ME338 – Manufacturing Process II
Lecture 2 : Basic mechanics of Machining

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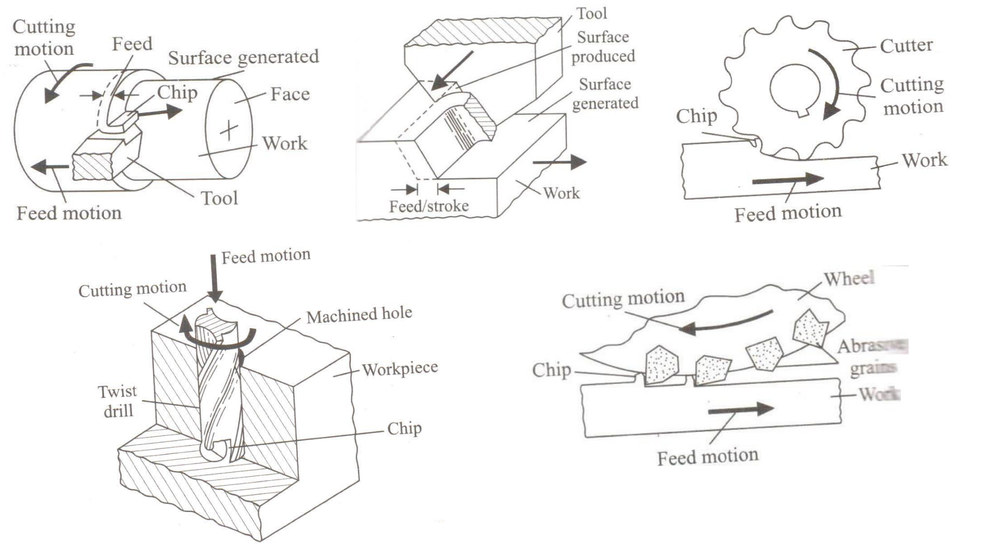
Machining process



Material removal is due to the 'shearing' caused by the harder sharp tool surface which is forced to move against a softer workpiece material

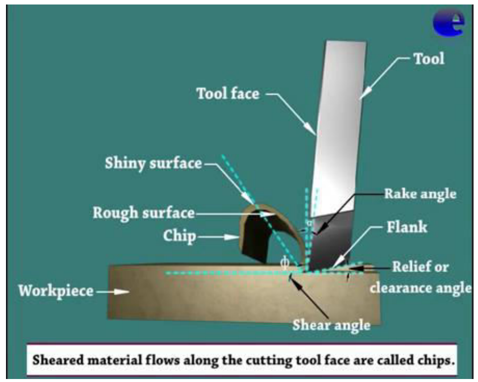
Machining Process:

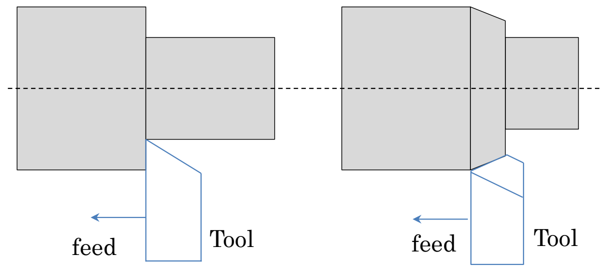
- Independent process variables
  - Feed, cutting speed, depth of cut
- Hardness of cutting tool
- Tool geometry/angles - rake/relief angle, nose radius
- Work holding devices (to reduce vibration)
- Cutting fluids, Lubricants (to take away heat, reduce friction)

Output variables:

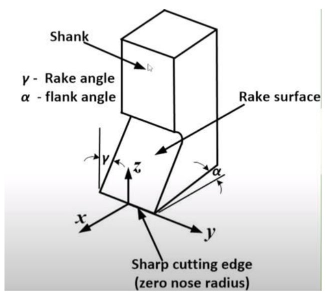
- Chip type: continuous, discontinuous
- Cutting forces and energy dissipation
- Temperature rise
- Tool wear
- Surface finish

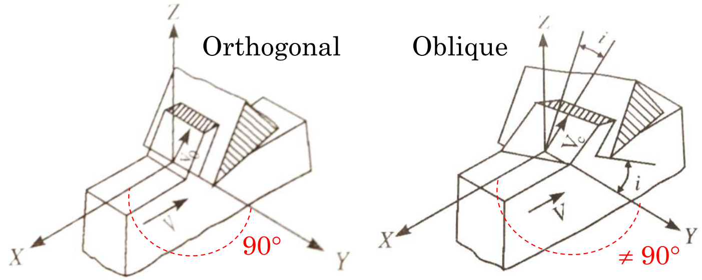
Orthogonal (2D) & Oblique (3D) machining





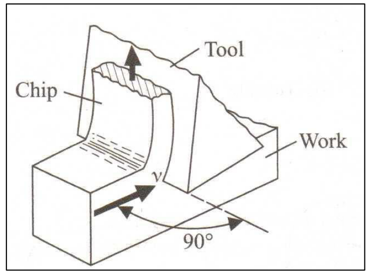
Orthogonal and Oblique machining

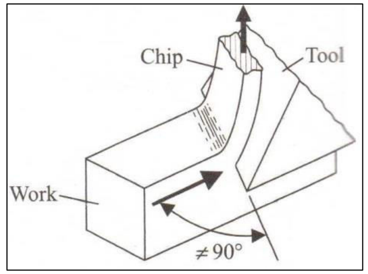




- Orthogonal cutting (2D):
  - Cutting edge of tool is perpendicular to the velocity vector
  - Forces act along X, Z axes only (Cutting force and thrust force)
- Oblique cutting (3D):
  - Cutting edge of tool is inclined at certain angle with the normal to the cutting velocity vector. Inclination angle ($i \neq 0$)
  - Chip also flows at angle i from the rake surface
  - Forces act along all three directions, X, Y, Z axes (cutting , thrust and feed forces)
  - Feed force : in direction of feed, Thrust force: direction perpendicular to the generated surface, Cutting force: along the cutting direction

Orthogonal and Oblique machining





Orthogonal machining (2D)

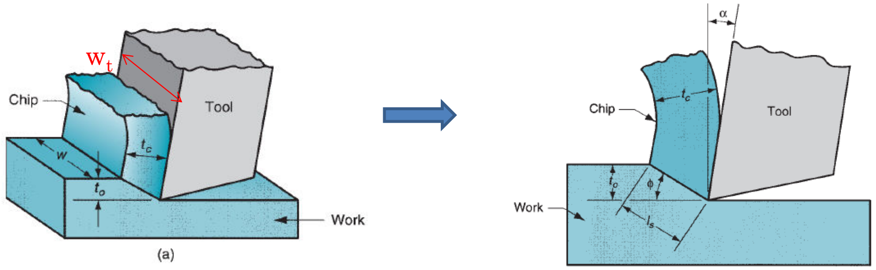
- Cutting edge ⊥ cutting velocity
- Shear force acts on smaller area
- All work/chip material move in parallel plane to rake surface
- Simple 2D analysis, still gives good results close to actual values

Oblique machining (3D)

- Cutting edge NOT ⊥ cutting velocity
- Shear force acts on larger area
- All work/chip material do not move in parallel plane, but at inclination angle
- Complex 3D analysis

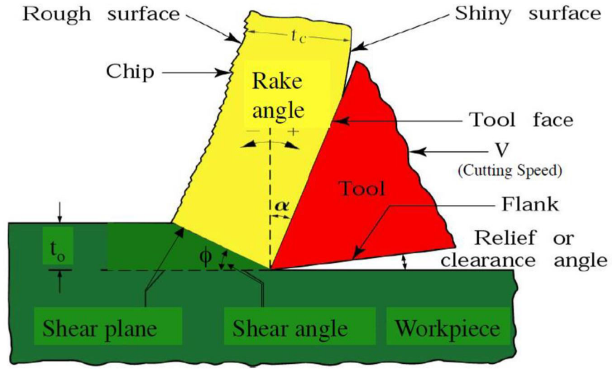
Orthogonal machining model is used for all the analysis purposes as its simple and gives close approximation to the actual results

Orthogonal cutting : from 3D to 2D problem



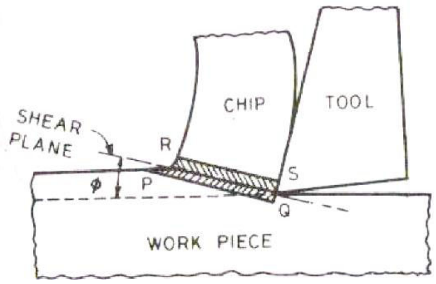
- Width of cutting tool (w_t) > width of chip (w)
  - Turning of hollow thin cylinder, where cutting tool exceed the thickness of the hollow cylinder can be considered as Orthogonal case
- Width of chip (w) >> t_0 (more than 10 times)
- The chip does not flow to either side (plane strain condition)
- The tool is perfectly sharp and does Machining. No 'plaughing' action
- Friction along the tool-workpiece, chip-rake surface is less

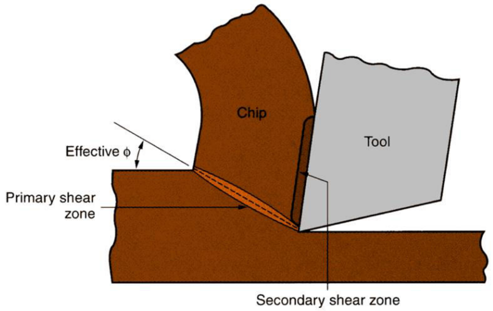
Orthogonal cutting



- The surface on which chip flows is called rake surface
- Inclination of tool rake surface from the normal to the cutting velocity is rake angle: Can be both positive and negative
- As the tool is forced into the material, the chip is formed by shear deformation along a plane called the shear plane
- The shear plane is oriented at an angle ϕ with the surface of the work
- Shear angle is decided by the material itself (to minimize the cutting energy)

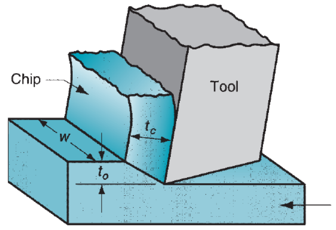
Orthogonal Machining - Basic mechanics

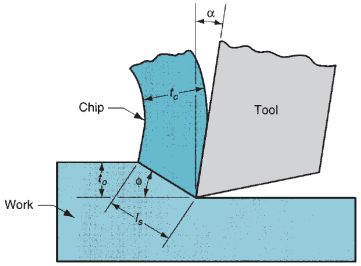




- Metal cutting involves concentrated shear along a shear plane
  - Cutting is due to shearing action (Mallock, 1881)
  - Shearing start at PQ and finish at RS, giving it a wedge shape, (reason for chip curling)
- Actual shear zone is wedges shaped, but a single shear plane is assumed for simple calculation
- Material does not deform until the shear plane is reached
  - Primary shear zone
  - Secondary shear zone

Basic terms in machining process





Shear plane length l_s

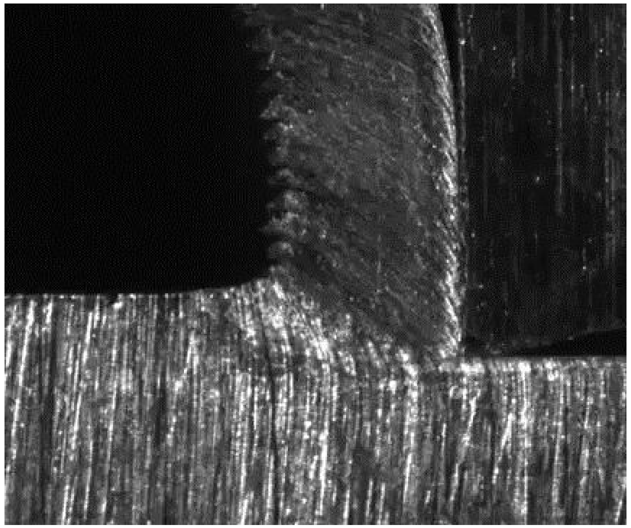
$$\frac{t_0}{l_s} = Sin\phi$$

$$\frac{t_c}{l_s} = Sin((90-(\phi-\alpha))$$

$$r = \frac{t_0}{t_c} = \frac{Sin\phi}{Cos(\phi-\alpha)}$$

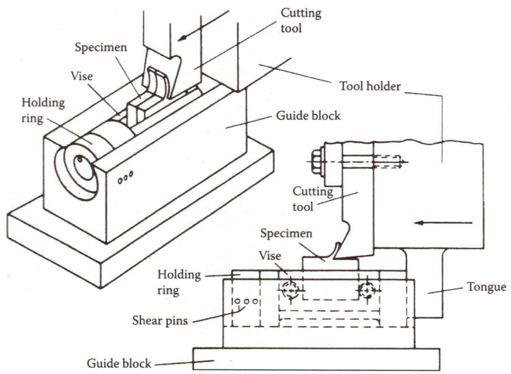
- Undeformed chip thickness (~depth of cut)
- Chip thickness increases after the shearing process
- Cutting ratio (r) OR chip thickness ratio or chip ratio
- Chip ratio (r) = chip thickness before cutting (t_0)/chip thickness after cutting (t_c): $r = Sin\,\phi / Cos\,(\phi - \alpha)$
- Relationship: rake angle (α), shear angle (ϕ) and chip thickness ratio (r) : $\tan\phi = r\,Cos\,\alpha\,/\,(1 - r\,Sin\,\alpha)$
- Chip reduction coefficient : Inverse of chip thickness ratio (r)

Machining video



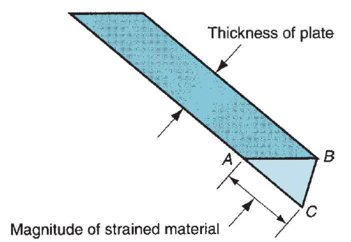
Measurement of shear angle (ϕ)

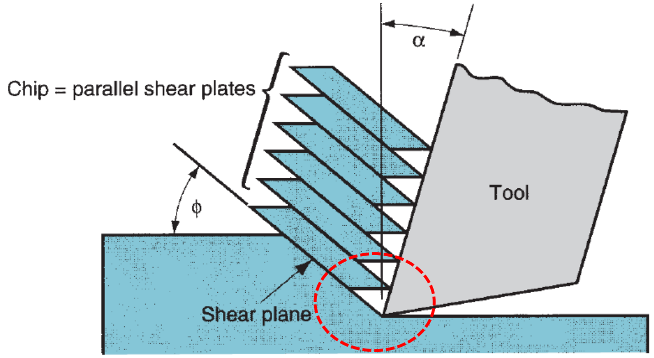
- How to measure shear angle (ϕ) ?
- Quick stopping device – suddenly stop the cutting action, e.g.:
  - Cutting speed 0.8 m/s,
  - Stopping time 0.17 ms
- Microscopic examination of chip thickness
- Uncut chip thickness or depth of cu
- Chip thickness ratio can be calculated
- Rake angle (α) is a cutting tool parameter – known value
- Shear angle (ϕ) can be calculated by following relationship
- $\tan\phi = r\,Cos\,\alpha\,/\,(1 - r\,Sin\,\alpha)$



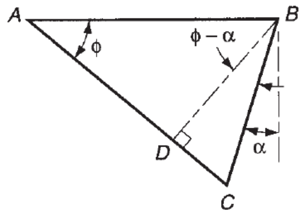
Quick-stopping device

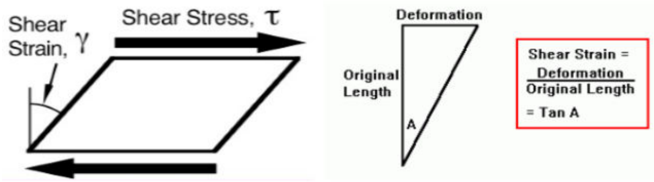
Piispanen's Stack of card model : shear strain



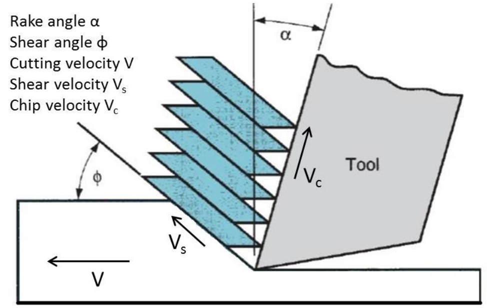


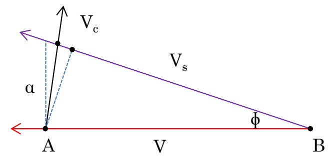
- Shear strain (γ) = AC/BD = (AD+DC)/BD
- Shear strain (γ) = Cot ϕ + tan (ϕ-α)
- Typical value of shear strain vary 2 – 5





Kinematics of orthogonal machining





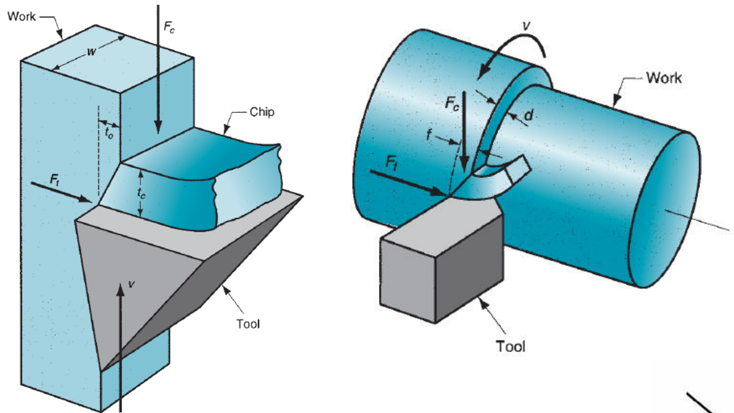
$$\frac{V}{\cos(\phi-\alpha)} = \frac{V_s}{\cos\alpha} = \frac{V_c}{\sin\phi}$$

- V cutting velocity, Vs shear velocity along shear plane, Vc chip velocity along the rake surface
- In orthogonal cutting, width of chip assumed to remained same
- Using material conservation law, Chip thickness ratio r can be calculated
- Chip thickness ratio r = V_c/V = Sin ϕ / Cos (ϕ-α)
- Shear strain rate (γ') = V_S/d; where d is shear plane thickness (0.001 – 0.01 mm)

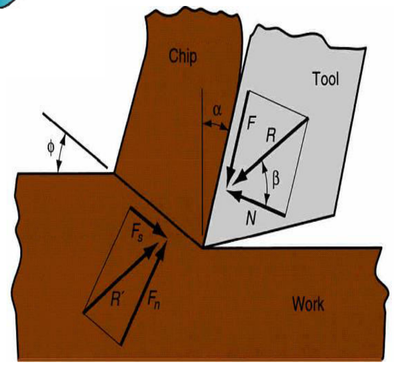
Kinematics of orthogonal machining

- Deformation in cutting generally takes place within a very narrow deformation zone
  - Thickness of shear plane is in order of 0.001 – 0.01 mm.
  - Therefore, the rate at which shearing takes place (shear rate) is high.
  - Shear strain rate (γ') = V_S/d; where d is shear plane thickness (0.001 – 0.01 mm). Typical shear strain rates, $\gamma = 10^4 \sim 10^6 s^{-1}$
  - Large shear strains are associated with low shear angles, or low or negative rake angles.
- Shear angle influences force and power requirements, chip thickness, and temperature.
- As the rake angle decreases and / or the friction at the tool – chip interface increases, the shear angle decreases and the chip becomes thicker,
- Thicker chips mean more energy dissipation because the shear strain is higher
- Because work done during cutting is converted into heat, temperature rise is also higher.

Cutting forces in shaping & Turning



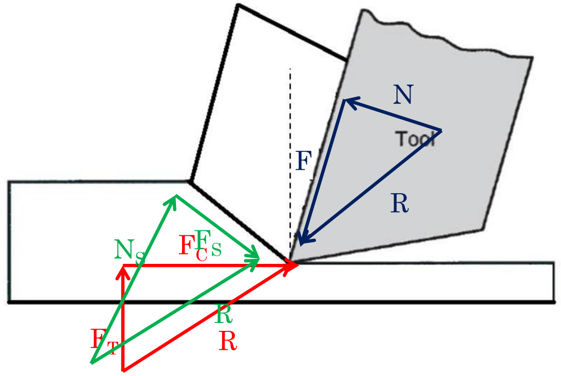
Cutting force (F_c) in direction of cutting direction,
Thurst force (F_t) direction perpendicular to the generated surface
Fc and Ft are perpendicular to each other



Forces in cutting motion: relationship

- Eugene Merchant has established relationship between different forces
- Assumptions:
  - Orthogonal cutting
  - Width of cut >> depth of cut
  - Cutting velocity remains constant
  - Cutting edge of tool is really sharp (no tool wear, point contact)
  - No sideways flow of chip
  - No BUE, No discontinuous chip
  - Chip behaves like free body in stable equilibrium, opposite and equal forces

Forces in cutting motion



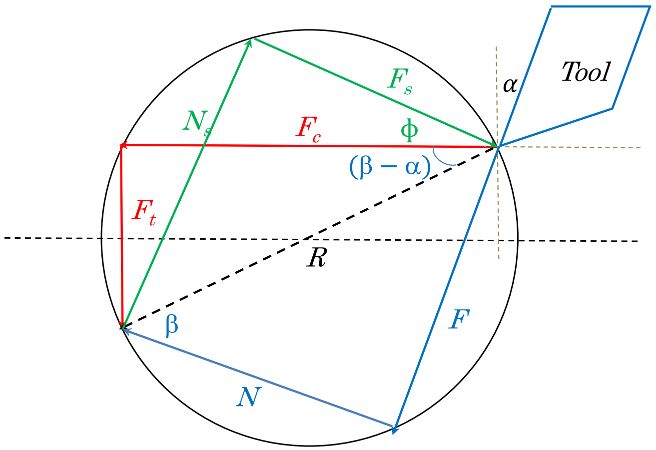
F_C, F_T can be measured during machining by dynamometer

F_C Horizontal cutting force by tool on the work piece (along cutting direction)
F_T Vertical thrust force which help in holding tool in position, acts on the tool nose (normal to cutting direction)

F Friction resistance of the tool against the chip flow (opposite to chip flow)
N Normal to the chip force provided by tool (normal to chip flow direction)

F_S Shear force acts along shear plane, resistance to shear of the metal in forming the chip
N_S Normal force, backing up force on chip by workpiece (normal to shear plane)

How to draw Merchant Circle



$$F_s = R\,Cos(\phi + \beta - \alpha)$$
$$F_c = R\,Cos(\beta - \alpha)$$
$$F = R\,Sin\,\beta$$

$$F_c = \frac{F_s\,Cos(\beta - \alpha)}{Cos(\phi + \beta - \alpha)}$$
$$F_s = \frac{F_c\,Cos(\phi + \beta - \alpha)}{Cos(\beta - \alpha)}$$

$$F_s = \tau A_s = \tau \frac{w t_0}{Sin\phi}$$

Forces in cutting motion: relationship

<u>Shear plane decomposition of resultant force</u>:

$$F_s = F_c \cos\phi - F_t \sin\phi$$
$$N_s = F_t \cos\phi + F_c \sin\phi = F_s \tan(\phi + \beta - \alpha)$$

<u>Tool-chip interface decomposition of resultant force</u>:

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

<u>Tool-chip interface mean friction</u>:

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

How to calculate F_C, F_T Theoretically : Merchant?

Shear plane stresses:

$$\tau = \frac{F_s}{A_s} \rightarrow F_s = \tau A_s$$

$$A_s = \frac{w t_0}{\sin\phi}$$

Material has shear strength τ (known)
Width w, depth of cut t_0 – known
Rake ankle α – tool parameter known
Deformed chip thickness can be measured
Shear angle ϕ can be calculated
B friction angle

Forces:

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

$$F_c = R\cos(\beta - \alpha)$$

$$\boxed{\begin{aligned} F_c &= \frac{\tau w t_0 \cos(\beta - \alpha)}{\sin\phi \cos(\phi + \beta - \alpha)} \\ F_t &= \frac{\tau w t_0 \sin(\beta - \alpha)}{\sin\phi \cos(\phi + \beta - \alpha)} \end{aligned}} \Bigg\} \boxed{\begin{aligned} F_c &\propto w t_0 \\ F_t &\propto w t_0 \end{aligned}}$$

Minimize cutting energy – Merchant theory

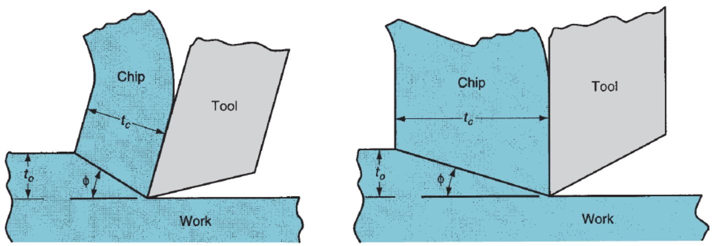
- Merchant's theory: Nature always tries to take the path of least resistance
- During machining process, shear angle ϕ assumes a value such that least amount of energy is consumed
  – Cutting force F_c should be minimum
- Assuming that β is independent of ϕ and shear yield stress of the work material is constant, we can show that:

$$F_c = \frac{\tau w t_0 \cos(\beta - \alpha)}{\sin\phi \cos(\phi + \beta - \alpha)}$$

$$\frac{dF_c}{d\phi} = 0 \Rightarrow \boxed{\phi = \frac{\pi}{4} - \frac{(\beta - \alpha)}{2}}$$

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

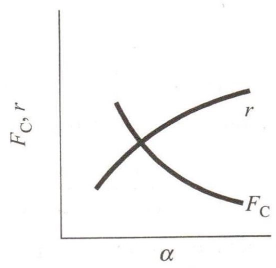
Effect of shear angle, rake angle on power



Larger shear angle >> lower shear plane area >> lower cutting energy >> lower power requirement >> lower cutting temperature

shear angle can be increased by either increasing rake angle (tool design) OR by reducing friction angle (lubricant cutting fluid)

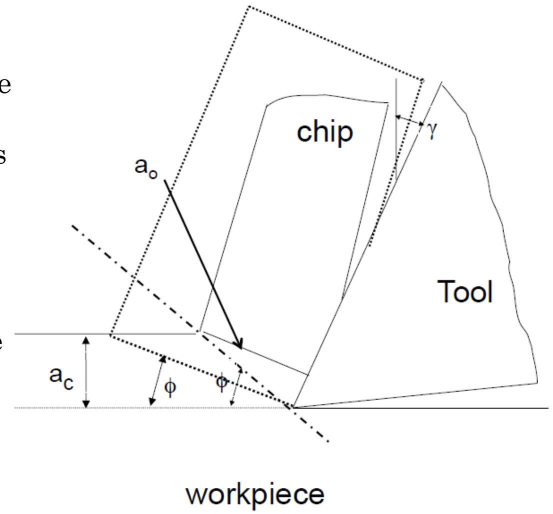
$$2\phi + \beta - \alpha = \frac{\pi}{2}$$



(b) Effect of α on F_C and r

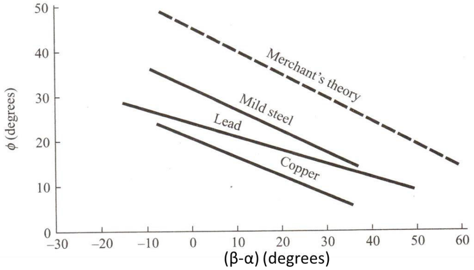
Effect of Changes in Shear Angle

- If φ decreases, the chip becomes thicker
  – Larger shear zone
  – More energy is dissipated since strains are larger
  – Higher temperature and forces
  – More deformation
- If φ increases, the chip becomes smaller
  – Smaller shear zone
  – Less energy is dissipated since strains are smaller
  – Temperatures and forces are lower
  – Less deformation occurs
  – Overall better machining process



Theoretical and experimental shear angle

- Merchant original theory works for soft materials e.g., plastic, but had errors when it was applied to metals. Why ?
- Model does not work well for metal ?
- Merchant has assumed that shear stress is independent of normal stress, which is not entirely true
- Om chip-rake surface, friction plays a critical role
- Shear stress also depends upon the normal stress
  - How?



Example 1

During an orthogonal machining operation on mild steel, the results obtained are

$t_1 = 0.25$ mm, $t_2 = 0.75$ mm, $w = 2.5$ mm,

$\alpha = 0°$, $F_C = 950$ N, $F_T = 475$ N.

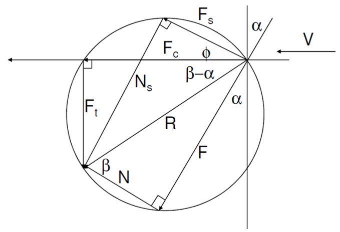
(i) Determine the coefficient of friction between the tool and the chip.

(ii) Determine the ultimate shear stress τ_s of the work material.

<u>Solution:</u>

Coefficient of friction μ = F/N

Ultimate shear strength τ



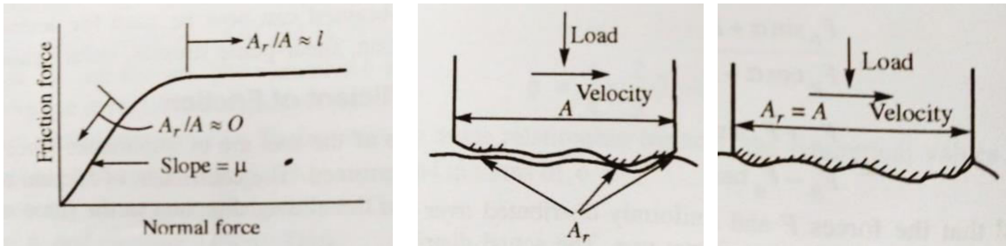
$$\tan\phi = \frac{r\,Cos\,\alpha}{(1 - r\,Sin\,\alpha)}$$

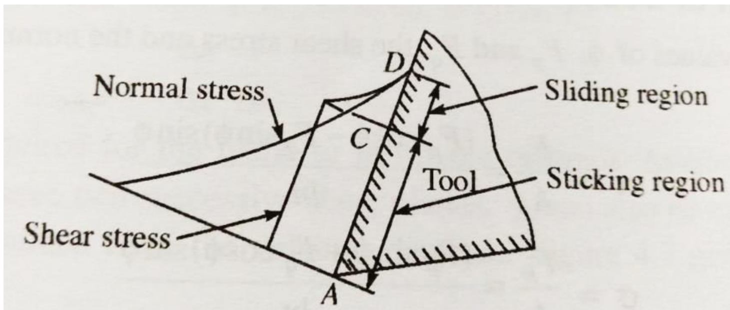
$$F_s = \tau A_s = \tau\frac{wt_0}{Sin\phi} \qquad F_s = \frac{F_c\,Cos(\phi+\beta-\alpha)}{Cos(\beta-\alpha)}$$

Example 2

Mild steel is being machined at a cutting speed of 200 m/min with a tool of rake angle 10°. The width of cut and the uncut thickness are 2 mm and 0.2 mm, respectively. If the average value of the coefficient of friction between the tool and the chip is 0.5 and the shear stress τ_s of the work material is 400 N/mm^2, determine (i) the shear angle, and (ii) the cutting and the thrust components of the machining force.

Stress distribution along the rake face





Actual distribution of shear and normal stress on the rake face

Modified Merchant theory

- With modified Merchant theory:

$$\tau_S = \tau_{S0} + K\sigma$$

$$\sigma = \frac{N_s}{wt/Sin\phi}$$

$$\tau_S = \tau_{S0} + K\frac{N_s}{wt/Sin\phi}$$

$$2\phi + \beta - \alpha = C_m$$

$$C_m = cot^{-1}K$$

Machining constant: C_m (degree)

Work material (hot rolled steel)		C_m (degrees)
AISI	1010	69.8
AISI	1020	69.6
AISI	1045	78.0
AISI	2340	76.2
AISI	3140	70.6
AISI	4340	74.5
Stainless	303	92
Stainless	304	82

Other theories

Ernst & Merchant equation : $2\phi + \beta - \alpha = \pi/2$

Merchant's second solution : $2\phi + \beta - \alpha = C_m$

Lee & Shaffer equation : $\phi + \beta - \alpha = \pi/4$

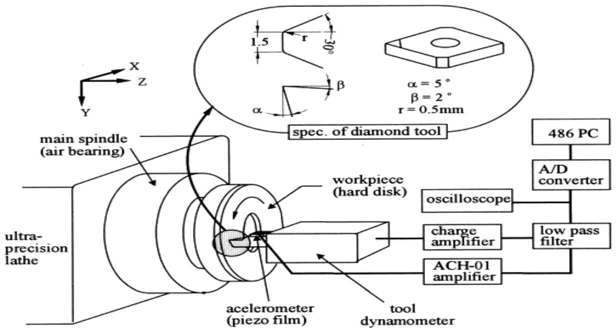
Stabler equation : $\phi + \beta - \alpha/2 = \pi/4$

Specific cutting energy

- Power consumption during machining process
  - Cutting Force F_c, Cutting velocity v
  - Power consumed: F_c.v
  - Volume of material removed: w.t_1.v (w: width, t_1: depth of cut)
- Specific energy = Total power consumed / volume of metal removed
  - Specific energy: F_c/wt_1

Material	Unit Power (kW/cm³/min)
Cast irons	0.044–0.08
Steels	
Soft	0.05–0.066
$0 < R_c < 45$	0.065–0.09
$50 < R_c < 60$	0.09–0.2
Stainless steels	0.055–0.09
Magnesium alloys	0.007–0.009
Titanium	0.053–0.066
Aluminum alloys	0.012–0.022

Dynamometer to measure F_c and F_t



Specification: **Force** : XYZ direction.
Range of force : **For 12.5mm tool bits**
Model 620A - 100kg. force in XYZ direction
Model 620B - 200kg. force in XYZ direction.
Model 620C - 500kg. force in XYZ direction.
For 25mm tool bits
Model 621A - 100kg. force in XYZ direction
Model 621B - 200kg. force in XYZ direction.
Model 621C - 500kg. force in XYZ direction.
Sensor : 4 arm bounded strain gauge component bridge for each force.
Bridge resistance : 350 Ohms typical
Bridge voltage : 12 volts Maximum.
Linearity : 1% of full scale
Accuracy : 1% of full scale
Tool post dia : 20mm (any other size required to be indicated)
Center height : To be indicated.