MACHINING
(ORTHOGONAL/FORCES ANALYSIS/POWER REQUIREMENTS)

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(adopted from Intr of Manu Procss)

THEORY OF METAL MACHINING

1. Machining Technology Overview
2. Chip Formation in Metal Machining
3. Force Relationships/Merchant Equation
4. Power/Energy Relationships in Machining
5. Cutting Temperature

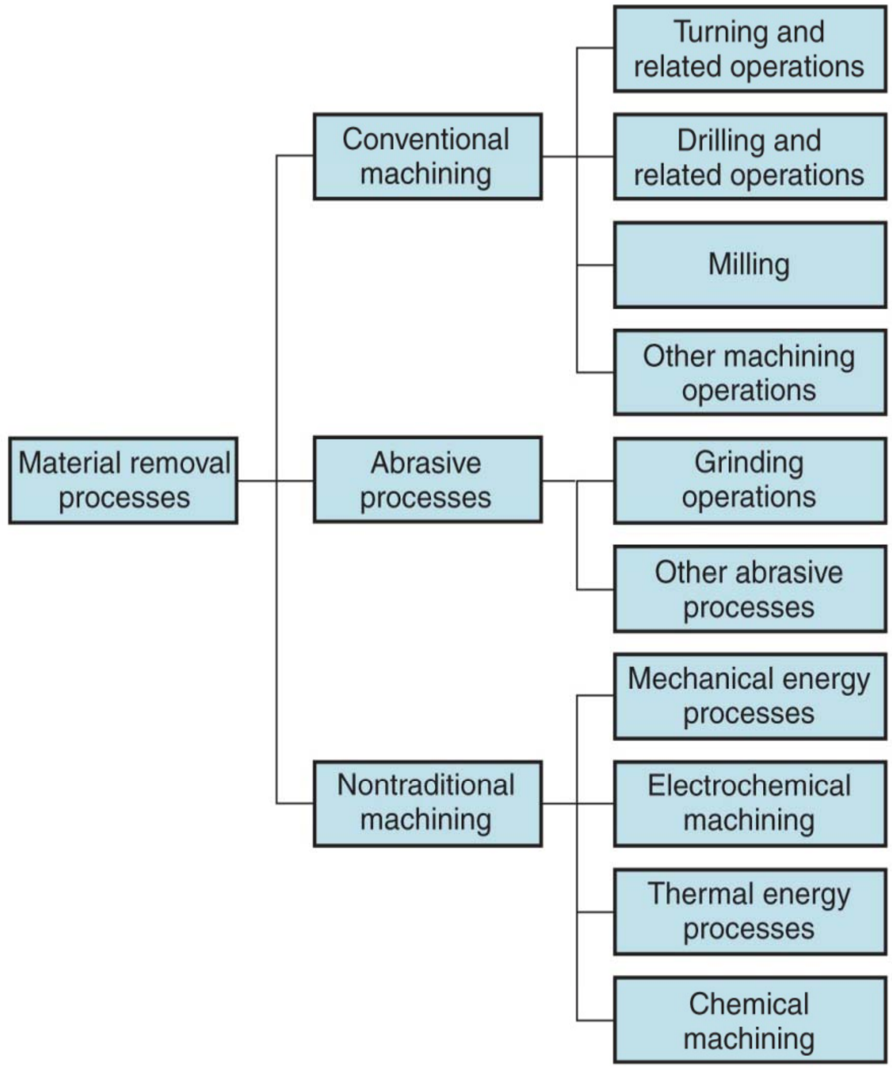
MATERIAL REMOVAL PROCESSES

A family of shaping operations, the main feature of which is removal of material from a starting work part 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

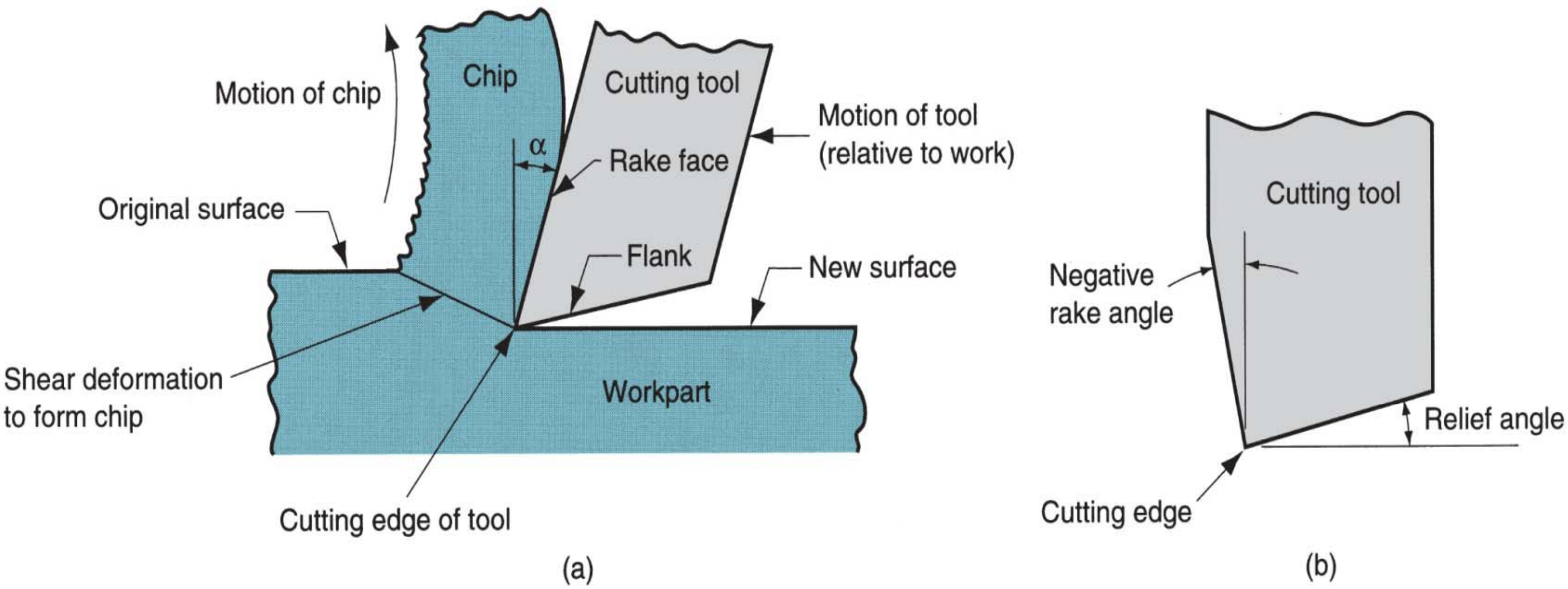
Material Removal Processes

- The family tree



Machining

- Cutting action involves shear deformation of work material to form a chip, and as chip is removed, new surface is exposed: (a) positive and (b) negative rake tools



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:
  - 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 longer to shape a given part than alternative shaping processes

Machining in the Manufacturing Sequence

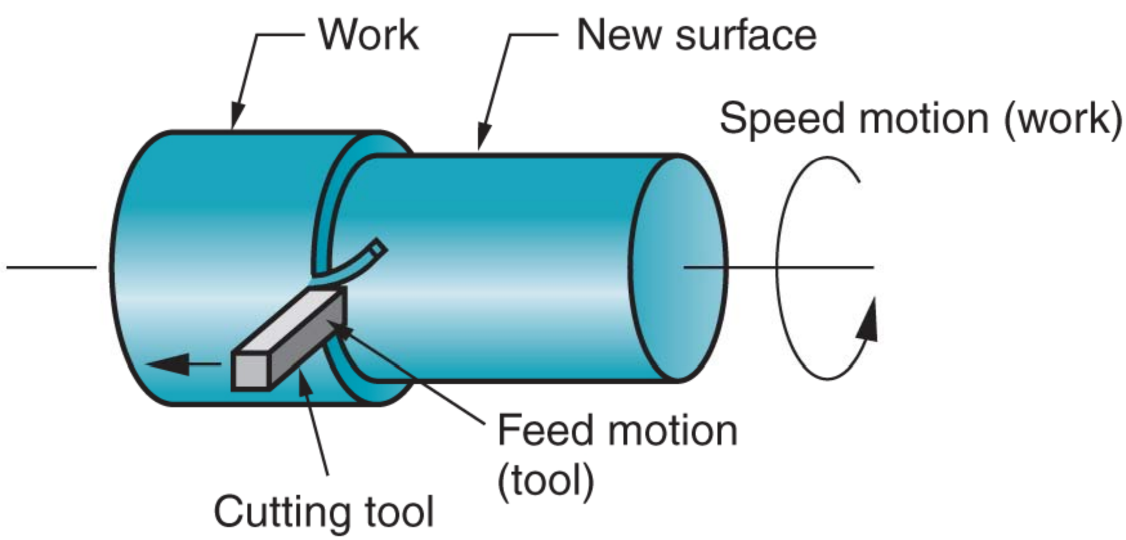
- Generally performed after other manufacturing processes, such as casting, forging, and bar drawing
  - Other processes create the general shape of the starting workpart
  - Machining provides the final shape, dimensions, finish, and special geometric details that other processes cannot create

Machining Operations

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

Turning

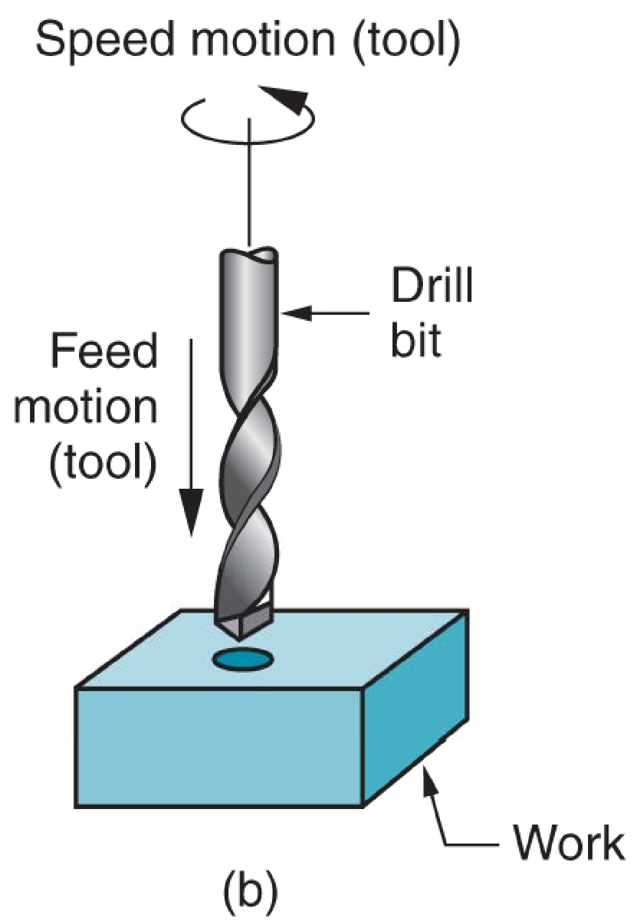
- Single point cutting tool removes material from a rotating work piece to form a cylindrical shape



(a)

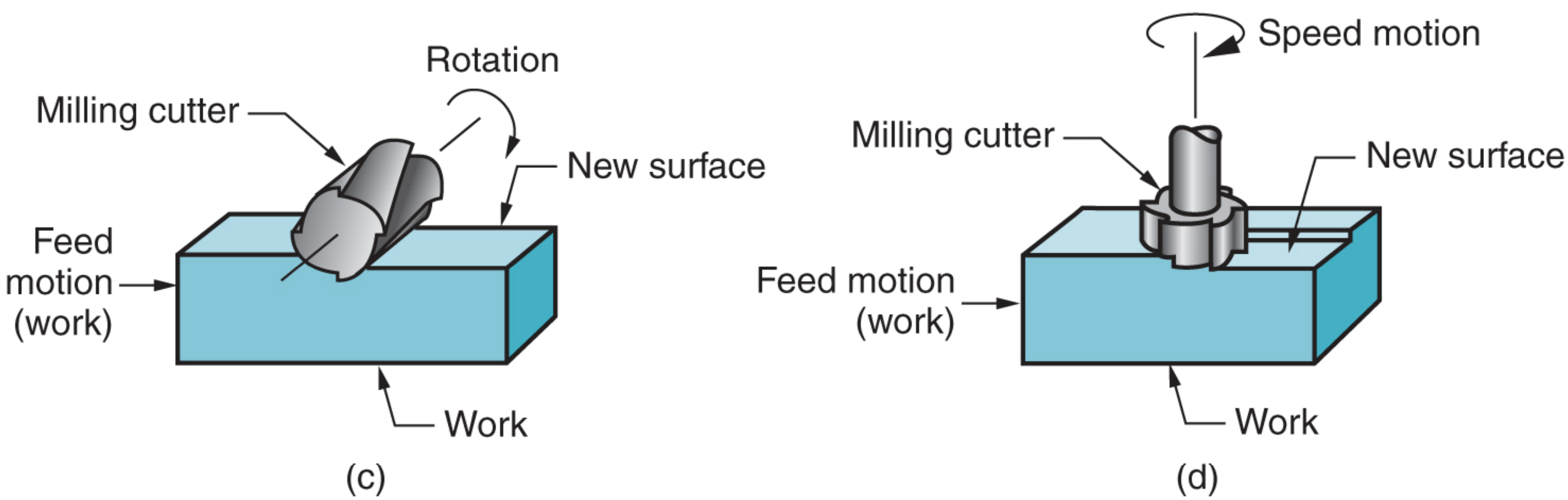
Drilling

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



Milling

- Rotating multiple-cutting-edge tool is moved across work to cut a plane or straight surface
- Two forms: (c) peripheral milling and (d) face milling

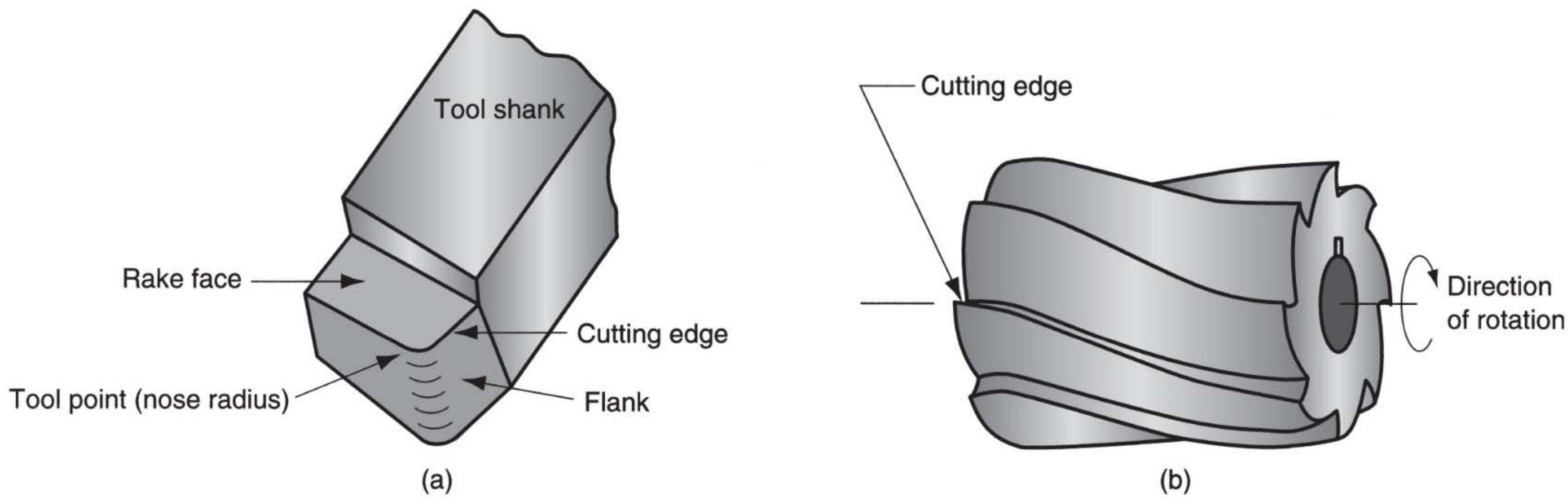


Cutting Tool Classification

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

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



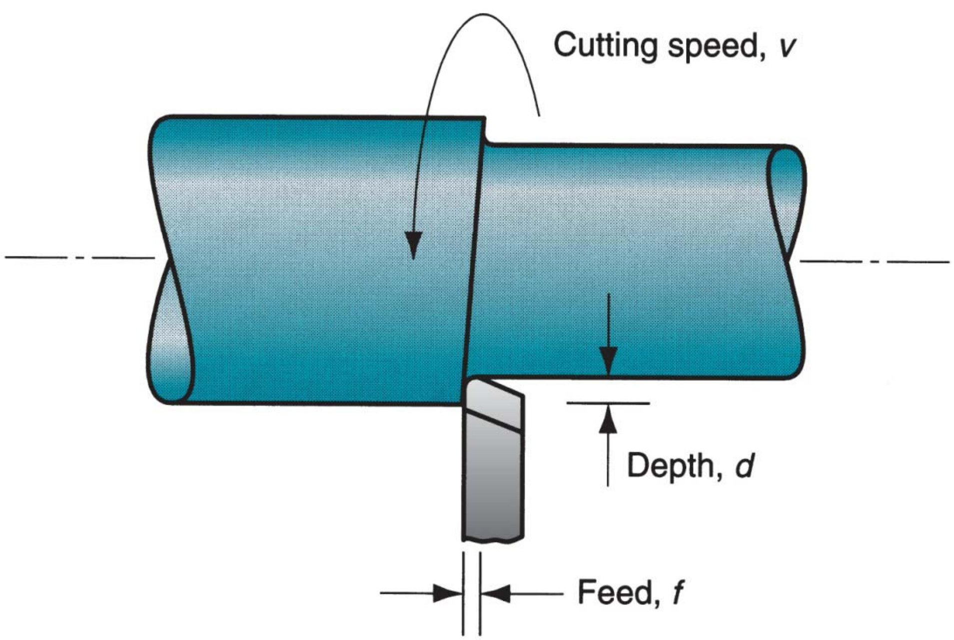
Cutting Conditions in Machining

- 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 (e.g., turning), material removal rate R_{MR} can be computed as

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

Cutting Conditions in Turning

- Speed, feed, and depth of cut in a turning operation



Roughing vs. Finishing Cuts

- In production, several roughing cuts are usually taken on a part, followed by one or two finishing cuts
  - Roughing - removes large amounts of material from starting workpart
    - Some material remains 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

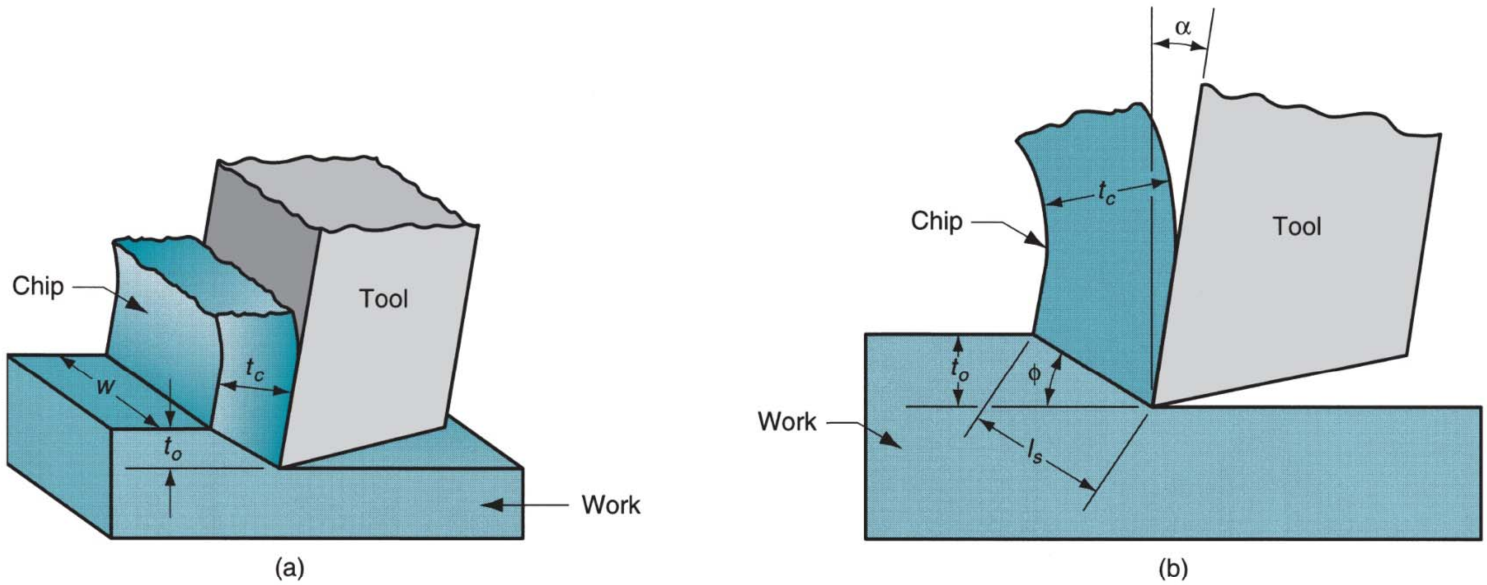
Machining Equipment

A power-driven machine that performs a machining operation, including grinding

- Functions in machining:
  - Holds workpart
  - Positions tool relative to work
  - Provides power at speed, feed, and depth that have been set
- The term also applies to machines that perform metal forming operations

Orthogonal Cutting Model

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



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 is always greater than before, so chip ratio is always less than 1.0
- Why is $t_c > t_o$?

Determining Shear Plane Angle

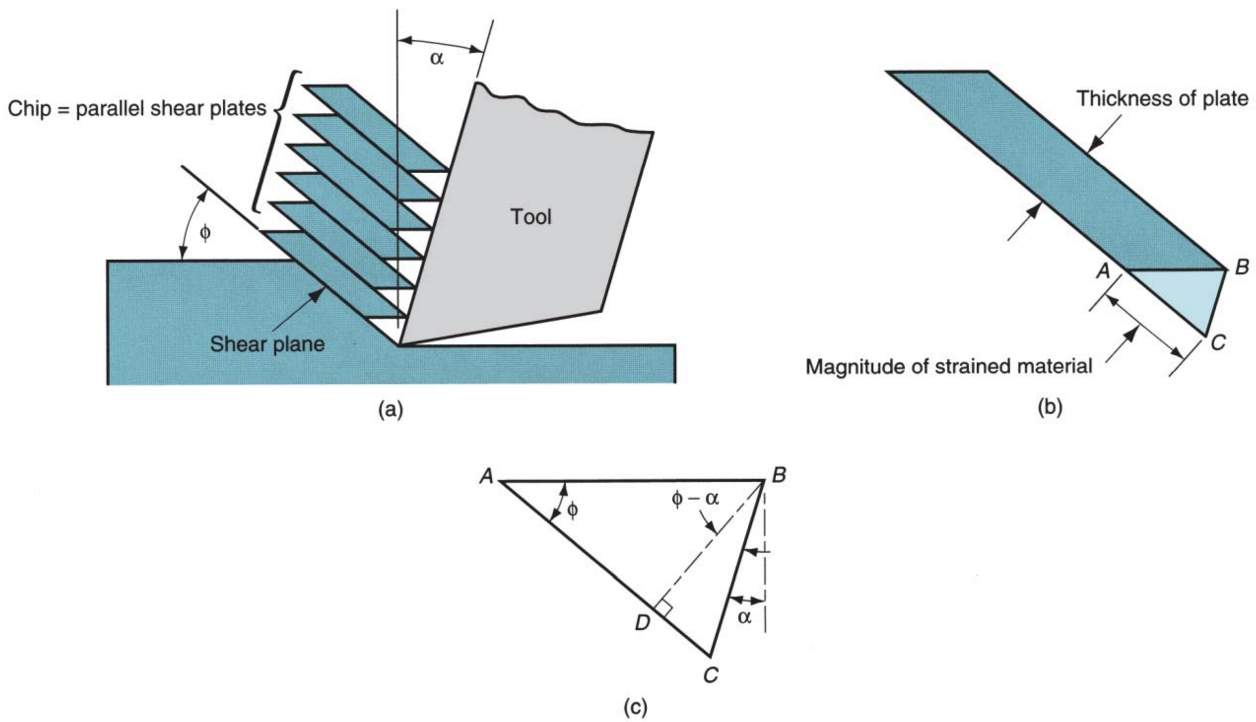
- Based on the geometric parameters of the orthogonal model, the shear plane angle ϕ can be determined as:

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

where r = chip ratio, and α = rake angle

Shear Strain in Chip Formation

- (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

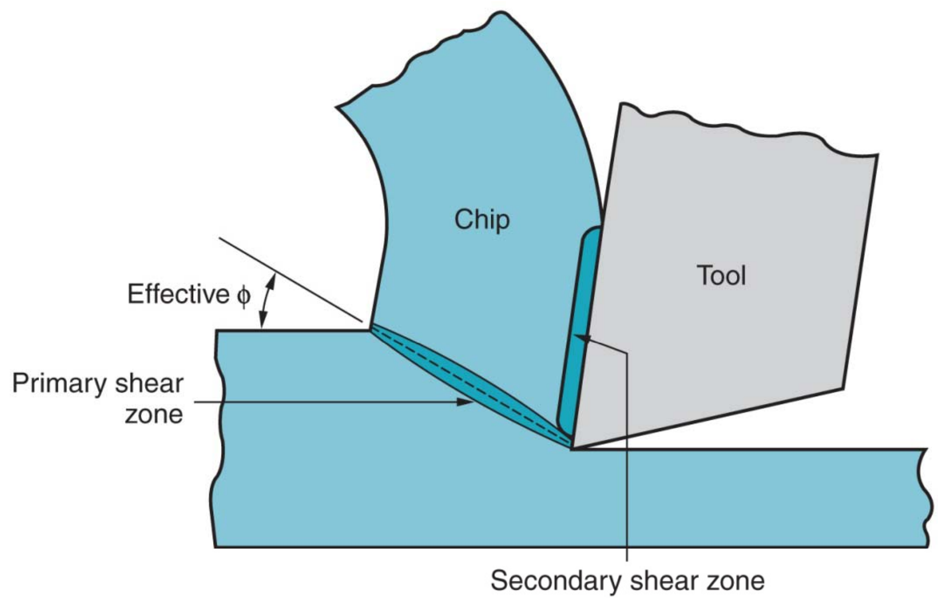
Shear strain in machining can be computed from the following equation, based on the preceding parallel plate model

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

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

Chip Formation

- 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



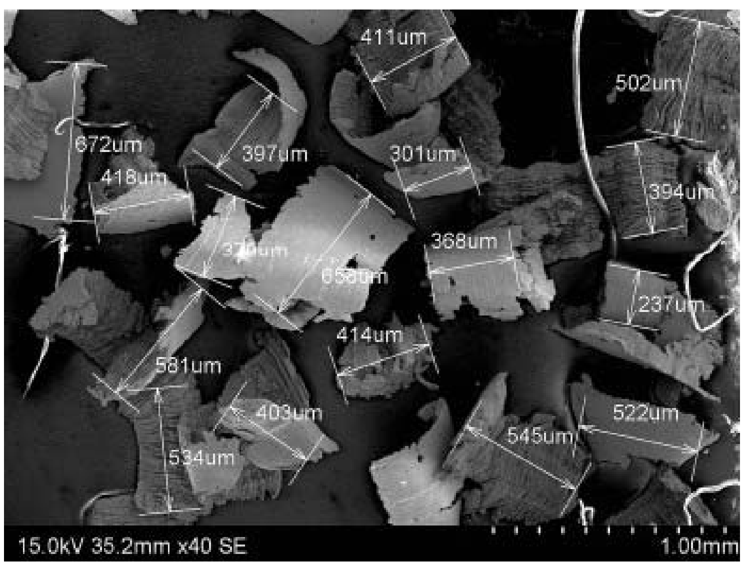
Four Basic Types of Chip in Machining

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

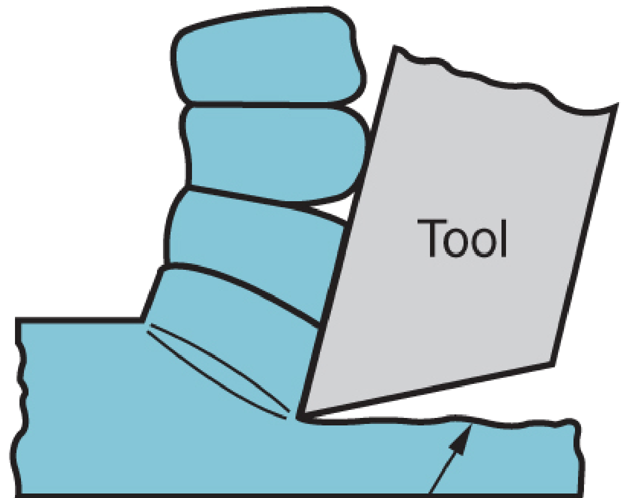
Discontinuous Chip

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

Optics and Lasers in Engineering, Volume 49, Issue 2, February 2011, Pages 240–247



Discontinuous chip



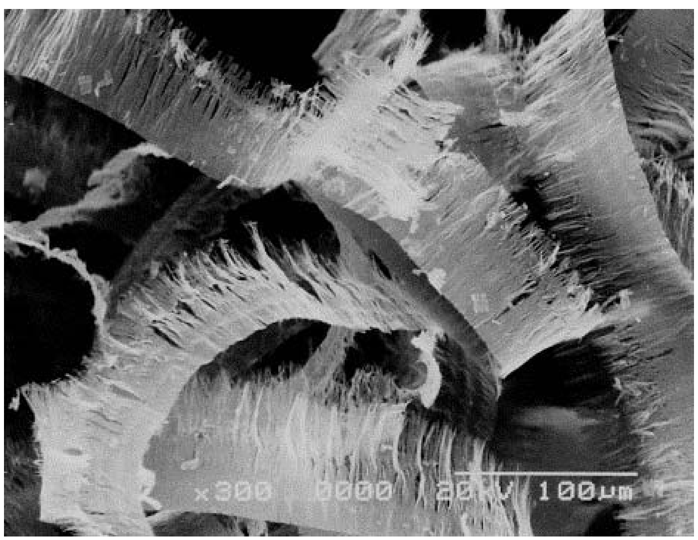
Irregular surface due to chip discontinuities

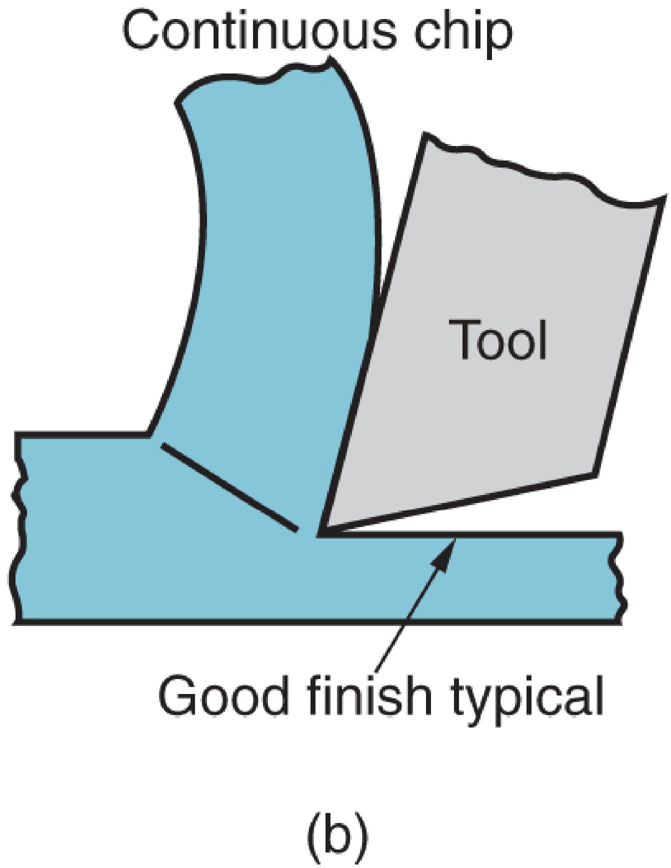
(a)

Continuous Chip

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

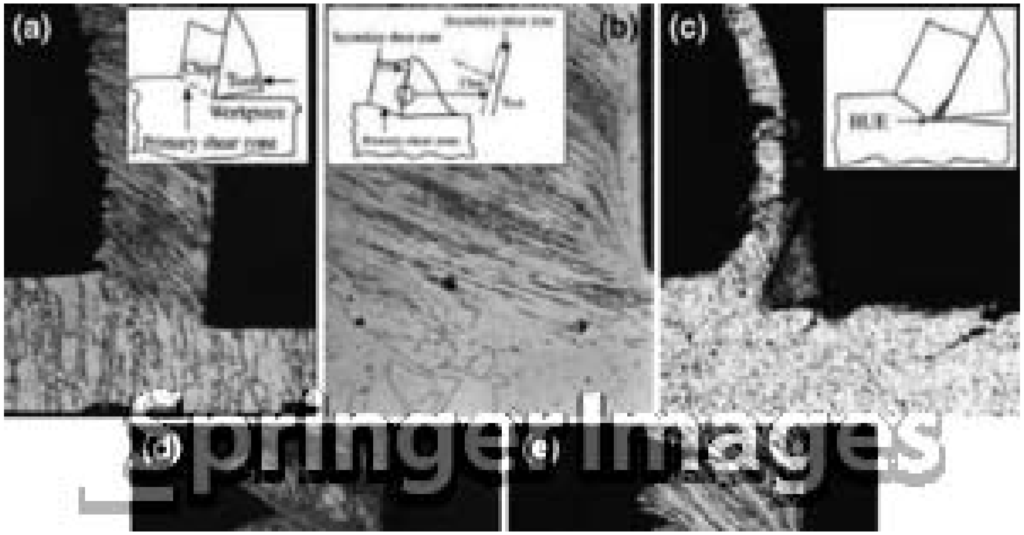
Journal of Materials Processing Technology, Volume 121, Issues 2–3, 28 February 2002, Pages 363–372

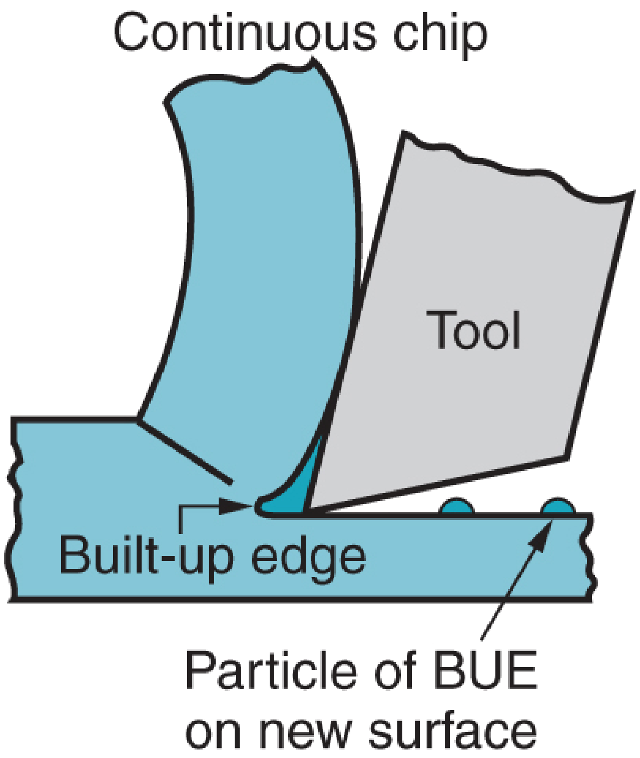




Continuous with BUE

- 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

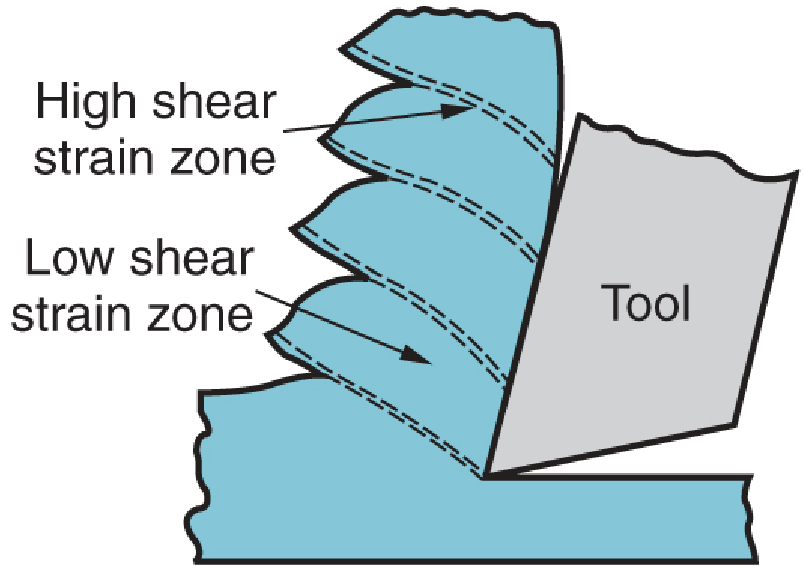




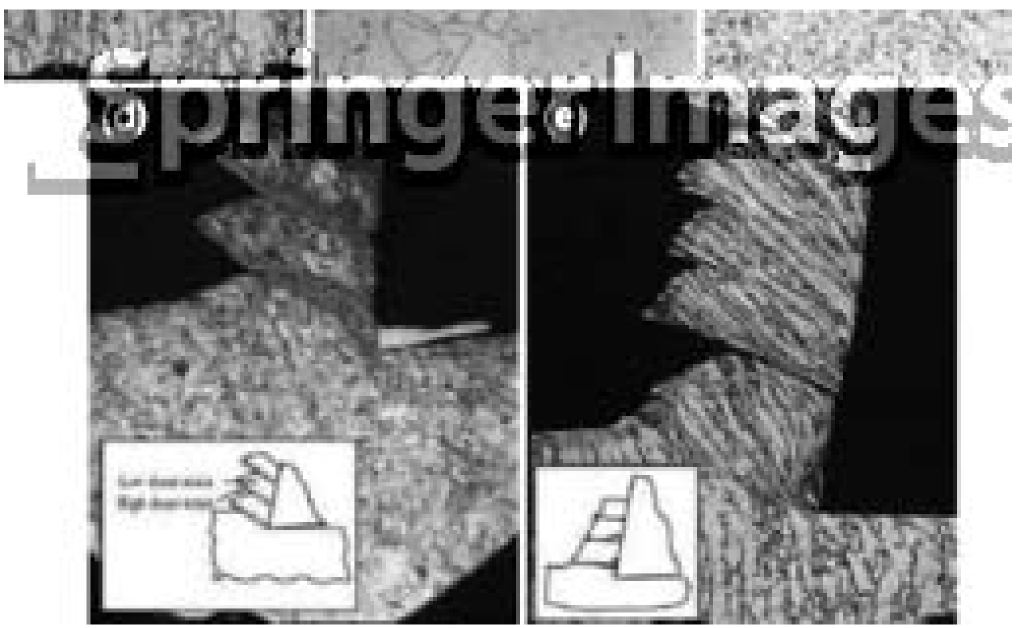
(c)

Serrated Chip

- Semi-continuous - 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

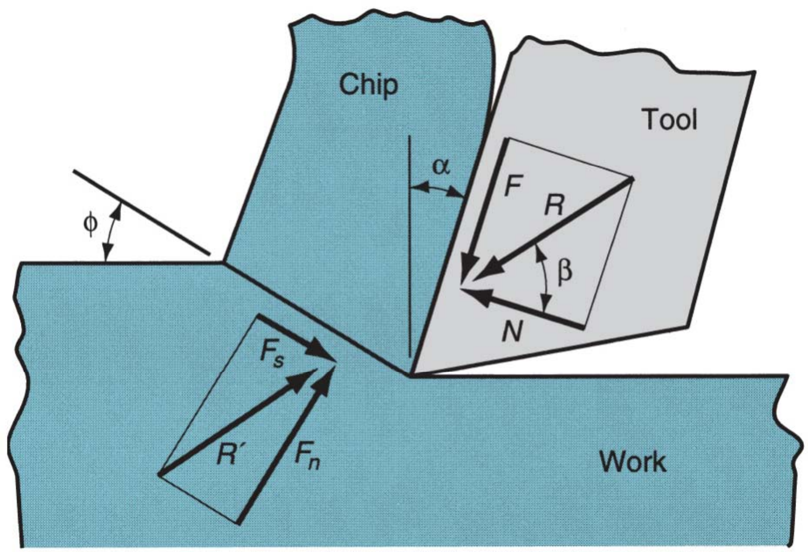


(d)



Forces Acting on Chip

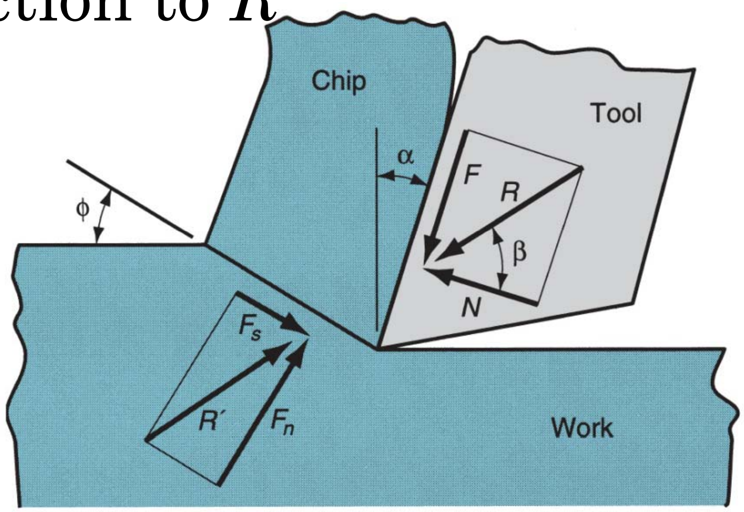
- (a) Friction force F and Normal force to friction N
- (b) Shear force F_s and Normal force to shear F_n



(a)

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



(a)

Coefficient of Friction

- Coefficient of friction between tool and chip

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

- Friction angle related to coefficient of friction as

$$\mu = \tan \beta$$

Shear Stress

- Shear stress acting along the shear plane

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

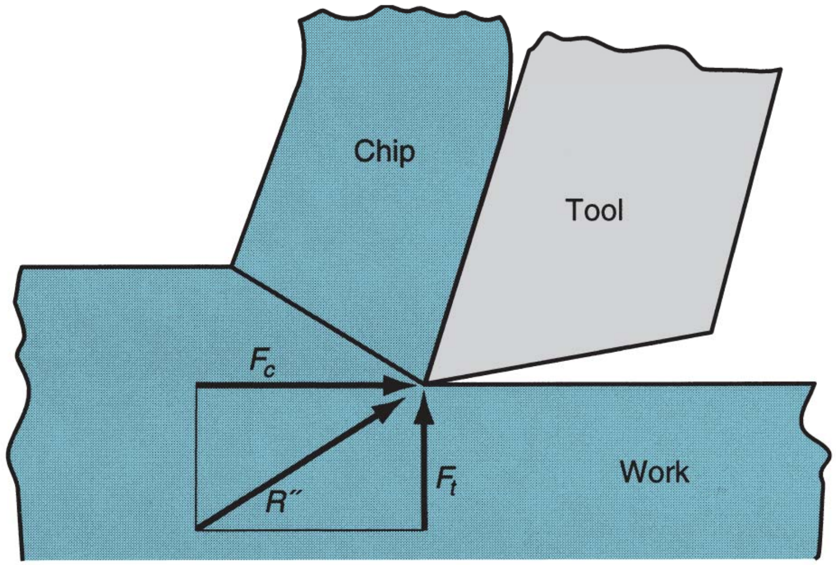
where A_s = area of the shear plane

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

- 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



(b)

Forces in Metal Cutting

- Equations 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

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

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

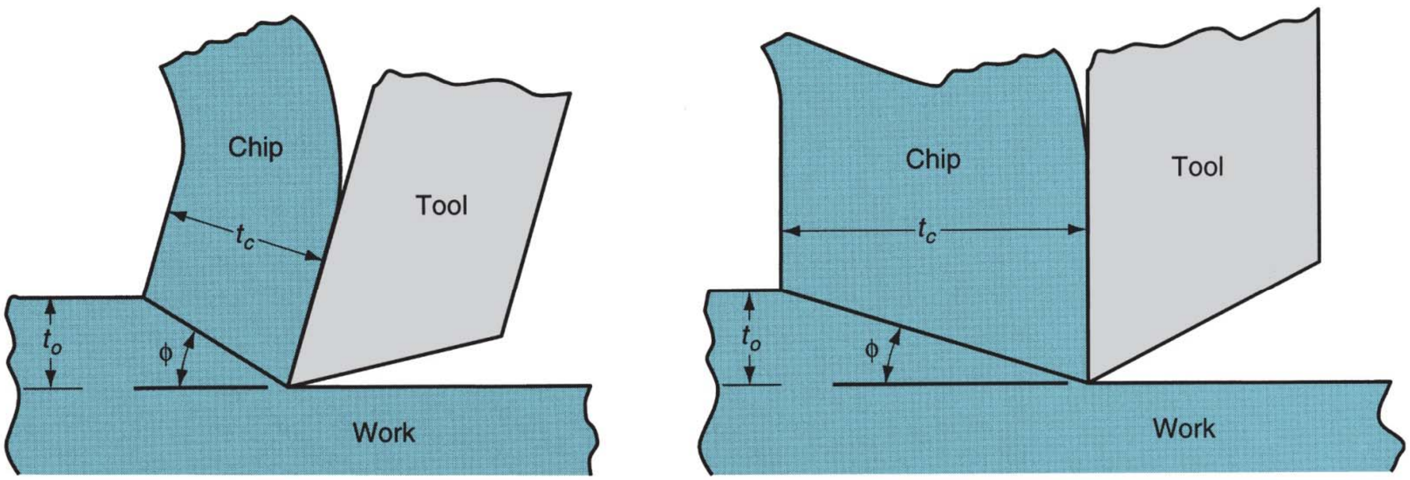
What the Merchant Equation Tells Us

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

- To increase shear plane angle
  - Increase the rake angle
  - Reduce the friction angle (or reduce the 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



(a) (b)

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

- 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

Power and Energy Relationships

- Gross power to operate the machine tool P_g or HP_g is given by

$$P_g = \frac{P_c}{E} \quad \text{or} \quad HP_g = \frac{HP_c}{E}$$

where E = mechanical efficiency of machine tool

- Typical E for machine tools ~ 90%

Unit Power in Machining

- Useful to convert power into power per unit volume rate of metal cut
- Called *unit power*, P_u or *unit horsepower*, HP_u

$$P_U = \frac{P_c}{R_{MR}} \quad \text{or} \quad HP_u = \frac{HP_c}{R_{MR}}$$

where R_{MR} = material removal rate

Specific Energy in Machining

- Unit power is also known as the *specific energy U*

$$U = P_u = \frac{P_c}{R_{MR}} = \frac{F_c v}{v t_o w}$$

where Units for specific energy are typically $N\text{-}m/mm^3$ or J/mm^3 ($in\text{-}lb/in^3$)

Cutting Temperature

- Approximately 98% of the energy in machining is converted into heat
- This can cause temperatures to be very high at the tool-chip
- The remaining energy (about 2%) is retained as elastic energy in the chip

Cutting Temperatures are Important

High cutting temperatures

1. Reduce tool life
2. Produce hot chips that pose safety hazards to the machine operator
3. Can cause inaccuracies in part dimensions due to thermal expansion of work material

Cutting Temperature

- Analytical method derived by Nathan Cook from dimensional analysis using experimental data for various work materials

$$T = \frac{0.4U}{\rho C}\left(\frac{vt_o}{K}\right)^{0.333}$$

where T = temperature rise at tool-chip interface; U = specific energy; v = cutting speed; t_o = chip thickness before cut; ρC = volumetric specific heat of work material; K = thermal diffusivity of work material

Cutting Temperature

- Experimental methods can be used to measure temperatures in machining
  - Most frequently used technique is the *tool-chip thermocouple*
- Using this method, Ken Trigger determined the speed-temperature relationship to be of the form:

$$T = K\, v^m$$

where T = measured tool-chip interface temperature, and v = cutting speed

EXAMPLE 1

- In an orthogonal cutting operation, the 0.250 in wide tool has a rake angle of 5°. The lathe is set so the chip thickness before the cut is 0.010 in. After the cut, the deformed chip thickness is measured to be 0.027 in. Calculate (a) the shear plane angle and (b) the shear strain for the operation.
- **Solution**: (a) $r = t_o/t_c$ = 0.010/0.027 = 0.3701
- $\phi = \tan^{-1}(0.3701 \cos 5/(1 - 0.3701 \sin 5)) = \tan^{-1}(0.3813) =$ **20.9°**
- (b) Shear strain $\gamma = \cot 20.9 + \tan (20.9 – 5) =$ 2.623 + 0.284 = **2.907**

EXAMPLE 2

- In a turning operation on stainless steel with hardness = 200 HB, the cutting speed = 200 m/min, feed = 0.25 mm/rev, and depth of cut = 7.5 mm. How much power will the lathe draw in performing this operation if its mechanical efficiency = 90%. Use Table 21.2 to obtain the appropriate specific energy value.
- **Solution**: From Table 21.2, $U = 2.8$ N-m/mm^3 = 2.8 J/mm^3
- $R_{MR} = vfd$ = (200 m/min)(10^3 mm/m)(0.25 mm)(7.5 mm) = 375,000 mm^3/min = 6250 mm^3/s
- P_c = (6250 mm^3/s)(2.8 J/mm^3) = 17,500 J/s = 17,500 W = 17.5 kW
- Accounting for mechanical efficiency, P_g = 17.5/0.90 = **19.44 kW**

EXAMPLE 3

- Consider a turning operation performed on steel whose hardness = 225 HB at a speed = 3.0 m/s, feed = 0.25 mm, and depth = 4.0 mm. Using values of thermal properties found in the tables and definitions of Section 4.1 and the appropriate specific energy value from Table 21.2, compute an estimate of cutting temperature using the Cook equation. Assume ambient temperature = 20°C.
- **Solution**: From Table 21.2, $U = 2.2$ N-m/mm^3 = 2.2 J/mm^3
- From Table 4.1, $\rho = 7.87$ g/cm^3 = $7.87(10^{-3})$ g/mm^3
- From Table 4.1, $C = 0.11$ Cal/g-°C. From note "a" at the bottom of the table, 1 cal = 4.186 J.
- Thus, $C = 0.11(4.186) = 0.460$ J/ g-°C
- ρC = (7.87 g/cm^3)(0.46 J/g-°C) = $3.62(10^{-3})$ J/mm^3-°C
- From Table 4.2, thermal conductivity $k = 0.046$ J/s-mm-°C
- From Eq. (4.3), thermal diffusivity $K = k/\rho C$
- K = 0.046 J/s-mm-°C /[(7.87 x 10^{-3} g/mm^3)(0.46 J/g-°C)] = 12.7 mm^2/s
- Using Cook's equation, $t_o = f = 0.25$ mm
- $T = (0.4(2.2)/3.62(10^{-3}))[3(10^3)(0.25)/12.7]^{0.333} = 0.2428(10^3)(59.06)^{0.333}$
- = 242.8(3.89) = 944.4 C°
- Final temperature, taking ambient temperature in account T = 20 + 944 = **964°C**