THEORY OF METAL MACHINING

1. Overview of Machining Technology
2. Theory of Chip Formation in Metal Machining
3. Force Relationships and the Merchant Equation
4. Power and Energy Relationships in Machining

Material Removal Processes

A family of shaping operations, the common feature of which is removal of material from a starting workpart so the remaining part has the desired geometry

- Machining – material removal by a sharp cutting tool, e.g., turning, milling, drilling
- Abrasive processes – material removal by hard, abrasive particles, e.g., grinding
- Nontraditional processes - various energy forms other than sharp cutting tool to remove material

Machining

Cutting action involves shear deformation of work material to form a chip

- As chip is removed, new surface is exposed

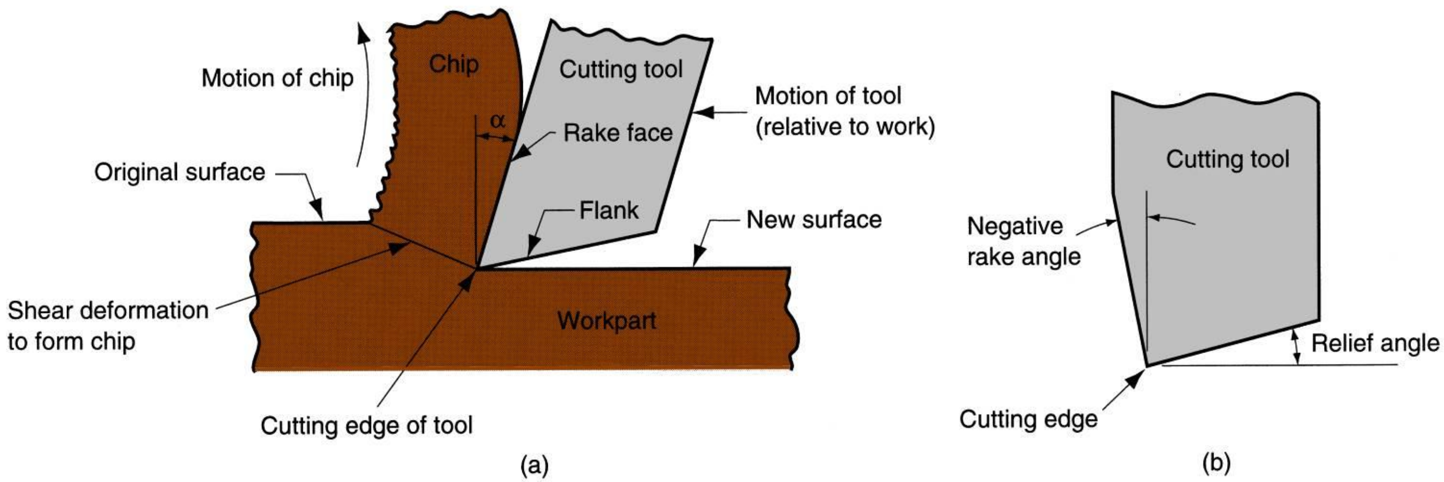


Figure 21.2 (a) A cross-sectional view of the machining process, (b) tool with negative rake angle; compare with positive rake angle in (a).

Why Machining is Important

- Variety of work materials can be machined
  - Most frequently used to cut metals
- Variety of part shapes and special geometric features possible, such as:
  - Screw threads
  - Accurate round holes
  - Very straight edges and surfaces
- Good dimensional accuracy and surface finish

Disadvantages with Machining

- Wasteful of material
  - Chips generated in machining are wasted material, at least in the unit operation
- Time consuming
  - A machining operation generally takes more time to shape a given part than alternative shaping processes, such as casting, powder metallurgy, or forming

Machining in Manufacturing Sequence

- Generally performed after other manufacturing processes, such as casting, forging, and bar drawing
  - Other processes create the general shape of the starting workpart
  - Machining provides the final shape, dimensions, finish, and special geometric details that other processes cannot create

Machining Operations

- Most important machining operations:
  - Turning
  - Drilling
  - Milling
- Other machining operations:
  - Shaping and planing
  - Broaching
  - Sawing

Turning

Single point cutting tool removes material from a rotating workpiece to form a cylindrical shape

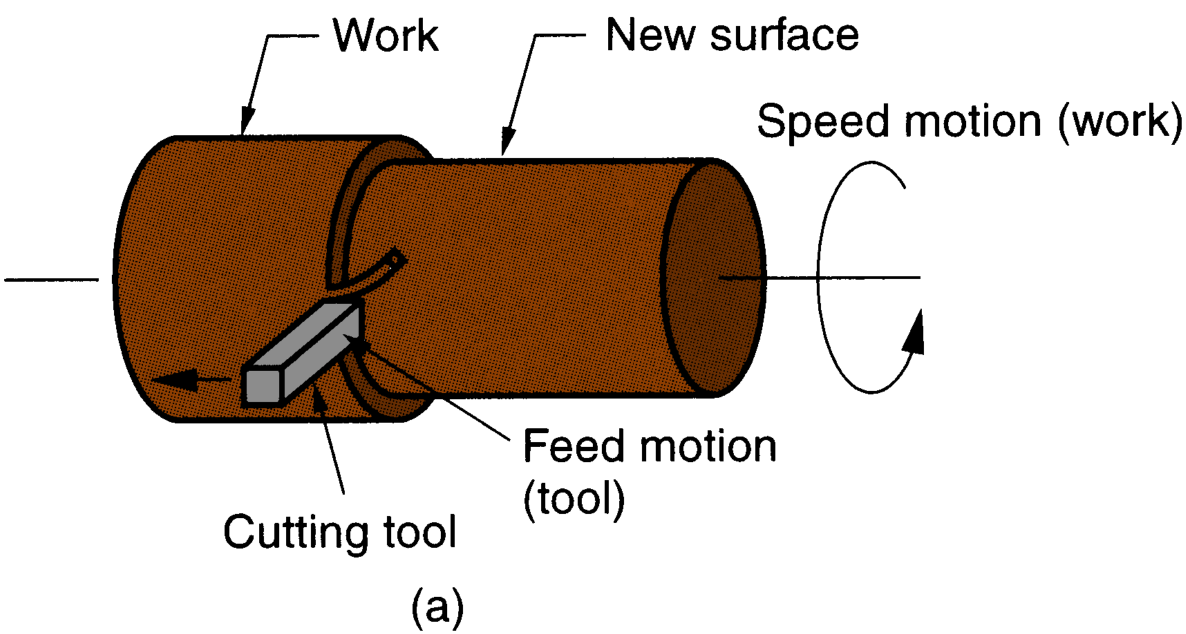
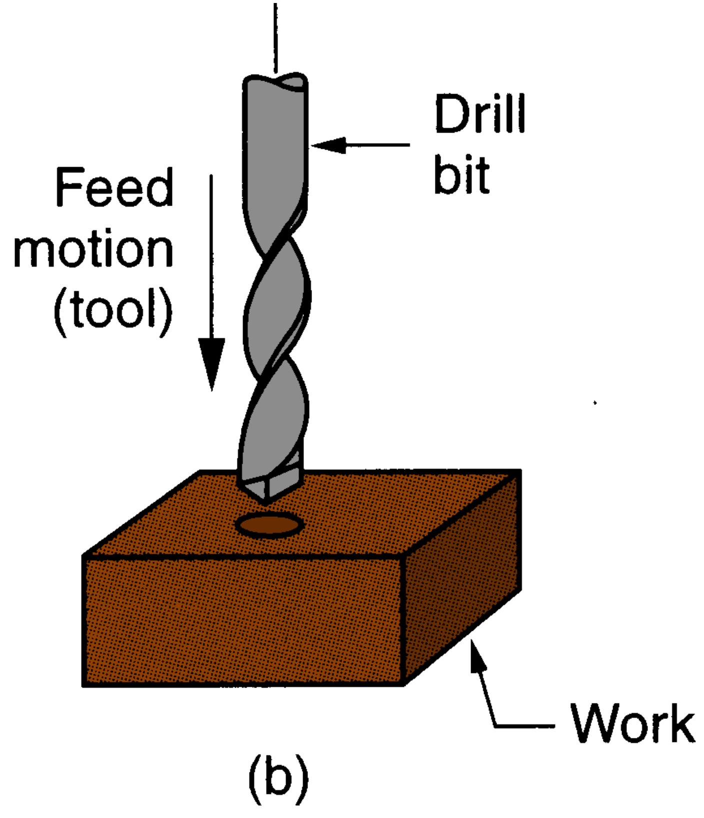


Figure 21.3 Three most common machining processes: (a) turning,

Drilling

Used to create a round hole, usually by means of a rotating tool (drill bit) with two cutting edges

Figure 21.3 (b) drilling,



Milling

Rotating multiple-cutting-edge tool is moved across work to cut a plane or straight surface

- Two forms: peripheral milling and face milling

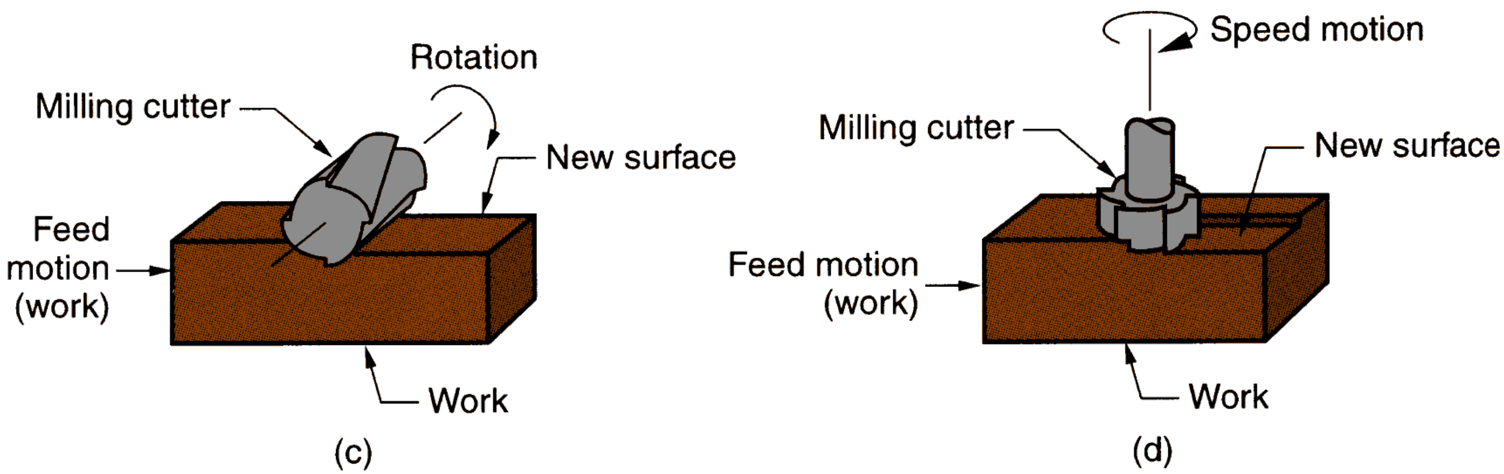


Figure 21.3 (c) peripheral milling, and (d) face milling.

Cutting Tool Classification

1. Single-Point Tools
   - One dominant cutting edge
   - Point is usually rounded to form a nose radius
   - Turning uses single point tools
2. Multiple Cutting Edge Tools
   - More than one cutting edge
   - Motion relative to work achieved by rotating
   - Drilling and milling use rotating multiple cutting edge tools

Cutting Tools

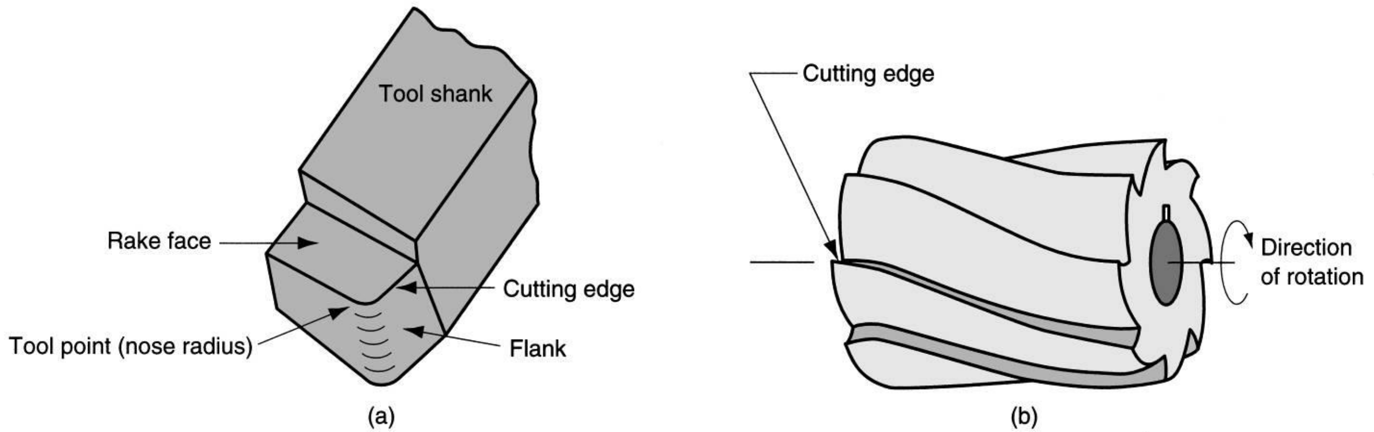


Figure 21.4 (a) A single-point tool showing rake face, flank, and tool point; and (b) a helical milling cutter, representative of tools with multiple cutting edges.

Cutting Conditions in Machining

- Three dimensions of a machining process:
  - Cutting speed v – primary motion
  - Feed f – secondary motion
  - Depth of cut d – penetration of tool below original work surface
- For certain operations, material removal rate can be computed as

$$R_{MR} = v\, f\, d$$

where v = cutting speed; f = feed; d = depth of cut

Cutting Conditions for Turning

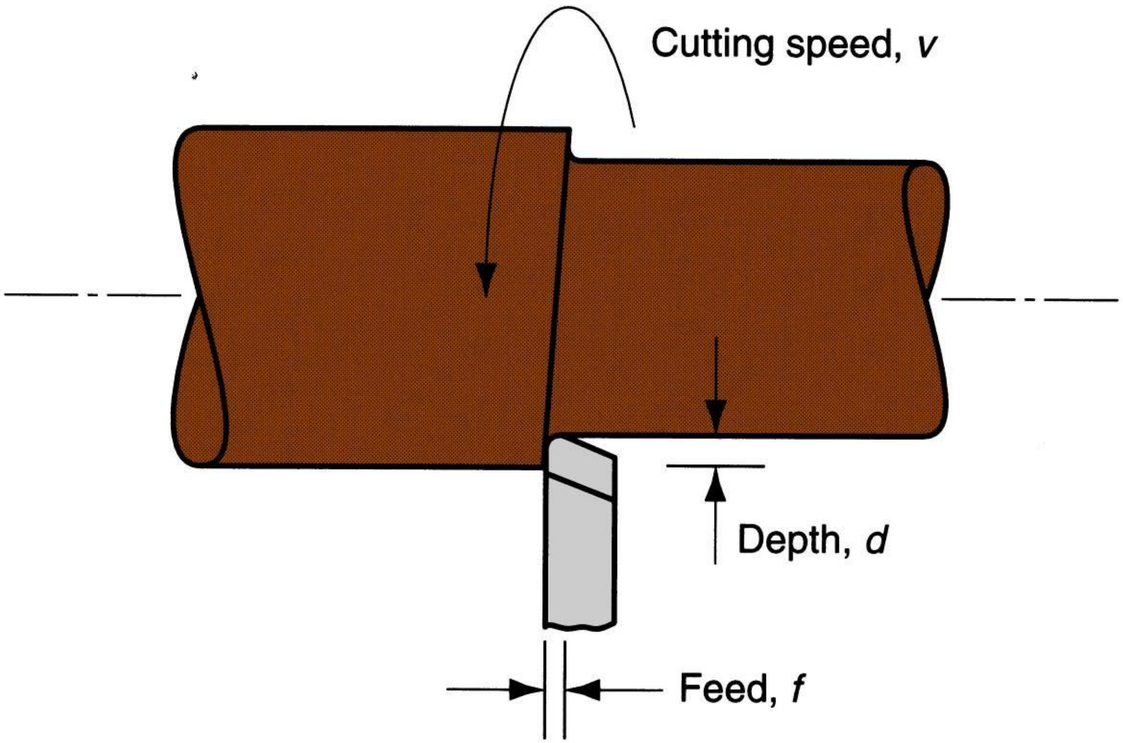


Figure 21.5 Speed, feed, and depth of cut in turning.

Roughing vs. Finishing

In production, several roughing cuts are usually taken on the part, followed by one or two finishing cuts

- Roughing - removes large amounts of material from starting workpart
  - Creates shape close to desired geometry, but leaves some material for finish cutting
  - High feeds and depths, low speeds
- Finishing - completes part geometry
  - Final dimensions, tolerances, and finish
  - Low feeds and depths, high cutting speeds

Examples 1

A cylindrical workpart 200 mm in diameter and 700 mm long is to be turned in an engine lathe. Cutting conditions are as follows: cutting speed is 2.30 m/s, feed is 0.32 mm/rev, and depth of cut is 1.80 mm. Determine (a) cutting time, and (b) metal removal rate.

Solution:

(a) $N = v/(\pi D)$ = (2.30 m/s)/0.200π = 3.66 rev/s

$f_r = Nf$ = 6.366(.3) = 1.17 mm/s

$T_m = L/f_r$ = 700/1.17 = 598 s = **9.96 min**

Alternative calculation using Eq. (22.5), T_m = 200(700)π/(2,300 x 0.32) = 597.6 sec = 9.96 min

(b) $R_{MR} = vfd$ = (2.30 m/s)(10^3)(0.32 mm)(1.80 mm) = **1320 mm³/s**

Examples 2

- A tapered surface is to be turned on an automatic lathe. The workpiece is 750 mm long with minimum and maximum diameters of 100 mm and 200 mm at opposite ends. The automatic controls on the lathe permit the surface speed to be maintained at a constant value of 200 m/min by adjusting the rotational speed as a function of workpiece diameter. Feed = 0.25 mm/rev and depth of cut = 3.0 mm. The rough geometry of the piece has already been formed, and this operation will be the final cut. Determine (a) the time required to turn the taper and (b) the rotational speeds at the beginning and end of the cut.

Solution:

(a) $R_{MR} = vfd$ = (200 m/min)(10^3 mm/m)(0.25 mm)(3.0 mm) = 150,000 mm^3/min

Area of frustrum of cone $A = \pi(R_1 + R_2)\{h^2 + (R_1 - R_2)^2\}^{0.5}$

Given R_1 = 100 mm, R_2 = 50 mm, and h = 750 mm,

$A = \pi(100 + 50)\{750^2 + (100 - 50)^2\}^{0.5} = 150\pi(565{,}000)^{0.5}$ = 354,214 mm^2

Given depth of cut d = 3.0 mm, volume cut $V = Ad$ = (354,214 mm^2)(3.0 mm) = 1,062,641 mm^3

$T_m = V/R_{MR}$ = (1,062,641 mm^3)/(150,000 mm^3/min) = **7.084 min**

(b) At beginning of cut (D_1 = 100 mm), $N = v/\pi D$ = 200,000/100π = **636.6 rev/min**

At end of cut (D_2 = 200 mm), N = 200,000/200π = **318.3 rev/min**

Examples 3

- A drilling operation is to be performed with a 12.7 mm diameter twist drill in a steel workpart. The hole is a blind hole at a depth of 60 mm and the point angle is 118°. The cutting speed is 25 m/min and the feed is 0.30 mm/rev. Determine (a) the cutting time to complete the drilling operation, and (b) metal removal rate during the operation, after the drill bit reaches full diameter.

Solution:

(a) $N = v/\pi D = 25(10^3) / (12.7\pi) = 626.6$ rev/min

$f_r = Nf = 626.6(0.30) = 188$ mm/min

$T_m = L/f_r = 60/188 = 0.319$ min

(b) $R_{MR} = 0.25\pi D^2 f_r = 0.25\pi(12.7)^2(188) = 23{,}800$ mm^3/min

Orthogonal Cutting Model

Simplified 2-D model of machining that describes the mechanics of machining fairly accurately

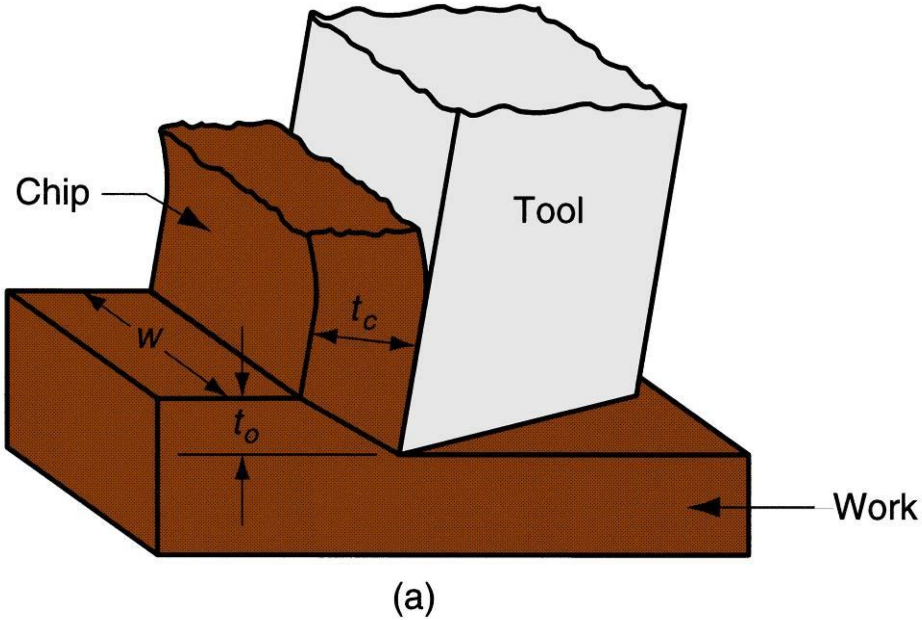


Figure 21.6 Orthogonal cutting: (a) as a three-dimensional process.

Chip Thickness Ratio

$$r = \frac{t_o}{t_c}$$

where r = *chip thickness ratio*; t_o = thickness of the chip prior to chip formation; and t_c = chip thickness after separation

- Chip thickness after cut always greater than before, so chip ratio always less than 1.0

Determining Shear Plane Angle

- Based on the geometric parameters of the orthogonal model, the shear plane angle ϕ can be determined as:

$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}$$

where r = chip ratio, and α = rake angle

Shear Strain in Chip Formation

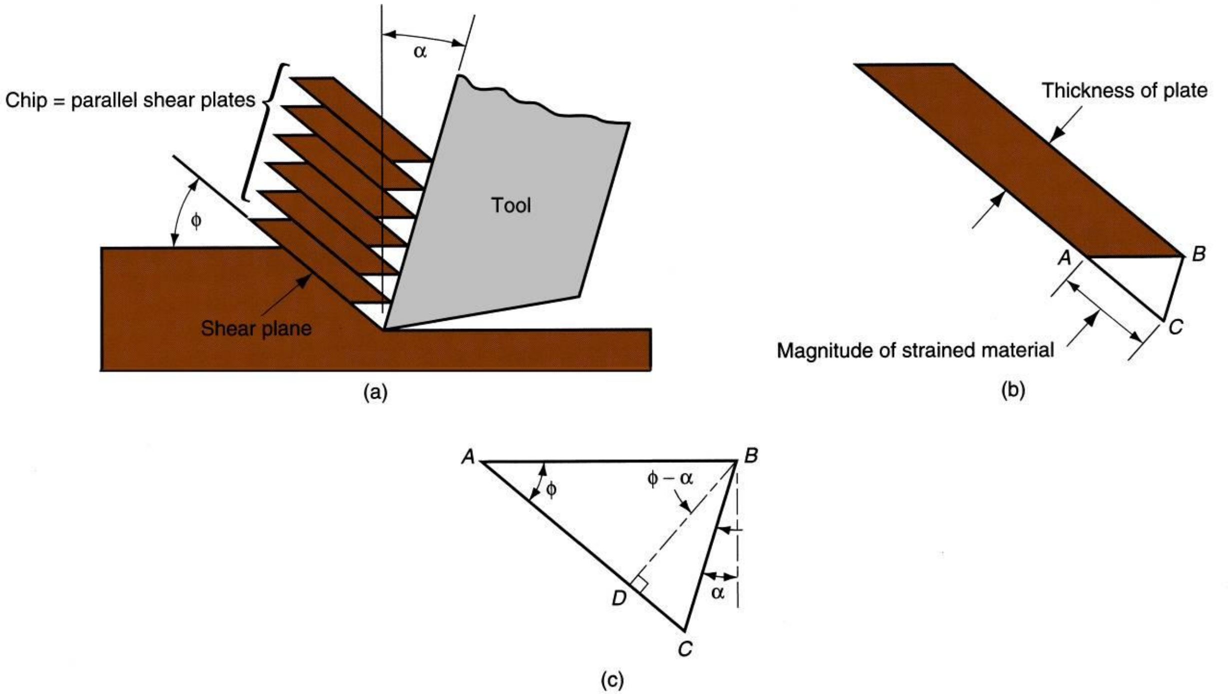


Figure 21.7 Shear strain during chip formation: (a) chip formation depicted as a series of parallel plates sliding relative to each other, (b) one of the plates isolated to show shear strain, and (c) shear strain triangle used to derive strain equation.

Shear Strain

Shear strain in machining can be computed from the following equation, based on the preceding parallel plate model:

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

where γ = shear strain, ϕ = shear plane angle, and α = rake angle of cutting tool

Chip Formation

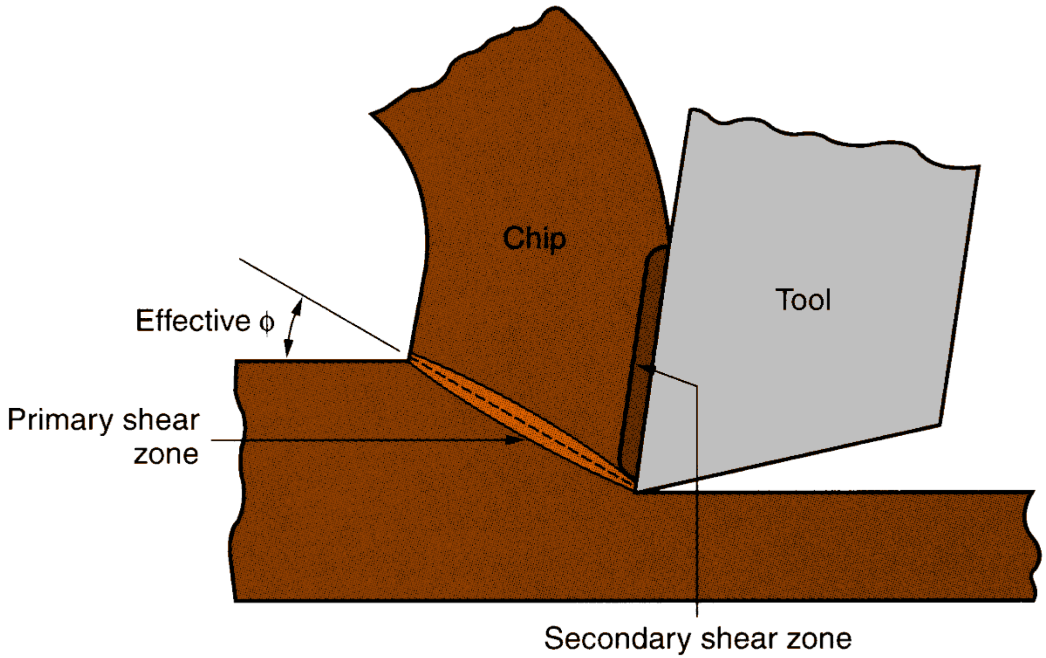


Figure 21.8 More realistic view of chip formation, showing shear zone rather than shear plane. Also shown is the secondary shear zone resulting from tool-chip friction.

Four Basic Types of Chip in Machining

1. Discontinuous chip
2. Continuous chip
3. Continuous chip with Built-up Edge (BUE)
4. Serrated chip

Discontinuous Chip

- Brittle work materials
- Low cutting speeds
- Large feed and depth of cut
- High tool-chip friction

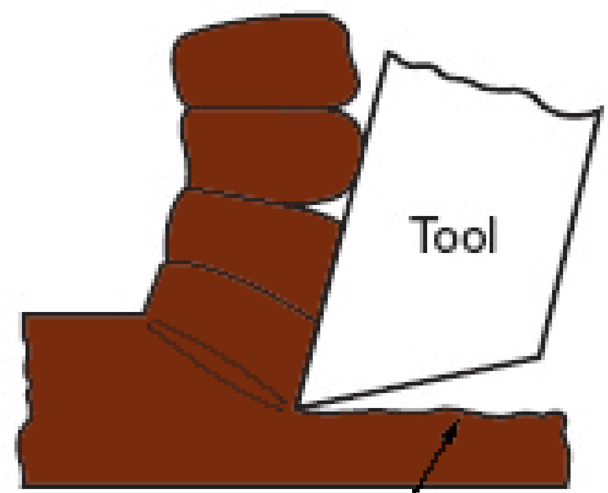


Figure 21.9 Four types of chip formation in metal cutting: (a) discontinuous

Continuous Chip

- Ductile work materials
- High cutting speeds
- Small feeds and depths
- Sharp cutting edge
- Low tool-chip friction

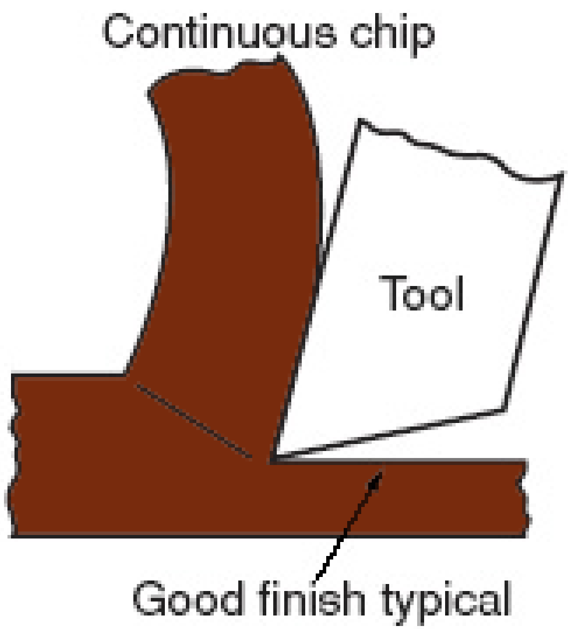


Figure 21.9 (b) continuous

(b)

Continuous with BUE

- Ductile materials
- Low-to-medium cutting speeds
- Tool-chip friction causes portions of chip to adhere to rake face
- BUE forms, then breaks off, cyclically

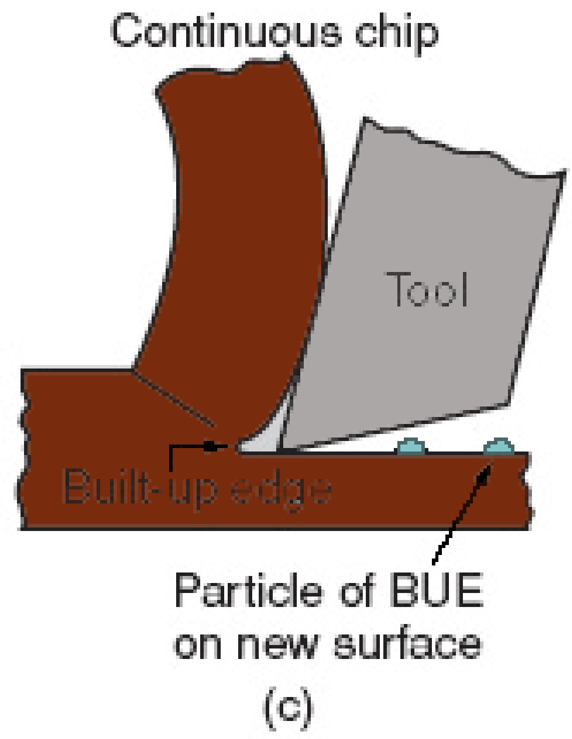


Figure 21.9 (c) continuous with built-up edge

Serrated Chip

- Semicontinuous - saw-tooth appearance
- Cyclical chip forms with alternating high shear strain then low shear strain
- Associated with difficult-to-machine metals at high cutting speeds

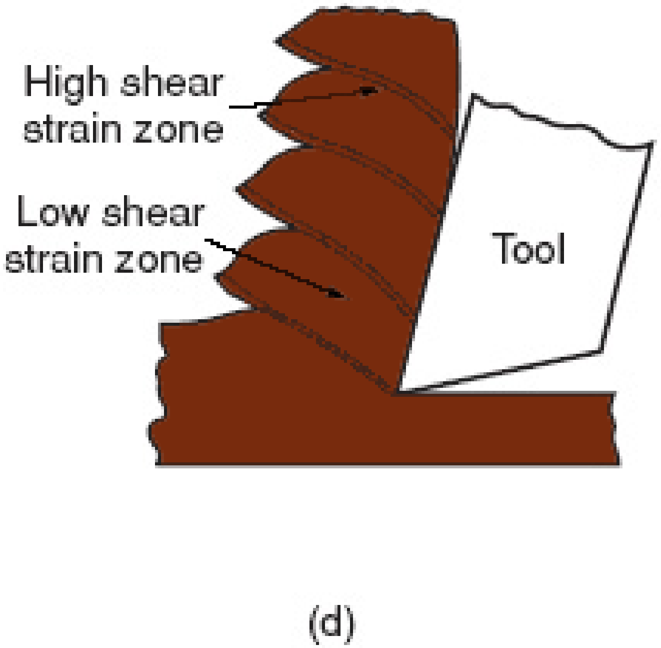


Figure 21.9 (d) serrated.

Forces Acting on Chip

- Friction force *F* and Normal force to friction *N*
- Shear force F_s and Normal force to shear F_n

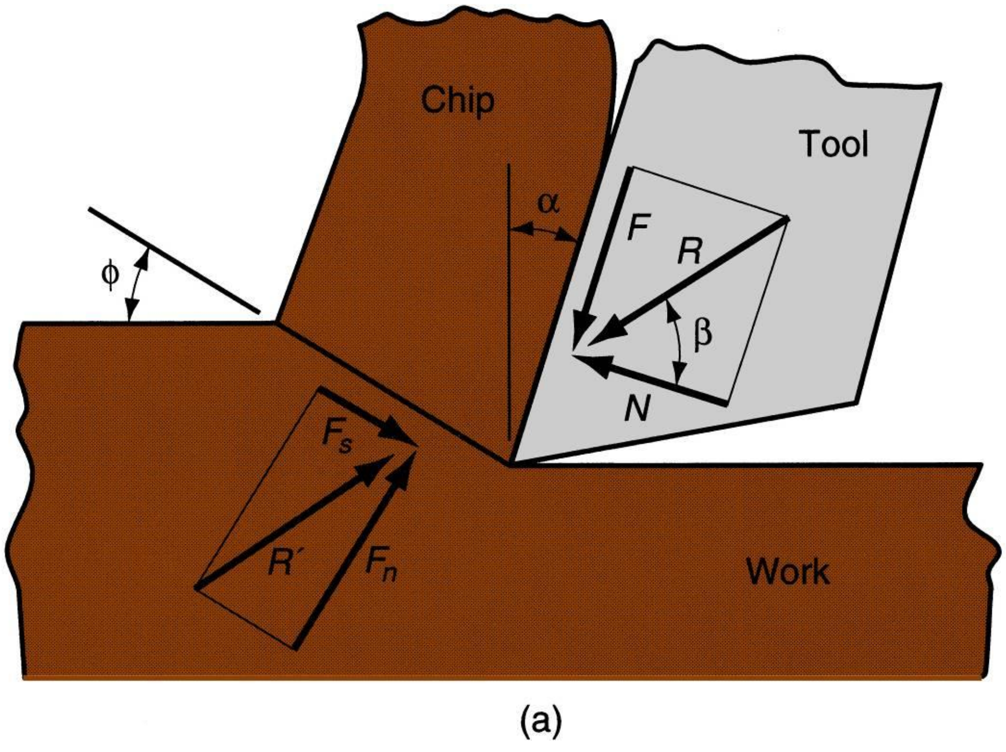


Figure 21.10 Forces in metal cutting: (a) forces acting on the chip in orthogonal cutting

Resultant Forces

- Vector addition of F and N = resultant R
- Vector addition of F_s and F_n = resultant R'
- Forces acting on the chip must be in balance:
  - R' must be equal in magnitude to R
  - R' must be opposite in direction to R
  - R' must be collinear with R

Coefficient of Friction

Coefficient of friction between tool and chip:

$$\mu = \frac{F}{N}$$

Friction angle related to coefficient of friction as follows:

$$\mu = \tan \beta$$

Shear Stress

Shear stress acting along the shear plane:

$$S = \frac{F_s}{A_s}$$

where A_s = area of the shear plane

$$A_s = \frac{t_o w}{\sin\phi}$$

Shear stress = shear strength of work material during cutting

Cutting Force and Thrust Force

- F, N, F_s, and F_n cannot be directly measured
- Forces acting on the tool that can be measured:
  - Cutting force F_c and Thrust force F_t

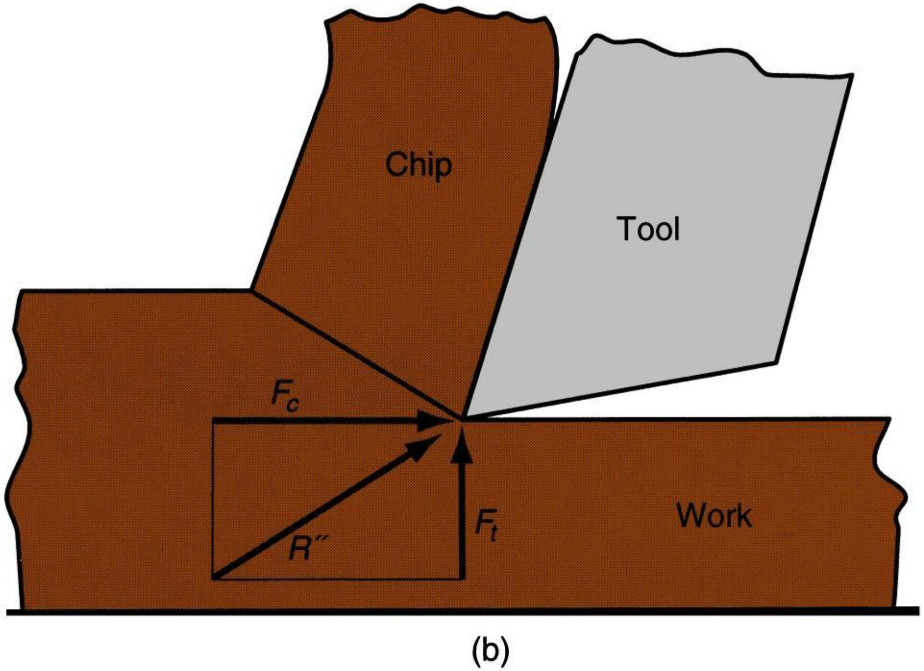


Figure 21.10 Forces in metal cutting: (b) forces acting on the tool that can be measured

Forces in Metal Cutting

- Equations can be derived to relate the forces that cannot be measured to the forces that can be measured:

$$F = F_c \sin\alpha + F_t \cos\alpha$$

$$N = F_c \cos\alpha - F_t \sin\alpha$$

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

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

- Based on these calculated force, shear stress and coefficient of friction can be determined

The Merchant Equation

- Of all the possible angles at which shear deformation can occur, the work material will select a shear plane angle ϕ that minimizes energy, given by

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

- Derived by Eugene Merchant
- Based on orthogonal cutting, but validity extends to 3-D machining

What the Merchant Equation Tells Us

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

- To increase shear plane angle
  - Increase the rake angle
  - Reduce the friction angle (or coefficient of friction)

Effect of Higher Shear Plane Angle

- Higher shear plane angle means smaller shear plane which means lower shear force, cutting forces, power, and temperature

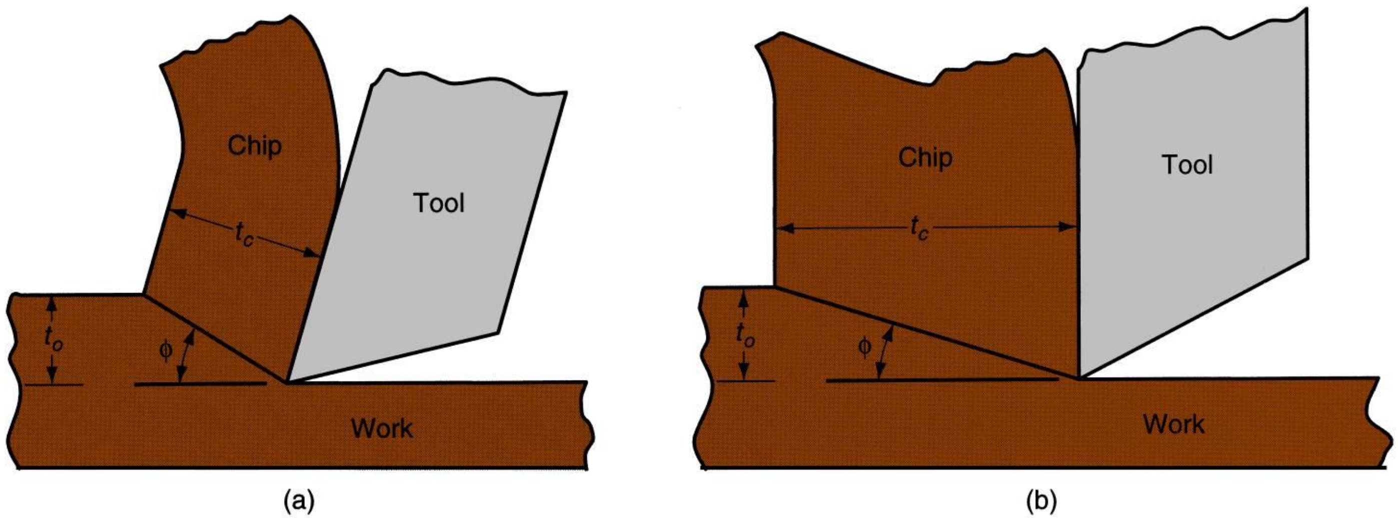


Figure 21.12 Effect of shear plane angle ϕ: (a) higher ϕ with a resulting lower shear plane area; (b) smaller ϕ with a corresponding larger shear plane area. Note that the rake angle is larger in (a), which tends to increase shear angle according to the Merchant equation

Power and Energy Relationships

- A machining operation requires power
- The power to perform machining can be computed from:

$$P_c = F_c v$$

where P_c = cutting power; F_c = cutting force; and v = cutting speed

Power and Energy Relationships

- In U.S. customary units, power is traditional expressed as horsepower (dividing ft-lb/min by 33,000)

$$HP_c = \frac{F_c v}{33{,}000}$$

where HP_c = cutting horsepower, hp

Examples 4

- A lathe performs a turning operation on a workpiece of 6.0 in diameter. The shear strength of the work is 40,000 lb/in^2 and the tensile strength is 60,000 lb/in^2. The rake angle of the tool is 6°. The machine is set so that cutting speed is 700 ft/min, feed = 0.015 in/rev, and depth = 0.090 in. The chip thickness after the cut is 0.025 in. Determine (a) the horsepower required in the operation, (b) unit horsepower for this material under these conditions.

- **Solution**:

(a) Must find F_c and v to determine HP.

$r = 0.015/0.025 = 0.6$

$\varphi = \tan^{-1}(0.6 \cos 6/(1 - 0.6 \sin 6)) = \tan^{-1}(0.6366) = 32.5°$

$\beta = 2(45) + \alpha - 2(\varphi) = 90 + 6 - 2(32.5) = 31.0°$

$A_s = t_o w/\sin \varphi = (0.015)(0.09)/\sin 32.5 = 0.00251 \text{ in}^2$

$F_s = SA_s = 40{,}000(0.00251) = 101$ lb.

$F_c = F_s \cos(\beta - \alpha)/\cos(\varphi + \beta - \alpha)$

$F_c = 101 \cos(31 - 6)/\cos(32.5 + 31.0 - 6) = 170$ lb.

$HP_c = F_c v/33{,}000 = 170(700)/33{,}000 =$ **3.61 hp.**

(b) $R_{MR} = 700 \times 12(0.0075)(0.075) = 11.3 \text{ in}^3/\text{min}$

$HP_u = HP_c/R_{MR} = 3.61/11.3 =$ **0.319 hp/(in³/min)**

Try the following Examples

- A two-spindle drill simultaneously drills a ½ in hole and a ¾ in hole through a workpiece that is 1.0 inch thick. Both drills are twist drills with point angles of 118°. Cutting speed for the material is 230 ft/min. The rotational speed of each spindle can be set, individually. The feed rate for both holes must be set to the same value because the 2 spindles lower at the same rate. The feed rate is set so the total metal removal rate does not exceed 1.50 in^3/min. Determine (a) the maximum feed rate (in/min) that can be used, (b) the individual feeds (in/rev) that result for each hole, and (c) the time required to drill the holes.

- A turning operation is made with a rake angle of 10°, a feed of 0.010 in/rev and a depth of cut = 0.100 in. The shear strength of the work material is known to be 50,000 lb/in^2, and the chip thickness ratio is measured after the cut to be 0.40. Determine the cutting force and the feed force. Use the orthogonal cutting model as an approximation of the turning process.

- The cutting force and thrust force in an orthogonal cutting operation are 1470 N and 1589 N, respectively. The rake angle = 5°, the width of the cut = 5.0 mm, the chip thickness before the cut = 0.6, and the chip thickness ratio = 0.38. Determine (a) the shear strength of the work material and (b) the coefficient of friction in the operation.