TA 202A

Lecture 4

Mechanics of metal cutting

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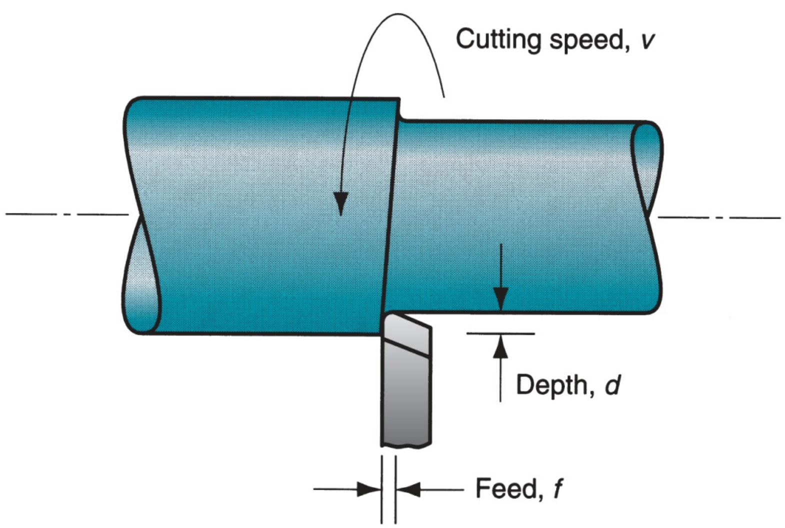
Cutting Conditions in Machining

- Three characteristics of a machining process
  - Cutting speed *v* – primary motion [m/min]
    Relates velocity of the cutting tool to the work piece
  - Feed *f* – secondary motion [mm/rev]
    Movement (advancement) of the tool per revolution of the workpiece
  - Depth of cut *d* – penetration of tool below original work surface [mm]



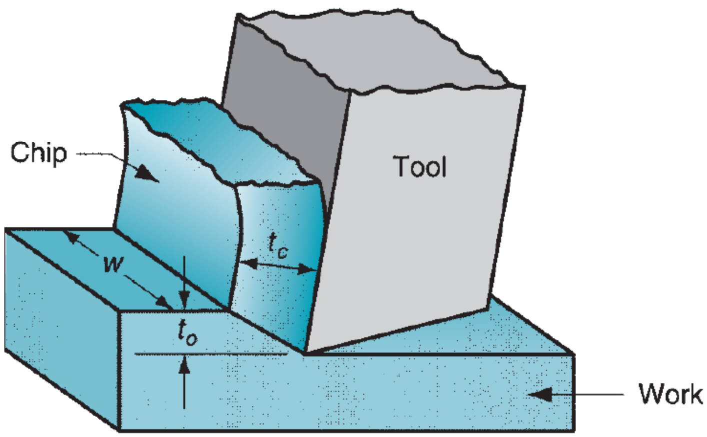
Basic Mechanics Issues

- Friction, Forces
- Shear strain
- Power, Plastic work
- Temperature rise
- Tool materials, Rate limits

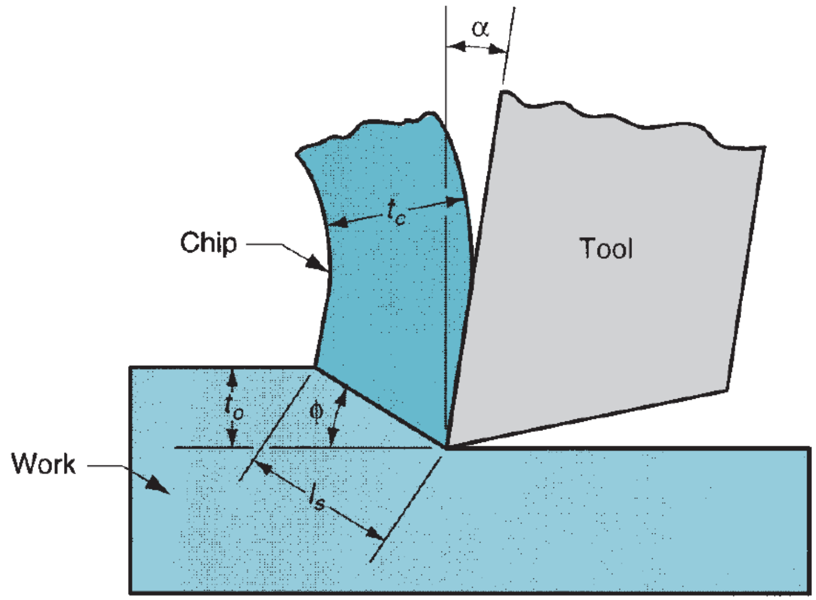
Orthogonal Cutting Model (2-D Cutting)

In orthogonal cutting:

- Cutting tool is wedge-shaped
- Cutting edge is straight
- Cutting edge is parallel to the original plane surface on the work piece
- Cutting edge is perpendicular to the direction of cutting speed
- Example: Operations: Lathe cut-off operation, Straight milling, etc.



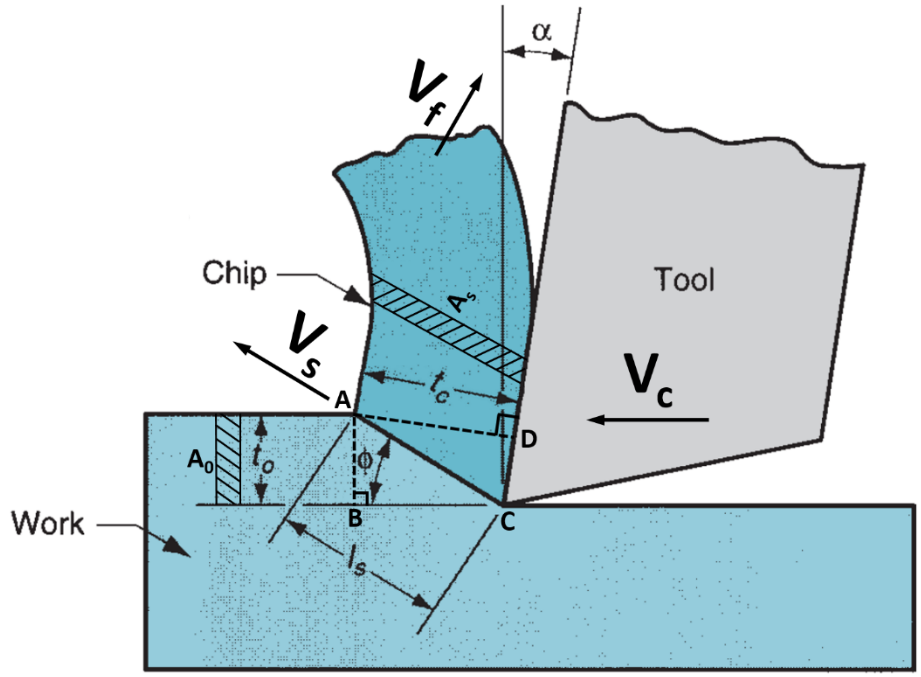
Orthogonal cutting as a three-dimensional process



2D side view of orthogonal cutting

Geometry of Chip Formation

t_c	: Chip thickness
t_o	: Uncut chip thickness
l_s	: Length of shear plane
r	: Chip thickness ratio
V_f	: Chip Sliding Velocity
V_s	: Shear Velocity
V_c	: Cutting Velocity
ϕ	: Shear Angle
α	: Rake Angle
A_s	: Area of shear plane
w	: width of cut



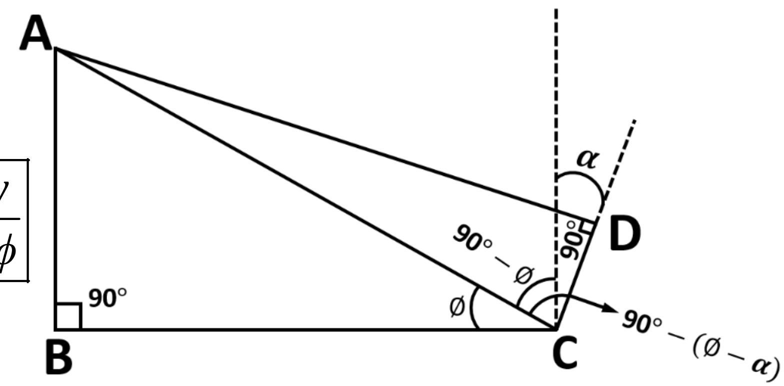
ΔABC & ΔADC

$$AC = l_s = \frac{t_o}{\sin\phi}$$

$$\text{also, } AC = l_s = \frac{t_c}{\sin(90-(\phi-\alpha))} = \frac{t_c}{\cos(\phi-\alpha)}$$

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

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



$$AC = l_s,\ AB = t_o,\ AD = t_c$$

Shear Angle and Chip Thickness Ratio

$$Chip\ thickness\ Ratio\,(r) = \frac{t_o}{t_c} = \frac{\sin\phi}{\cos(\phi-\alpha)}$$

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

$$1 = r cot\phi cos\alpha + r sin\alpha$$

$$r cos\alpha = (1 - r sin\alpha)\tan\phi$$

$$\therefore \boxed{\tan\phi = \left(\frac{r\ cos\alpha}{1 - r sin\alpha}\right)}$$

- How to determine ϕ & r ?
- **t_c should be determined from the chip. t_o (= feed) and α are already known.**
- To determine t_c, with micrometer, is difficult and **not so accurate** because of uneven surface. **How? *(say, f = 0.2 mm/rev. An error of even 0.05 mm will cause an error of 25 % in the measurement of t_c)***

Volume Constancy Condition: Volume of uncut chip = Volume of cut chip

$$L_o t_o w = L_c t_c w \qquad \therefore L_o t_o = L_c t_c \qquad or, r = \frac{t_o}{t_c} = \frac{L_c}{L_o}$$

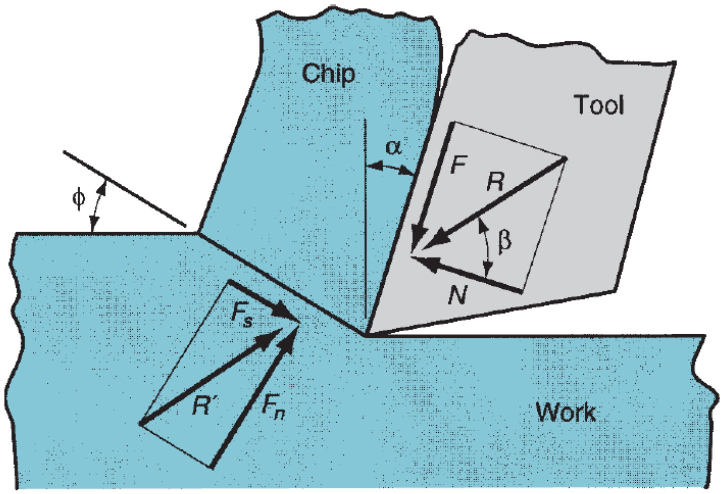
L_c = Chip length
L_o = Uncut chip length
w = Chip width
(2-D Cutting)

Length of the chip may be many centimeters hence the error in evaluation of *r* will be comparatively much lower.

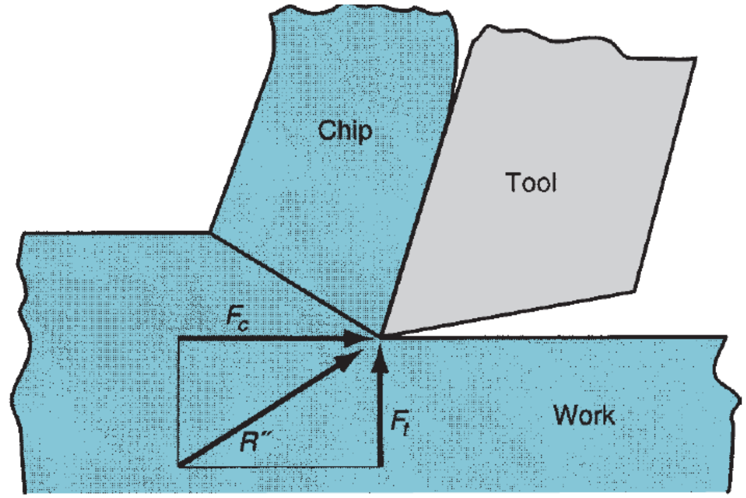
- Since chip thickness after cutting is always greater than the corresponding thickness before cutting, the chip ratio will always be less than 1.0.
- Why is $t_c > t_o$?

➢ **Alternatively, by mass conservation – density measurement as the curly length measurement may not be easy**

Forces in Machining



Forces acting on the chip in orthogonal cutting



Forces acting on the tool that can be measured by using dynamometers

F = Frictional force between the tool and chip
N = Normal force
F_S = Shear force
F_n = Normal force to shear

F_C = Cutting force
F_t = Thrust force

- F is the frictional force resisting the flow of the chip along the rake face of the tool.
- F_S is the force that causes shear deformation to occur in the shear plane.
- F, N, F_s, and F_n cannot be directly measured: As directions of these forces changes with different tool geometries and cutting conditions.
- Forces acting on the tool (Cutting force F_c and Thrust force F_t) can be measured by using force measuring device called a **dynamometer**.

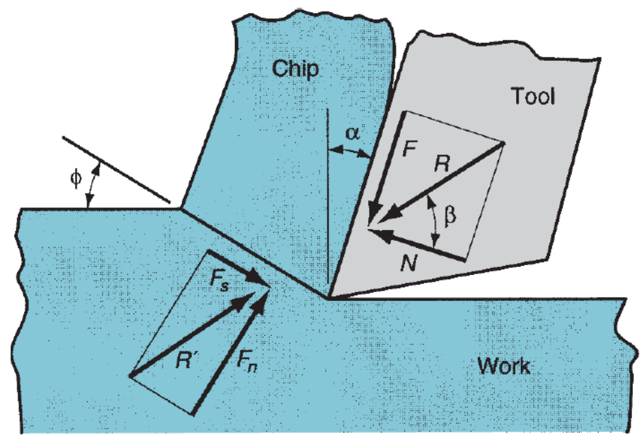
Coefficient of Friction

- Coefficient of friction (μ) between tool and chip

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

- Friction angle (β) related to coefficient of friction as

$$\mu = \tan \beta$$



Shear Stress

- Shear stress acting along the shear plane

$$\tau = \frac{F_s}{A_s} \qquad A_s = \frac{t_o w}{\sin\phi}$$

where A_s = area of the shear plane

- The shear stress represents the level of stress required to perform the machining operation.
- Under the conditions at which cutting occurs:

Shear stress (τ) = Shear strength of the work material (S)

Resultant Forces

Vector addition of F and N = resultant R

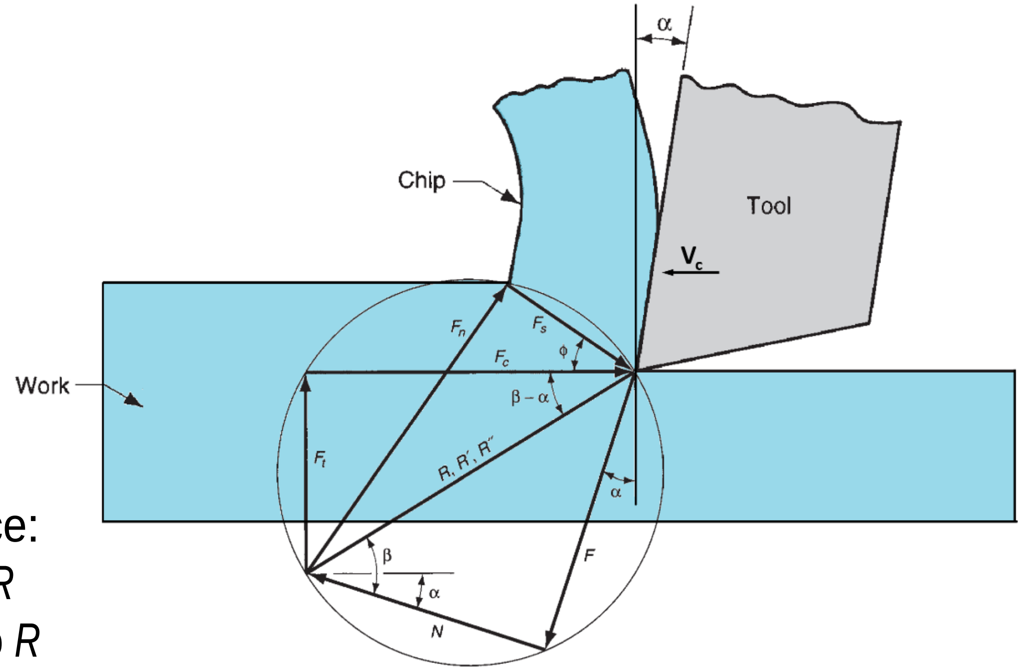
$$F = R \sin\beta$$
$$N = R \cos\beta$$

Vector addition of F_s and F_n = resultant R'

$$F_s = R' \cos(\phi + \beta - \alpha)$$
$$F_n = R' \sin(\phi + \beta - \alpha)$$

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



- F, N, F_s, and F_n cannot be directly measured.
- Cutting force F_c and Thrust force F_t can be measured using dynamometers.
- The cutting force F_c is in the direction of cutting speed v.
- Vector addition of F_c and F_t = resultant R''

$$F_c = R'' \cos(\beta - \alpha)$$
$$F_t = R'' \sin(\beta - \alpha)$$

Forces acting on the chip must be in balance to the forces acting on the tool, i.e.

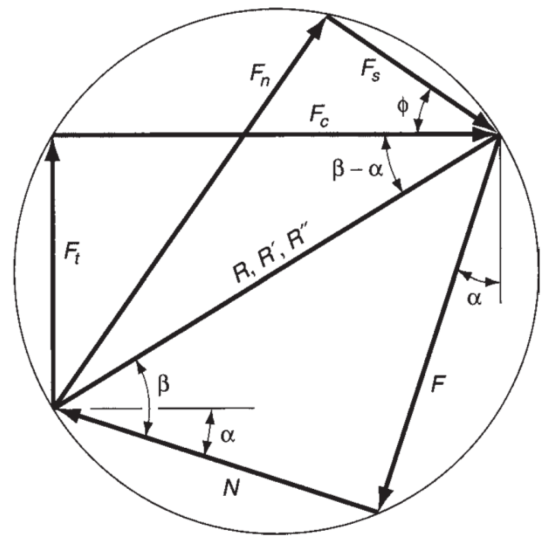
$$R = R' = R''$$

F, N, F_s, F_n in terms of F_c and F_t

Using the force diagram: $R = R' = R''$

$$R = \frac{F_c}{\cos(\beta-\alpha)} = \frac{F_t}{\sin(\beta-\alpha)}$$

$$\boxed{\begin{aligned} F &= F_c \sin\alpha + F_t \cos\alpha \\ N &= F_c \cos\alpha - F_t \sin\alpha \\ F_s &= F_c \cos\phi - F_t \sin\phi \\ F_n &= F_c \sin\phi + F_t \cos\phi \end{aligned}}$$



- If cutting force and thrust force are known, these four equations can be used to calculate estimates of shear force, friction force, and normal force to friction.
- Based on these force estimates, shear stress and coefficient of friction can be determined.

Special case of orthogonal cutting: $\boxed{when\ \alpha = 0 \Rightarrow F = F_t\ and\ N = F_c}$

- Friction force and its normal force could be directly measured by the dynamometer.

Stresses on chip:

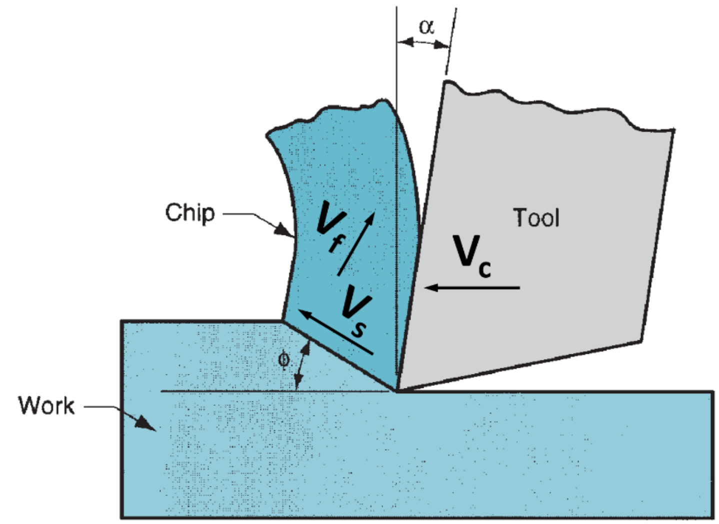
$$Mean\ Shear\ Stress\ (\tau_{chip}) = \frac{F_s}{A_s} \qquad Mean\ Normal\ Stress\ (\sigma_{chip}) = \frac{F_n}{A_s}$$

Velocity Analysis

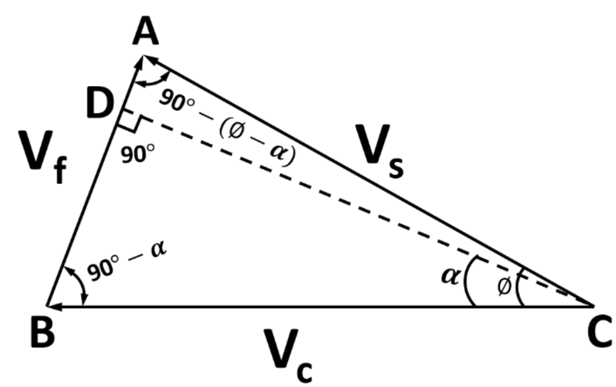
V_c : *Cutting velocity of tool relative to workpiece*

V_f : *Chip flow velocity*

V_s : *Shear velocity*



Using sine Rule:



$$\frac{V_c}{\sin(90-(\phi-\alpha))} = \frac{V_f}{\sin\phi} = \frac{V_s}{\sin(90-\alpha)}$$

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

$$\boxed{V_s = \frac{V_c\cos\alpha}{\cos(\phi-\alpha)} \Rightarrow \frac{V_s}{V_c} = \frac{\cos\alpha}{\cos(\phi-\alpha)}}$$

and $V_f = \dfrac{V_c\sin\phi}{\cos(\phi-\alpha)} = V_c\cdot r$

Shear Strain & Strain Rate

Two approaches of analysis:

Thin Plane Model: Merchant, Piispanen, Kobayashi & Thomson

Thick Plane Model: Palmer, Piispanen, Oxley, Kushina, Hitoni

Thin Zone Model: Merchant

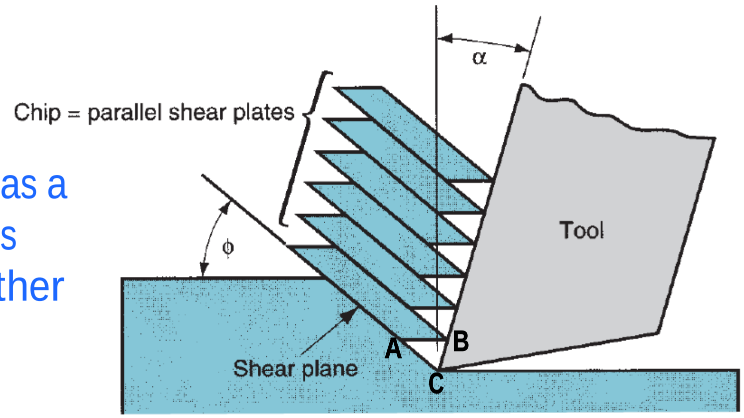
ASSUMPTIONS

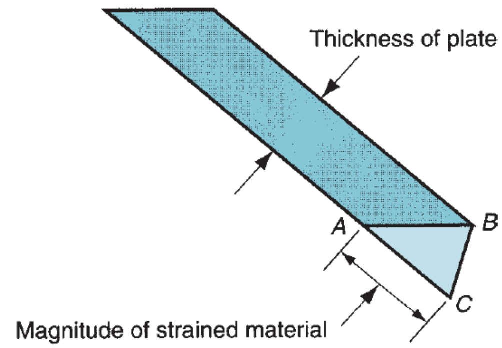
- Tool tip is sharp, No Rubbing, No Ploughing.
- 2-D deformation.
- Stress on shear plane is uniformly distributed.
- Resultant force R on chip applied at shear plane is equal, opposite and collinear to force R’ applied to the chip at tool-chip interface.

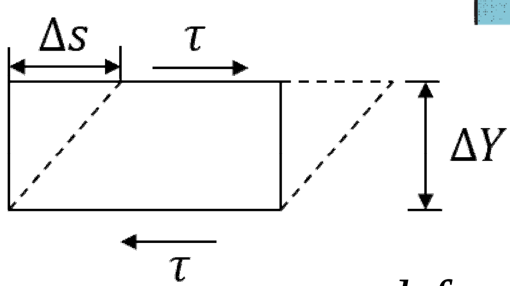
Expression for Shear Strain

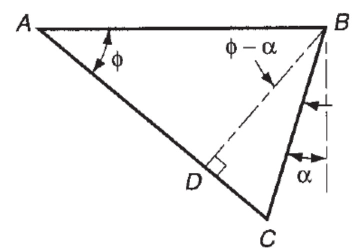
The deformation can be idealized as a process of block slip (or preferred slip planes)

Chip formation depicted as a series of parallel plates sliding relative to each other









$$ShearStrain(\gamma) = \frac{deformation}{Length}$$

$$\gamma = \frac{\Delta s}{\Delta y} = \frac{AC}{BD} = \frac{AD + DC}{BD} = \frac{AD}{BD} + \frac{DC}{BD} = \tan(\phi - \alpha) + \cot\phi$$

$$\therefore \gamma = \frac{\sin(\phi - \alpha)\sin\phi + \cos\varphi\cos(\phi - \alpha)}{\sin\phi\cos(\phi - \alpha)} = \frac{\cos\alpha}{\sin\phi\cos(\phi - \alpha)}$$

Expression for Shear Strain Rate

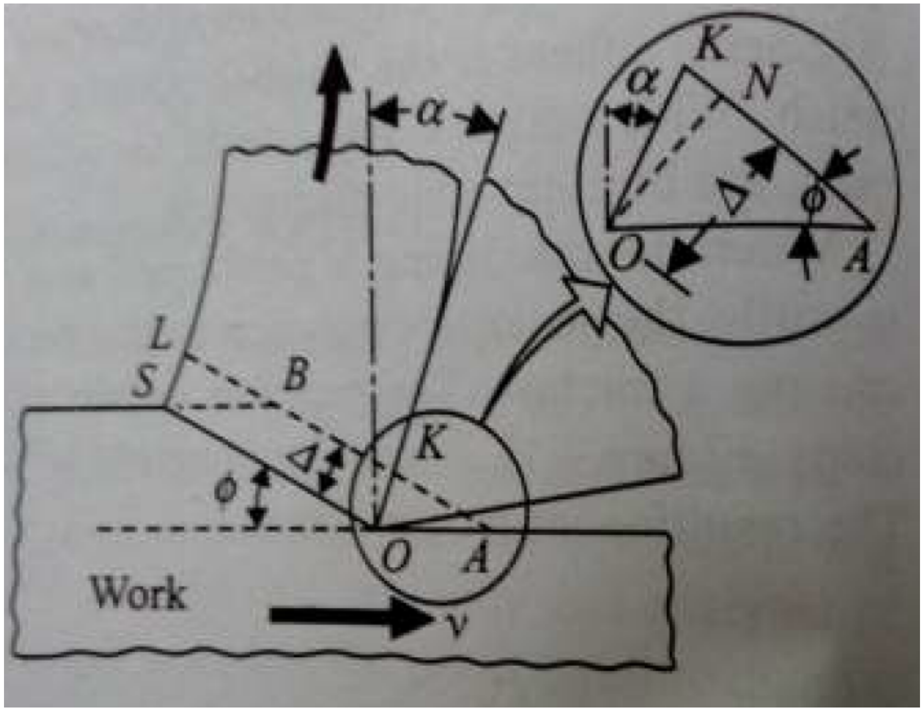
In terms of shear velocity (V_s) and chip velocity (V_f), it can be written as

$$\therefore \quad \gamma = \frac{V_s}{V_c \sin\phi} \qquad \left(\text{since} \frac{V_s}{V_c} = \frac{\cos\alpha}{\cos(\phi-\alpha)} \right)$$

$$\textit{Shear strain rate } (\dot{\gamma})$$

$$\dot{\gamma} = \frac{d\gamma}{dt} = \frac{\left(\dfrac{\Delta s}{\Delta y}\right)}{dt} = \left(\frac{\Delta s}{\Delta y}\right)\frac{1}{\Delta t} = \frac{V_s}{\Delta y} = \frac{V_c \cos\alpha}{\cos(\phi-\alpha)\Delta y}$$

$$\textit{where, } \Delta y : \textit{Mean thickness of PSDZ}$$



Consider an element of the undeformed work material ABSO of thickness Δ.

Due to presence of the tool, it is sheared to the shape KLSO.

$$\angle KAO = \phi$$

$$\angle OKA = \frac{\pi}{2} + \alpha - \phi$$

Shear strain $\gamma = \dfrac{AK}{\Delta} = \dfrac{AN + NK}{ON} = \cot\phi + \tan\angle KON$

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

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

Shear Angle Relationship

- Helpful to predict position of shear plane (angle ϕ)

- **Relationship between-**
  - ✓Shear Plane Angle (ϕ)
  - ✓Rake Angle (α)
  - ✓Friction Angle(β)

Several Theories

Earnst-Merchant(Minimum Energy Criterion):
Shear plane is located where least energy is required for shear.

Assumptions:
- Tool tip is sharp
- Orthogonal case
- Continuous chip without BUE
- μ along chip-tool contact is constant

Shear Angle Relationship

Assuming No Strain hardening:

$$F_S = A_S\tau = \frac{t_o w\tau}{sin\phi} = \mathrm{R}\ cos(\phi+\beta-\alpha) \Rightarrow R = \left(\frac{t_o w\tau}{sin\phi}\right)\times\left(\frac{1}{cos(\phi+\beta-\alpha)}\right)$$

$$\mathrm{F}_c = R\ \cos(\beta-\alpha) = \left(\frac{t_o w\tau}{sin\phi}\right)\left(\frac{cos(\beta-\alpha)}{cos(\phi+\beta-\alpha)}\right)$$

Condition for minimum energy: $\dfrac{dF_c}{d\phi} = 0$

$$\frac{dF_c}{d\phi} = t_o w\tau\cos\,(\beta-\alpha)\left[\frac{\cos\phi\cos(\phi+\beta-\alpha)-\sin\phi\sin(\phi+\beta-\alpha)}{\sin^2\phi\cos^2(\phi+\beta-\alpha)}\right] = 0$$

$$\therefore \cos\phi\cos(\phi+\beta-\alpha)-\sin\phi\sin(\phi+\beta-\alpha) = 0$$

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

Known as Merchant's First Equation

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

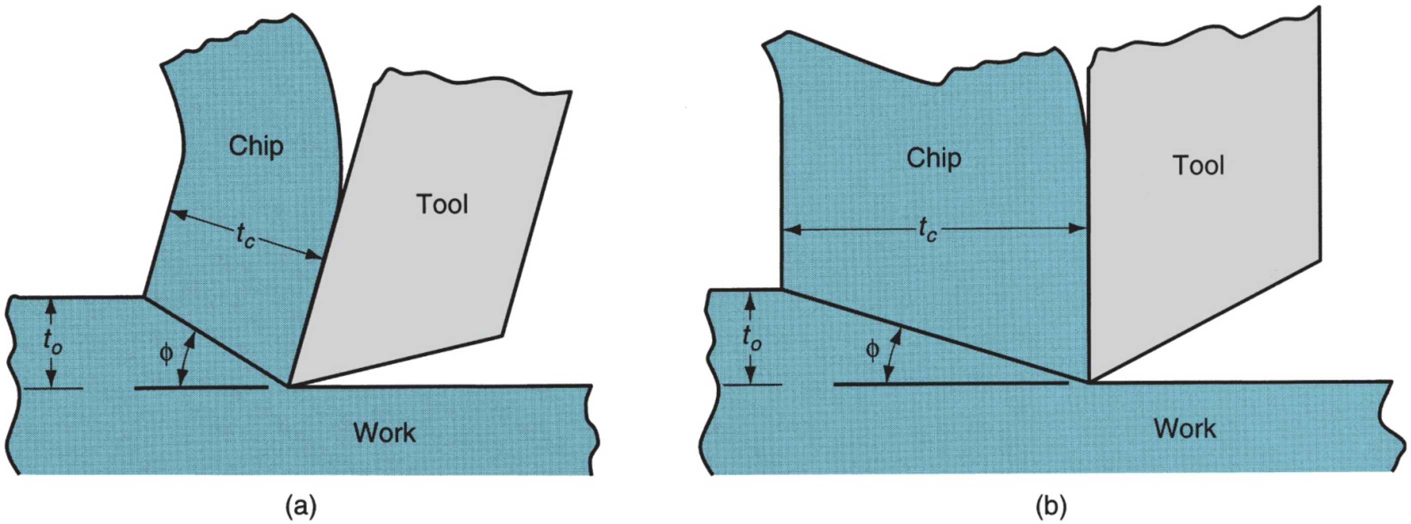
$$\phi = 45 + \frac{\alpha}{2} - \frac{\beta}{2}$$

- Based on orthogonal cutting, but validity extends to 3-D machining

- 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



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:

$$P_c = F_c V_c + F_f V_f = F_c V_c \ (For \ \ V_f \ll V_c)$$

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

Specific Energy in Machining: Power required to remove a unit volume of metal during machining.

$$U = \frac{P_c}{MRR} = \frac{F_c V_c}{V_c t_o w}$$

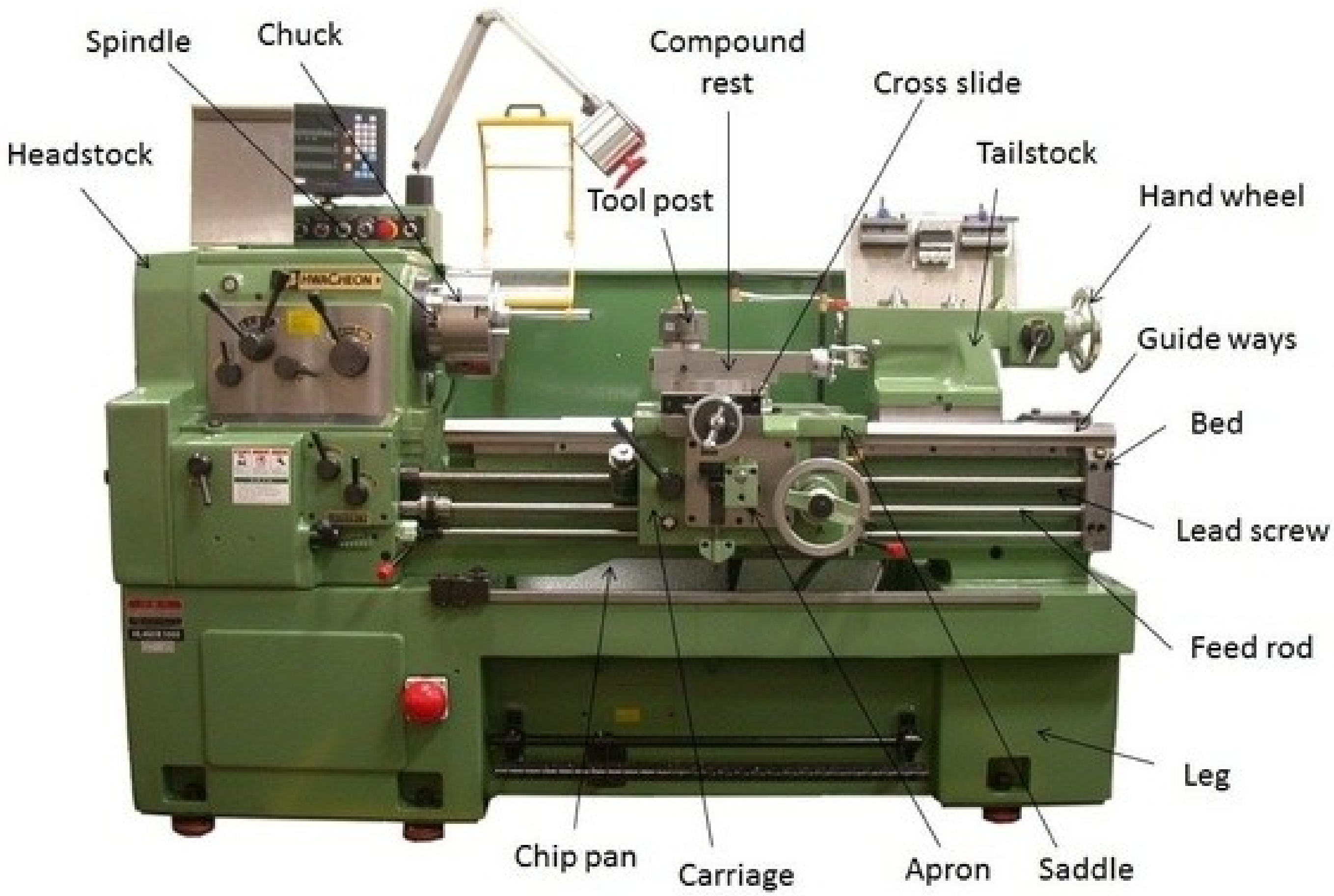
$$P_c = U \ . \ MRR$$

$$MRR = V_c t_o w$$

where MRR = Material Removal Rate

Units for specific energy are typically N-m/mm^3 or J/mm^3

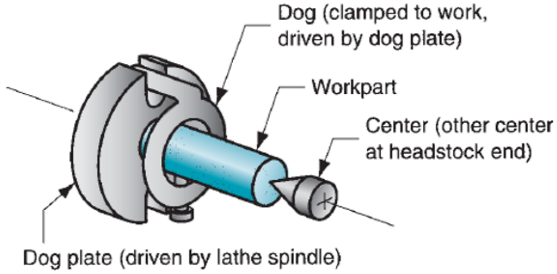
Machine Tools in Turning



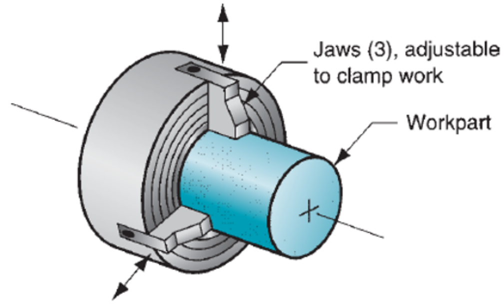
Lathe Machine

$$MRR = Vfd$$

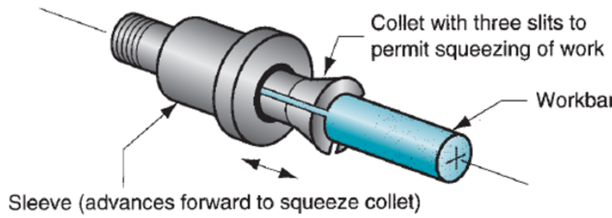
Methods of Holding the Work in a Lathe



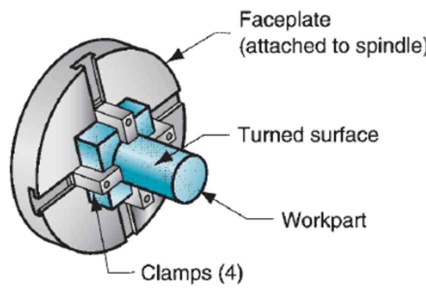
(a) Holding the work between centres using a dog



(b) Chuck



(c) Collet

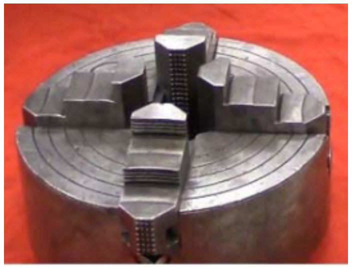


(d) Face plate

Lathe Chucks

3-Jaw chuck

- self-centering
- All jaws move simultaneously

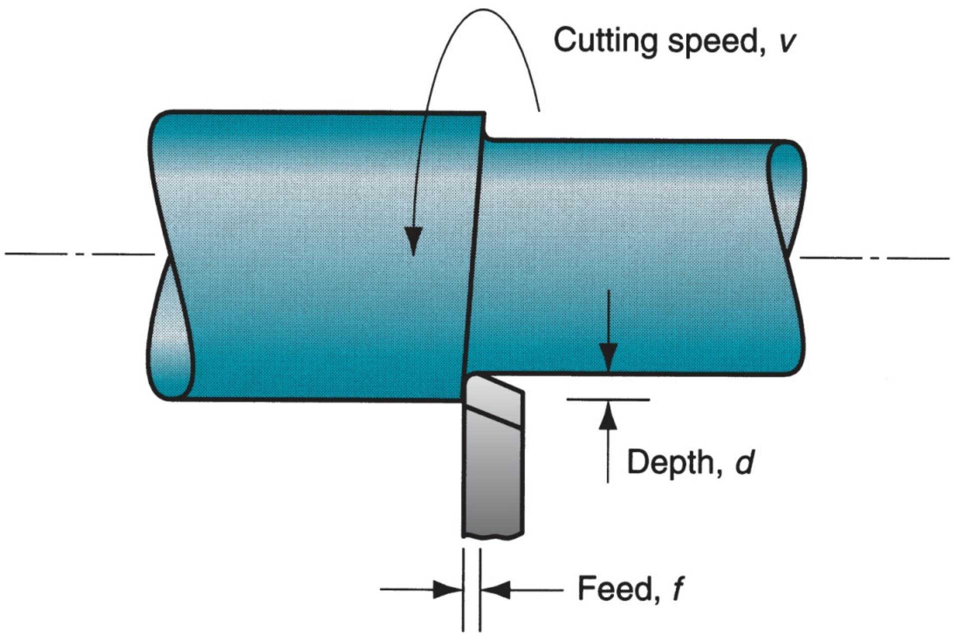


4-Jaw chuck

Independent operation of each jaw

Cutting Conditions in Turning

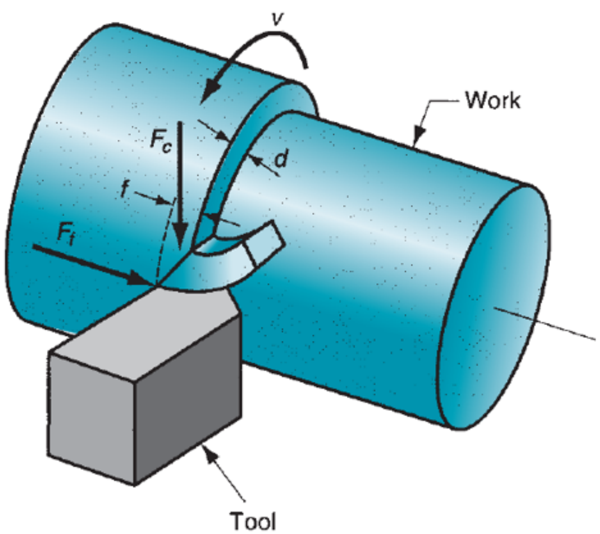
- Speed, feed, and depth of cut in a turning operation

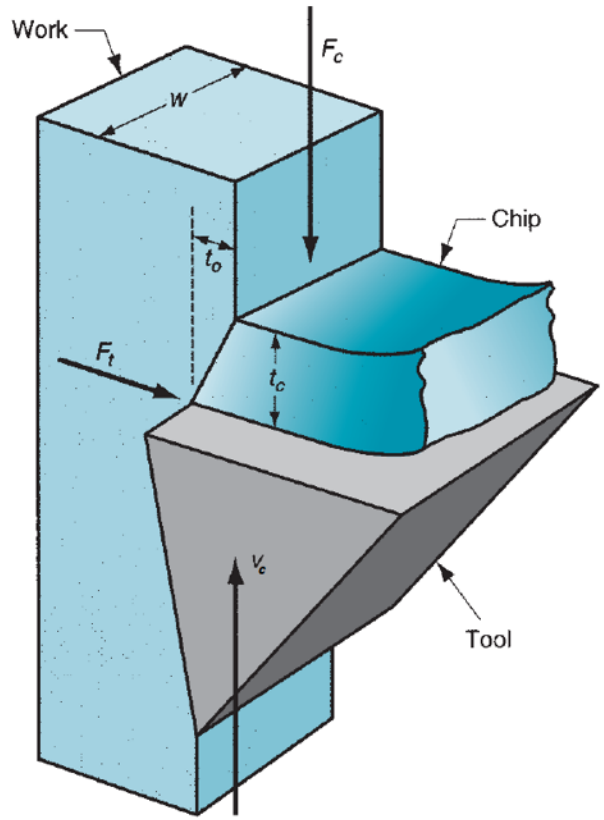


Roughing vs. Finishing Cuts

- 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

Approximation of Turning by Orthogonal Cutting



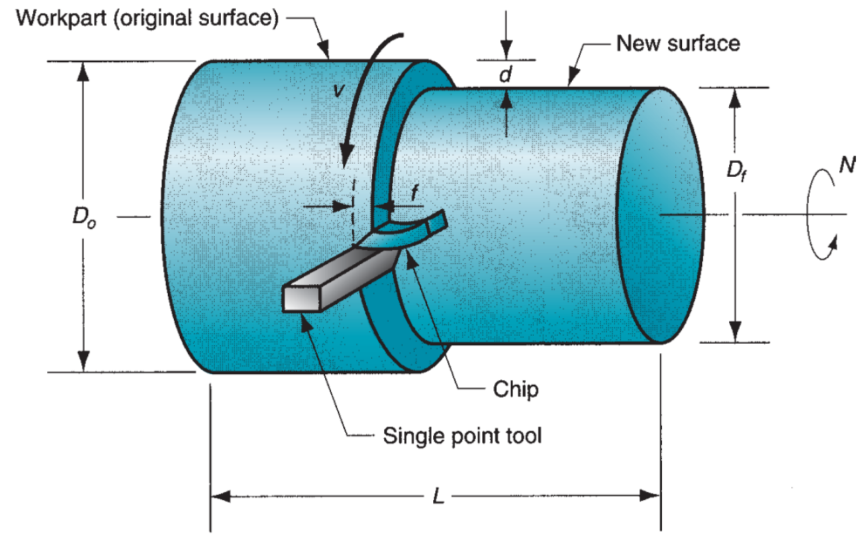


$$MRR = Vfd$$

Conversion key: turning operation vs. orthogonal cutting	
Turning Operation	**Orthogonal Cutting Model**
Feed $f =$	Chip thickness before cut t_o
Depth $d =$	Width of cut w
Cutting speed $v =$	Cutting speed v_c
Cutting force $F_c =$	Cutting force F_c
Feed force $F_f =$	Thrust force F_t

$$MRR = V_c t_o w$$

Cutting Conditions in Turning



The rotational speed in turning is related to the desired cutting speed at the surface of the cylindrical workpiece. The rotational speed in turning:

$$N = \frac{V}{\pi D_o}$$

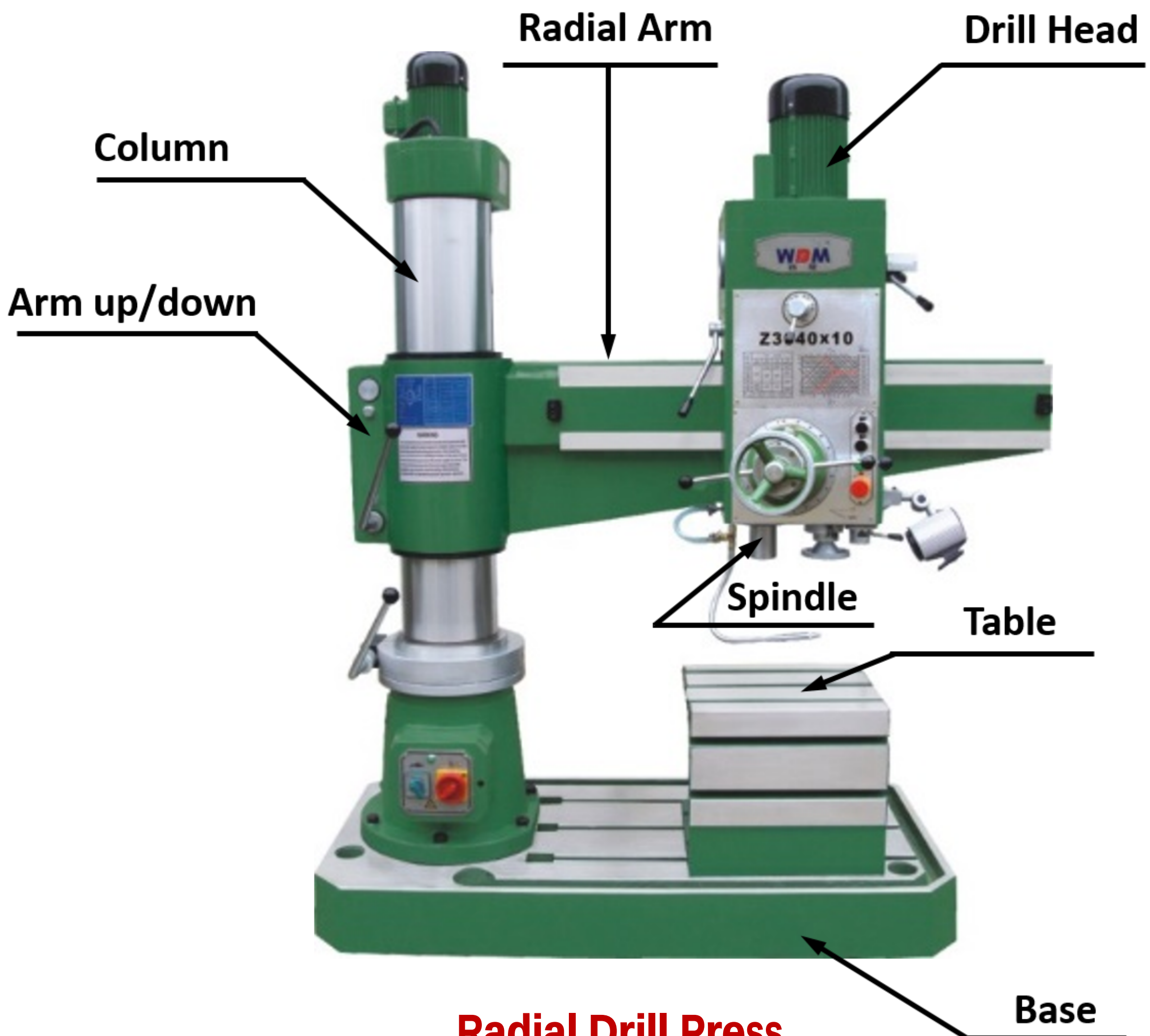
Final diameter: $$D_f = D_o - 2d$$

The feed (f) in turning is generally expressed in mm/rev. This feed can be converted to a linear travel rate (f_r) in mm/min: $$f_r = Nf$$

The Machining Time: $$T_m = \frac{L}{f_r} = \frac{\pi D_o L}{f V}$$

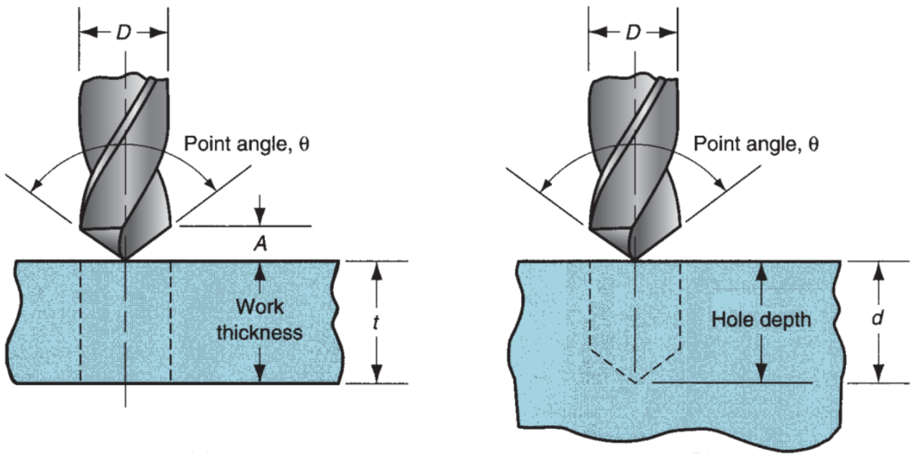
$$MRR = Vfd$$

Drilling Machine



Radial Drill Press

Cutting Conditions in Drilling



The cutting speed in a drilling operation is the surface speed at the outside diameter of the drill. The rotational speed in turning:

$$N = \frac{V}{\pi D}$$

The feed (*f*) in turning is generally expressed in mm/rev. This feed can be converted to a linear travel rate (f_r) in mm/min:

$$f_r = Nf$$

The Machining time can be computed as:

$$T_m = \frac{t + A}{f_r}$$

$$A = 0.5D\tan(90 - \frac{\theta}{2})$$

A = An approach allowance that accounts for the drill point angle, representing the distance the drill must feed into the work before reaching full diameter.

Machining time for blind hole:

$$T_m = \frac{d + A}{f_r}$$

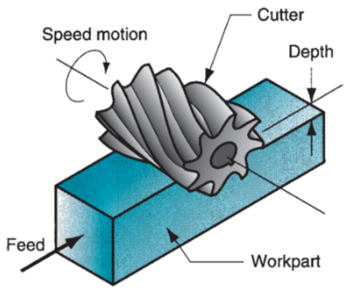
$$MRR = \frac{\pi D^2 f_r}{4}$$

Milling Machines

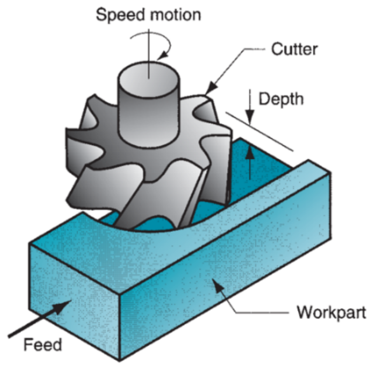
Horizontal Milling Machine

Vertical Milling Machine

Two basic types of milling operations:



(a) Peripheral or plain milling



(b) Face milling

Peripheral milling:

- The axis of the tool is parallel to the surface being machined
- Operation is performed by cutting edges on the outside periphery of the cutter

Face milling:

- The axis of the cutter is perpendicular to the surface being milled
- Machining is performed by cutting edges on both the end and outside periphery of the cutter

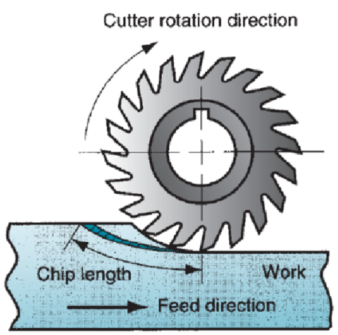
Two forms of peripheral milling operation:

Up milling (conventional milling):

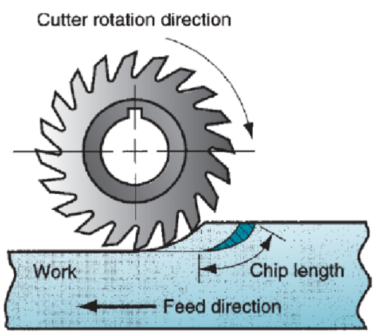
- Cutter motion and the feed are in opposite direction
- Each chip starts out very thin and increases in thickness throughout the cut
- Poor surface finish since chips gets accumulated at the cutting zone
- Used for hard materials

Down milling (climb milling):

- Cutter motion and the feed are in same direction
- Each chip starts out thick and reduces in thickness throughout the cut
- Good surface finish
- Used for soft materials and finishing operations



(a) Up milling



(b) Down milling

The length of a chip in down milling is less than in up milling: Increased tool life in down milling

Cutting Conditions in Milling

The cutting speed is determined at the outside diameter of a milling cutter. The rotational speed in milling:

$$N = \frac{V}{\pi D}$$

Feed rate in milling (mm/min):

$$f_r = N n_t f$$

$$MRR = w d f_r$$

f = feed in milling (mm/tooth) also called as chip load

n_t = number of teeth on the cutter

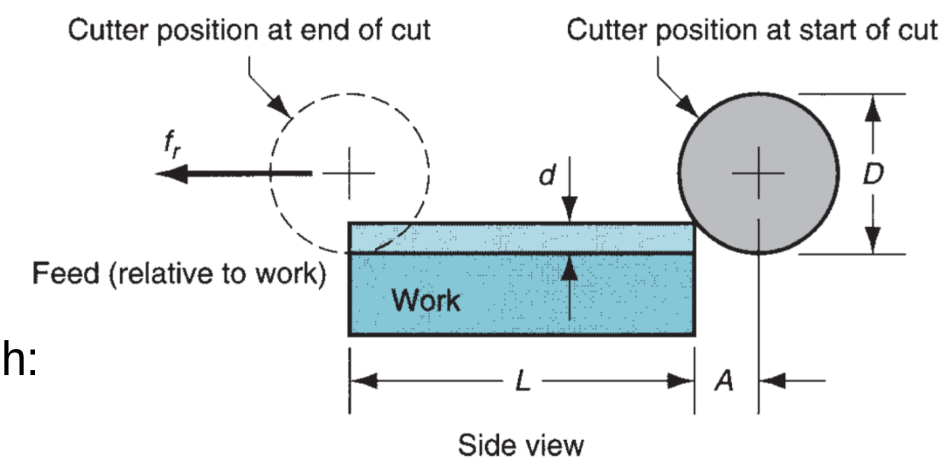
Slab (peripheral) milling

Machining time:

$$T_m = \frac{L + A}{f_r}$$

Approach distance to reach full cutter depth:

$$A = \sqrt{d(D - d)}$$

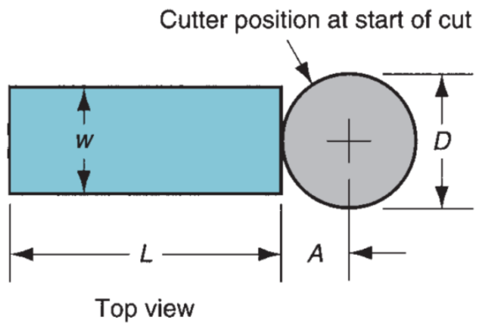


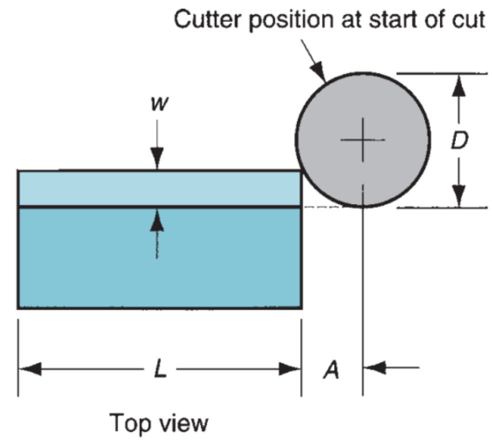
Cutting Conditions in Milling

Face milling

Machining time:

$$T_m = \frac{L + A}{f_r}$$





Approach distance:

when the cutter is centred over a rectangular workpiece:

$$A = 0.5(D - \sqrt{D^2 + w^2})$$

when the cutter is offset to one side of the workpiece:

$$A = \sqrt{w(D - w)}$$

Problem-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) Shear Plane angle (∅):

$$Chip\ thickness\ Ratio\,(r) = \frac{t_o}{t_c} = \frac{0.010}{0.027} = 0.3701$$

$$\tan\phi = \left(\frac{r\ cos\alpha}{1 - rsin\alpha}\right)$$

$$\phi = \tan^{-1}\left(\frac{r\ cos\alpha}{1 - rsin\alpha}\right) = \tan^{-1}\left(\frac{0.3701\ cos5}{1 - 0.3701sin5}\right) = \tan^{-1}(0.3813) = 20.9^{o}$$

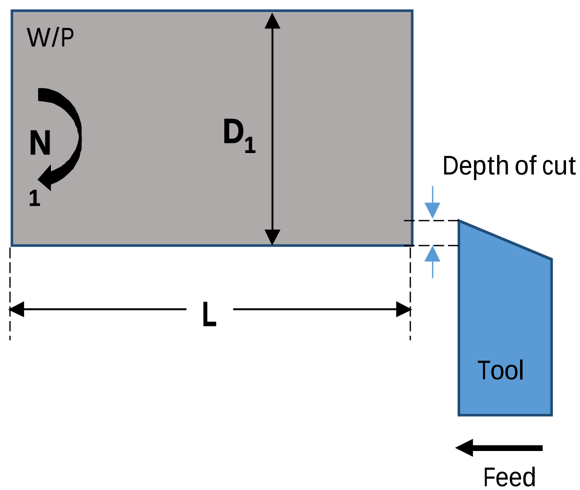
(b) Shear strain(γ):

$$\gamma = \tan(\phi - \alpha) + \cot\phi = \tan(29.9 - 5) + \cot 20.9 = 0.284 + 2.623 = 2.907$$

Problem-2:

A turning operation has to be performed on an aluminum rod of diameter 50 mm and length 300 mm. The Spindle speed of lathe is given to be 500 RPM. The feed and depth of cut are 0.15 mm/rev and 0.3 mm, respectively. Draw a neat sketch of the turning operation described above. Find out the cutting speed in mm/s and the volumetric material removal rate (MRR_v) in mm^3 / s.

Solution:



Turning operation

$$N_1 = 500RPM, D1 = 50mm$$
$$f_1 = 0.15mm/rev$$
$$d_1 = 0.3mm$$
$$CuttingSpeed, V_c = \omega.R$$
$$V_c = \left[\frac{500 \times 2\pi}{60}\right] \times 25$$
$$V_c = 1308.9mm/s$$

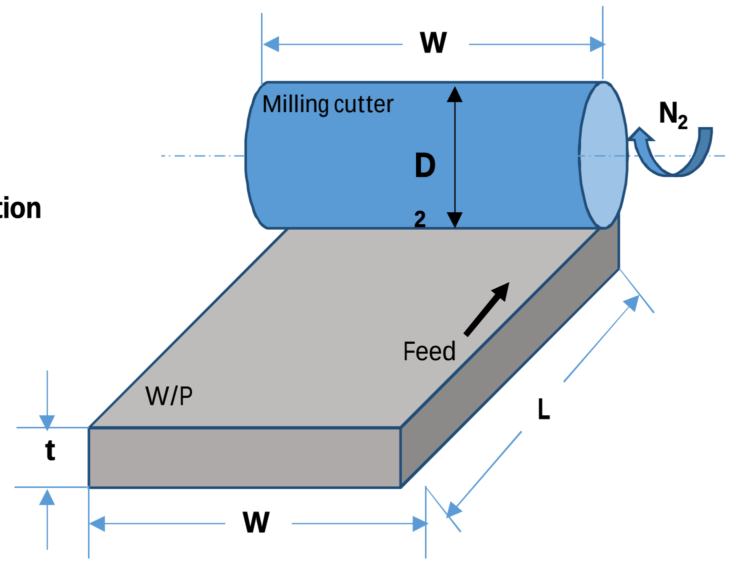
$$MRR_v = (\pi \times D_1 \times N_1) f_1 \cdot d_1 / 60$$
$$MRR_v = (V_c) f_1 \cdot d_1$$
$$MRR_v = 1308.9 \times 0.15 \times 0.3$$
$$MRR_v = 58.905 \ mm^3/s$$

Problem-3

An aluminum block of length 50 mm and width 70 mm is being milled using a slab milling cutter with 50 mm diameter. The feed of the table is 15 mm/min. The milling cutter rotates at 60 RPM in clockwise direction and width of cut is equal to the width of the workpiece. Draw a neat sketch of the milling operation describing above conditions. The thickness of the workpiece is 20 mm. If depth of cut of 2 mm is used then find out cutting speed and volumetric material removal rate (MRR_v).

Solution:

Milling operation



$$Milling\ Cutter\ Diameter, D_2 = 50mm$$

$$Width\ of\ cut, WOC = 70mm$$

$$Depth\ of\ cut, d_2 = 2mm$$

$$feed,\ f_2 = 15mm / \min$$

$$Cutting\ Speed,\ V_c = \frac{\pi D_2 N_2}{1000} m / \min$$

$$V_c = \left[\frac{50 \times \pi \times 60}{1000}\right]$$

$$V_c = 9.424m / \min$$

$$MRR_v = WOC \cdot f_2 \cdot d_2$$

$$MRR_v = 70 \times \frac{15}{60} \times 2$$

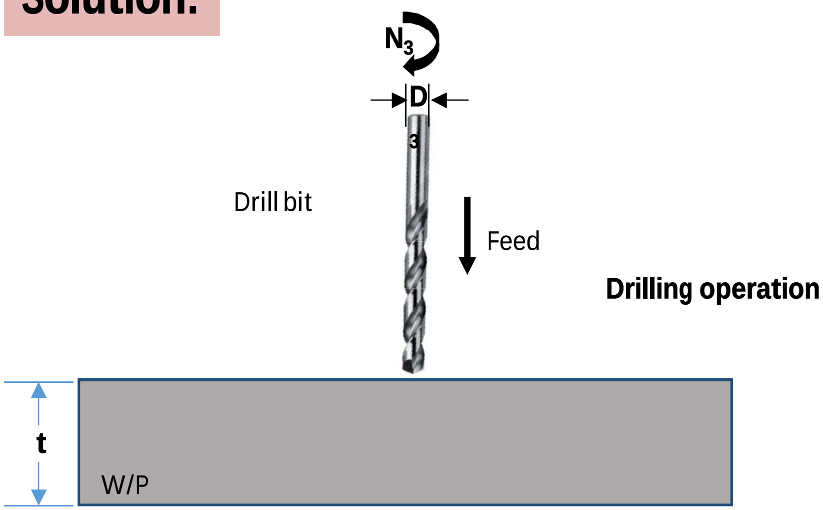
$$MRR_v = 35\ mm^3 / s$$

Problem-4

Following the milling operation, a through hole is to be drilled on the same workpiece.

Find out the cutting speed and volumetric material removal rate if the drill of diameter 10 mm is being rotated at the same RPM as in case of milling cutter with feed rate as 0.5 mm/rev.

Solution:



$$Diameter\ of\ Drill, D_3 = 10mm$$

$$N_3 = 60RPM$$

$$feed,\ f_3 = 0.5mm/rev$$

$$Cutting\ Speed,\ V_c = \frac{\pi N_3 D_3}{1000} m/\min$$

$$V_c = \left[\frac{\pi \times 60 \times 10}{1000}\right] m/\min$$

$$V_c = 1.884m/\min = 31.4mm/s$$

$$MRR_v = \frac{\pi \times D_3^{\ 2}}{4} \times f_3 \times N_3$$

$$MRR_v = \frac{\pi \times 10^2}{4} \times 0.5 \times 60$$

$$MRR_v = 2356.19\ mm^3/\min = 39.27mm^3/s$$

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

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

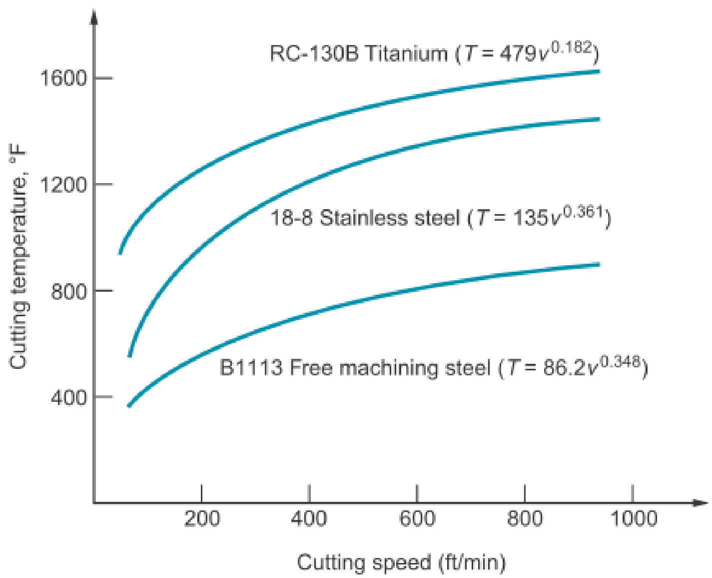
where T = temperature rise at tool-chip interface, ºC; U = specific energy, N-m/mm^3 or J/mm^3; v = cutting speed, m/s; t_o = chip thickness before cut, m; ρC = volumetric specific heat of work material, J/mm^3-ºC; K = thermal diffusivity of work material (m^2/s)

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, The parameters K and m depend on cutting conditions (other than v) and work material.



Recap of the Lecture

- Orthogonal (2-D) cutting model
- Geometry of chip Formation
- Forces in Machining
- Shear Strain & Strain Rate
- Cutting Conditions in Turning, Drilling and Milling
- Cutting Temperature

Next Lecture

Cutting tool technology, tool wear, tool life