Machining Process

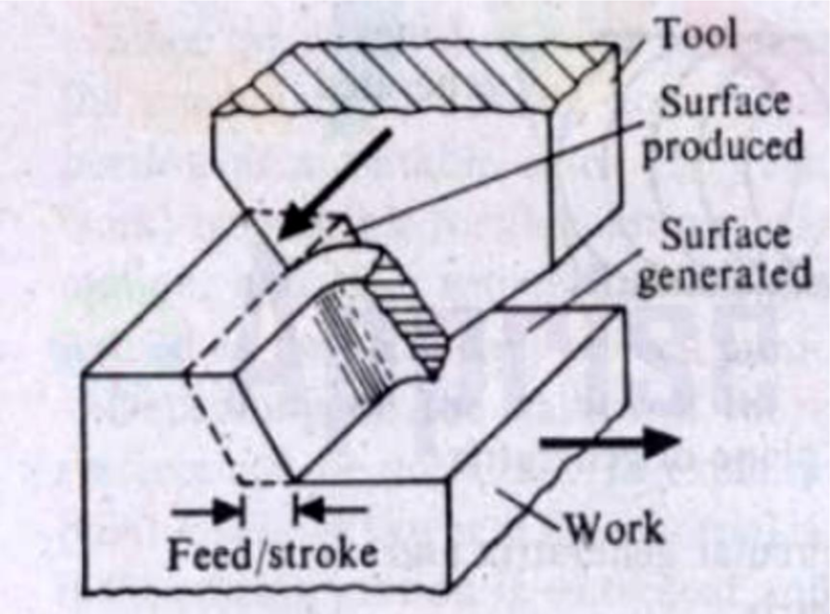
Machining Process: In this process, the desired shape, size, and finish are obtained through the removal of excess material from the original workpiece in the form of small chips.

Cutting Tool: The body which removes the excess material from the workpiece through a direct mechanical contact.

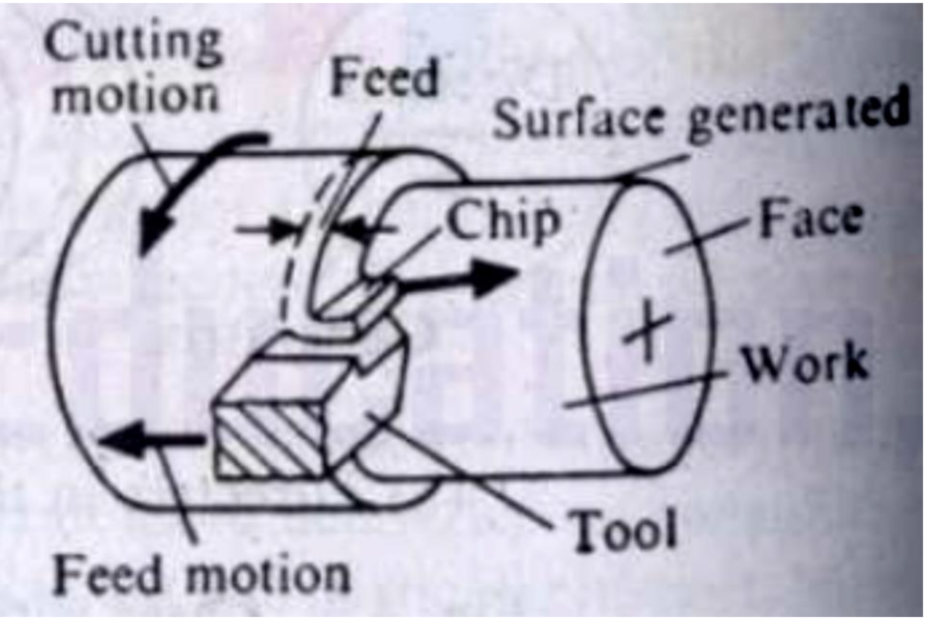
Machine Tool: The machine which provide the necessary relative motions between the work and the tool.

Primary/Cutting Motion: The relative motion between the tool and the work responsible for the cutting action.

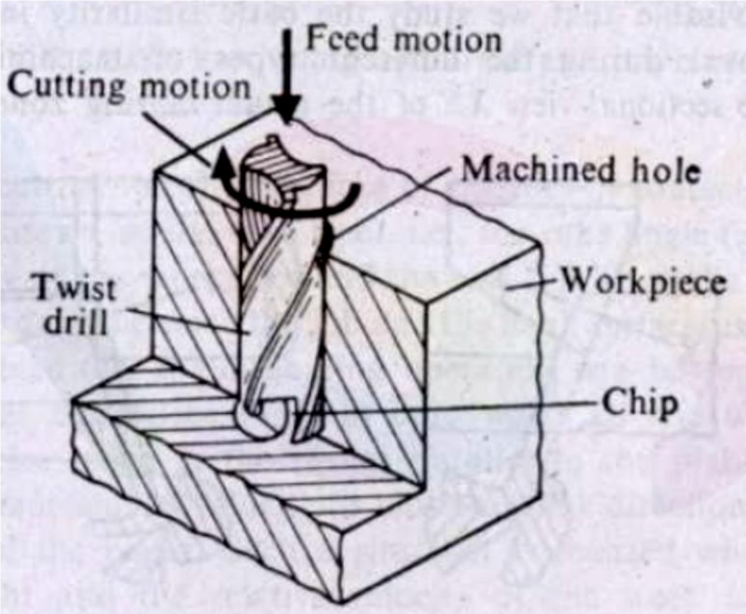
Secondary/feed motion: The relative motion between the tool and the work responsible for gradually feeding the uncut portion.



Shaping

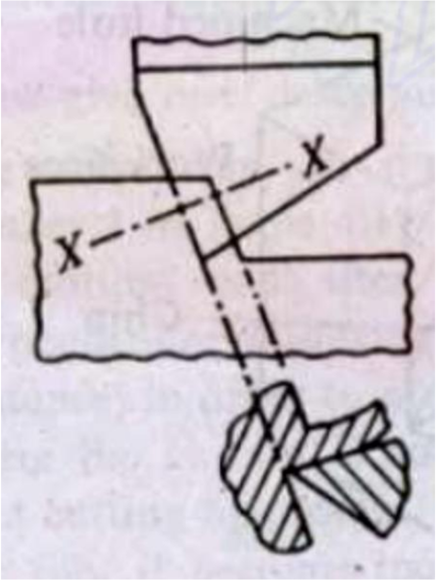


Turning

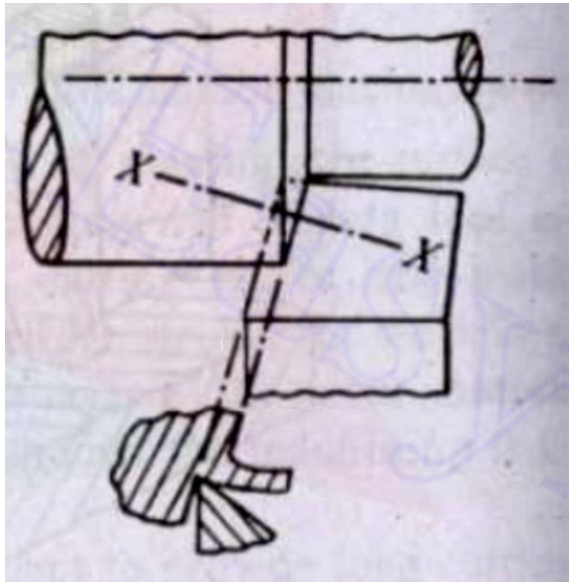


Drilling

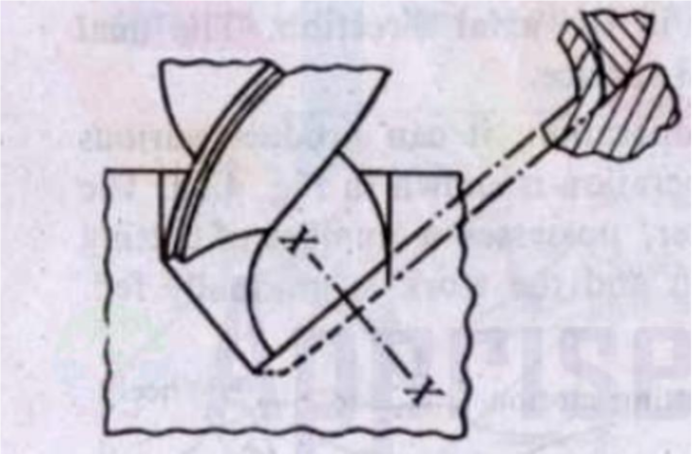
Mechanics of basic machining operation



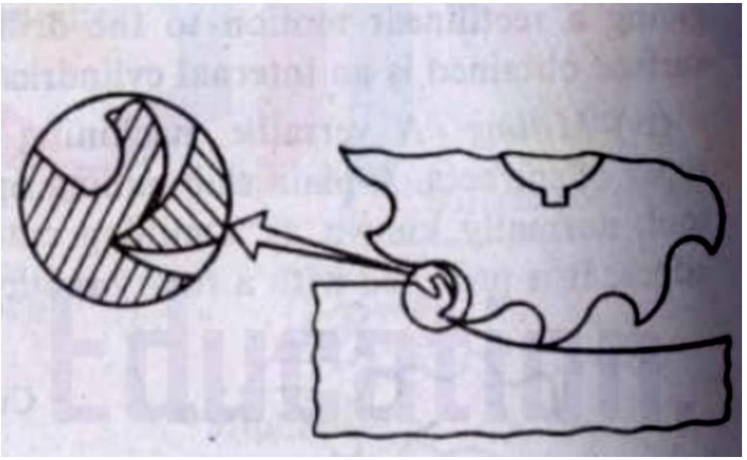
Shaping



Turning

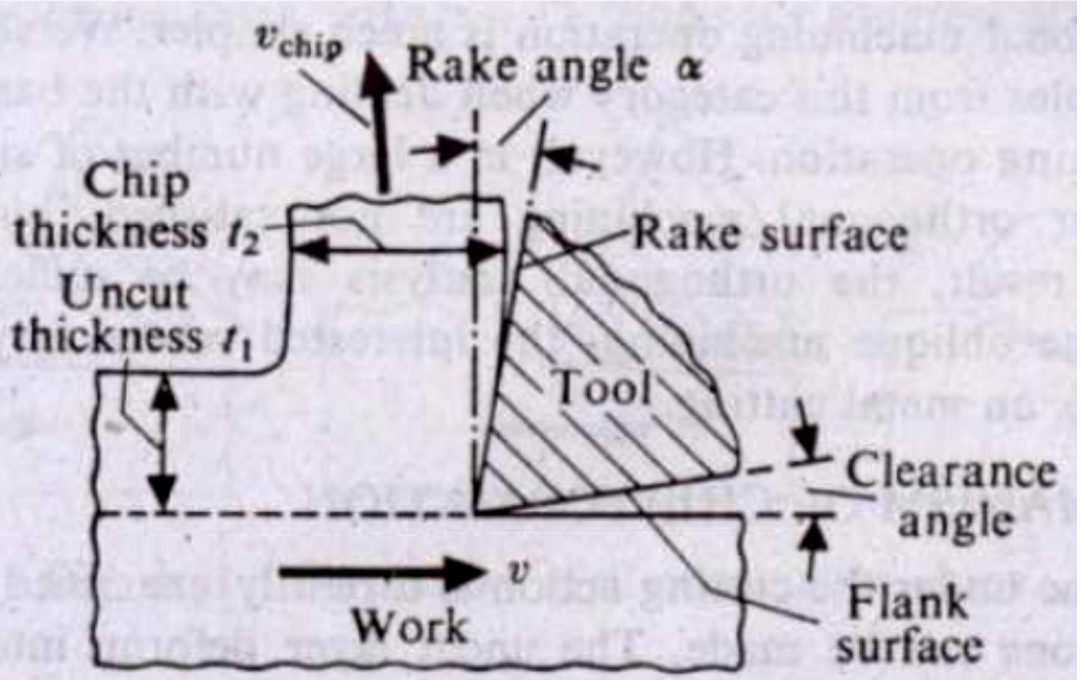


Drilling



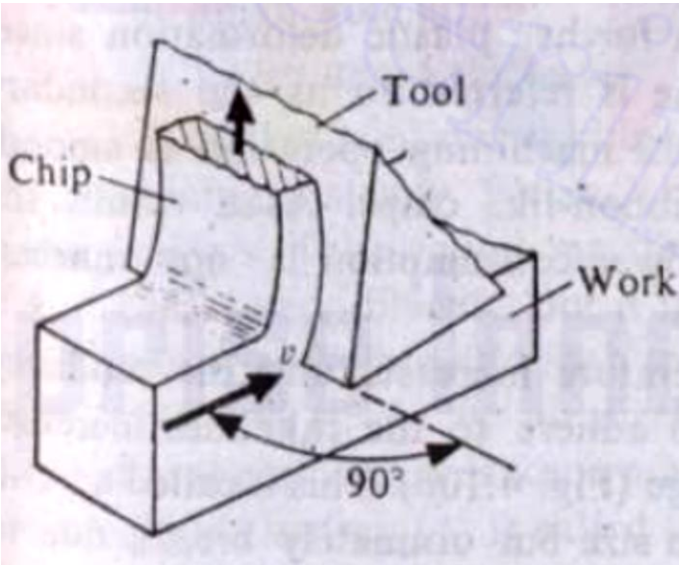
Milling

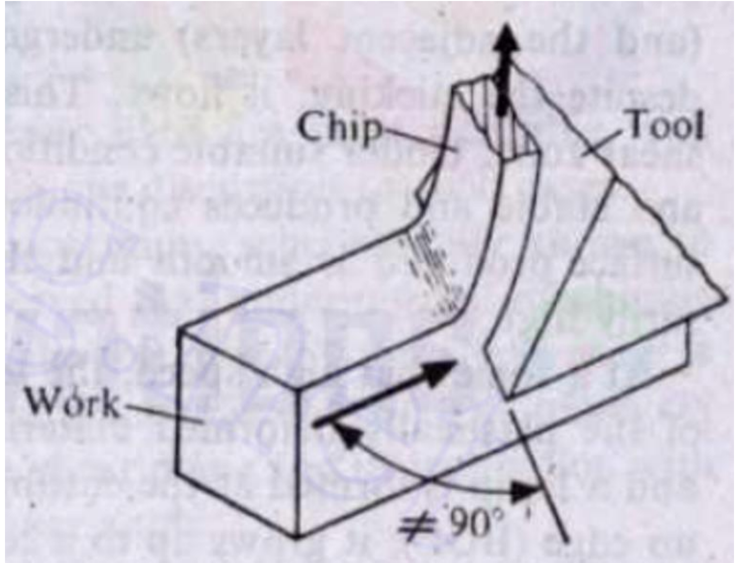
Basic nature of material removal in each of the above operations is similar and can be represented in a 2-D diagram.



Important parameters

1. Thickness of uncut layer (t_1)
2. Thickness of chip produced (t_2)
3. Inclination of chip-tool interface w.r.t. cutting velocity (rake angle, α)
4. Clearance angle between flank surface of tool and workpiece
5. Relative velocity of workpiece and tool (v)



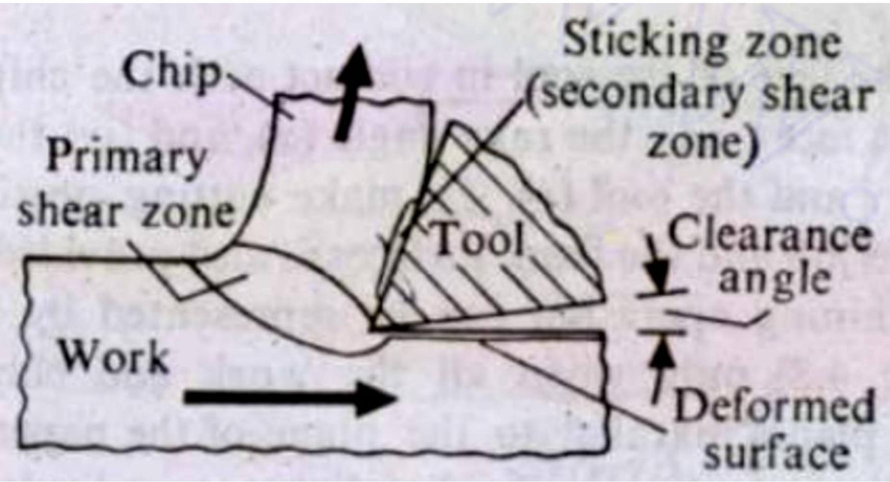


Orthogonal Machining **Oblique Machining**

Orthogonal Machining: Cutting edge is straight and relative velocity of tool and workpiece is perpendicular to the cutting edge.

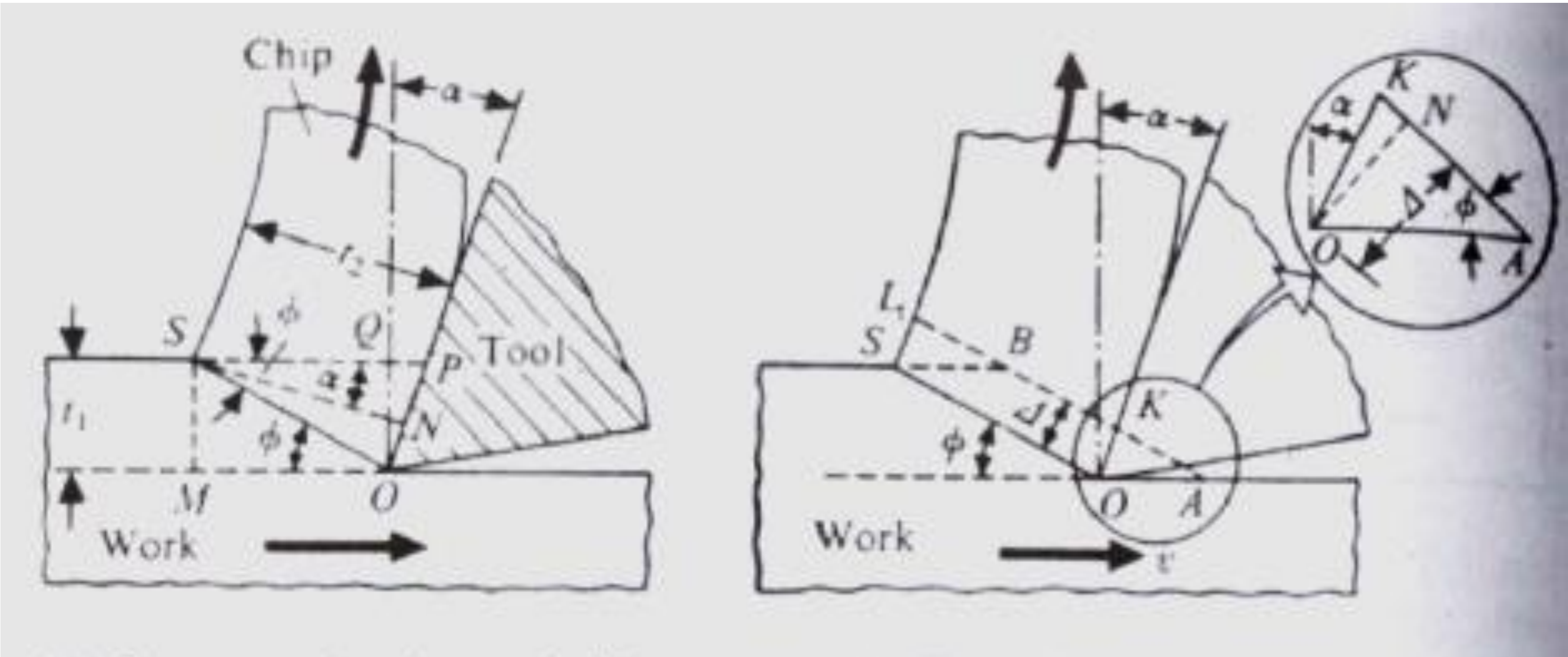
Oblique Machining: Relative velocity of tool and workpiece is not perpendicular to the cutting edge.

Mechanism of chip formation



Shear Zone

At moderate and high speeds the thickness of the shear zone is very small and it can be idealized as a plane. The plane OS Where the shear occurs is known as the shear plane and its inclination with the machined surface is called the shear angle.



(a) Geometry of orthogonal chip formation

(b) Determination of shear strain

Features of orthogonal chip formation.

t_1 = uncut thickness

t_2 = chip thickness

$r = t_1/t_2$ = cutting ratio

ϕ = shear angle

α = rake angle

γ = shear strain

$$\frac{t_1}{t_2} = \frac{\sin\phi}{\cos(\phi - \alpha)} = r \qquad (1)$$

$$\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha} \qquad (2)$$

$$\gamma = \cot\phi + \tan(\phi - \alpha) \qquad (3)$$

Problem

During orthogonal machining with a cutting tool having a 10° rake angle, the chip thickness is measured to be 0.4 mm, the uncut thickness being 0.15 mm. Determine the shear plane angle and also the magnitude of the shear strain.

Solution

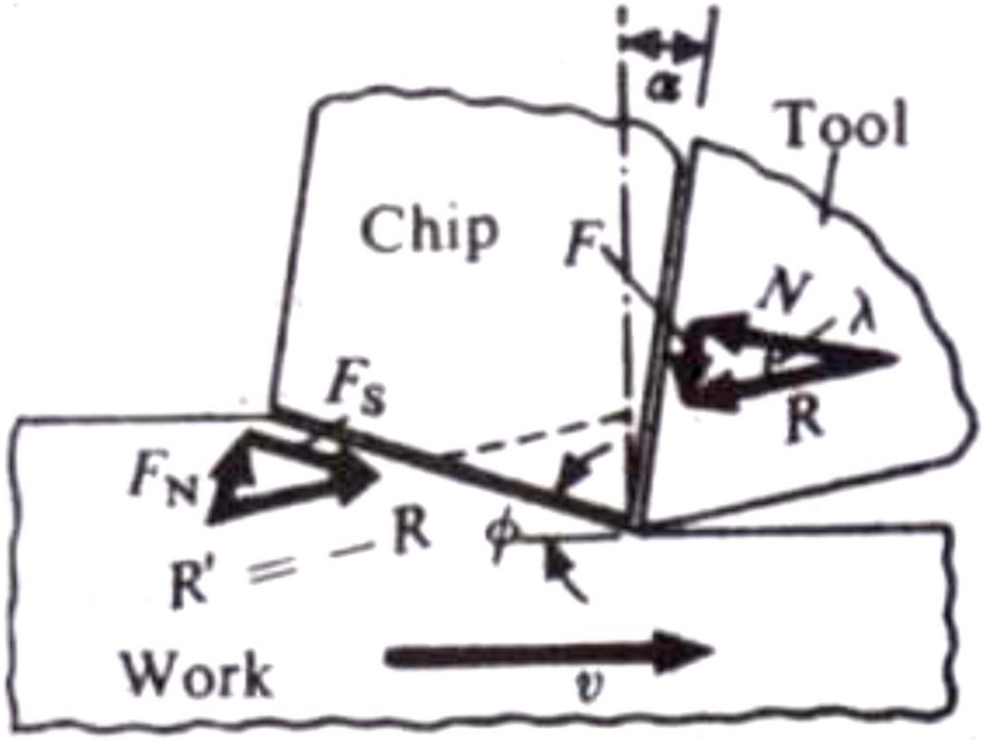
$$\textbf{Cutting ratio}, r = \frac{t_1}{t_2} = \frac{0.15}{0.4} = 0.38$$

$$\boldsymbol{Shear\ plane\ angle}, \emptyset = tan^{-1}\left[\frac{0.38\cos 10^o}{1 - 0.38\sin 10^o}\right] = 21.8^o$$

$$\boldsymbol{Shear\ strain}, \gamma = \cot 21.8^o + \tan(21.8^o - 10^o) = 2.71$$

Forces and Power Consumption During Machining

Ernst and Merchant model of single shear plane



Equilibrium of chip

$F/N = \mu = \tan \lambda$ λ = Friction Angle

α = rake angle ϕ = shear angle

μ = average coefficient of friction between chip and tool

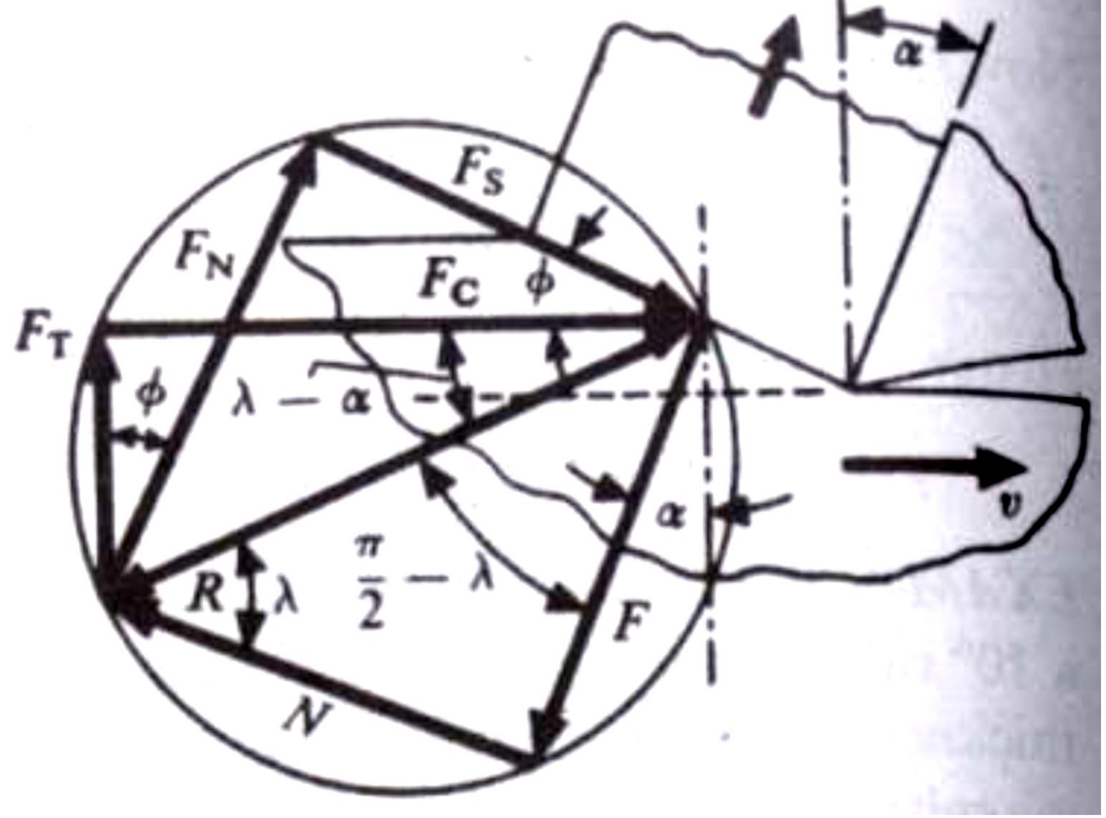
F = friction force N = normal force

F_S = force component parallel to shear plane

F_N = force component normal to shear plane

R = resultant force on chip from tool

R' = - R = resultant force on chip from uncut material



Merchant's Circle Diagram

F_C = cutting force (parallel to relative velocity)

F_T = thrust force (normal to relative velocity)

F_C and F_T are measured by dynamometers

Resultants of (F_C, F_T), (F_N, F_S), (F, N) = R. Therefore, tips of all these force vectors must lie on an imaginary circle of diameter R. This imaginary circle is called as the Merchant's circle.

$$F_C = F_S \cos\phi + F_N \sin\phi, \tag{4a}$$

$$F_T = F_N \cos\phi - F_S \sin\phi, \tag{4b}$$

$$F = F_C \sin\alpha + F_T \cos\alpha, \tag{5a}$$

$$N = F_C \cos\alpha - F_T \sin\alpha, \tag{5b}$$

$$F_S = F_C \cos\phi - F_T \sin\phi, \tag{6a}$$

$$F_N = F_C \sin\phi + F_T \cos\phi, \tag{6b}$$

$$R = \frac{F_S}{\cos(\phi + \lambda - \alpha)}, \tag{7}$$

$$F_C = R\cos(\lambda - \alpha), \tag{8a}$$

$$F_T = R\sin(\lambda - \alpha). \tag{8b}$$

$$\mu = \frac{F}{N} = \frac{F_C \sin\alpha + F_T \cos\alpha}{F_C \cos\alpha - F_T \sin\alpha}, \tag{9}$$

Theoretical estimation of F_C and F_T

$$F_S = wt_1\tau_s/\sin\phi \qquad (10)$$

τ_s = ultimate shear stress of the material, w = width of workpiece, t_1 = uncut thickness, ϕ = shear angle

Combining eqs. (7) and (8a), we get

$$F_C = \frac{F_S\cos(\lambda-\alpha)}{\cos(\phi+\lambda-\alpha)} \qquad (11)$$

Combining eqs. (10) and (11)

$$F_C = \frac{wt_1\tau_s\cos(\lambda-\alpha)}{\sin\phi\cos(\phi+\lambda-\alpha)} \qquad (12)$$

Power consumption

$$W = F_C v = \frac{vwt_1\tau_s\cos(\lambda-\alpha)}{\sin\phi\cos(\phi+\lambda-\alpha)} \qquad (13)$$

Where, v = cutting velocity

For given v, w, t_1, τ_s, λ, α

$$W(\phi) = \frac{constant}{\sin\phi\cos(\phi+\lambda-\alpha)}$$

For minimum power consumption, denominator should be maximum

Differentiating the denominator with respect to ϕ

$$\cos\phi\cos(\phi+\lambda-\alpha) - \sin\phi\sin(\phi+\lambda-\alpha) = 0 \quad \rightarrow \quad \cos(2\phi+\lambda-\alpha) = 0$$

$2\phi + \lambda - \alpha = \pi/2$ **(14)** **Merchant's first solution**

Using eq. (14) in eq. (12) we get $$F_C = \frac{2wt_1\tau_s \cos(\lambda - \alpha)}{1 - \sin(\lambda - \alpha)} \qquad \textbf{(15)}$$

Minimum power consumption is obtained by multiplying eq. (15) with cutting velocity, v

Merchant's second solution

Merchant's first solution agrees poorly with the experimental results of machining metals.

Further analysis shows $\tau_s = \tau_{s_0} + k_1\sigma$ **(16)** Where, k_1 = constant, σ = normal stress on the shear plane

$$\sigma = \frac{F_N}{w\,t_1/\sin\emptyset}$$

Further calculations lead to $$F_C = \frac{wt_1\tau_s \cos(\lambda - \alpha)}{\sin\phi[\cos(\phi + \lambda - \alpha) - k_1 \sin(\phi + \lambda - \alpha)]} \qquad \textbf{(17)}$$

Applying the principle of minimum energy conservation, we get **$2\phi + \lambda - \alpha = C_m$** **(18)**

C_m = machining constant = $\cot^{-1} k_1$

Eq. (18) shows that ϕ increases with increase in α, while ϕ decreases with increase in λ.

Problem

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

t1 = 0.25 mm, t2 = 0.75 mm, w = 2.5 mm α = 0 degree, F_C = 950 N, F_T = 475 N.

Determine the coefficient of friction between the chip and the tool.

Determine the ultimate shear stress of the work material.

Solution

$$\mu = \frac{F_C sin\,\alpha + F_T \cos\alpha}{F_C cos\,\alpha - F_T \sin\alpha} = \frac{950 \times sin\,0^o + 475 \times \cos 0^o}{950 \times cos\,0^o - 475 \times \sin 0^o} = \frac{475}{950} = \mathbf{0.5}$$

$$Shear\ angle, \phi = tan^{-1}\left(\frac{r\cos\alpha}{1 - r\sin\alpha}\right) = tan^{-1}\left(\frac{r\cos 0^o}{1 - r\sin 0^o}\right) = tan^{-1}\,r = tan^{-1}\left(\frac{t_1}{t_2}\right) = tan^{-1}\left(\frac{0.25}{0.75}\right) = 18.4^o$$

$$F_S = F_C cos\,\phi - F_T \sin\phi = 950 \times \cos 18.4^o - 475 \times \sin 18.4^o = 751.3\text{ N}$$

$$\boldsymbol{F_S = wt_1\tau_s/\sin\phi} \qquad \tau_s = \frac{F_S \sin\phi}{wt_1} = \frac{751.3 \times \sin 18.4^o}{2.5 \times 0.25} = \mathbf{379.4\ N/mm^2}$$

Problem

Mild steel is being machined at a cutting speed of 200 m/min with a cutting tool of rake angle 10 degree. The width of cut is 2 mm, and uncut thickness is 0.2 mm. Coefficient of friction between the chip and the tool is 0.5. Shear stress of the work material is 400 N/mm2. Determine (i) the shear angle, (ii) cutting force, (iii) thrust force.

Solution

Merchant's first solution $2\phi + \lambda - \alpha = \pi/2$

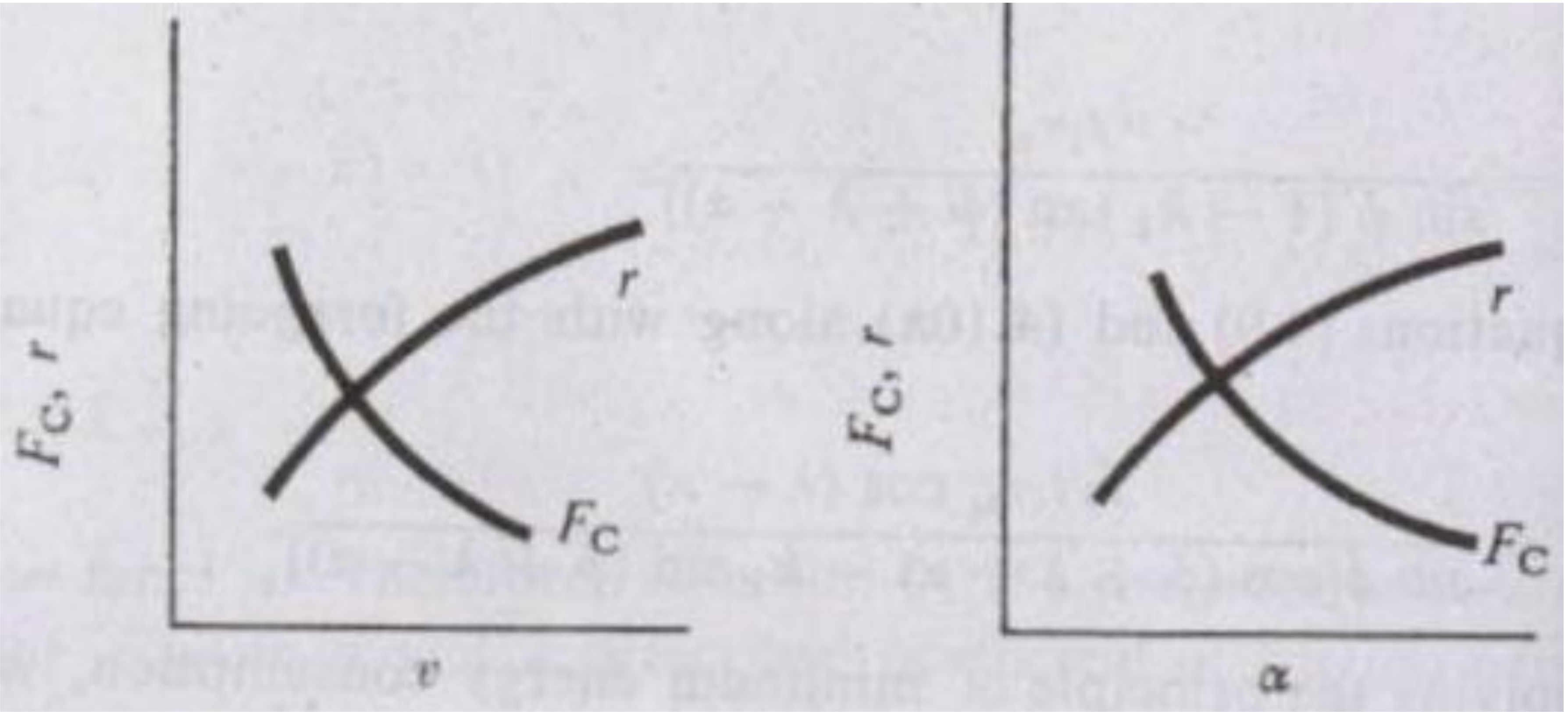
$$\lambda = tan^{-1}\mu = tan^{-1}0.5 = 26.57^o \qquad \alpha = 10^o \qquad \rightarrow \qquad \phi = (90 + 10 - 26.57)/2 = \mathbf{36.7^o}$$

$$F_S = wt_1\tau_s/\sin\phi = (2 \times 0.2 \times 400)/\times\, sin\, 36.7^o = 262.3\ N$$

$$R = F_s/\cos(\phi + \lambda - \alpha) = 262.3/\cos(36.7^o + 26.57^o - 10^o) = 438.6\ N$$

$$F_C = R\cos(\lambda - \alpha) = 438.6 \times \cos(26.57^o - 10^o) = \mathbf{420\ N}$$

$$F_T = R\, sin(\lambda - \alpha) = 438.6 \times \sin(26.57^o - 10^o) = \mathbf{125\ N}$$



When **v** increases, μ decreases. Accordingly λ decreases, thereby causing increase in ϕ and decrease in $\mathbf{F_c}$.

Increase in **v** and α increases ϕ, causing decrease in $\mathbf{F_c}$ and increase in cutting ratio, **r.**

Machining Constant for different materials

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

Different shear angle relations

Source	Result
Ernst and Merchant	$2\phi + \lambda - \alpha = \pi/2$
Merchant's second solution	$2\phi + \lambda - \alpha = C_m$
Lee and Shaffer	$\phi + \lambda - \alpha = \pi/4$
Stabler	$\phi + \lambda - \alpha/2 = \pi/4$

Power consumption during machining, $W = F_C v$

Volumetric rate of material removal, $Q = w t_1 v$

Specific energy consumption (energy consumption per unit volume of material removal), $U_C = W / Q = F_C / w t_1$

Experimental data shows $U_C = U_0 \widetilde{t_1}^{-0.4}$

Therefore, $F_C = 1000 w t_1 U_0 \widetilde{t_1}^{-0.4}\ N$

Where, w and t_1 are in mm, and U_0 is in J/mm^3

Cutting Tool Materials

The cutting tool must resist any tendency to alter its shape.

Tool material must be harder than the work material by at least 35% - 50%.

Effective hardness of the tool decreases at high temperature of machining.

Effective strength of workpiece increases due to high strain rate of plastic deformation

Condition of hardness ratio should be applied by considering modified hardness values $$1.35 < \left[\frac{H_{tool}}{H_{work}}\right]_{modified} < 1.5$$

Tool material	Work material	Static hardness ratio	Modified hardness ratio	Remark
Copper	Zinc	1.98	≈ 1	No successful machining possible
Zinc	Cadmium	2.2	≈ 1	No successful machining possible
Tin	Lead	1.5	<1	No machining possible
Cadmium	Tin	2.2	<1	No machining possible
Heat treat-ed steel	Steel 65γ	1.45	≈ 1	No successful machining possible

Performance of various tool/work combinations

Commonly used tool materials

(i) high carbon steel, high speed steel (HSS), cemented carbide, ceramic coated carbide, and ceramic.

(ii) For grinding, abrasive minerals, e.g., silicon carbide, aluminum oxide, and diamond are used.

Properties of an ideal tool material:

- It should maintain its hardness appreciably higher than that of the work at the elevated temperature.
- It should be tough enough to withstand shocks.
- It should provide a large resistance to the wearing action so that excessive wear does not occur.
- The coefficient of friction between the work and the tool should be low.
- Its thermal conductivity and specific heat should be high.

Composition of different tool materials

Material	C	W	Cr	V	Mn	Fe
Carbon tool steel	0.9				0.6	Rest
High speed steel	0.75	18.0	4.0	1.0	0.6	Rest

Composition carbide tool materials

WC	Co	TaC	TiC	Use
94	6			Cast iron
70.7	4.5	12.2	12.6	Steels
72	8.5	11.5	8	Ni alloy steels

Tool material	Cutting speed (m/min)
Carbon steel	5
High speed steel	30
Cemented carbide	150
Coated carbide	350
Ceramic	600