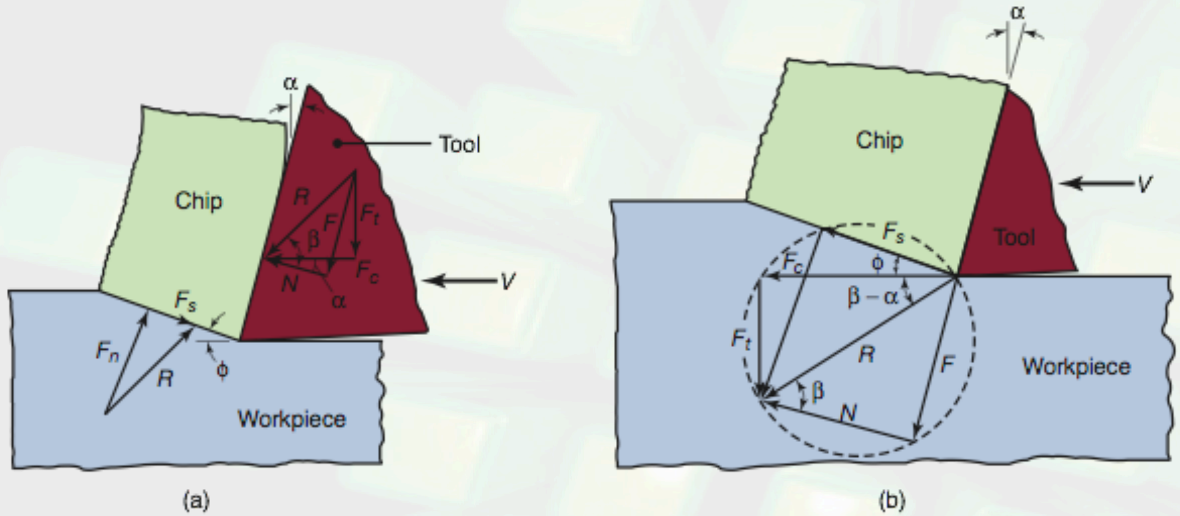


FIGURE 8.11 (a) Forces acting on a cutting tool in two-dimensional cutting. Note that the resultant forces, *R*, must be collinear to balance the forces. (b) Force circle to determine various forces acting in the cutting zone. *Source:* After M.E. Merchant.

Cutting force

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

Friction coefficient

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

Shear-Angle Relationships

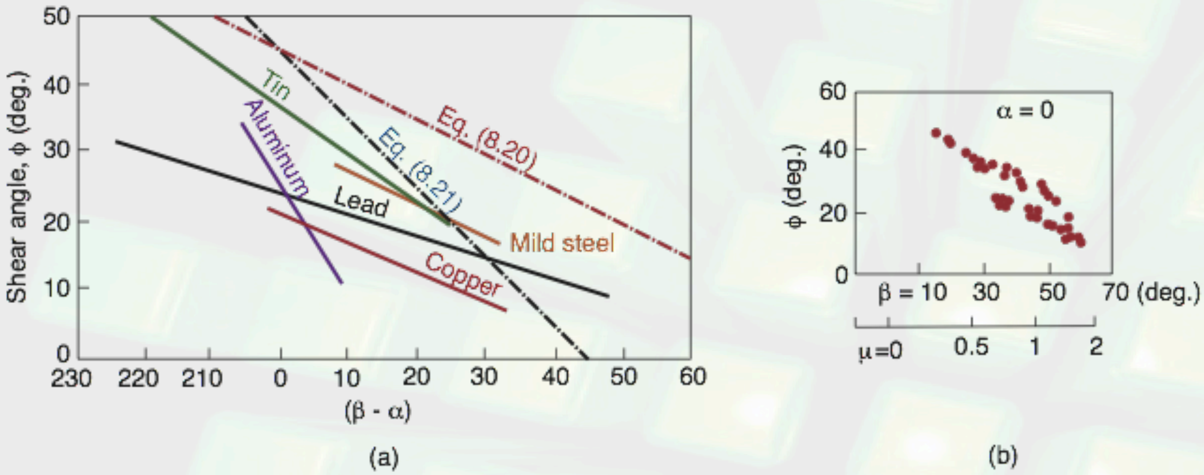


FIGURE 8.15 (a) Comparison of experimental and theoretical shear-angle relationships. More recent analytical studies have resulted in better agreement with experimental data. (b) Relation between the shear angle and the friction angle for various alloys and cutting speeds. *Source:* After S. Kobayashi.

Merchant [Eq. (8.20)]

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

Shaffer [Eq. (8.21)]

$$\phi = 45^\circ + \alpha - \beta$$

Mizuno [Eqs. (8.22)-(8.23)]

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

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

Specific Energy

- Total power input in cutting

$$Power = F_c V$$

- Specific energy

$$u_t = \frac{F_c V}{w t_0 V} = \frac{F_c}{w t_0}$$

- Specific energy for friction

$$u_f = \frac{F V_c}{w t_0 V} = \frac{F r}{w t_0} = \frac{(F_c \sin\alpha + F_t \cos\alpha)}{w t_0}$$

- Specific energy for shearing

$$u_s = \frac{F_s V_s}{w t_0 V}$$

- Total specific energy

$$u_t = u_f + u_s$$

Summary

- Force and power in cutting
  - Cutting force and thrust force at tool-chip interface
  - Friction force and normal force at tool-chip interface
  - Shear force and normal force on the shear plane
  - Cutting power
  - Specific energy (total, friction, shear)

Effect of Temperatures in Cutting

- **Mean temperature for orthogonal cutting**

$$T = \frac{1.2Y_f}{\rho c}\sqrt[3]{\frac{Vt_o}{K}}$$

- Effect of Temperature
  - Lower strength, hardness and wear resistance of cutting tool
  - Lower dimensional accuracy in workpiece
  - Thermal damage to machined surface
  - Temperature gradient in tool causing distortion and poor dimensional control

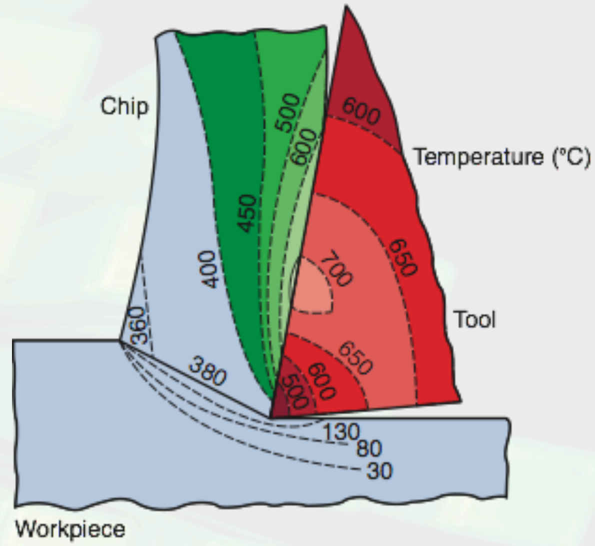
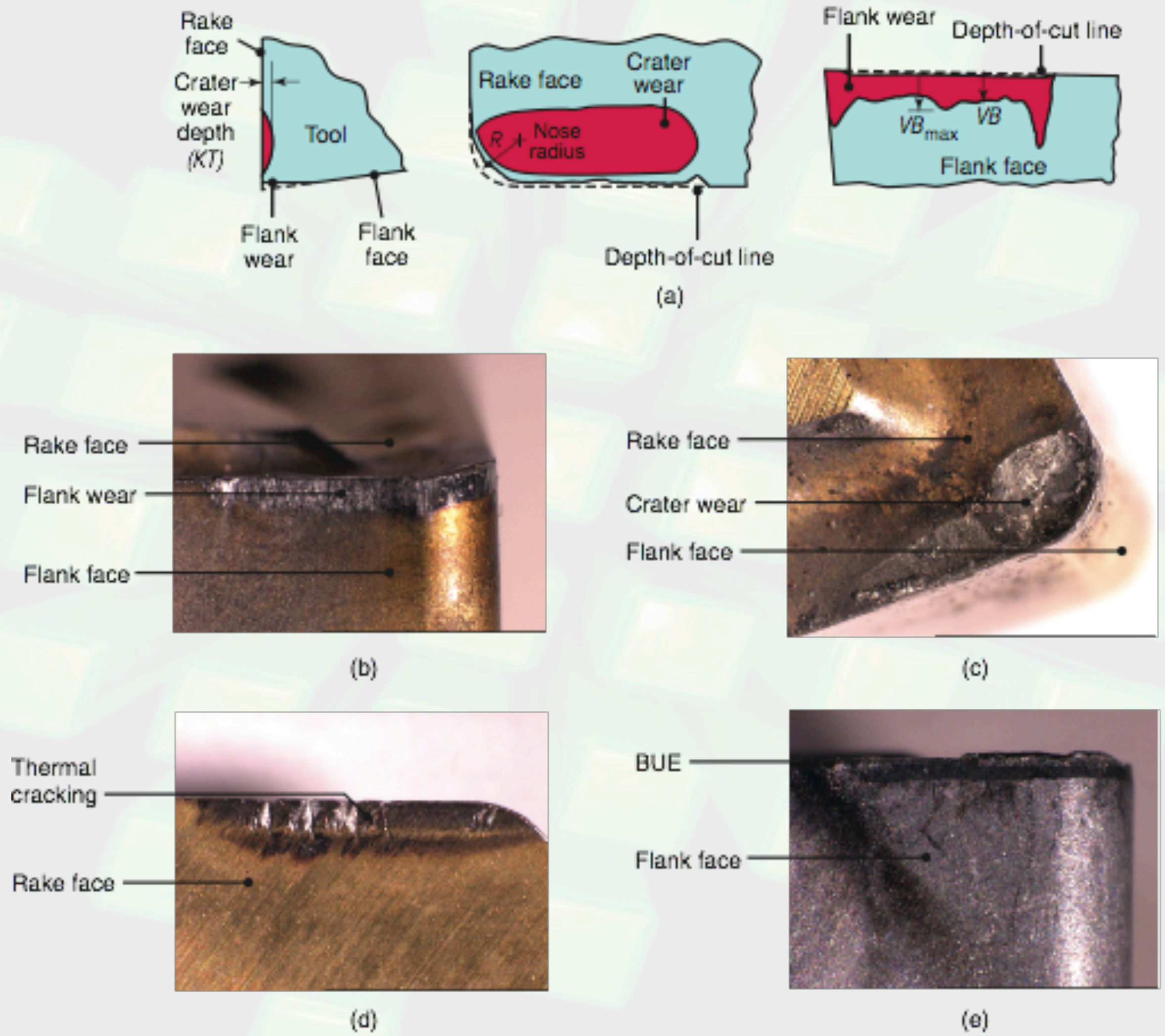


FIGURE 8.1 Typical temperature distribution in the cutting zone. Note the severe temperature gradients within the tool and the chip, and that the workpiece is relatively cool. *Source:* After G. Vieregge.

Tool Wear

- Factors causing tool wear
  - Tool and workpiece material
  - Processing parameter (cutting speed, feed, cutting depth, cutting fluid)
- Wear mechanisms
  - Flank wear
    - Sliding between tool and workpiece, adhesive or abrasive wear
    - Temperature rise
  - Crater wear
    - Temperature
    - Chemical affinity between workpiece material and tool
  - Chipping of cutting edge (catastrophic failure)
    - Mechanical shock
    - Thermal fatigue

Tool Wear



Rake face
Crater wear depth (KT)
Tool
Flank wear
Flank face
Rake face
Crater wear
R
Nose radius
Depth-of-cut line
Flank wear
Depth-of-cut line
VB_{max}
VB
Flank face
(a)
Rake face
Flank wear
Flank face
(b)
Rake face
Crater wear
Flank face
(c)
Thermal cracking
Rake face
(d)
BUE
Flank face
(e)

Tool Life

Taylor tool life equation

$$VT^n = C$$

V - cutting speed
T - time
n,C – constant

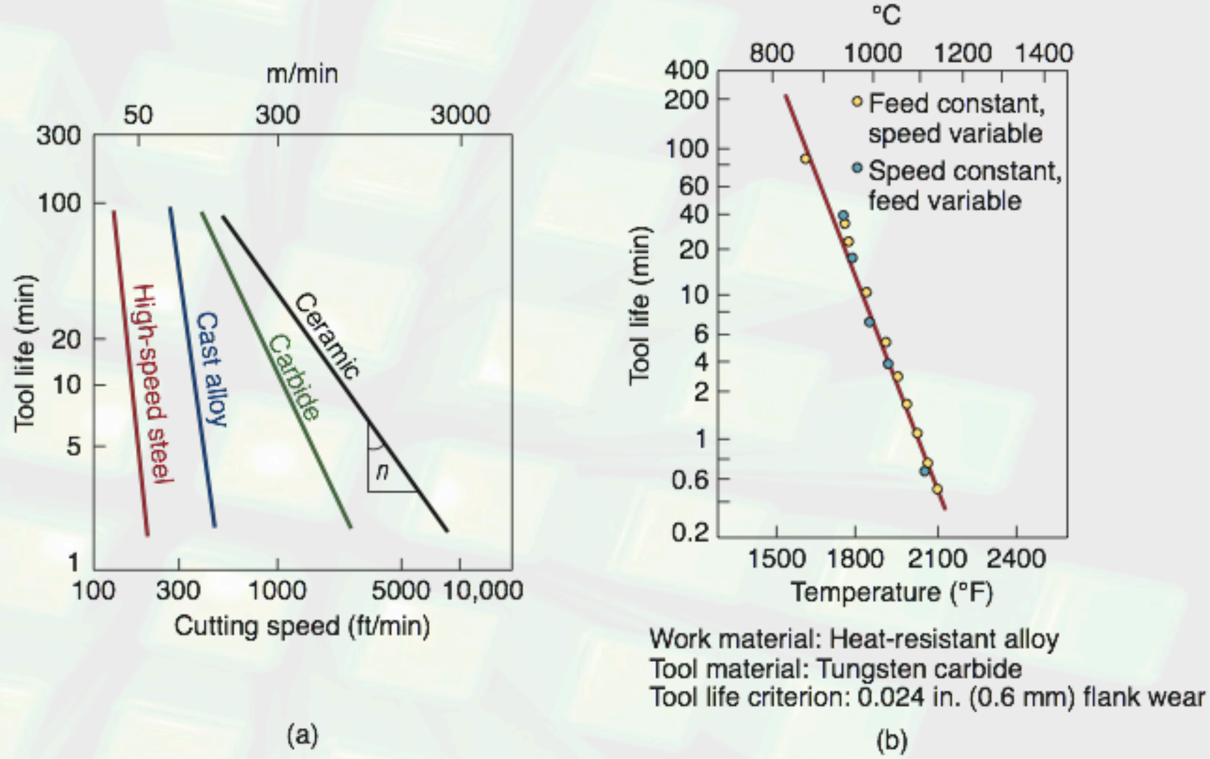


FIGURE 8.22 (a) Tool-life curves for a variety of cutting-tool materials. The negative inverse of the slope of these curves is the exponent *n* in tool-life equations. (b) Relationship between measured temperature during cutting and tool life (flank wear).

Tool Materials

- Tool Material Characteristics
  - Hardness (hot hardness)
  - Toughness
  - Wear resistance
  - Chemical stability or inertness

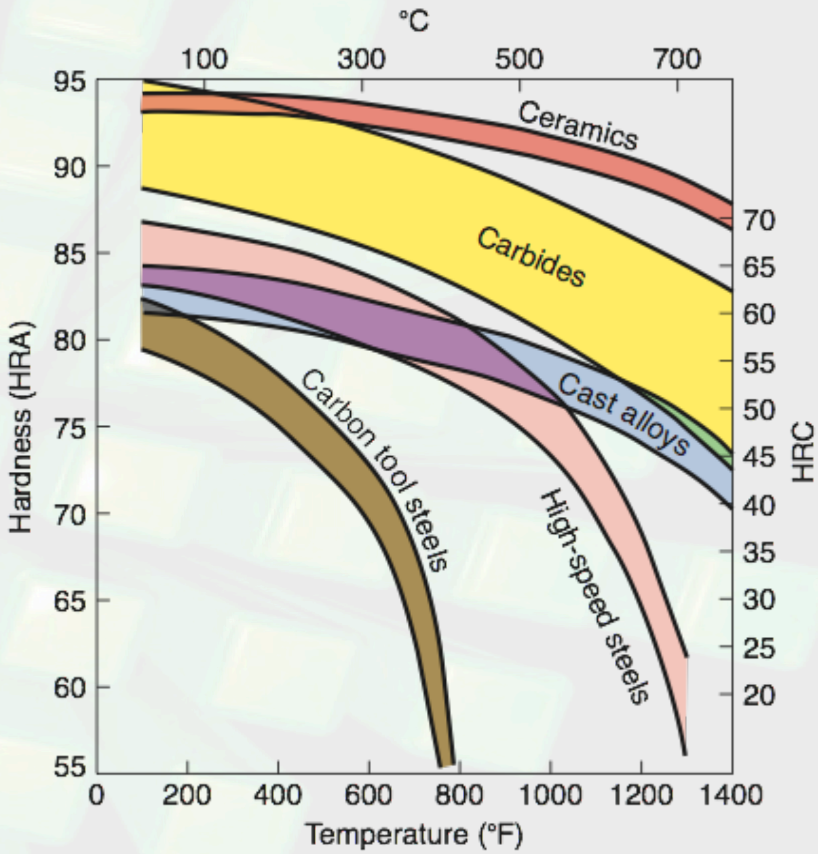


FIGURE 8.30 Hardness of various cutting-tool materials as a function of temperature (hot hardness). The wide range in each group of tool materials results from the variety of compositions and treatments available for that group.

Historical Tool Improvement

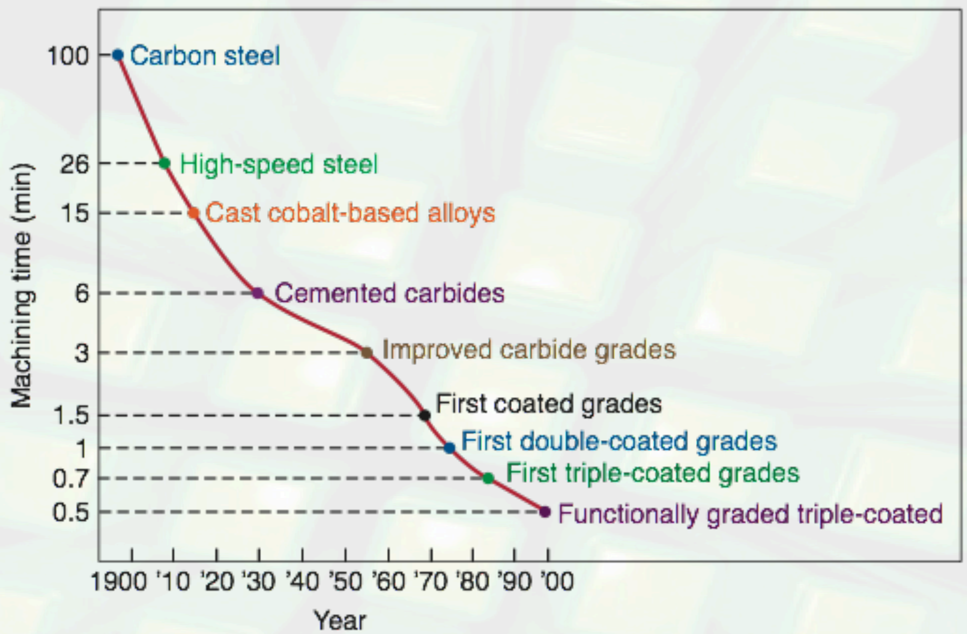


FIGURE 8.35 Relative time required to machine with various cutting-tool materials, with indication of the year the tool materials were introduced. Note that, within one century, machining time has been reduced by two orders of magnitude.

Coated Tools

- Coating characteristics
  - High hot hardness
  - Chemical stability and inertness to the workpiece material
  - Low thermal conductivity
  - Good bonding to substrate
  - Little or no porosity

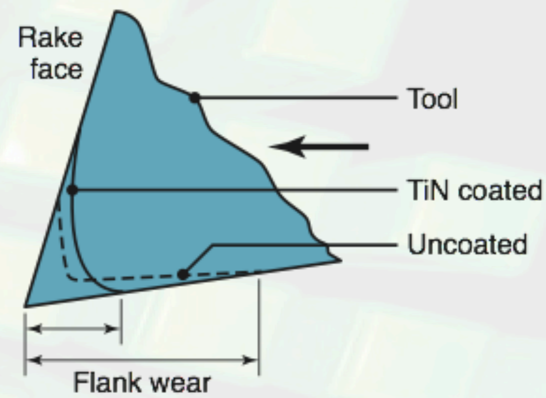


FIGURE 8.36 Wear patterns on high-speed-steel uncoated and titanium-nitride-coated cutting tools. Note that flank wear is lower for the coated tool.

Common Tool Coating Materials

- Titanium nitride (TiN)

  Low friction, high hardness, good high-T prop
  good adhesion to substrate

- Titanium carbide (TiC) on WC inserts

  High resistance to flank wear

- Titanium carbonitride (TiCN)
  - Harder and tougher than TiN
  - Very effective in cutting stainless steel
- Ceramic coating (eg, Al_2O_3)
  - Good high-T prop, chemical inertness
    low thermal conductivity, wear resistance
  - Poor bond strength
- Multiphase coating
- Diamond coating

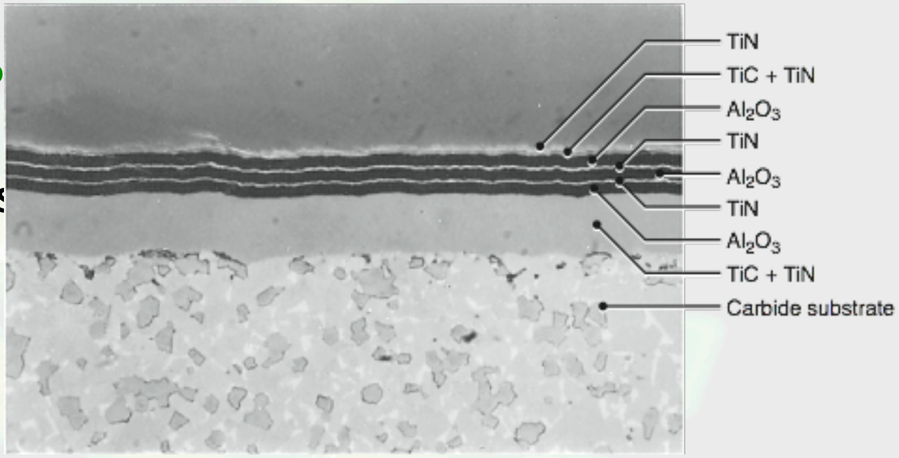
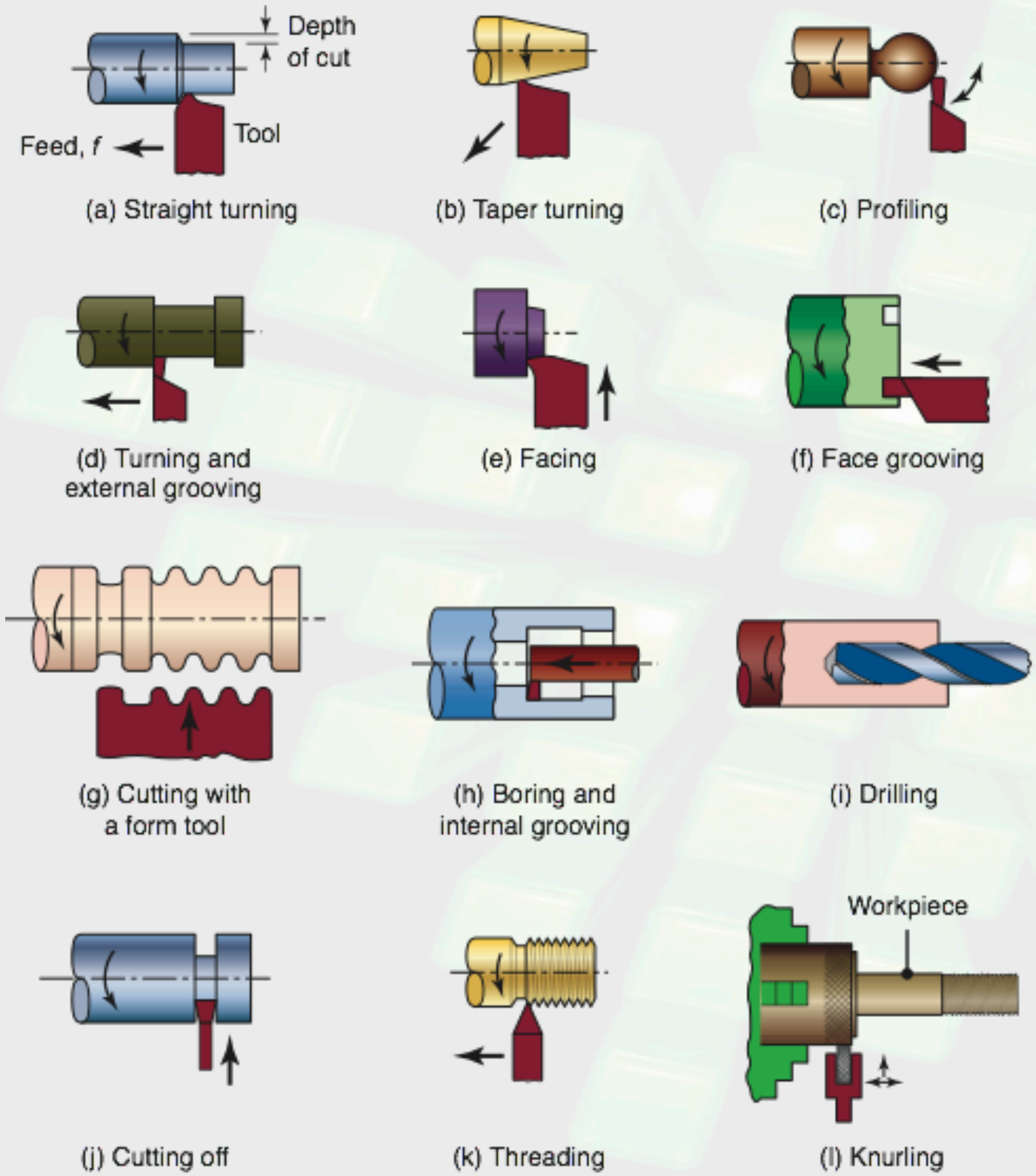


FIGURE 8.37 Multiphase coatings on a tungsten-carbide substrate. Three alternating layers of aluminum oxide are separated by very thin layers of titanium nitride. Inserts with as many as 13 layers of coatings have been made. Coating thicknesses are typically in the range of 2 to 10 μm

Cutting Fluids

- Objectives of cutting fluid
  - Cooling
  - Reduce friction and wear
  - Reduce force and energy consumption
  - Wash away chips
  - Protect machined surface from environmental attacks
- Dominant functions: coolant and/or lubricant
- Cons
  - Waste disposal
  - Environmental effect
- Types of cutting fluids (four)
  - Oils, emulsions, semisynthetics and synthetics
- Near-dry and dry-machining
  - Less or no waste disposal
  - Less or no environmental pollution
  - Good surface quality (near-dry)
  - May have surface oxidation (dry-machining)

Lathe Operations



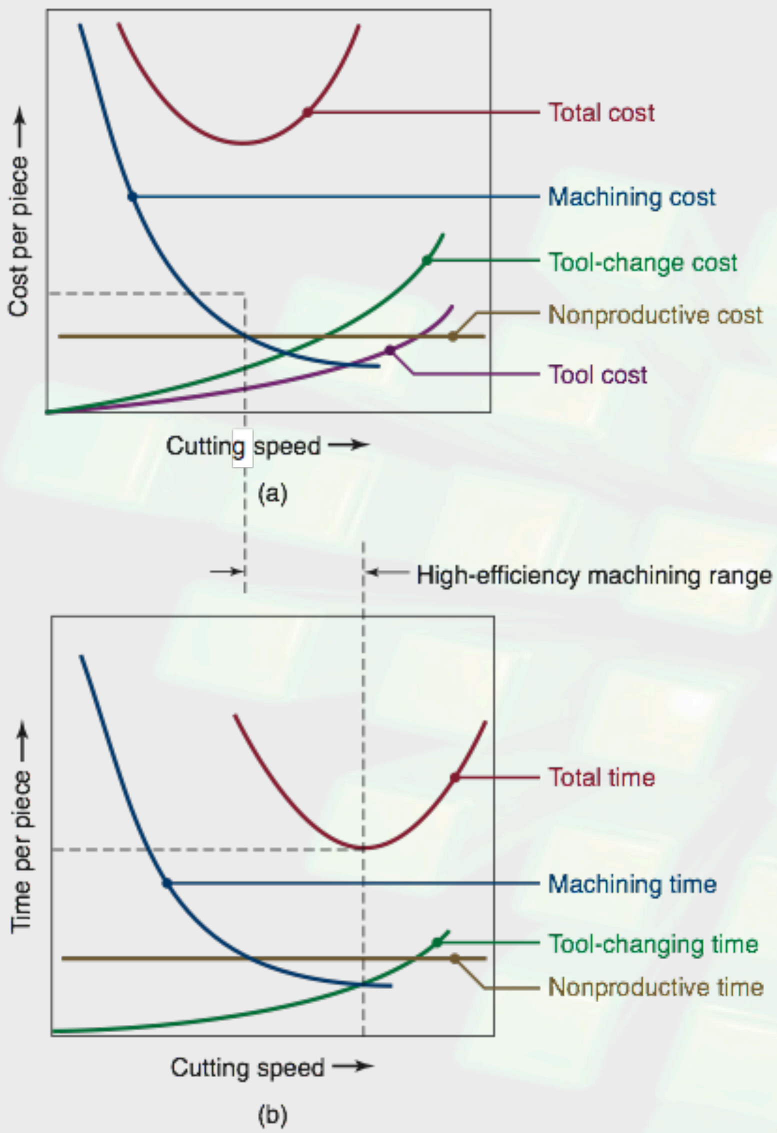
Characteristics of Machining

Process	Characteristics	Commercial tolerances (±mm)
Turning	Turning and facing operations are performed on all types of materials; requires skilled labor; low production rate, but medium to high rates can be achieved with turret lathes and automatic machines, requiring less skilled labor.	Fine: 0.05-0.13 Rough: 0.13 Skiving: 0.025-0.05
Boring	Internal surfaces or profiles, with characteristics similar to those produced by turning; stiffness of boring bar is important to avoid chatter.	0.025
Drilling	Round holes of various sizes and depths; requires boring and reaming for improved accuracy; high production rate, labor skill required depends on hole location and accuracy specified.	0.075
Milling	Variety of shapes involving contours, flat surfaces, and slots; wide variety of tooling; versatile; low to medium production rate; requires skilled labor.	0.13-0.25
Planing	Flat surfaces and straight contour profiles on large surfaces; suitable for low-quantity production; labor skill required depends on part shape.	0.08-0.13
Shaping	Flat surfaces and straight contour profiles on relatively small workpieces; suitable for low-quantity production; labor skill required depends on part shape.	0.05-0.13
Broaching	External and internal flat surfaces, slots, and contours with good surface finish; costly tooling; high production rate; labor skill required depends on part shape.	0.025-0.15
Sawing	Straight and contour cuts on flats or structural shapes; not suitable for hard materials unless the saw has carbide teeth or is coated with diamond; low production rate; requires only low skilled labor.	0.8

Vibration and Chatter

- Forced vibration vs self-excited vibration (chatter)
  - Forced vibration: periodic engagement of the cutter or the cutting tool with workpiece surface due to periodic force present in the machine tool
  - Chatter: self-excited large amplitude vibration due to interaction of the chip-removal process with structure of the machine tool
- Effect of chatter and vibration
  - Poor surface finish
  - Loss of dimensional accuracy
  - Premature wear, chipping and failure of cutting tool
  - Damage to machine tool components due to vibration
  - Noise generation
- How to overcome
  - Isolate or remove forcing element (for forced vibration)
  - Increasing stiffness or damping of the system

Machining Economics



Cost per piece

$$C_p = C_m + C_s + C_l + C_t$$

Machining Setup loading tooling

FIGURE 8.75 Qualitative plots showing (a) cost per piece, and (b) time per piece in machining. Note that there is an optimum cutting speed for both cost and time, respectively. The range between the two optimum speeds is known as the *high-efficiency machining range*.

Summary

- Temperature effect
- Tool wear
  - Wear mechanisms
    - Flank wear, Crater wear, Chipping
  - Taylor tool life equation $VT^n = C$
  - Tool wear monitoring
- Tool materials
- Metal cutting fluids
- Cutting machine characteristics
- Vibration and chatter
- Cutting economics

Summary of Machining Chapter

- Deep understanding
  - Chip formation mechanisms
    - Merchant orthogonal cutting model
  - Cutting forces and specific energy
  - Tool wear: mechanisms, tool life
- General understanding
  - Temperature effect
  - Tool materials
  - Cutting fluid
  - Machining characteristics
    - Different operation
    - Vibration and chatter
  - Machining economics
    - Optimum cutting speed