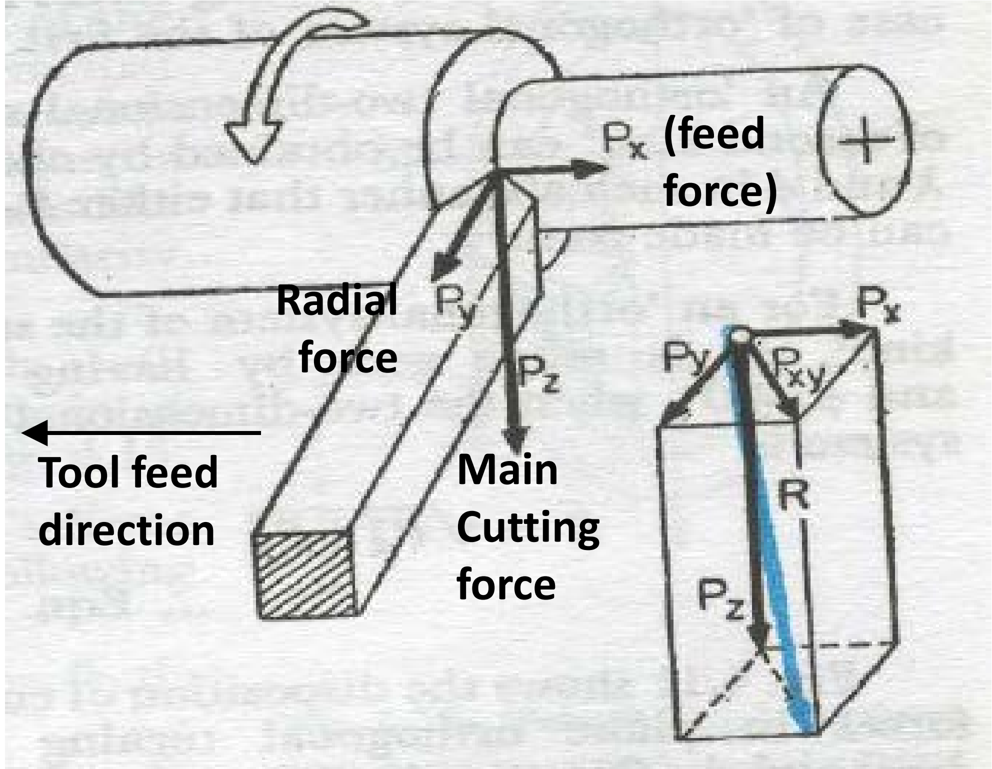
Lecture-02

Fundamentals of metal cutting

MECHANICS OF METAL CUTTING



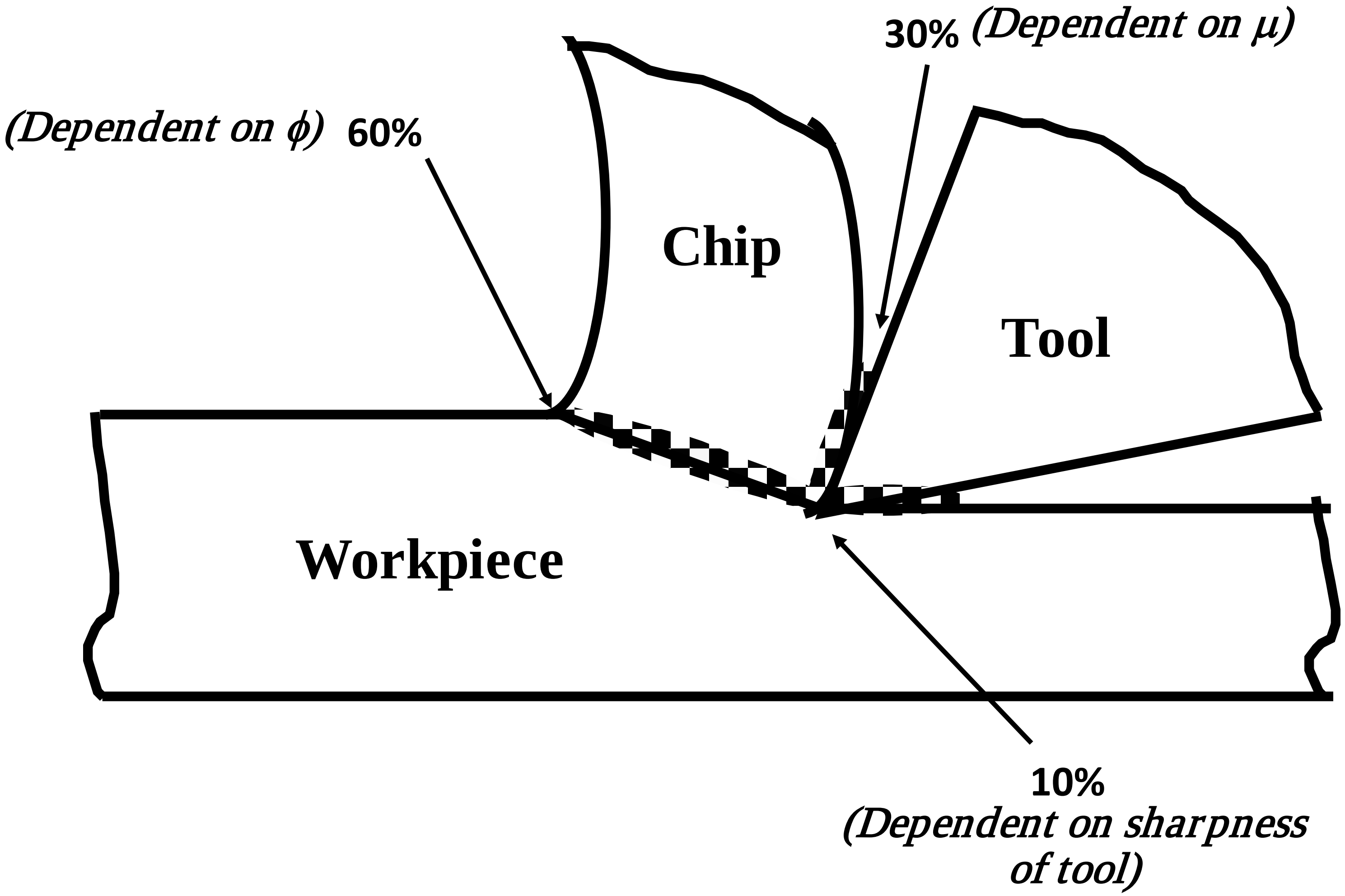
Topics to be covered

- ☐ **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??

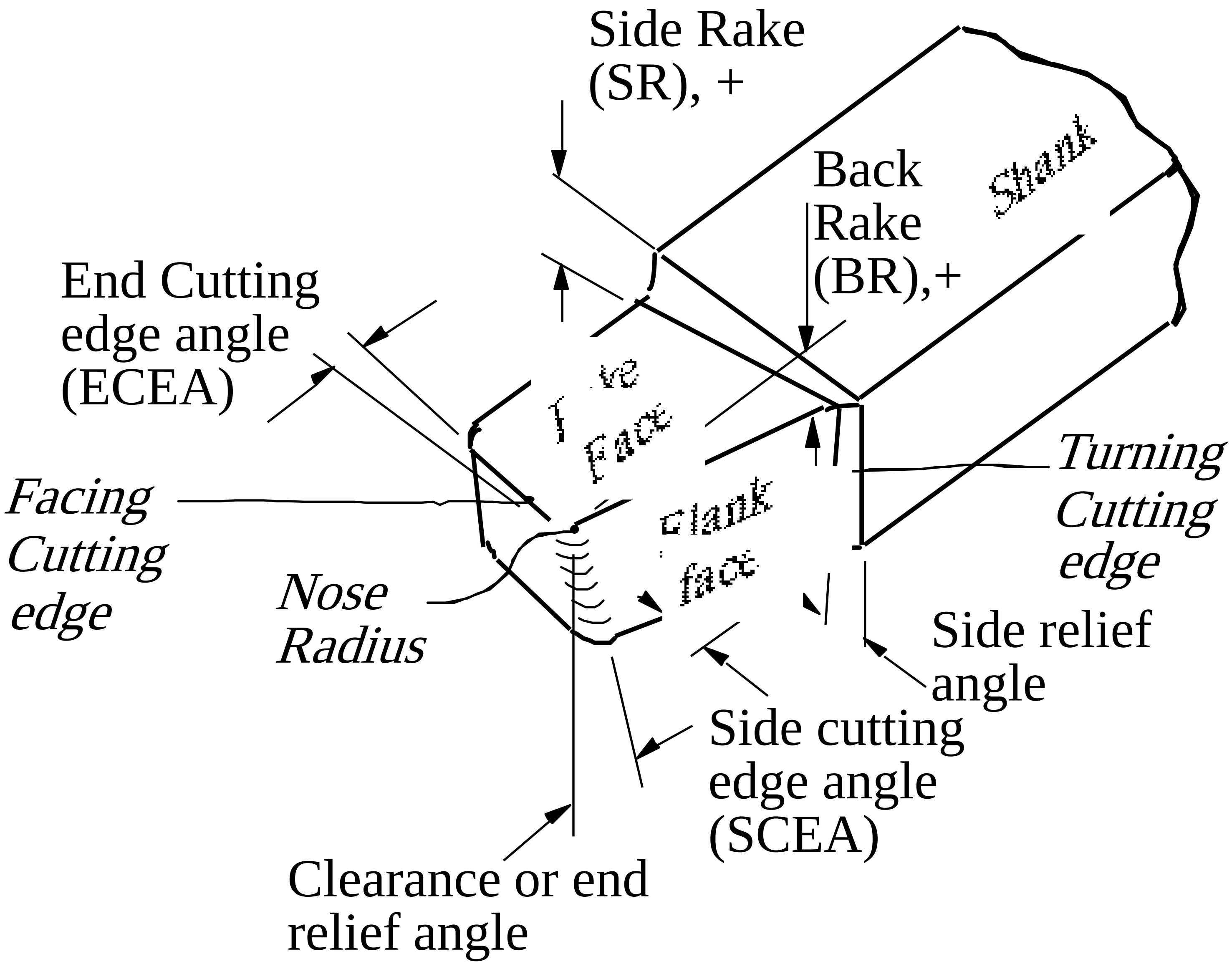
- We need to determine the cutting forces in turning for Estimation of cutting power consumption, which also enables selection of the power source (e.g. motors) during design of the machine tools.
- Structural design of the machine – fixture – tool system.
- Evaluation of role of the various machining 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

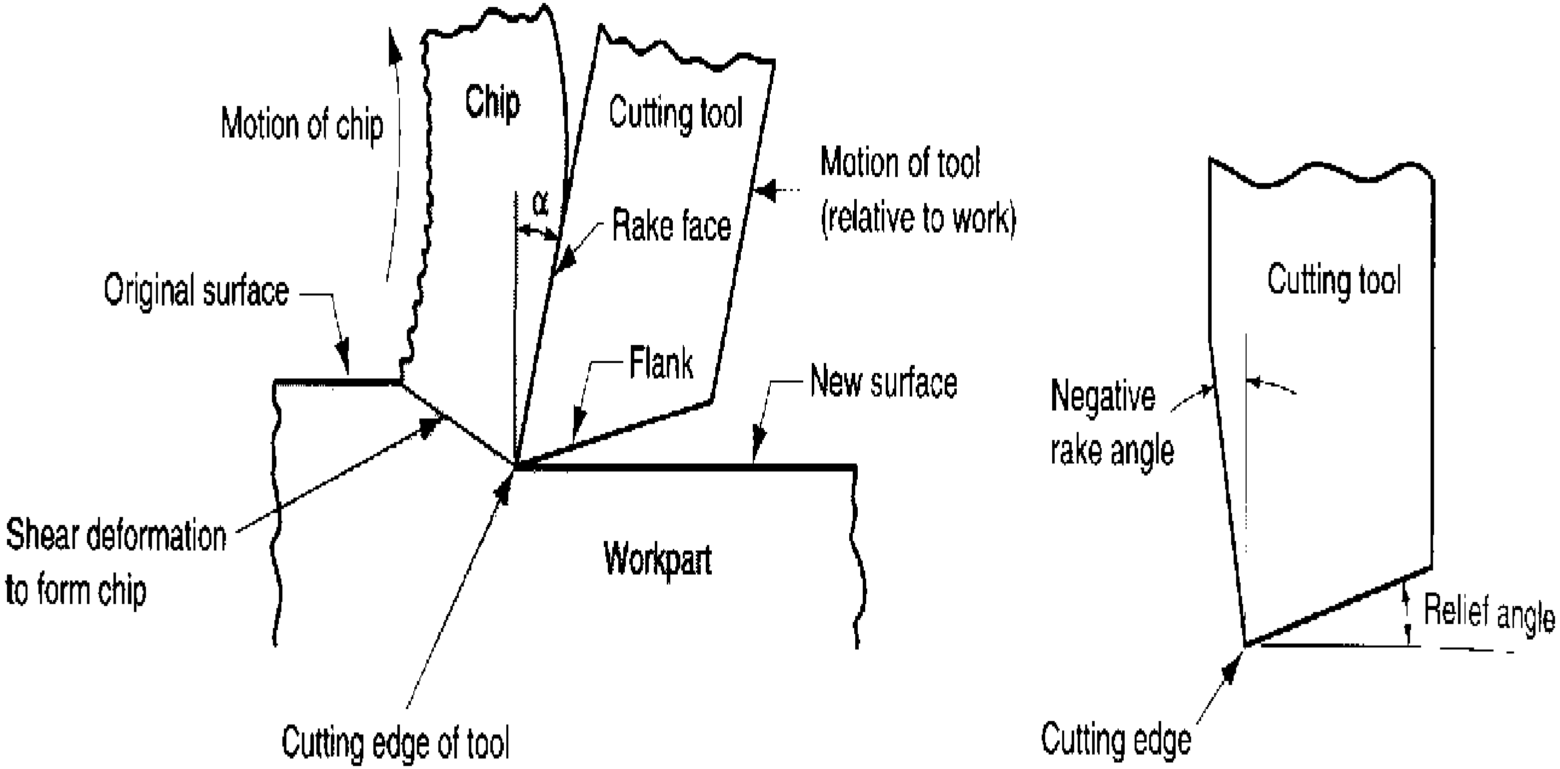


https://www.youtube.com/watch?v=8EsAxOnzEms
https://www.youtube.com/watch?v=bUrp8JMRwx4

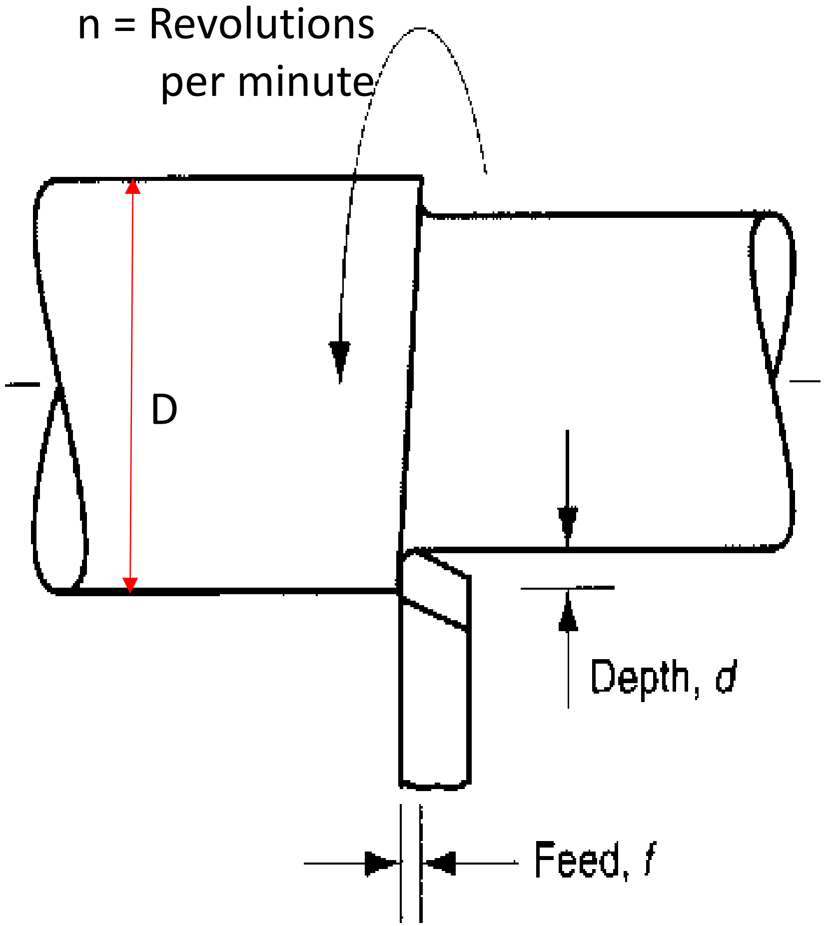
Tool Terminology



Cutting Geometry



Cutting Geometry



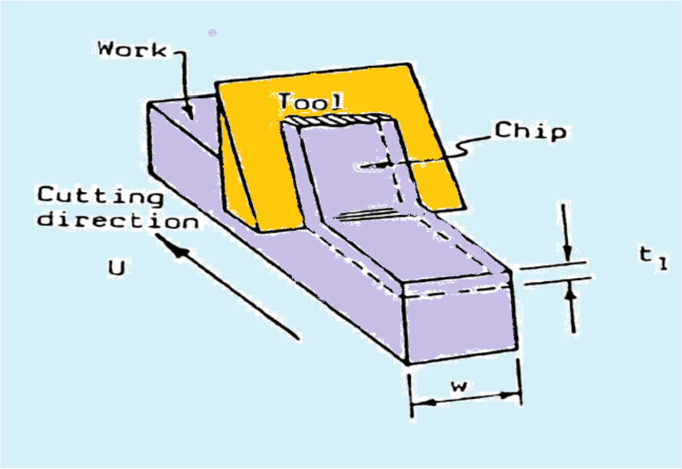
$$MRR = vfd$$

$$V = \pi D n$$

METAL CUTTING

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

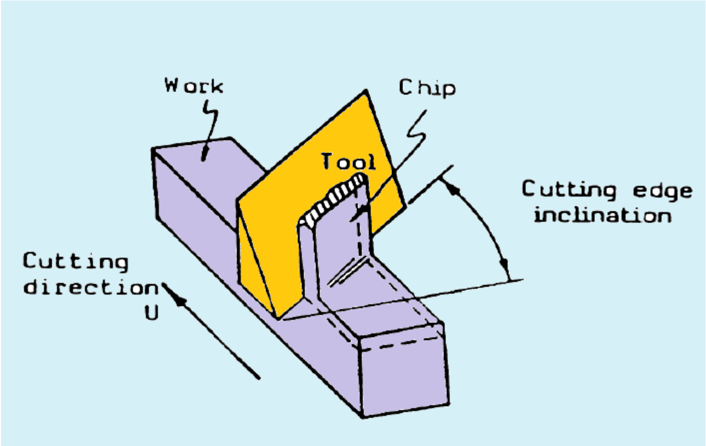
ORTHOGONAL CUTTING



- **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.**

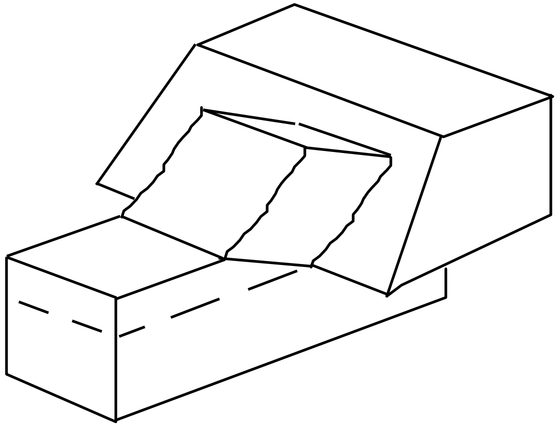
OBLIQUE CUTTING



- **Cutting Edge is inclined at an acute angle to tool feed.**
- **Here 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.**

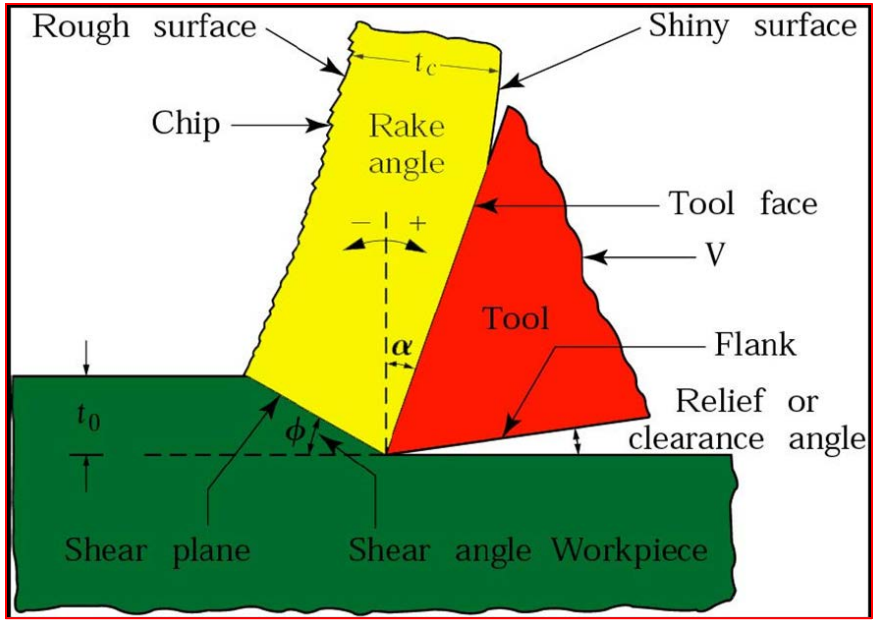
Assumptions

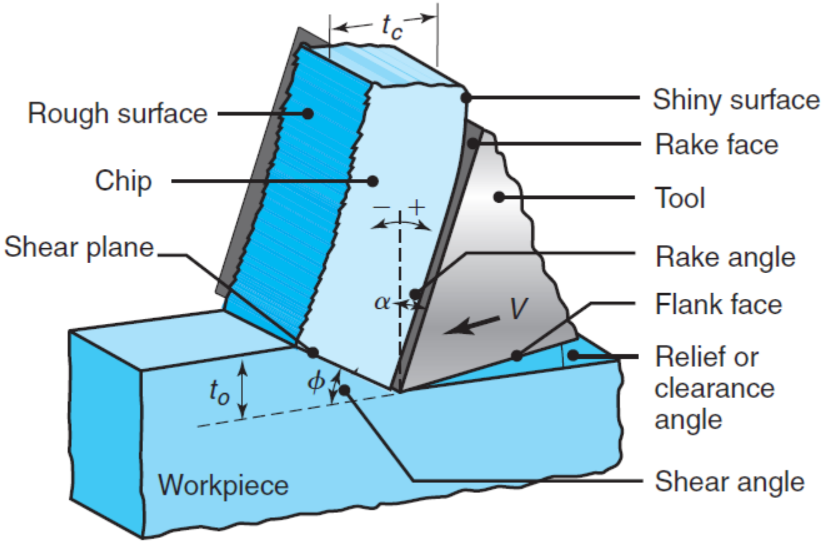
(Orthogonal Cutting Model)



- 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 to velocity between work and tool
- Continuous chip, no built-up-edge (BUE)

TERMINOLOGY



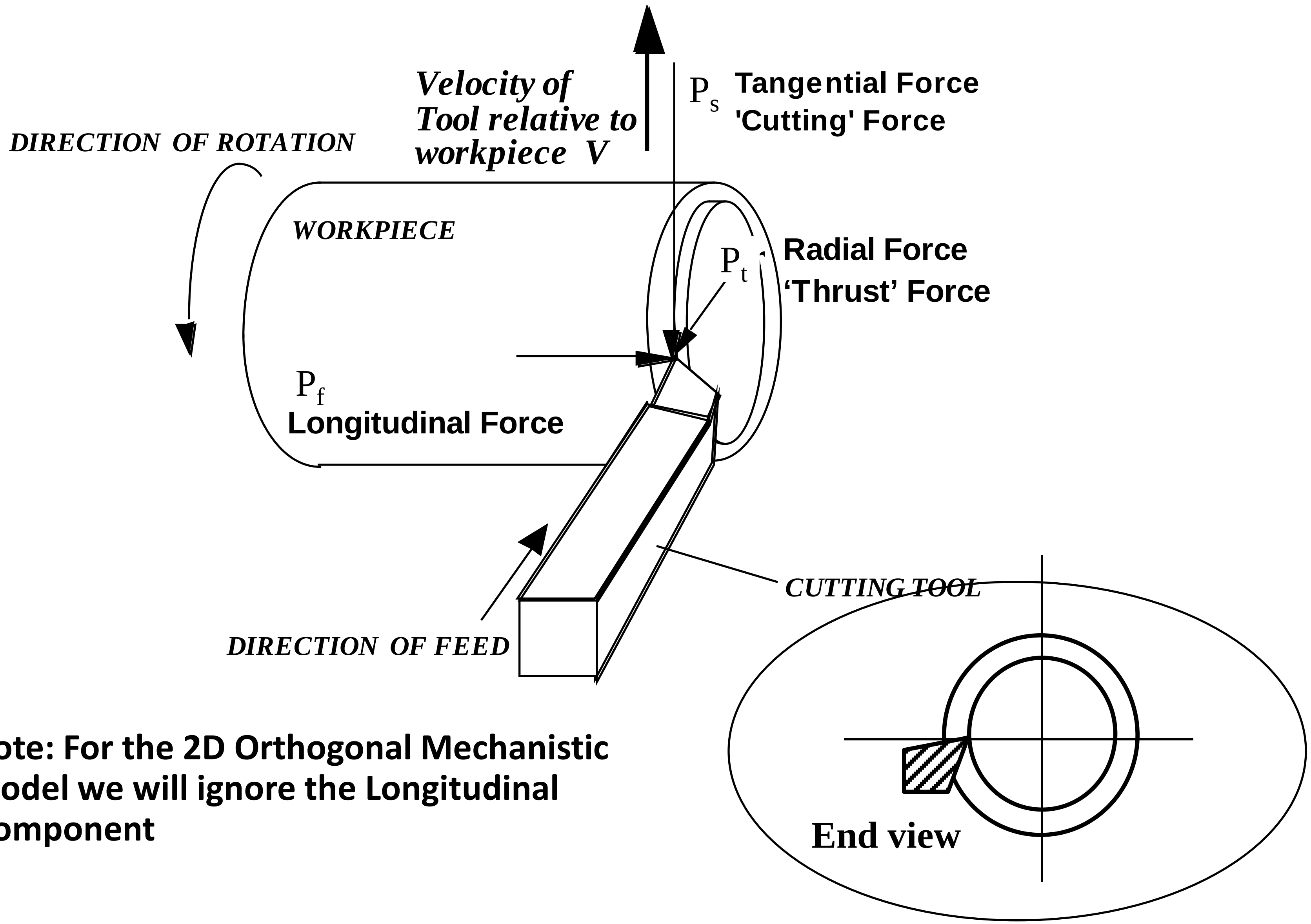


(a)

TERMINOLOGY

- α : Rake angle
- β : Frictional angle
- ϕ : Shear angle
- P_s: Cutting Force
- P_t : Thrust Force
- F_s: Shear Force
- F_n: Normal Shear Force
- F: Frictional Force
- N: Normal Frictional Force
- V: Cutting velocity
- V_c: Chip velocity
- V_s: Shear velocity

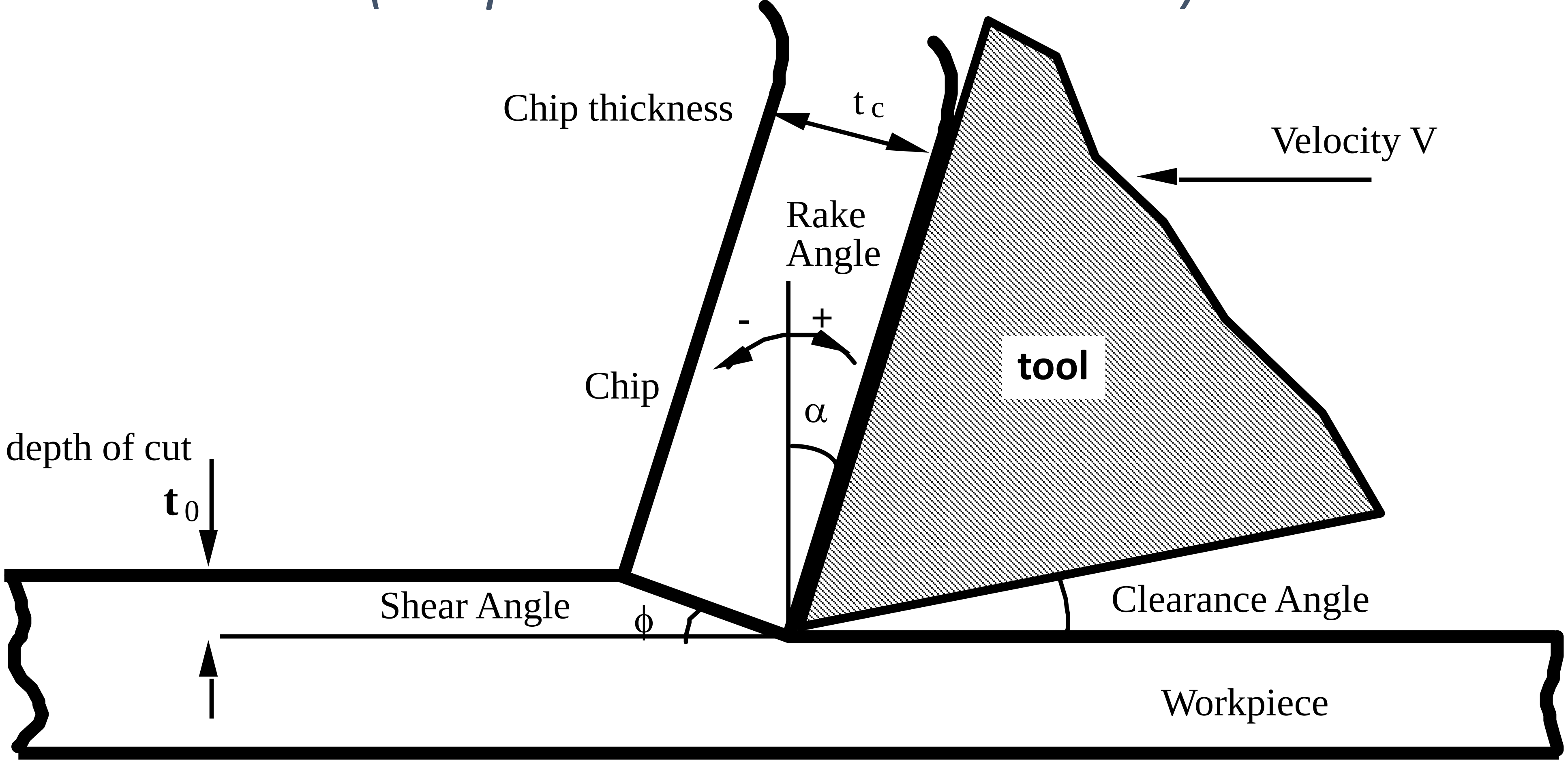
Forces For Orthogonal Model



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

Orthogonal Cutting Model

(Simple 2D mechanistic model)

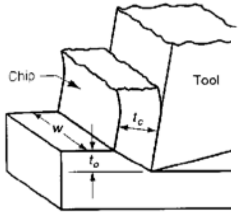


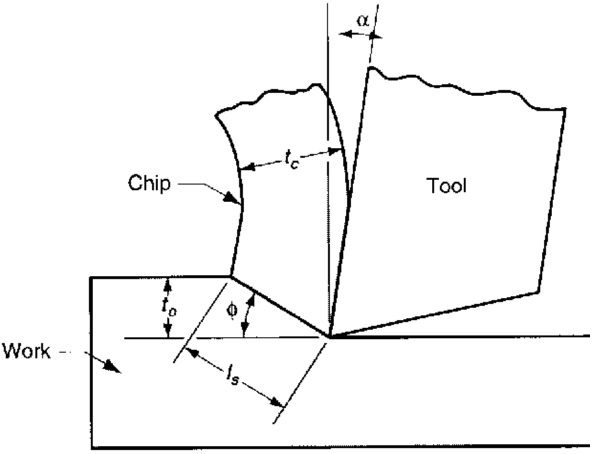
Mechanism: Chips produced by the shearing process along the shear plane

Orthogonal Cutting

Cutting Ratio

(or chip thickness ratio)

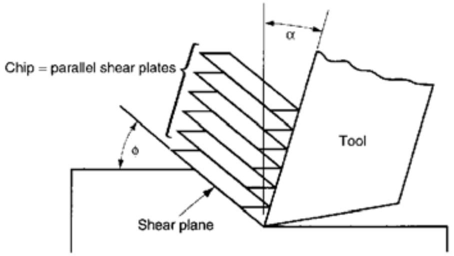


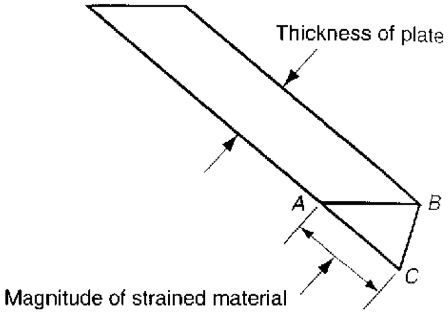


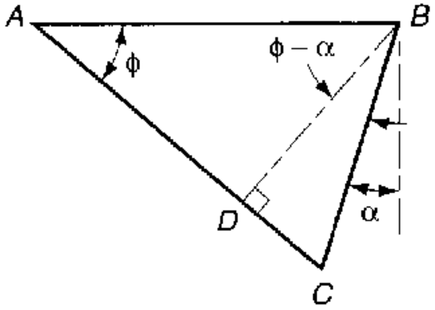
$$r = \frac{t_o}{t_c} = \frac{l_s \sin\phi}{l_s \cos(\phi - \alpha)}$$

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

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

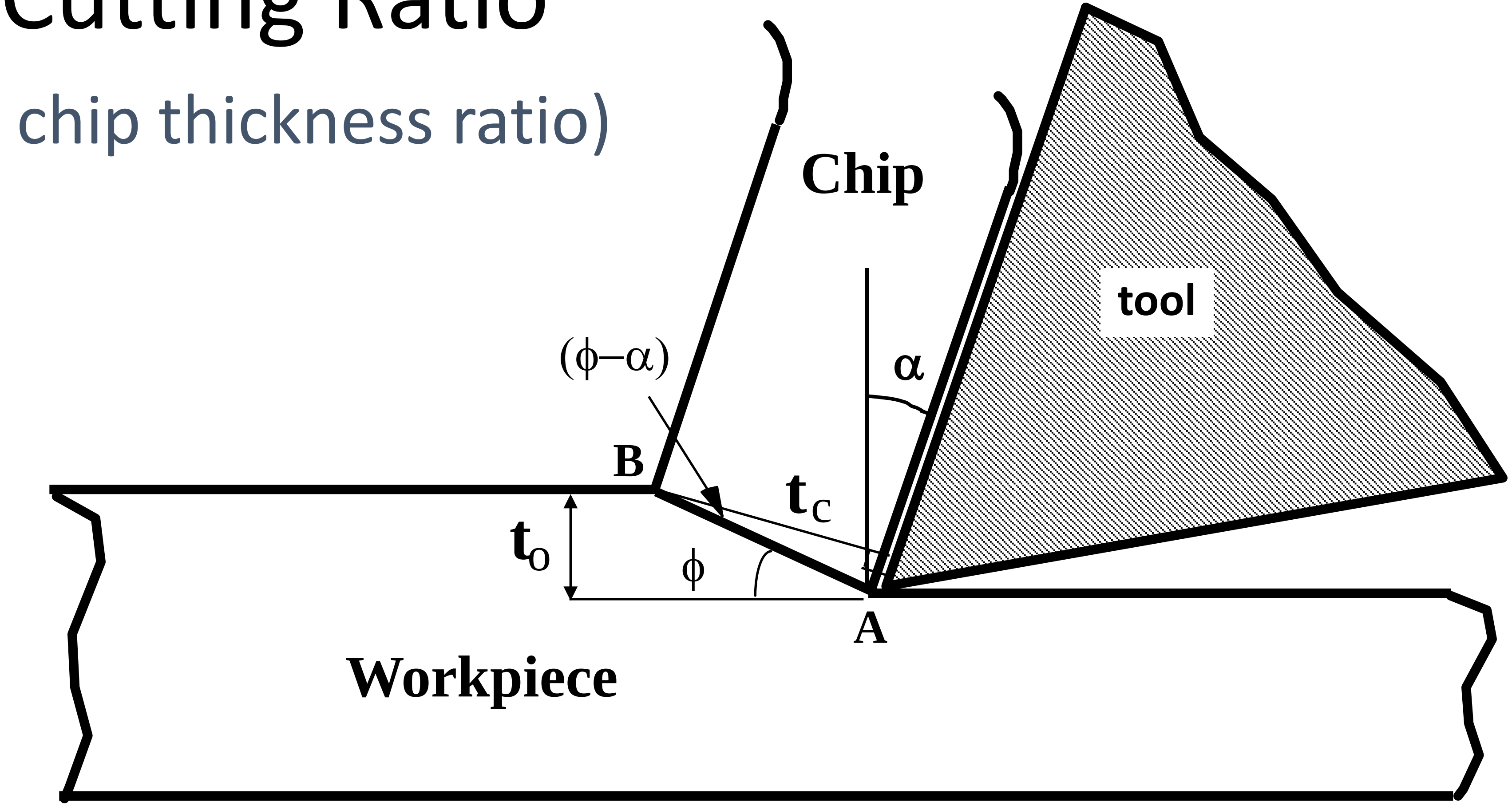






Cutting Ratio

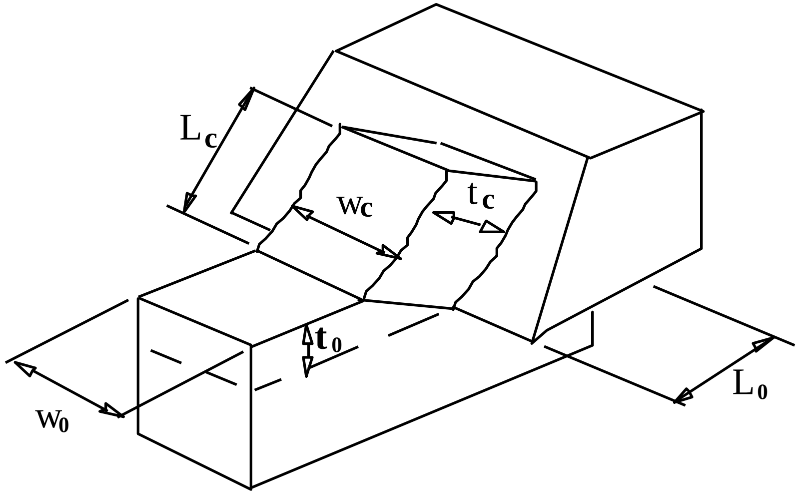
(or chip thickness ratio)



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

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

Experimental Determination of Cutting Ratio

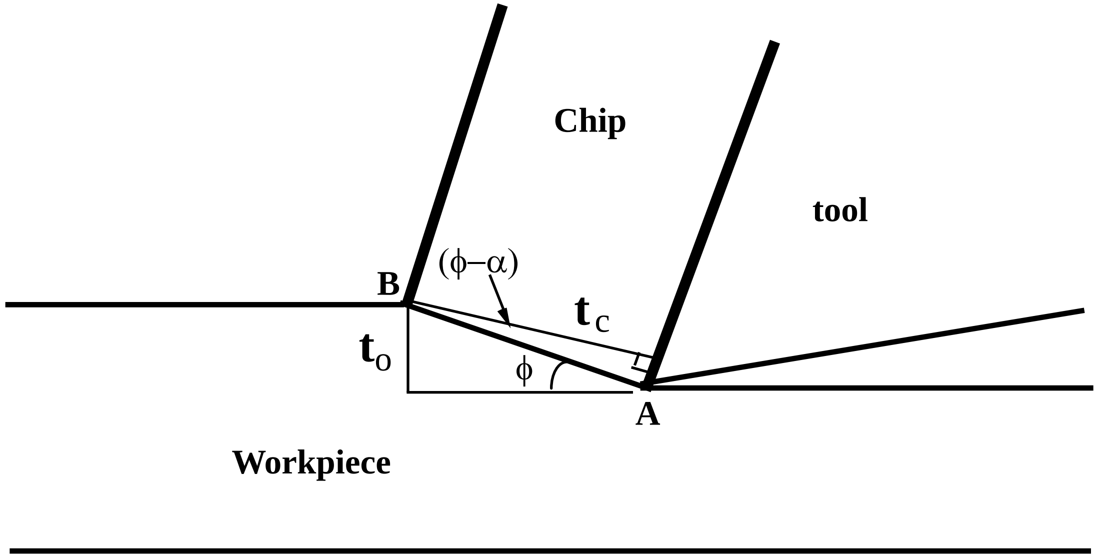


Shear angle ϕ may be obtained either from photo-micrographs or assume volume continuity (no chip density change):

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

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

Shear Plane Length and Angle ϕ



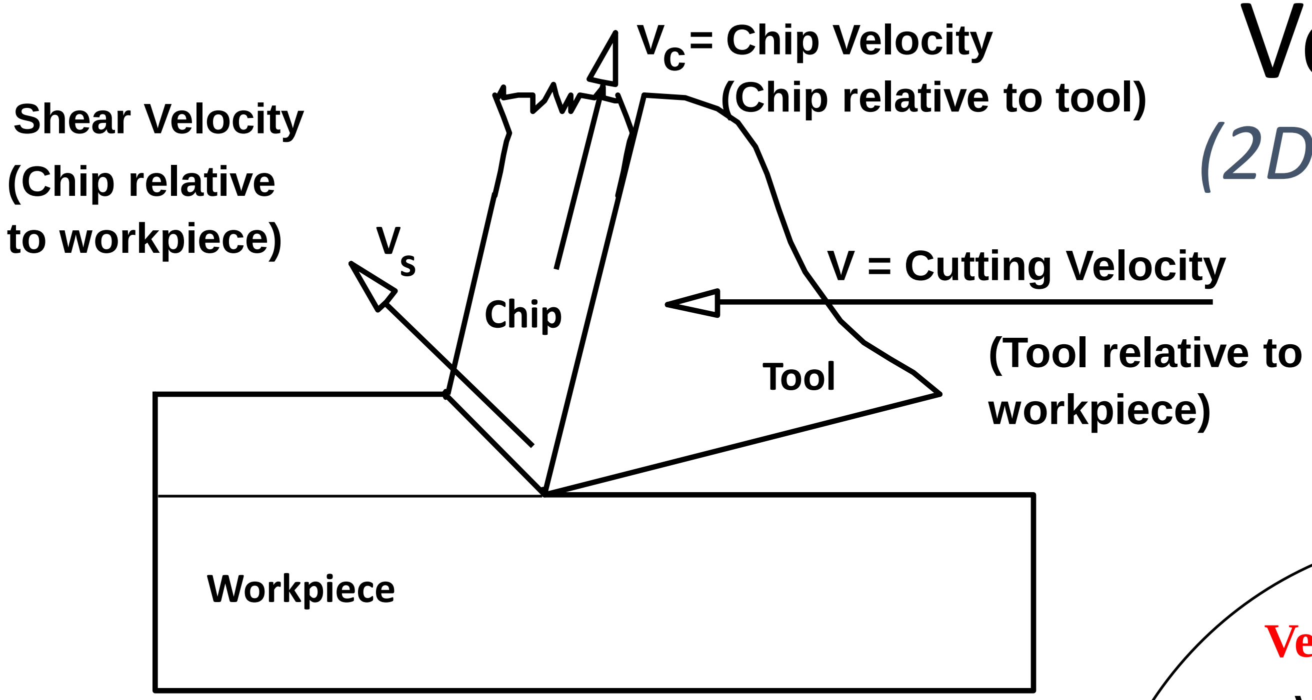
Shear plane length AB = $\dfrac{t_0}{\sin\phi}$

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)

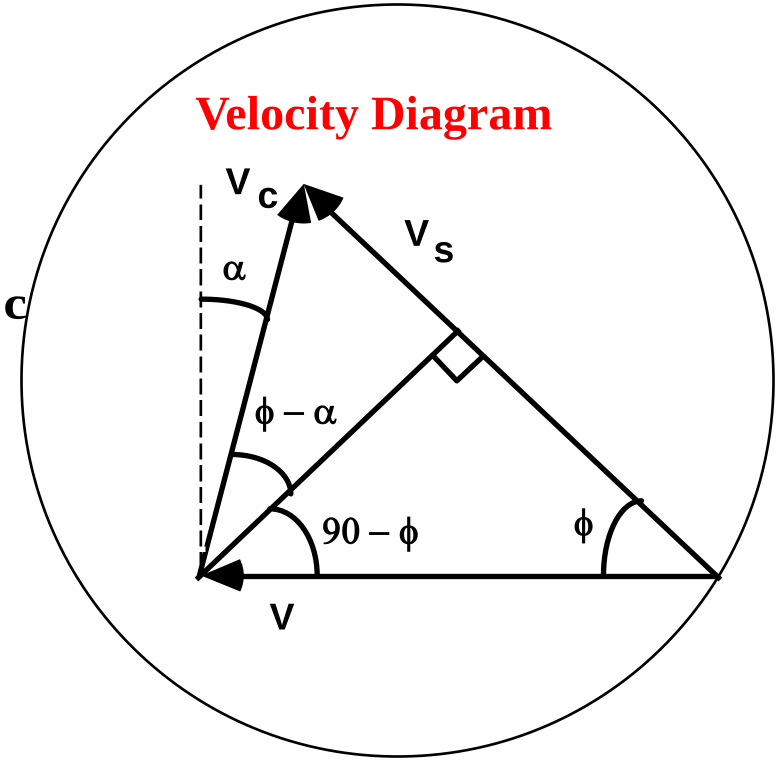


From mass continuity: $Vt_o = V_c t_c$

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

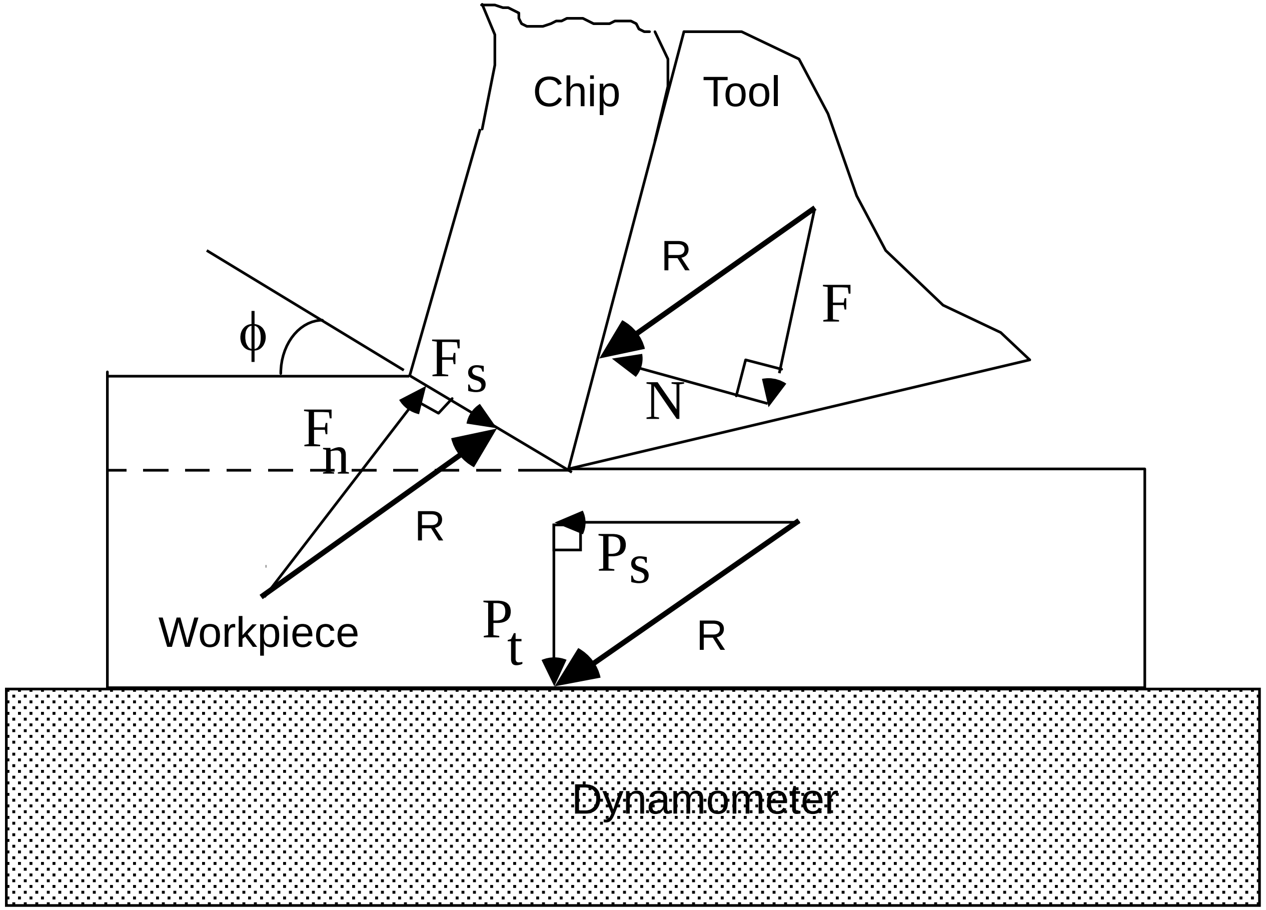
From the Velocity diagram:

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



Cutting Forces

(2D Orthogonal Cutting)



Free Body Diagram

Cutting Forces

(2D Orthogonal Cutting)

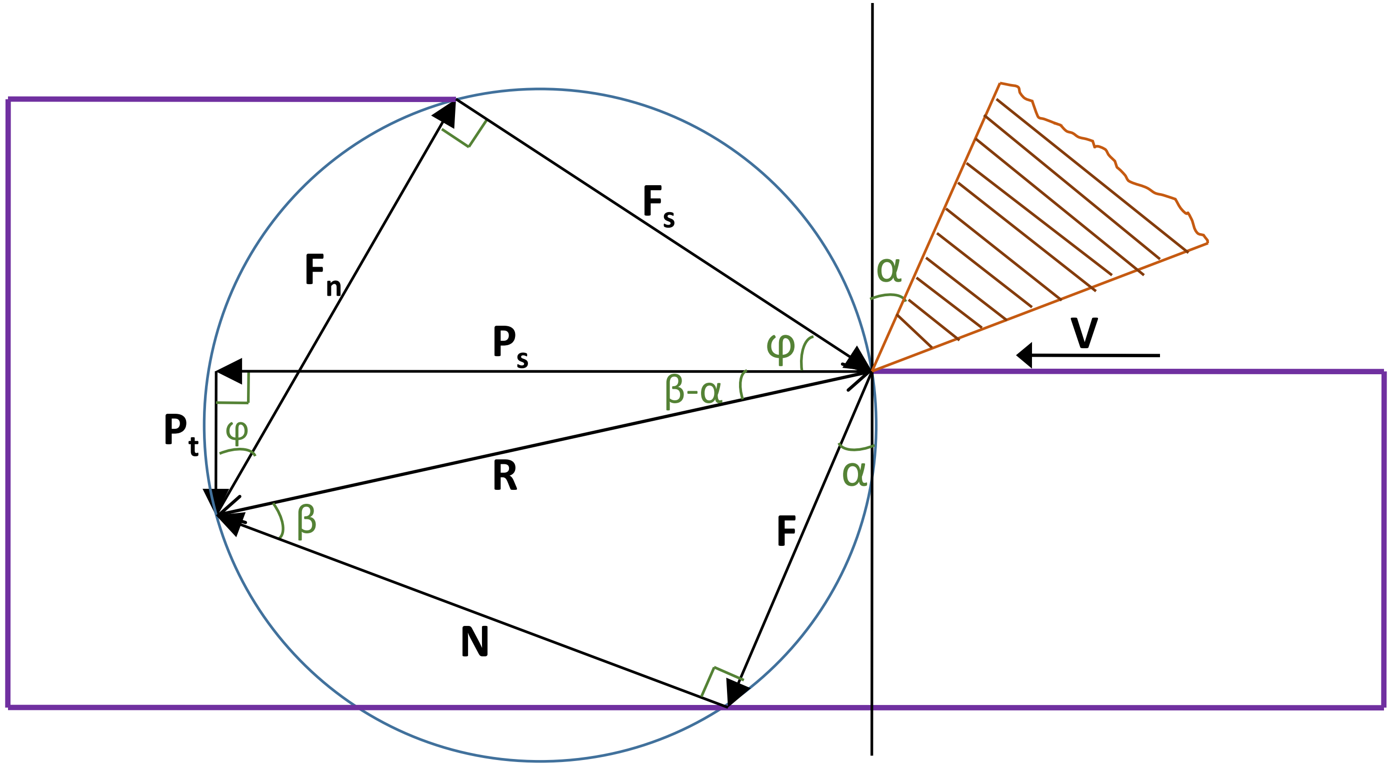
- **F_s , Resistance to shear of the metal in forming the chip. It acts along the shear plane.**

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

- **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.**

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

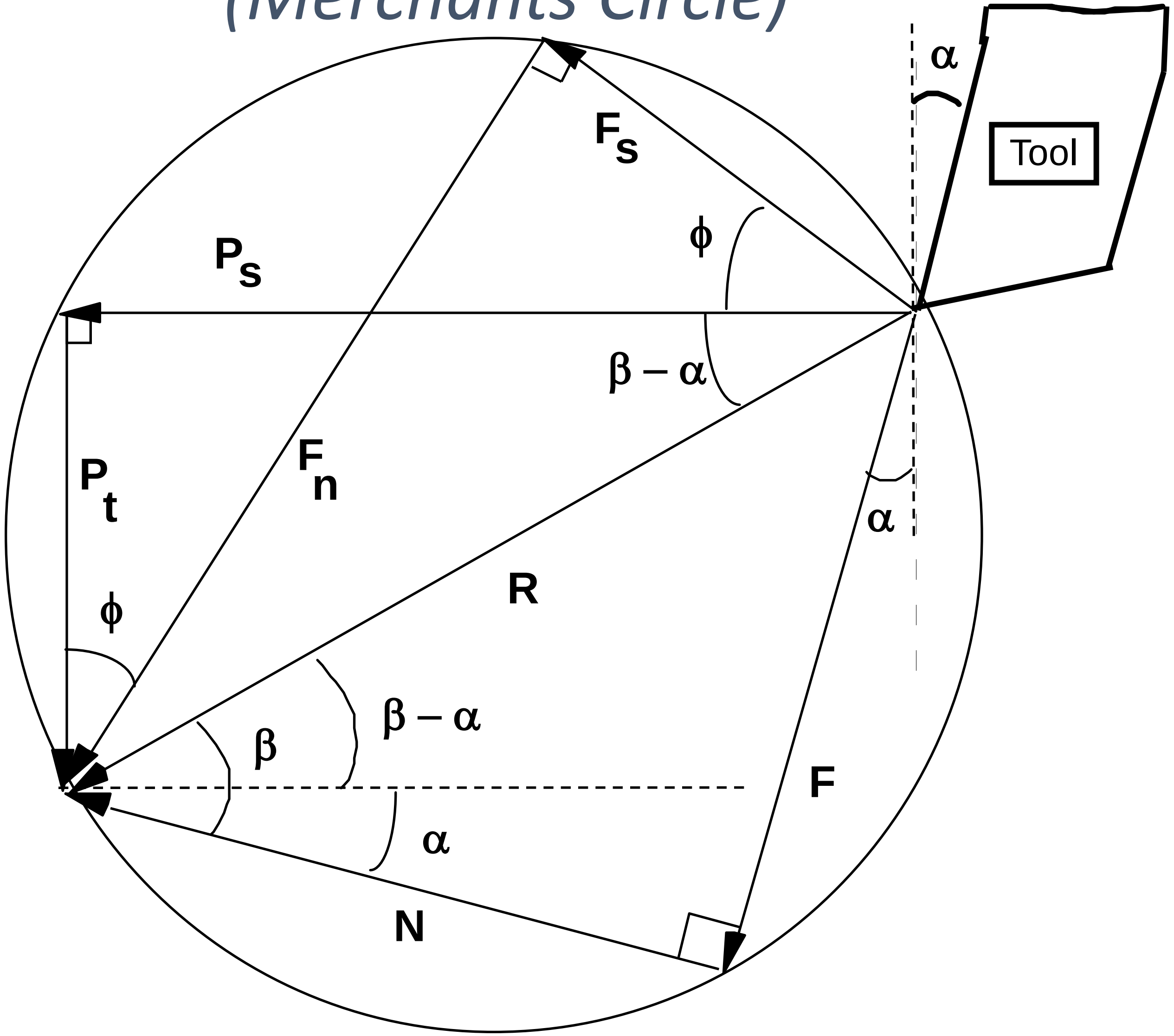
CONSTRUCTION OF MERCHANT'S CIRCLE



Knowing P_s, P_f, α and ϕ, all other component forces can be calculated.

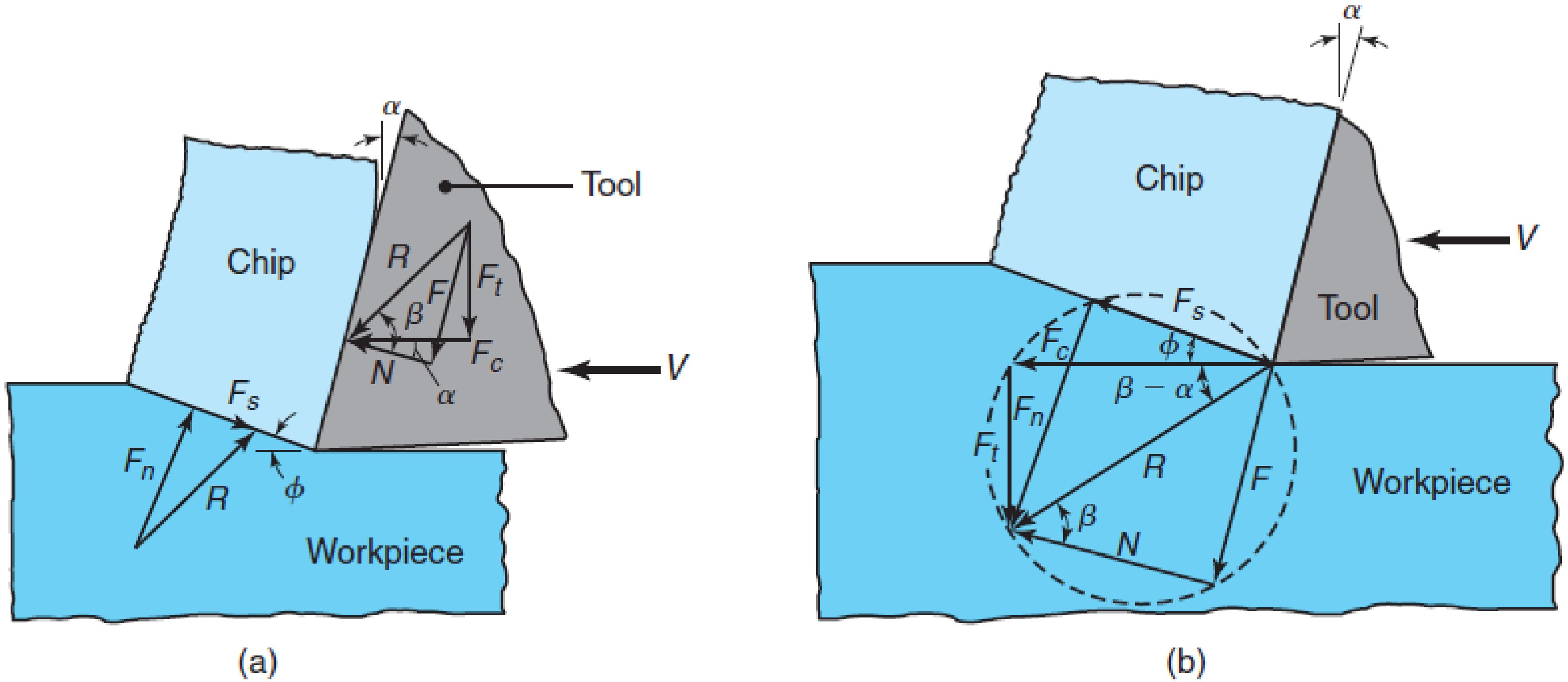
Force Circle Diagram

(Merchants Circle)



Force Circle Diagram

(Merchants Circle)



Cutting Forces

- Forces considered in orthogonal cutting include
  - Cutting, friction (tool face), and shear forces
- **Cutting force**, P_s acts in the direction of the cutting speed V, and supplies the energy required for cutting
  - Ratio of P_s to cross-sectional area being cut (i.e. product of width and depth of cut, t_0) is called: *specific cutting force*
- **Thrust force**, P_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 $\perp$ 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,

$$F_s = P_s\cos\phi - P_t\sin\phi$$

$$F_n = P_s\sin\phi + P_t\cos\phi$$

- The magnitude of **coefficient of friction, μ** is

$$\mu = \frac{F}{N} = \frac{P_t + P_s\tan\alpha}{P_s - P_t\tan\alpha}$$

Cutting Forces

- The tool holder, work-holding devices, and machine tool must be stiff to support thrust force with minimal deflections
  - If P_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

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

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

Forces from *Merchant's* Circle

Friction Force $F = P_s \sin\alpha + P_t \cos\alpha$

Normal Force $N = P_s \cos\alpha - P_t \sin\alpha$

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

Shear Force $F_s = P_s \cos\phi - P_t \sin\phi$

Force Normal to Shear plane $F_n = P_s \sin\phi + P_t \cos\phi$

$$R = \sqrt{P_s^2 + P_t^2} = \sqrt{F_s^2 + F_n^2} = \sqrt{F^2 + N^2}$$

Stresses

On the Shear plane:

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

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

On the tool rake face:

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

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

Power

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

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

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

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

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

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

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

Material Removal Rate (MRR)

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

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

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

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

$$\text{MRR} = \text{Cutting velocity} \times \text{width of cut} \times \text{depth of cut}$$

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:

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

$$\mathbf{U_t = \frac{Cutting\ Power\ (P_c)}{Material\ \ Removal\ Rate\ (MRR)} = \frac{P_s V}{Vwt_o} = \frac{P_s}{wt_o}}$$

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

Specific Energy for shearing $\mathbf{U_s = \frac{F_s V_s}{Vwt_o}}$

Specific Energy for friction $\mathbf{U_f = \frac{FV_c}{Vwt_o} = \frac{Fr}{wt_o} = \frac{F}{wt_c} = \tau}$

Cutting Forces and Power measurement

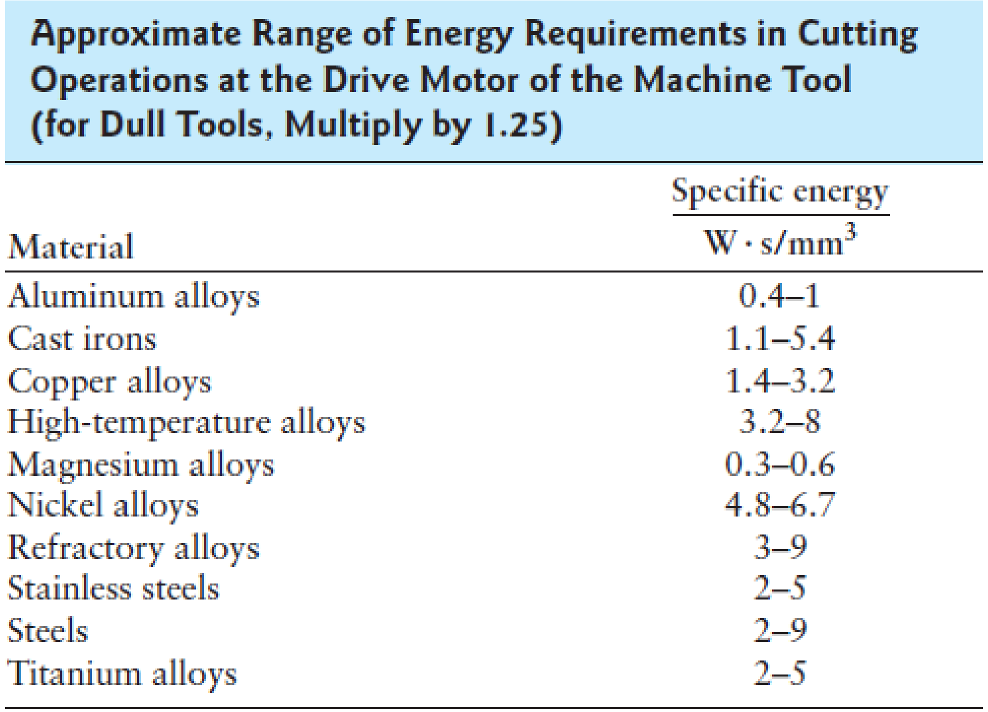
Measuring Cutting Forces and Power

- Cutting forces can be measured using a **force transducer**, a **dynamometer** 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