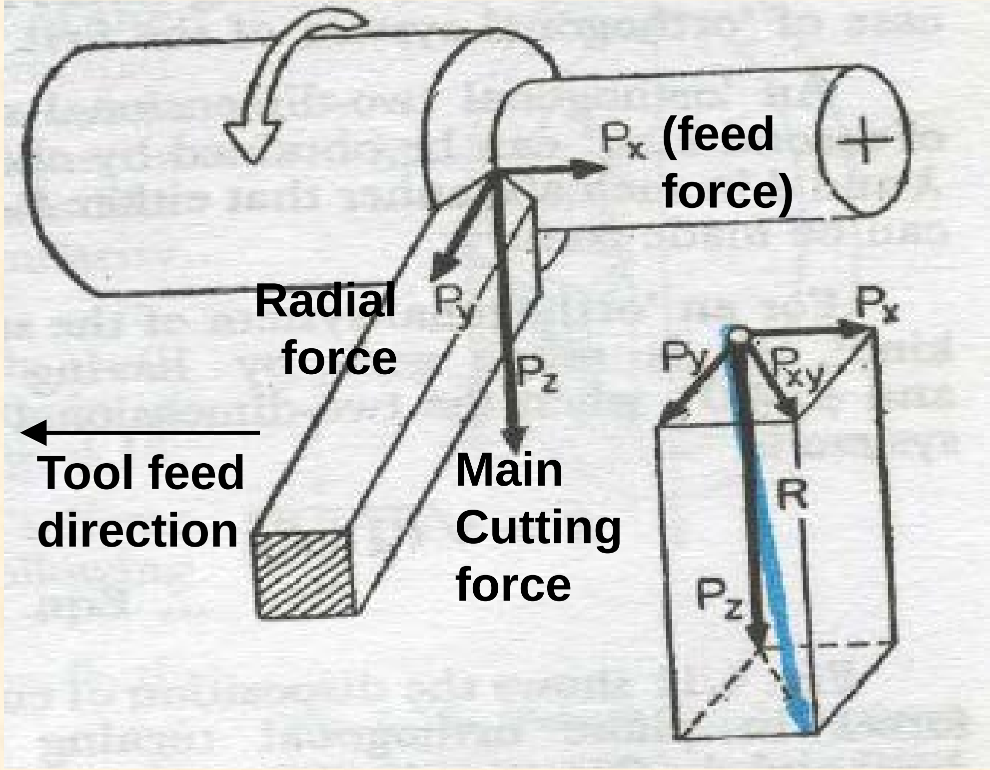
MECHANICS OF METAL CUTTING



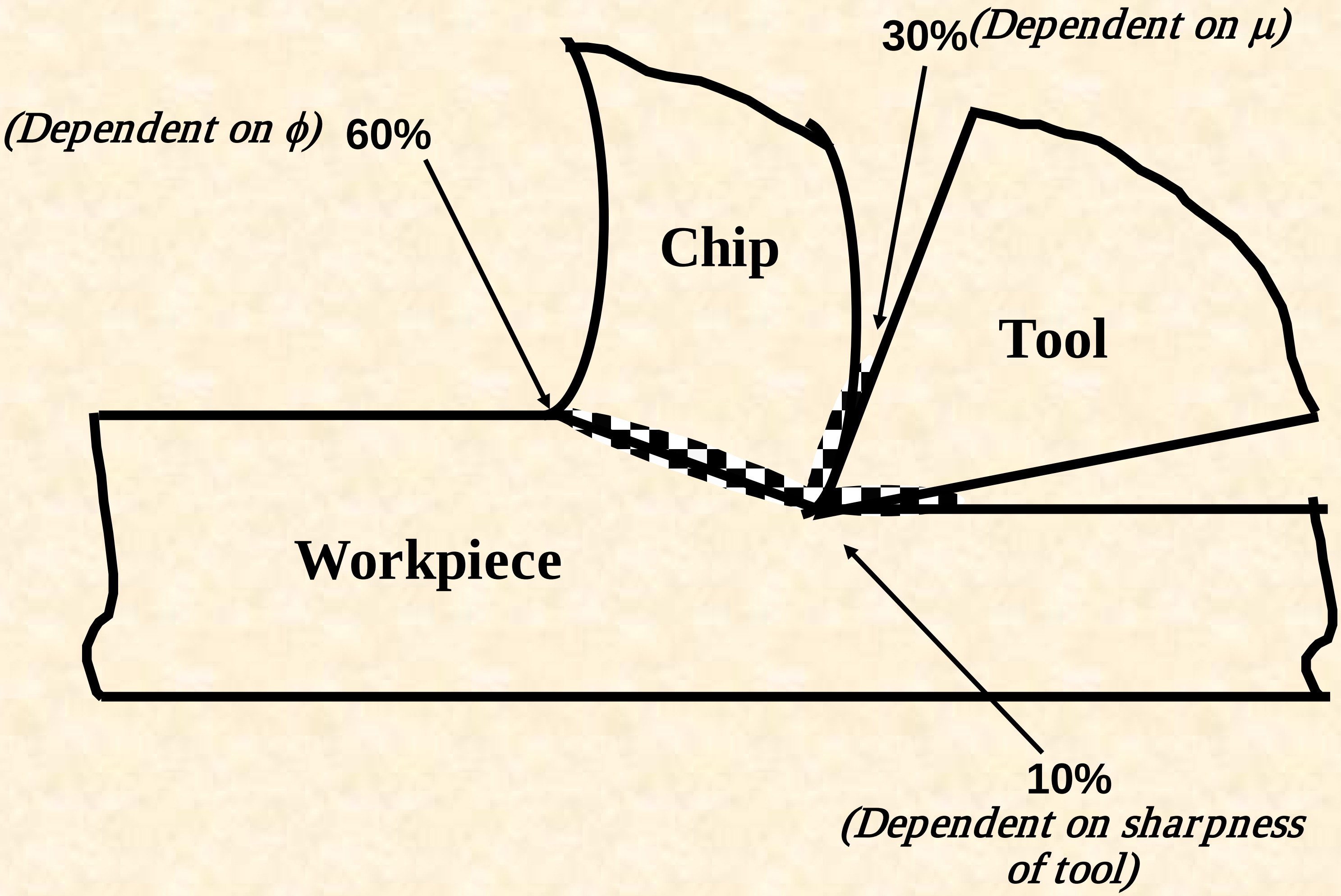
Topics to be covered

- Tool terminologies and geometry
- Orthogonal Vs Oblique cutting
- Turning Forces
- Velocity diagram
- Merchants Circle
- Power & Energies

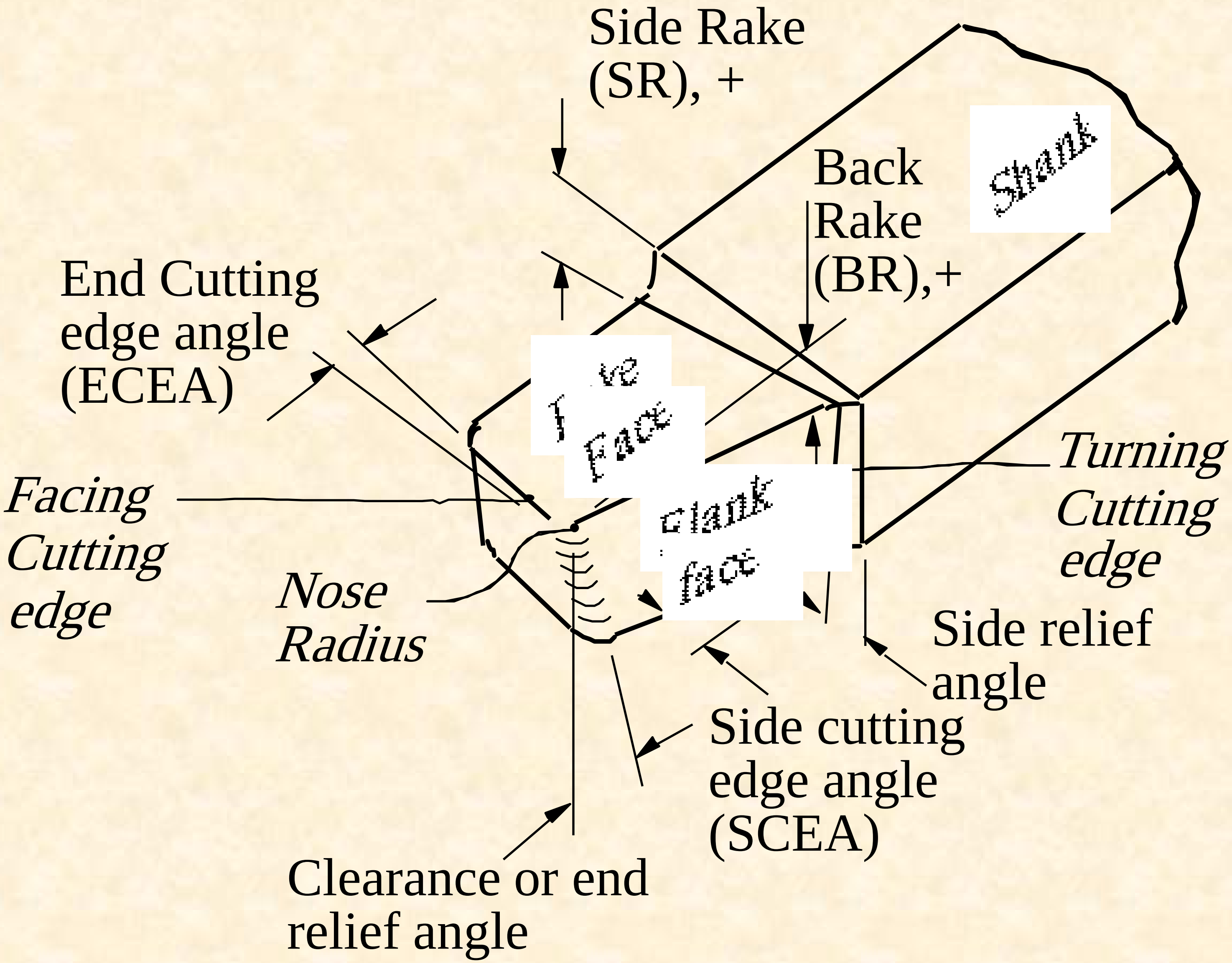
Need for calculating forces, velocities and angles during machining??

- We need to determine the cutting forces in turning for Estimation of cutting power consumption, which also enables selection of the power source(s) during design of the machine tools.
- Structural design of the machine – fixture – tool system.
- Evaluation of role of the various machining parameters (tool material and geometry) on cutting forces to make machining process more efficient and economical.
- Condition monitoring of the cutting tools and machine tools.

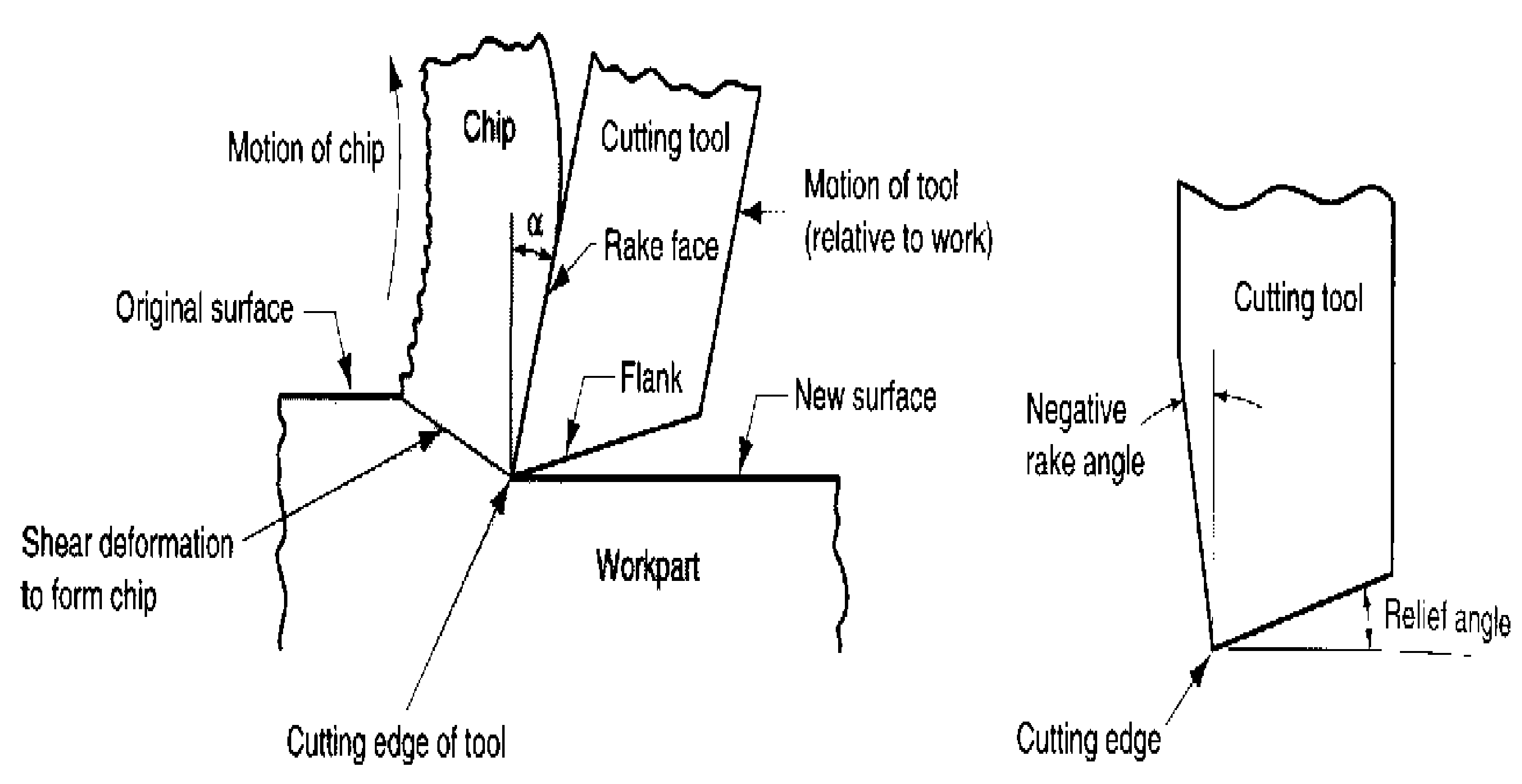
Heat Generation Zones



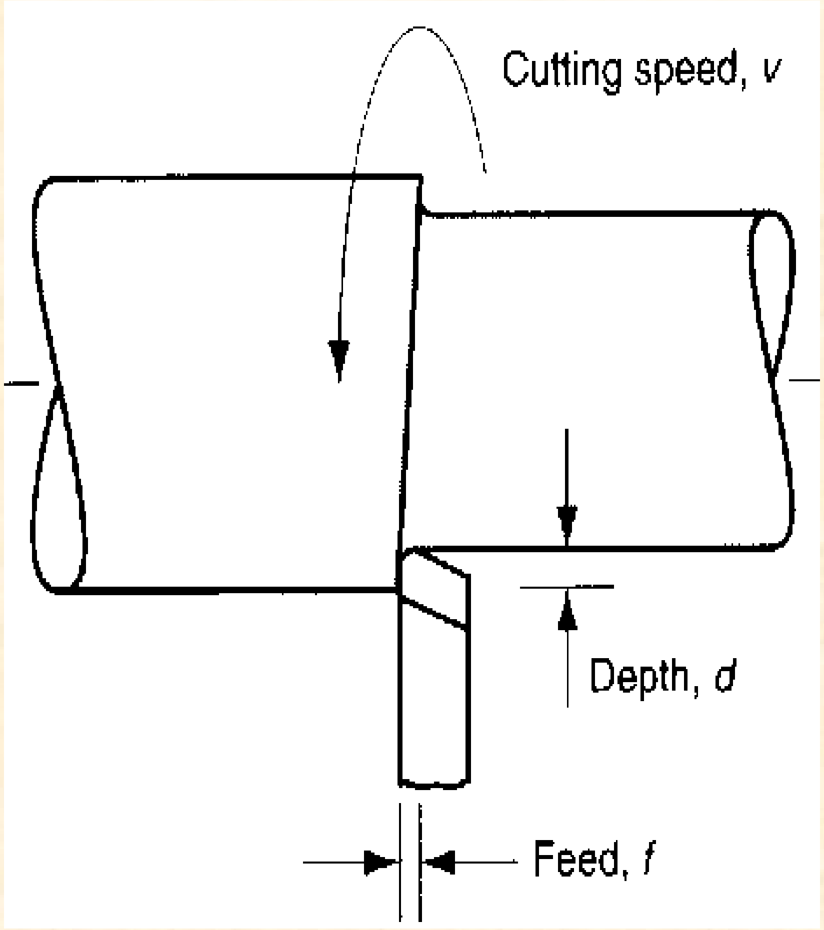
Tool Terminology



Cutting Geometry



Material Removal Rate



$$MRR = vfd$$

$$Roughing(R)$$

$$f = 0.4 - 1.25 mm / rev$$

$$d = 2.5 - 20 mm$$

$$Finishing(F)$$

$$f = 0.125 - 0.4 mm / rev$$

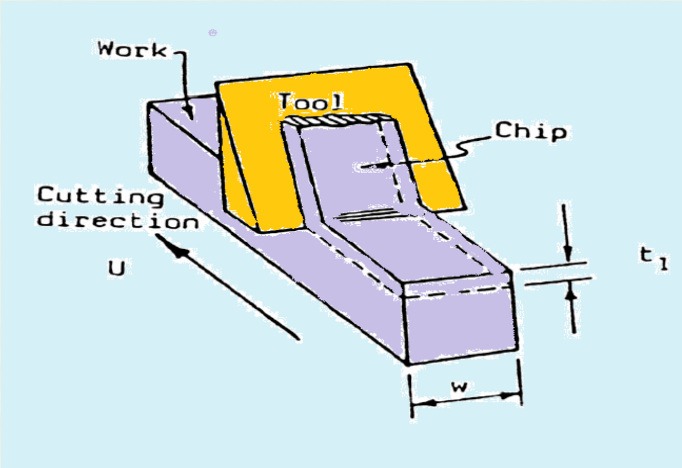
$$d = 0.75 - 2.0 mm$$

$$v_R << v_F$$

METAL CUTTING

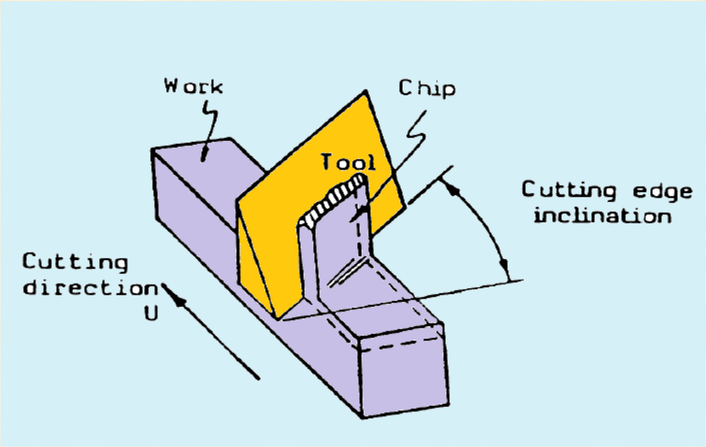
Metal Cutting is the process of removing unwanted material from the workpiece in the form of chips

ORTHOGONAL CUTTING



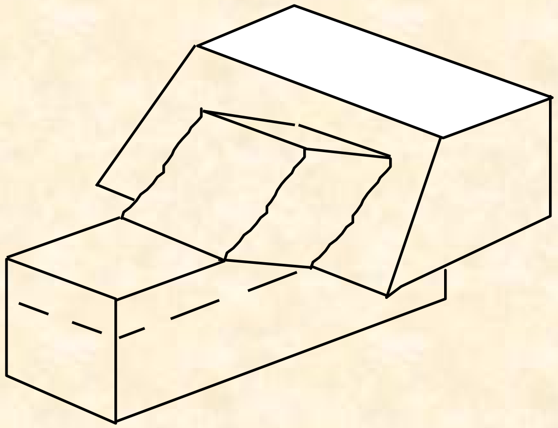
- **Cutting Edge is normal to tool feed.**
- **Here only two force components are considered i.e. cutting force and thrust force. Hence known as two dimensional cutting.**
- **Shear force acts on smaller area.**

OBLIQUE CUTTING



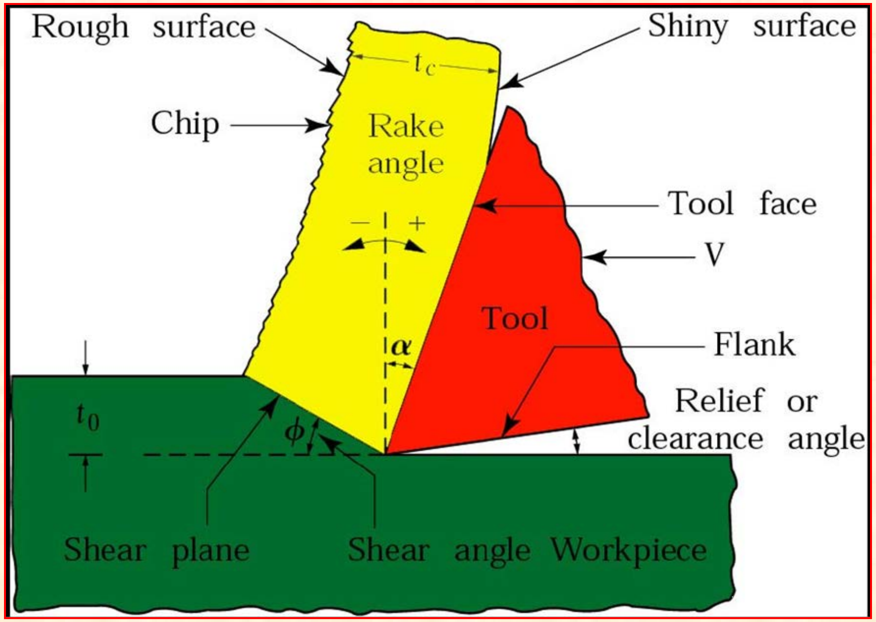
- **Cutting Edge is inclined at an acute angle to tool feed.**
- **Here only three force components are considered i.e. cutting force, radial force and thrust force. Hence known as three dimensional cutting.**
- **Shear force acts on larger area.**

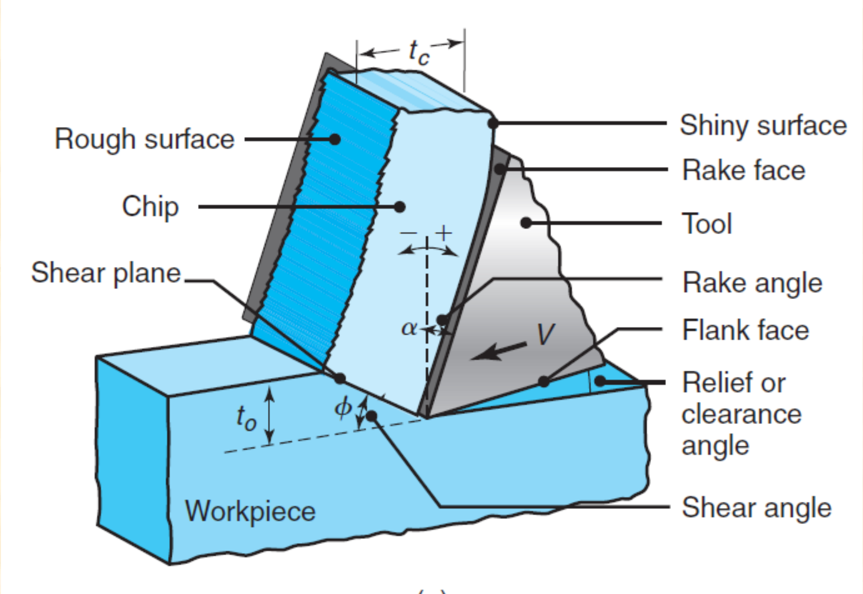
Assumptions
(Orthogonal Cutting Model)



- The cutting edge is a straight line extending perpendicular to the direction of motion, and it generates a plane surface as the work moves past it.
- The tool is perfectly sharp (no contact along the clearance face).
- The shearing surface is a plane extending upward from the cutting edge.
- The chip does not flow to either side
- The depth of cut/chip thickness is constant uniform relative velocity between work and tool
- Continuous chip, no built-up-edge (BUE)

TERMINOLOGY



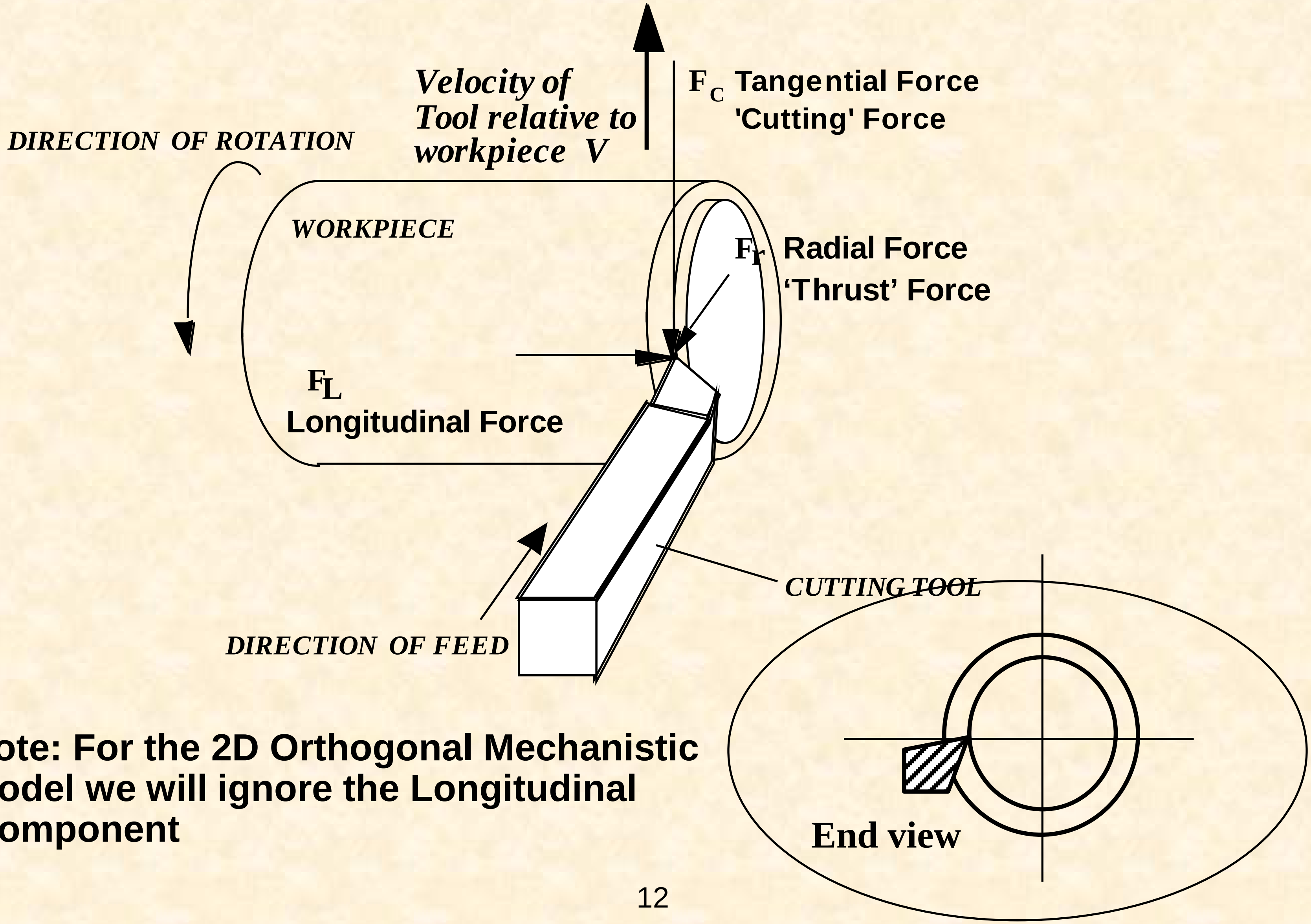


(a)

TERMINOLOGY

- **α : Rack angle**
- **β : Frictional angle**
- **ϕ : Shear angle**
- **F_t : Thrust Force**
- **F_c: Cutting Force**
- **F_s: Shear Force**
- **F_n: Normal Shear Force**
- **F: Frictional Force**
- **N: Normal Frictional Force**
- **V: Feed velocity**
- **Vc: Chip velocity**
- **Vs: Shear velocity**

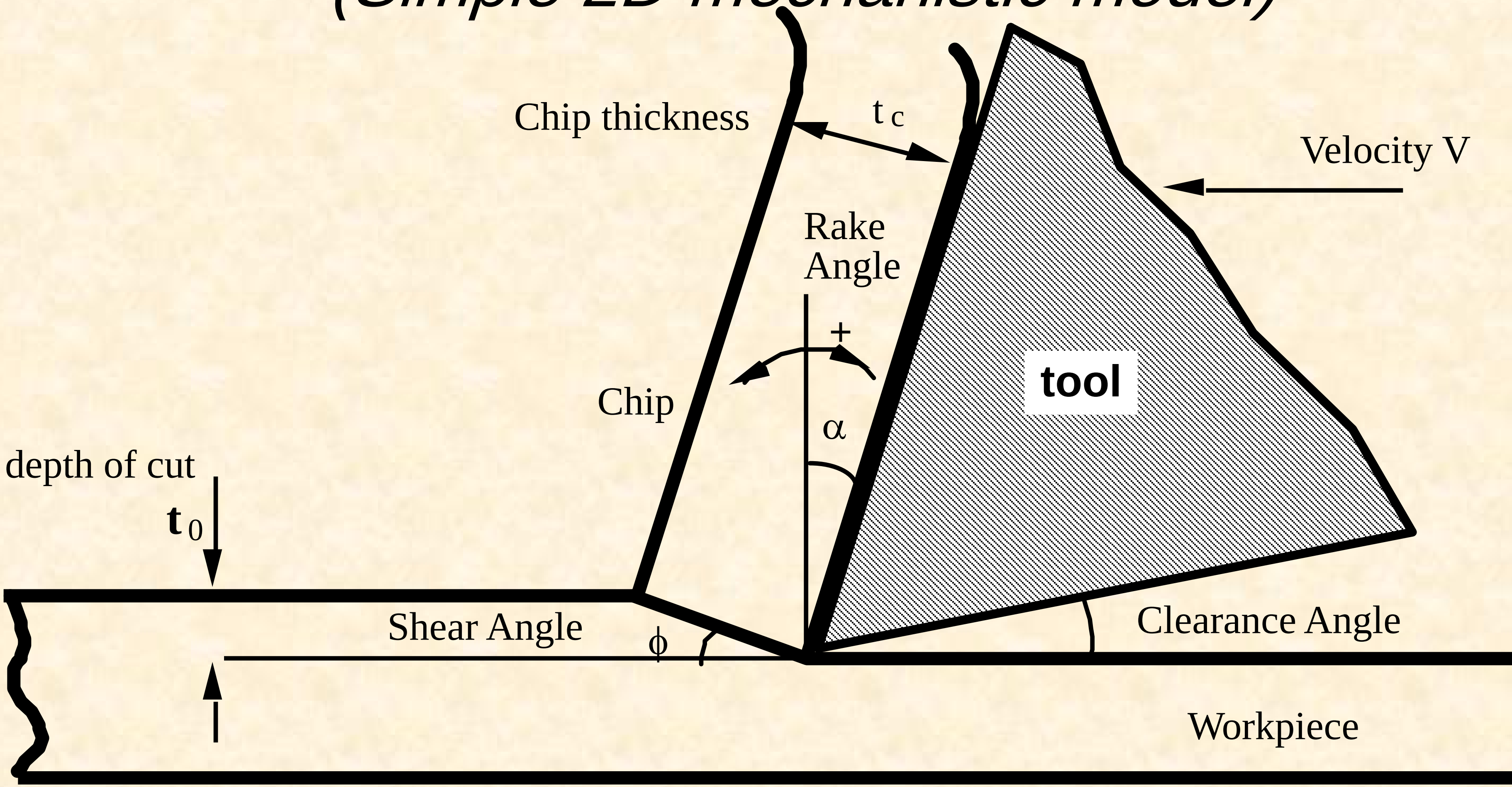
Forces For Orthogonal Model



Note: For the 2D Orthogonal Mechanistic Model we will ignore the Longitudinal component

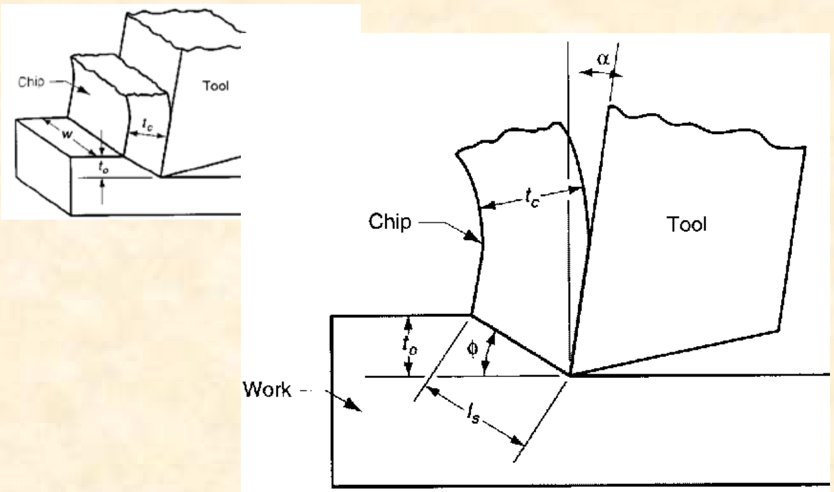
Orthogonal Cutting Model

(Simple 2D mechanistic model)



Mechanism: Chips produced by the shearing process along the shear plane

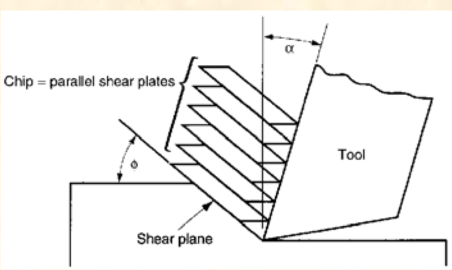
Orthogonal Cutting

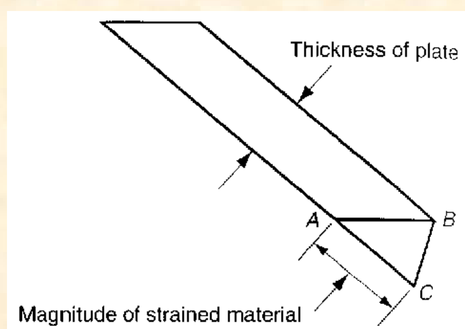


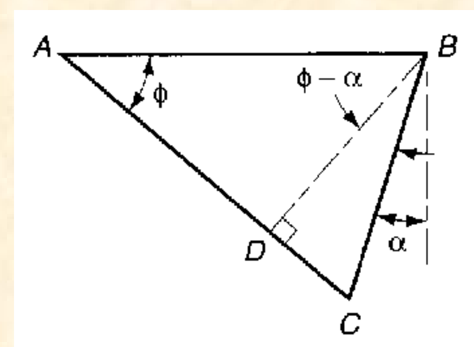
$$r = \frac{t_o}{t_c} = \frac{l_s \sin\phi}{l_s \cos(\phi - \alpha)}$$

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

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

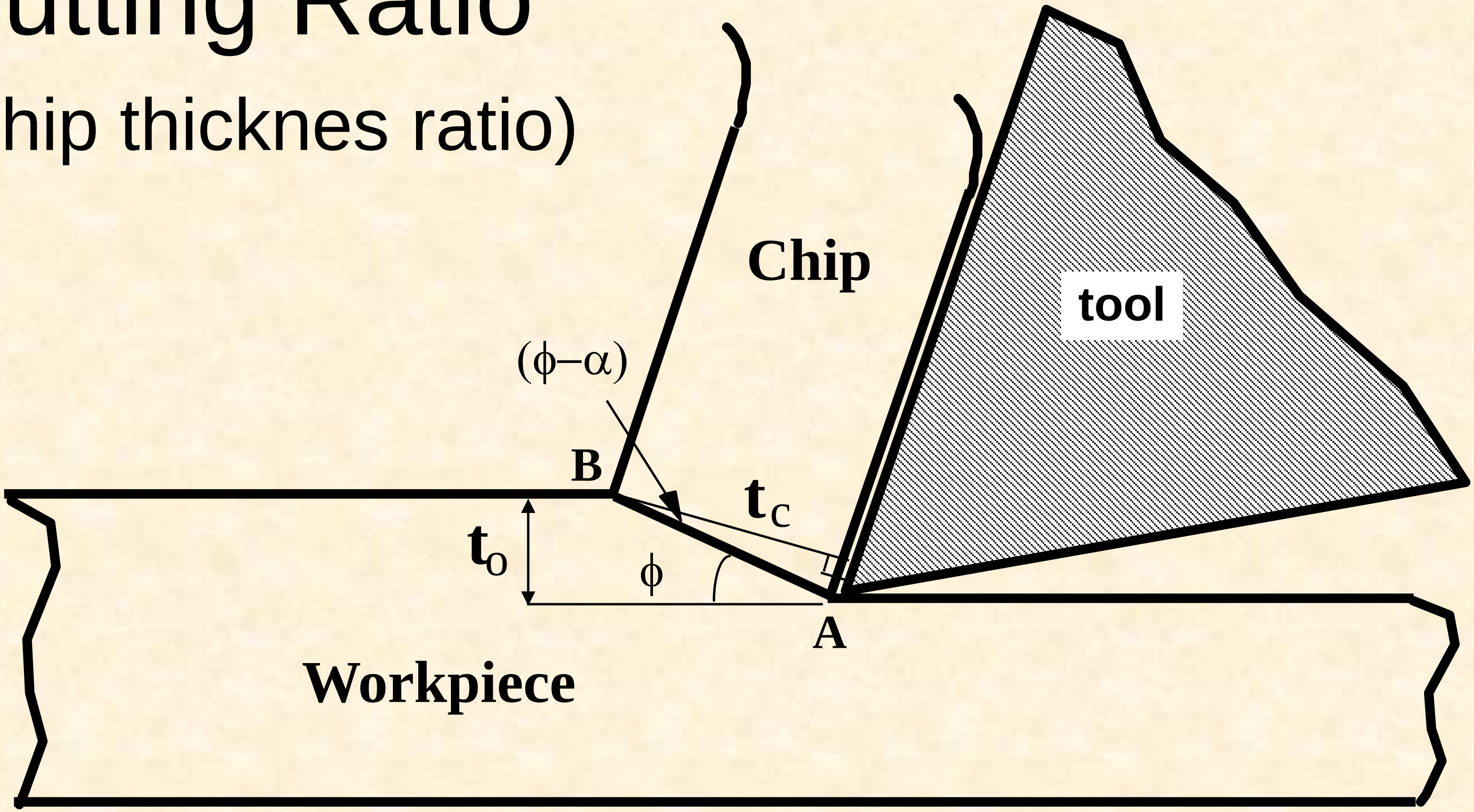






Cutting Ratio

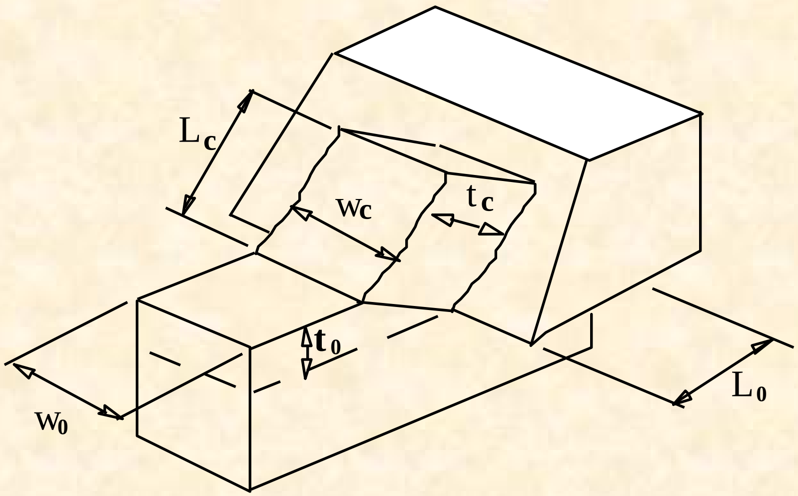
(or chip thicknes ratio)



$$\text{As } \sin\phi = \frac{t_o}{AB} \text{ and } \cos(\phi-\alpha) = \frac{t_c}{AB}$$

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

Experimental Determination of Cutting Ratio



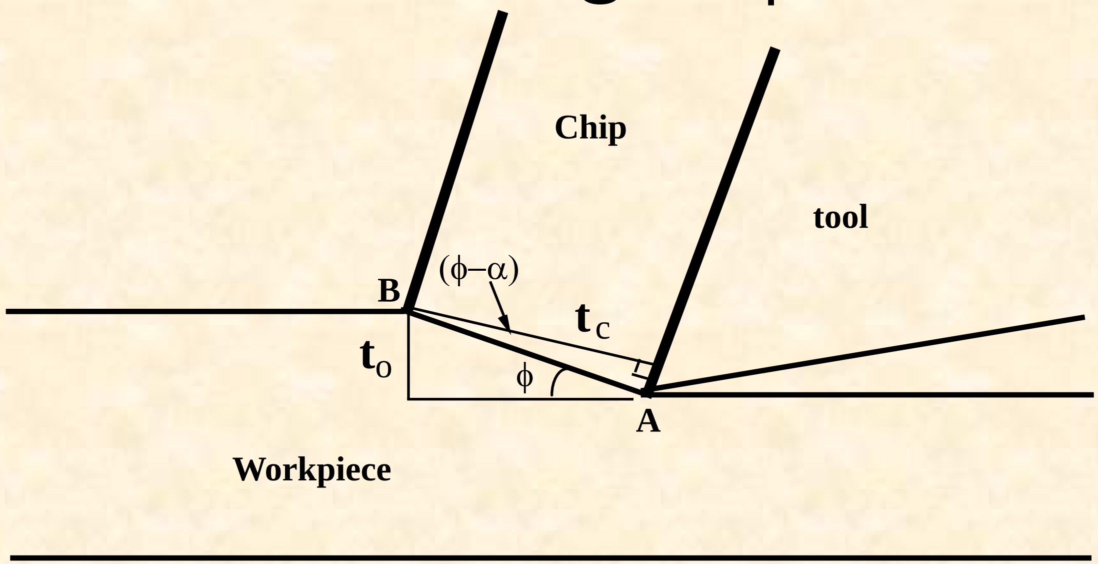
Shear angle ϕ may be obtained either from photo-micrographs or assume volume continuity (no chip density change):

Since $t_0 w_0 L_0 = t_c w_c L_c$ and $w_0 = w_c$ (exp. evidence)

$$\text{Cutting ratio}\quad, \; r = \frac{t_0}{t_c} = \frac{L_c}{L_0}$$

i.e. Measure length of chips (easier than thickness)

Shear Plane Length and Angle ϕ



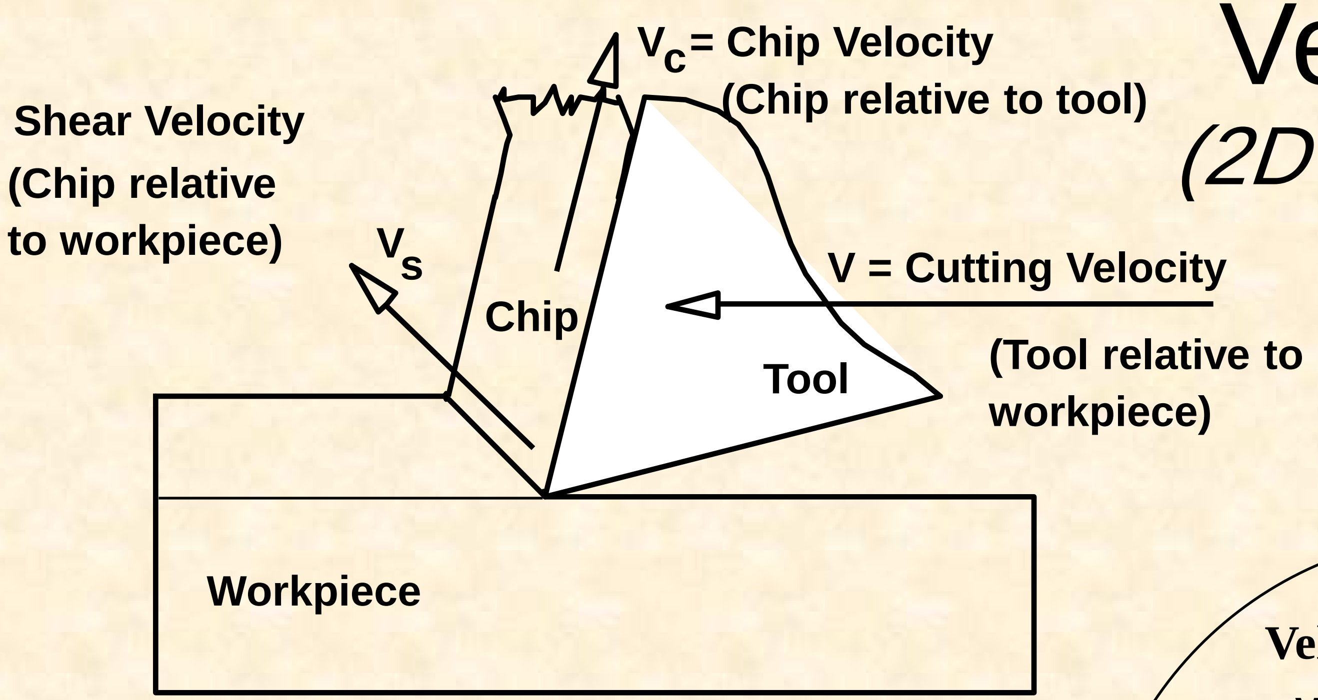
Shear plane length AB $= \dfrac{t_0}{\sin\phi}$

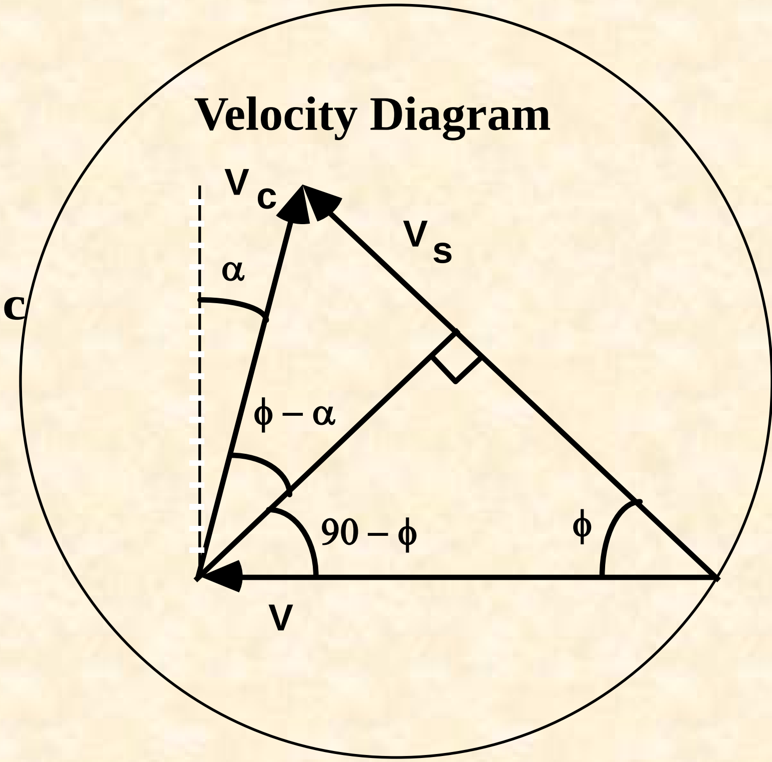
Shear plane angle $(\phi) = \mathrm{Tan}^{-1}\left[\dfrac{r\cos\alpha}{1 - r\sin\alpha}\right]$

or make an assumption, such as ϕ adjusts to minimize cutting force: $\phi = 45^0 + \alpha/2 - \beta/2$ **(Merchant)**

Velocities

(2D Orthogonal Model)





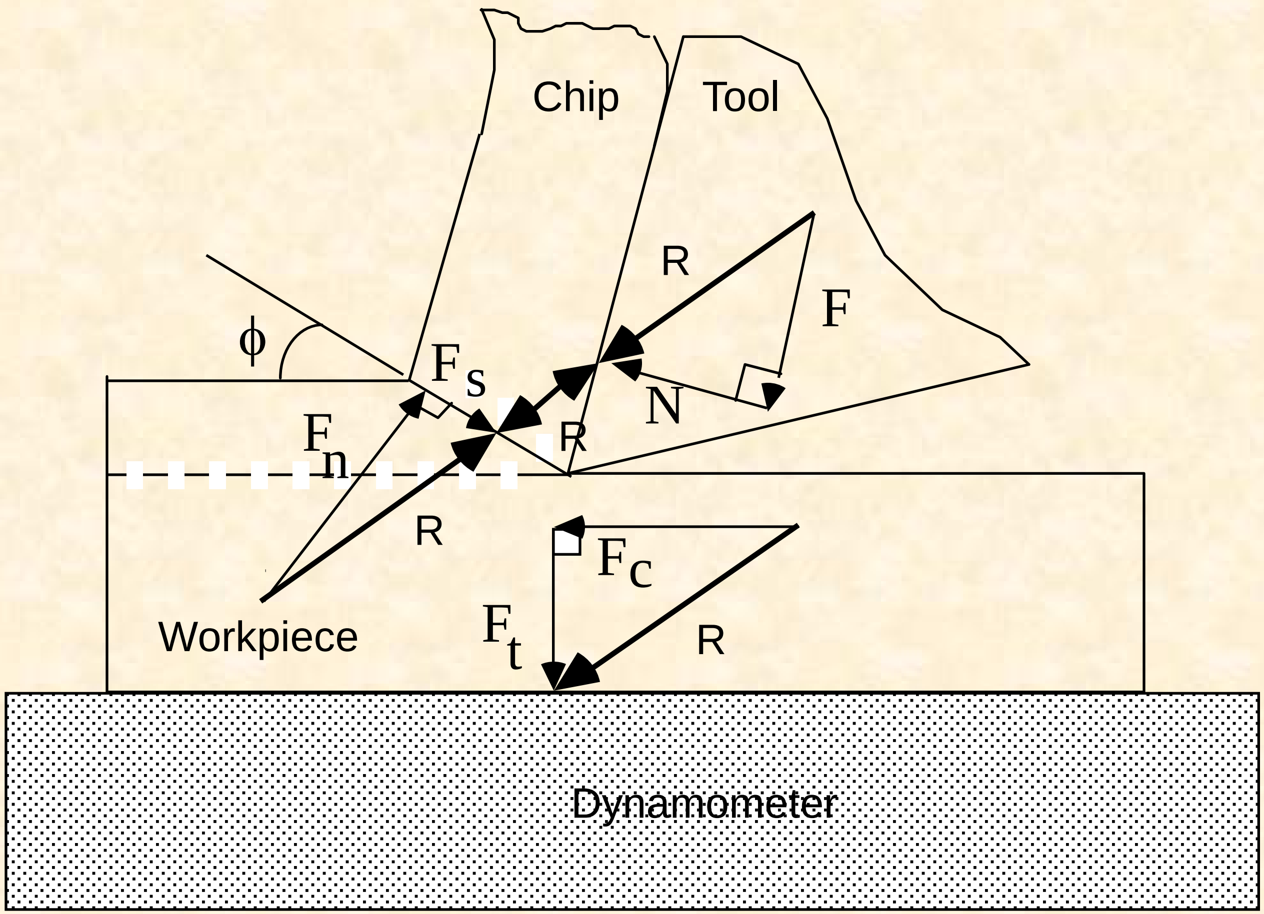
From mass continuity: $Vt_o = V_c t_c$

$$V_c = Vr \text{ and } \quad V_c = V\frac{\sin\phi}{\cos(\phi-\alpha)}$$

From the Velocity diagram:

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

Cutting Forces
(2D Orthogonal Cutting)



Free Body Diagram

Generally we know:
Tool geometry & type
Workpiece material

and we wish to know:
F = Cutting Force
F_c = Thrust Force
F_t = Friction Force
N = Normal Force
F_s = Shear Force
F_n = Force Normal

to Shear

Cutting Forces
(2D Orthogonal Cutting)

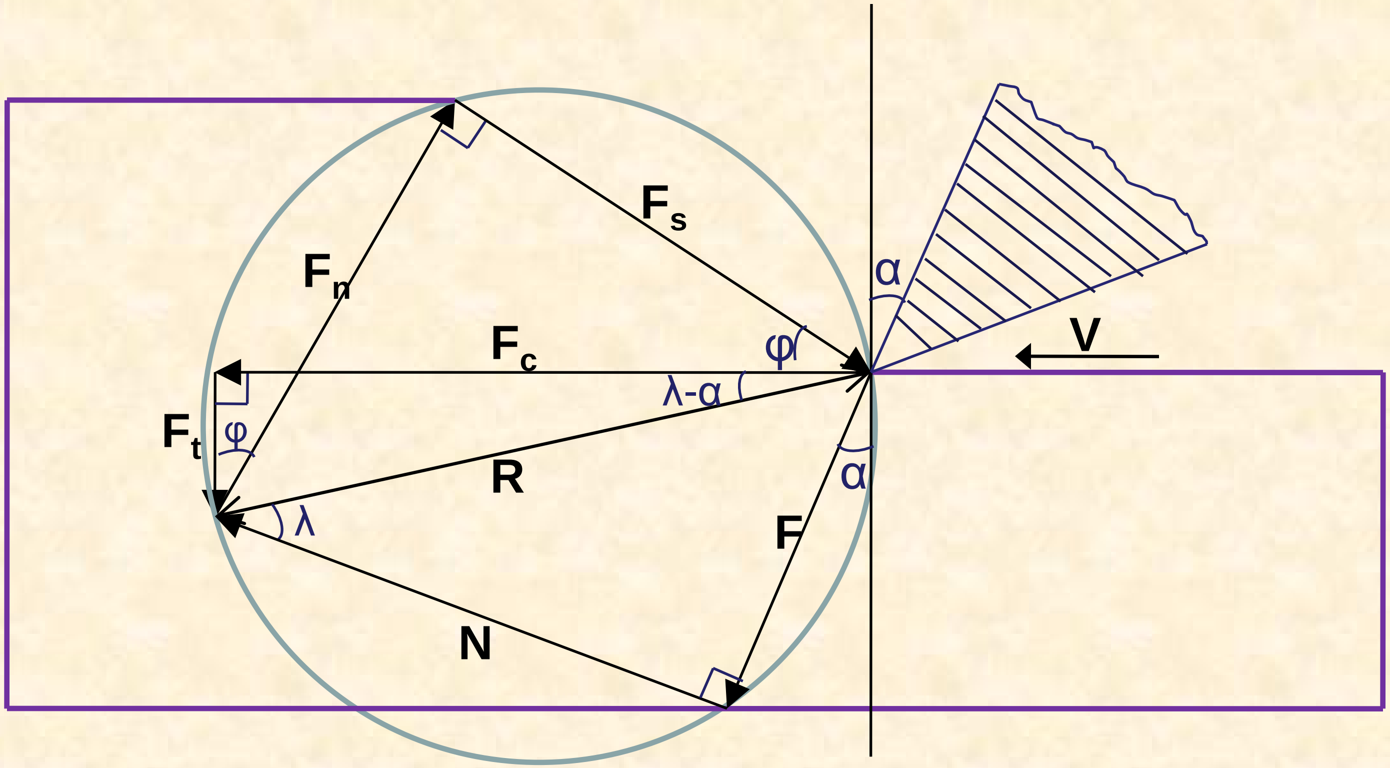
- **F_s , Resistance to shear of the metal in forming the chip. It acts along the shear plane.**

- **F_n , 'Backing up' force on the chip provided by the workpiece. Acts normal to the shear plane.**

- **N, It at the tool chip interface normal to the cutting face of the tool and is provided by the tool.**

- **F, It is the frictional resistance of the tool acting on the chip. It acts downward against the motion of the chip as it glides upwards along the tool face.**

CONSTRUCTION OF MERCHANT'S CIRCLE

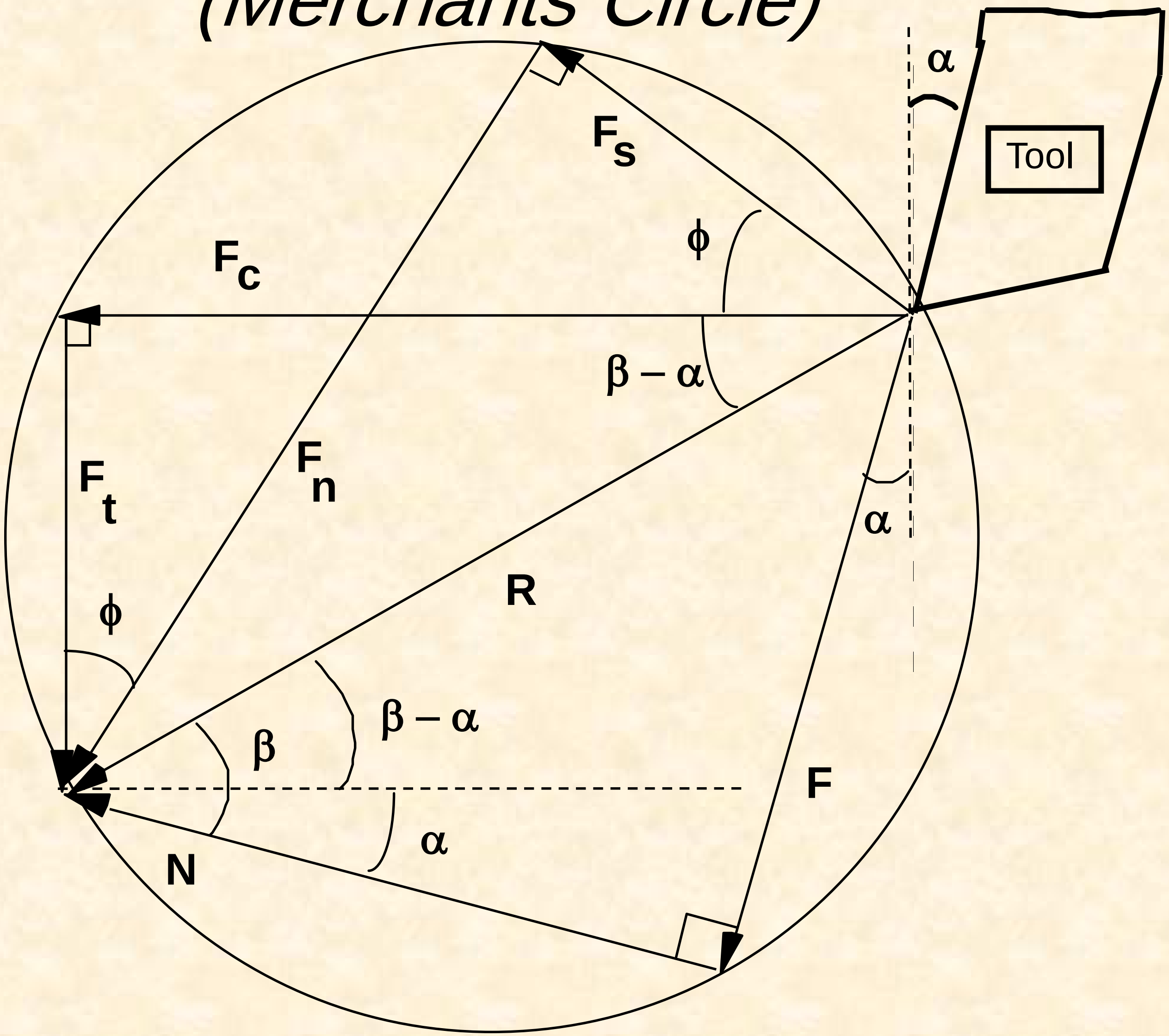


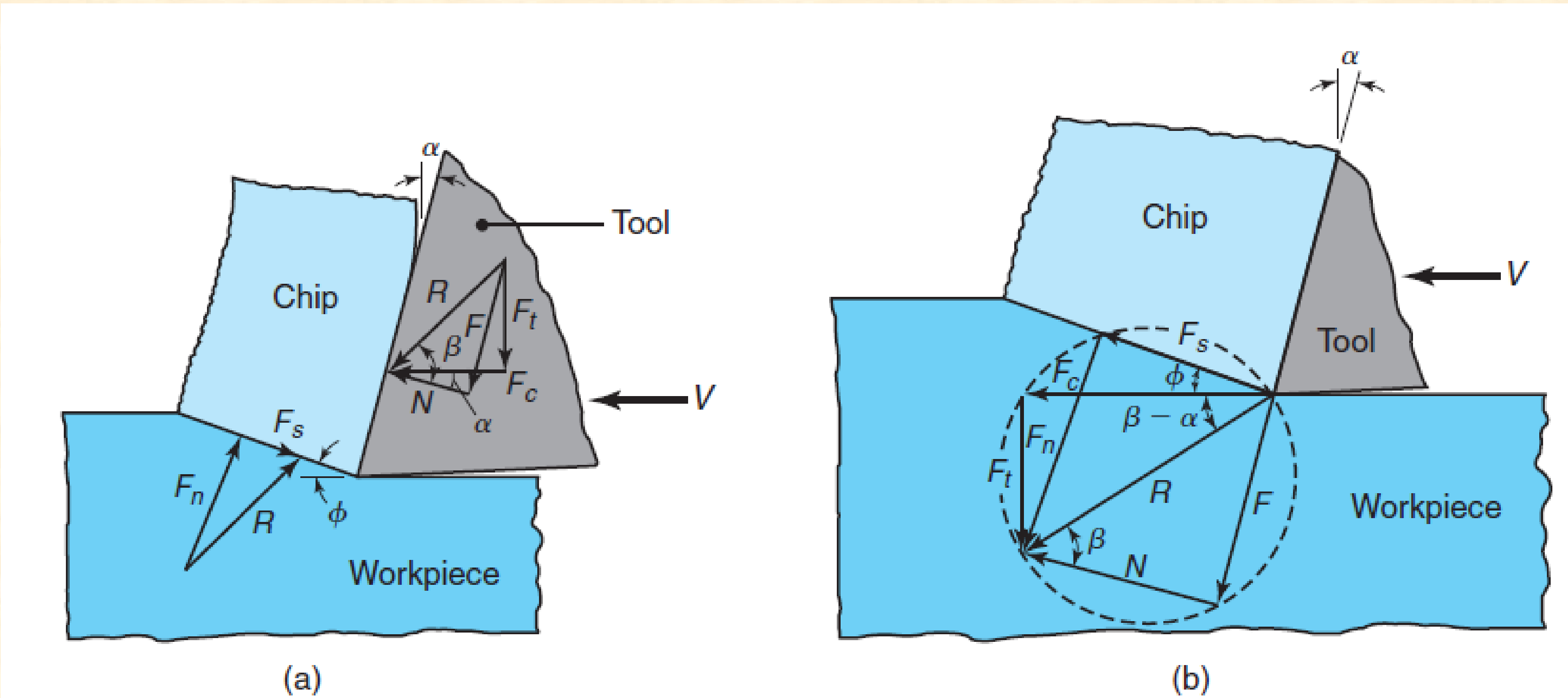
Knowing F_c , F_t , α and φ, all other component forces can be calculated.

Please note λ is same as β in next slide = friction angle

Force Circle Diagram

(Merchants Circle)





α
Tool
Chip
R
F
F_t
β
N
F_c
α
V
F_s
F_n
R
ϕ
Workpiece
(a)
α
Chip
V
F_s
Tool
F_c
ϕ
β − α
F_n
F_t
R
F
β
N
Workpiece
(b)

Cutting Forces

- Forces considered in orthogonal cutting include
  - Cutting, friction (tool face), and shear forces
- **Cutting force**, F_c acts in the direction of the cutting speed V, and supplies the energy required for cutting
  - Ratio of F_c to cross-sectional area being cut (i.e. product of width and depth of cut, t_0) is called: *specific cutting force*
- **Thrust force**, F_t acts in a direction normal to the cutting force
- These two forces produces the **resultant force**, R
- On tool face, resultant force can be resolved into:
  - **Friction force**, F along the tool-chip interface
  - **Normal force**, N to ⊥ to friction force

Cutting Forces

- It can also be shown that (β **is friction angle**)

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

- Resultant force, *R* is balanced by an equal and opposite force along the shear plane
- It is resolved into **shear force,** F_s and **normal force,** F_n
- 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,** μ is

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

Cutting Forces

- The toolholder, work-holding devices, and machine tool must be stiff to support thrust force with minimal deflections
  - If F_t is too high ⇒ tool will be pushed away from workpiece
  - this will reduce depth of cut and dimensional accuracy
- The effect of rake angle and friction angle on the direction of thrust force is

$$F_t = R\sin(\beta - \alpha)$$

- Magnitude of the cutting force, F_c is always positive as the force that supplies the work is required in cutting
- However, F_t can be +ve or –ve; i.e. F_t can be upward with a) high rake angle, b) low tool-chip friction, or c) both

Forces from *Merchant's* Circle

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

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

$\mu = F/N$ **and** $\mu = \tan\beta$ (**typically** 0.5 - 2.0)

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

Force Normal to Shear plane $F_n = F_c \sin\phi + F_t \cos\phi$

$$R = \sqrt{F_c^2 + F_t^2} = \sqrt{F_s^2 + F_n^2} = \sqrt{F^2 + N^2}$$

Stresses

On the Shear plane:

$$\textbf{Normal Stress} = \sigma_s = \textbf{Normal Force / Area} = \frac{F_n}{AB\, w} = \frac{F_n \sin\phi}{t_o w}$$

$$\textbf{Shear Stress} = \tau_s = \textbf{Shear Force / Area} = \frac{F_s}{AB\, w} = \frac{F_s \sin\phi}{t_o w}$$

On the tool rake face:

$$\sigma = \textbf{Normal Force / Area} = \frac{N}{t_c\, w}$$ **(often assume t_c = contact length)**

$$\tau = \textbf{Shear Force / Area} = \frac{F}{t_c\, w}$$

Power

•Power (or energy consumed per unit time) is the product of force and velocity. Power at the cutting spindle:

$$\textbf{Cutting Power} \quad P_c = F_c V$$

•Power is dissipated mainly in the shear zone and on the rake face:

$$\textbf{Power for Shearing} \quad P_s = F_s V_s$$

$$\textbf{Friction Power} \quad P_f = F V_c$$

•Actual Motor Power requirements will depend on machine efficiency E (%):

$$\textbf{Motor Power Required} = \frac{P_c}{E} \times 100$$

Material Removal Rate (MRR)

$$\textbf{Material Removal Rate (MRR)} = \frac{\textbf{Volume Removed}}{\textbf{Time}}$$

$$\textbf{Volume Removed} = Lwt_o$$

$$\textbf{Time to move a distance L} = L/V$$

$$\textbf{Therefore, MRR} = \frac{Lwt_o}{L/V} = Vwt_o$$

MRR = Cutting velocity x width of cut x depth of cut

Specific Cutting Energy

(or Unit Power)

Energy required to remove a unit volume of material (often quoted as a function of workpiece material, tool and process:

$$U_t = \frac{\text{Energy}}{\text{Volume Removed}} = \frac{\text{Energy per unit time}}{\text{Volume Removed per unit time}}$$

$$U_t = \frac{\text{Cutting Power } (P_c)}{\text{Material Removal Rate (MRR)}} = \frac{F_c V}{V w t_o} = \frac{F_c}{w t_o}$$

Specific Energy for shearing $U_s = \dfrac{F_s V_s}{V w t_o}$

Specific Energy for friction $U_f = \dfrac{F V_c}{V w t_o} = \dfrac{F r}{w t_o} = \dfrac{F}{w t_c} = \tau$

Specific Cutting Energy

Decomposition

1. Shear Energy/unit volume (Us)
   (required for deformation in shear zone)

2. Friction Energy/unit volume (Uf)
   (expended as chip slides along rake face)

3. Chip curl energy/unit volume (Uc)
   (expended in curling the chip)

4. Kinetic Energy/unit volume (Um)
   (required to accelerate chip)

$$\mathbf{U_t = U_s + U_f + U_c + U_m}$$

Cutting Forces and Power measurement

Measuring Cutting Forces and Power

- Cutting forces can be measured using a **force transducer**, a **dynamomometer** 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 (provided mechanical efficiency of the tool can be determined)
- The *specific energy* (*u*) in cutting can be used to calculate cutting forces

Cutting Forces and Power

Power

- Prediction of forces is based largely on experimental data (right)
- Wide ranges of values is due to differences in material strengths
- Sharpness of the tool tip also influences forces and power
- Duller tools require higher forces and 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	Specific energy $W \cdot s/mm^3$
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