ME 361Manufacturing Sciences
J.Ramkumar

Topics covered

- General introduction
- Classification of machining process
- Machining with single-edge tools
- Types of cutting
- Types of chip

Introduction

- Manufacturing process to produce
  - Specified shape
  - Material properties
- Process
  - Change in configuration and physical properties
- Following type of operations
  - Constant mass operations
    - Casting, rolling, extrusion, wire drawing, forging, etc
  - Material addition operations – **Bottom up approach**
    - Bolting, rivetting , keying, welding, rapid prototyping, etc
  - Material removal operations (surplus materials removed) – **Top down approach**
    - Machining, finishing, etc

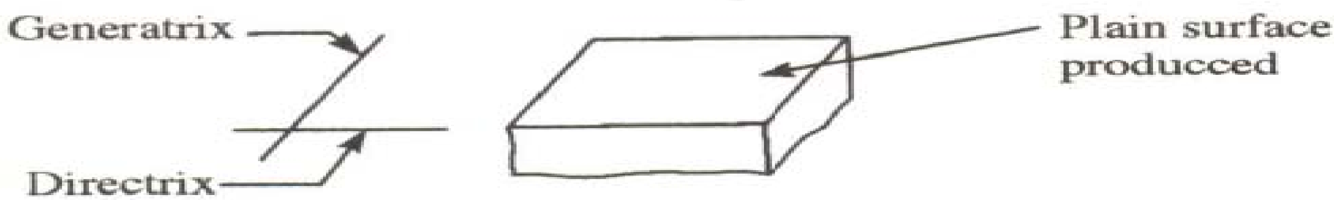
Basics of Machining process

- Relative motion obtained by combining rotatory and translatory movements of either the tool or workpiece or both
- Shape is obtained by relative motion of
  - Shape of the tool
  - Path it traverses
    - Tool path is parallel to the axis – cylindrical surface both internal and external
    - Tool/workpiece is reciprocated – flat surface – Shaping (tool reciprocates and workpiece feed) and planing (vice versa)
  - Other examples
    - Milling – Surface and end milling
    - drilling

Basics of Machining process

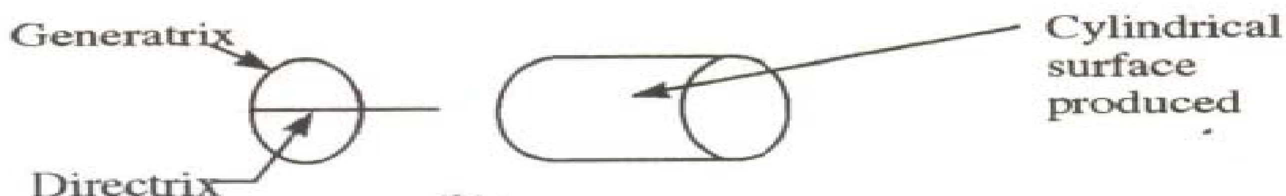
- Generatix
  - Lines generated by cutting motion
- Directrix
  - Lines from feed motion
- How is a taper made ?
- Methods of generating surfaces
  - Tracing method – direct tracing of the generatrices Eg: shaping, planing
  - Generation – surface produced is the envelop of the generatrices – milling, etc

Concept of generatrix and directrix



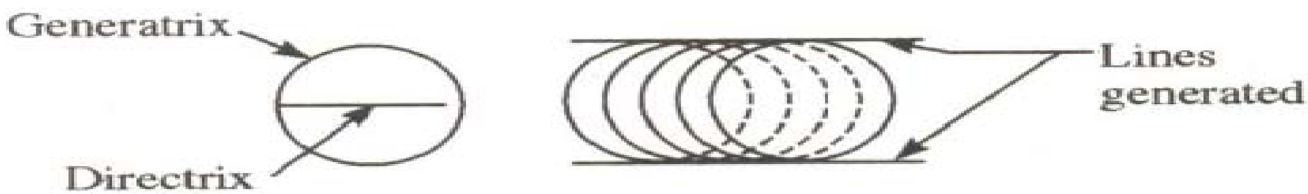
(a)

Rectilinear generatrix and directrix



(b)

Directrix perpendicular to the plane of generatrix



(c)

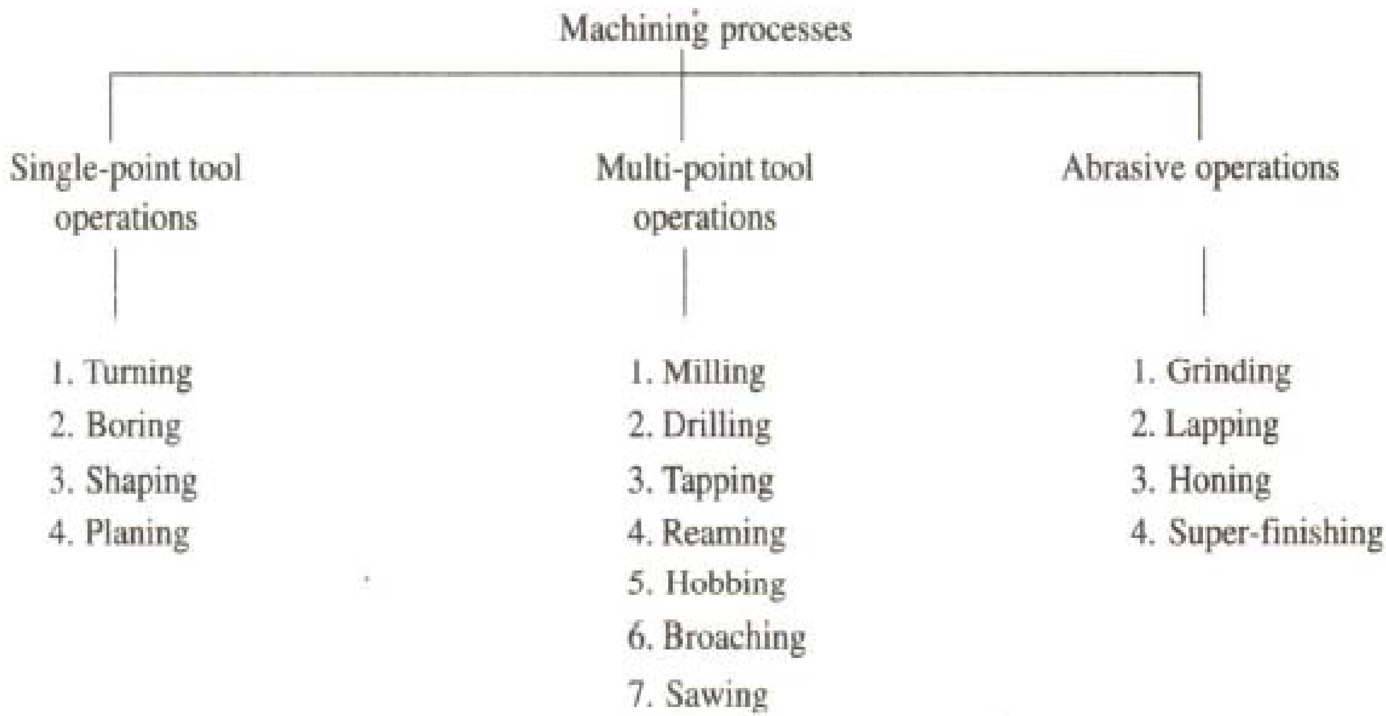
Directrix in the plane of generatix

Generation of Various Surfaces

Table 1: Generation of various surfaces

Number	Generatrix	Directrix	Process	Surface obtained
1	Straight line	Straight line	Tracing	Plain
2	Circular	Straight line	Tracing	Cylindrical
3	Plain curve	Circular	Tracing	Surface of revolution
4	Circular	Straight line	Generation	Straight line (plain surface in practice)

Classification of Machining Process



- Surplus material removed in the form of chip
- Difference between tool and machine-tool?
  - Machine tool relative motion
    - Primary – Power
    - Secondary - feed

Shaping and Planing Operation

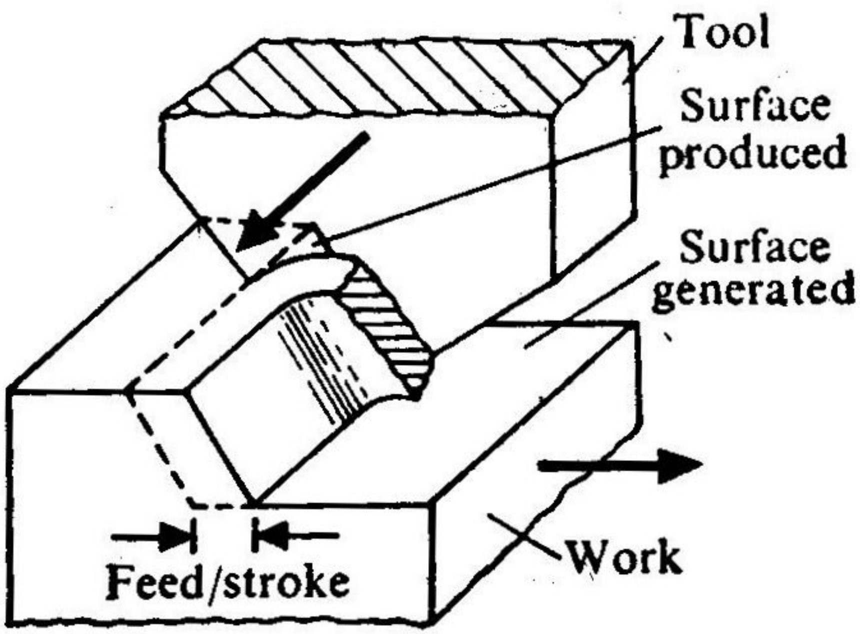


Fig. 3: Shaping operation.

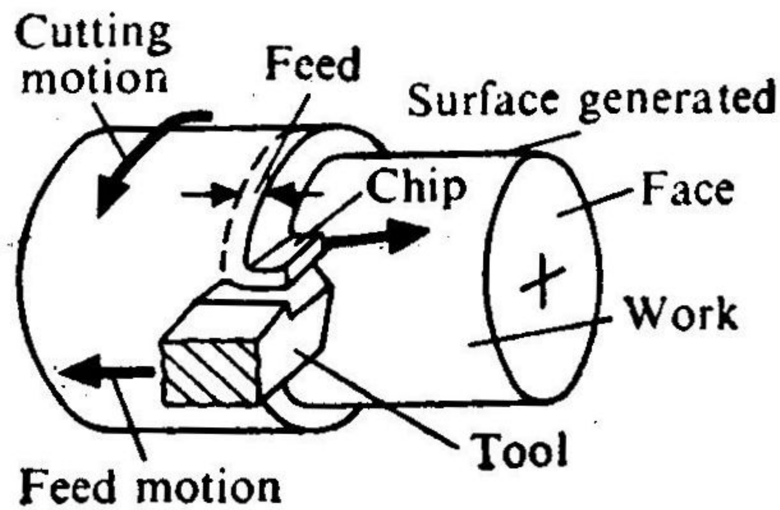


Fig. 4: Turning operation.

Turning Operation

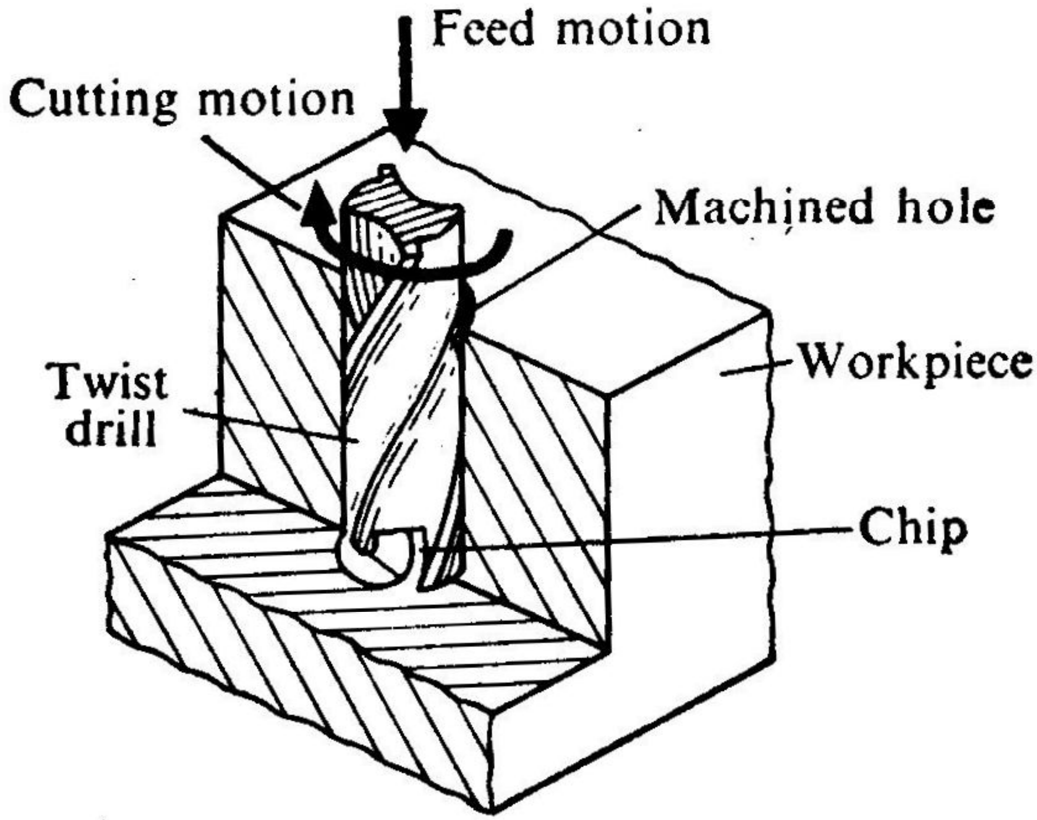
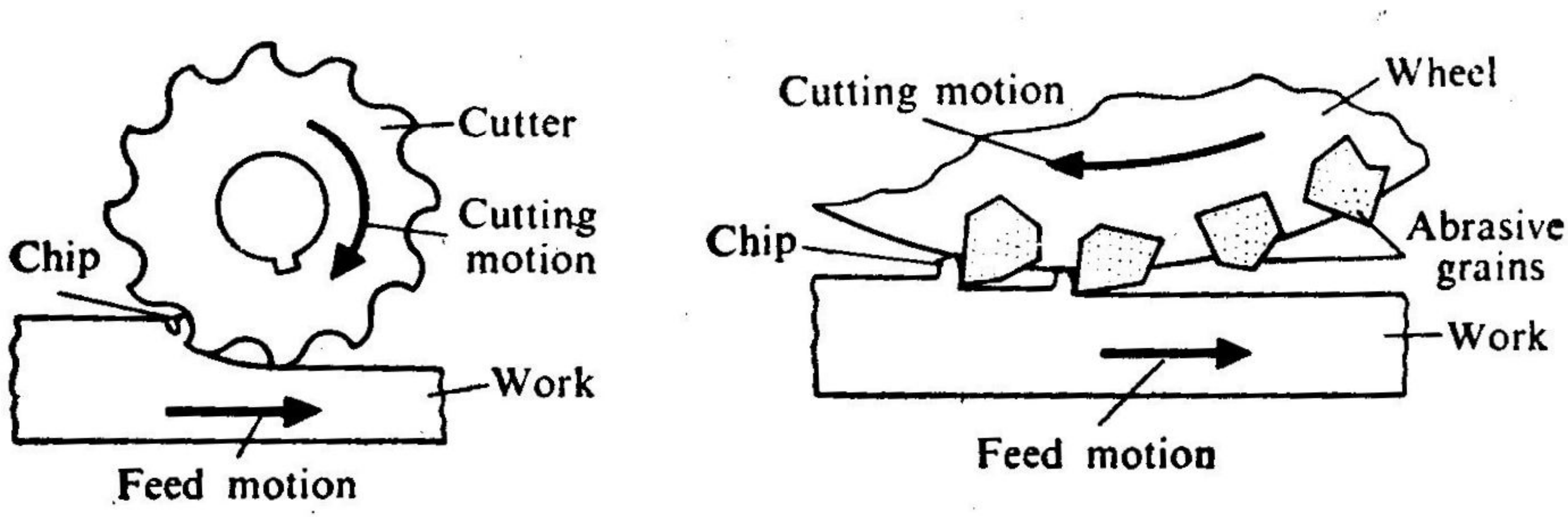


Fig. 5: **Drilling operation.**

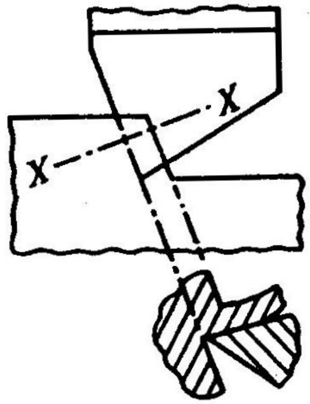
Milling and Grinding Operation



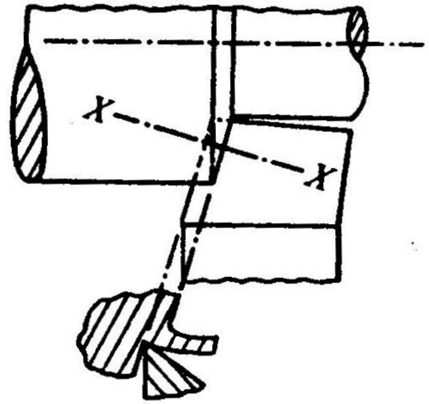
(a) Scheme of milling operation (b) Scheme of grinding operation

Fig. 6: Machining with multipoint tools.

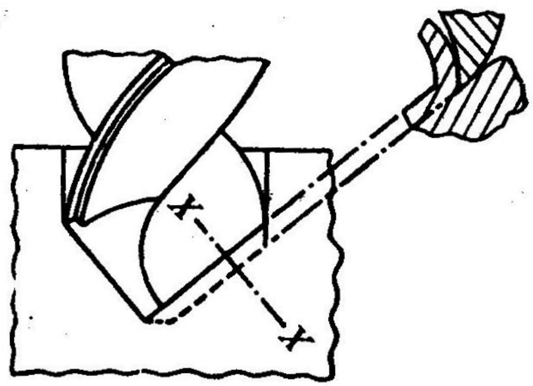
Simulation of Actual Machining Processes



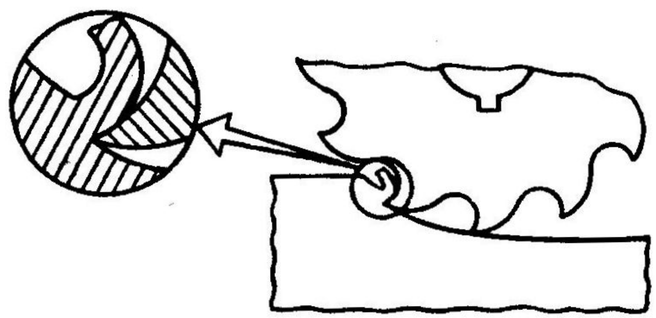
(a) Shaping



(b) Turning



(c) Drilling



(d) Milling

Fig. 7: Simulation of actual machining processes.

Basic Machining Operation

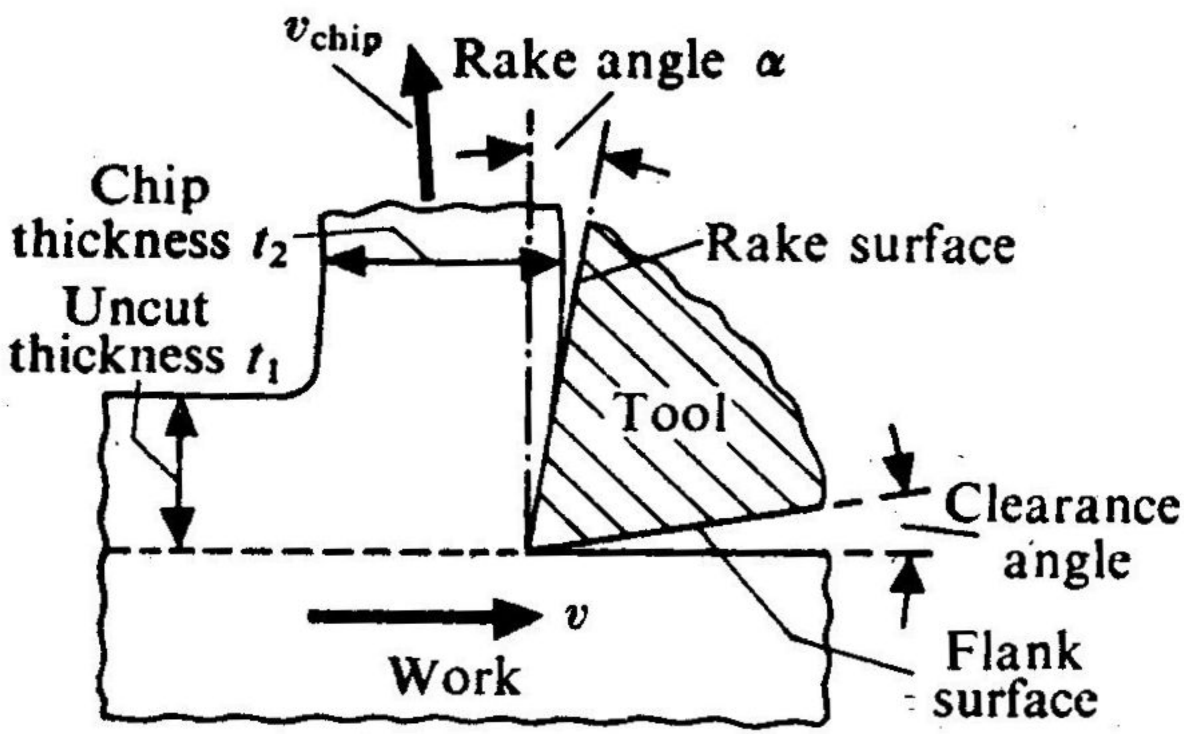
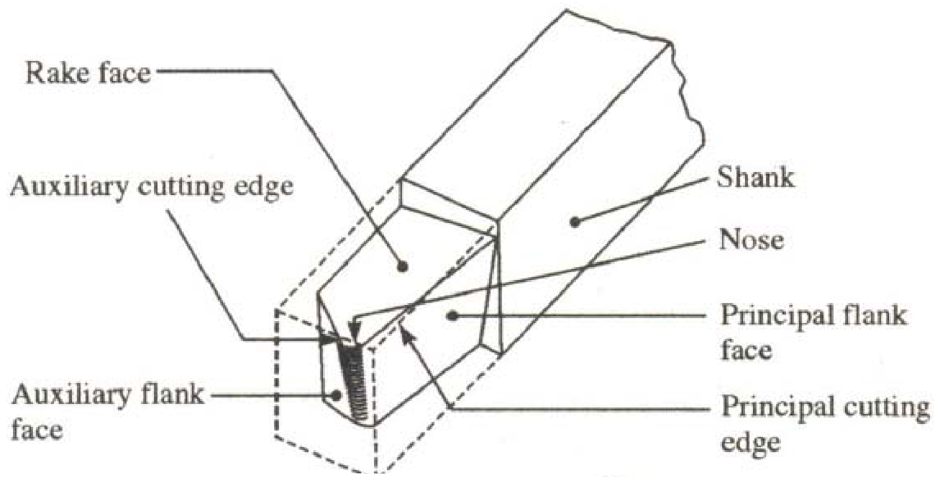


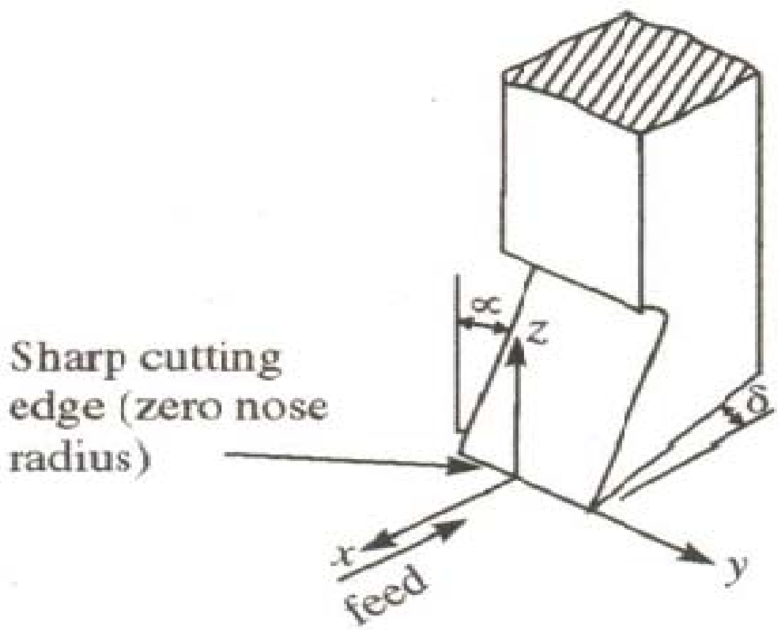
Fig. 8: Basic machining operation and important parameters.

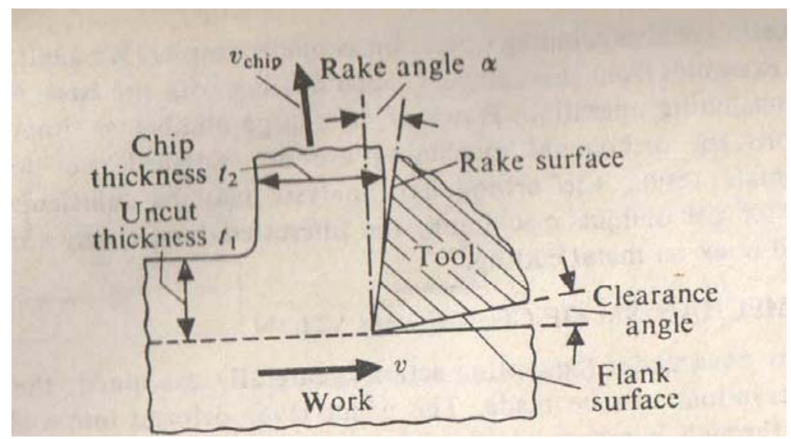
Machining with Single-edge tools

- Simple tool
  - Principal cutting edge
  - Auxiliary cutting edge
- Important angles in a wedge shape tool
  - Rake angle – tool face with a plane normal to cutting velocity vector and the machined surface
  - Flank angle – flank face and machined surface

Single point cutting tool

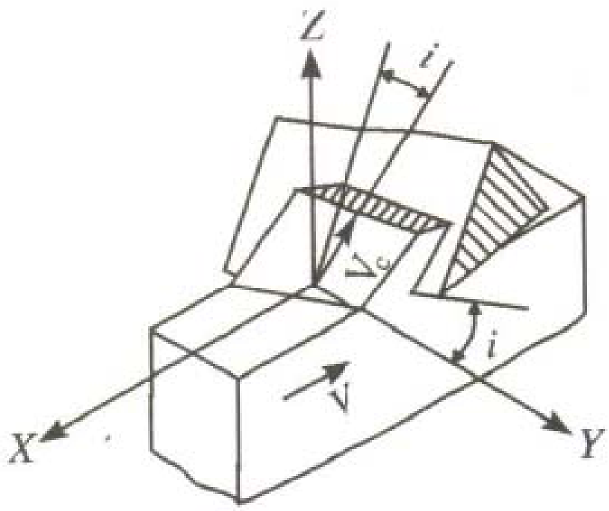


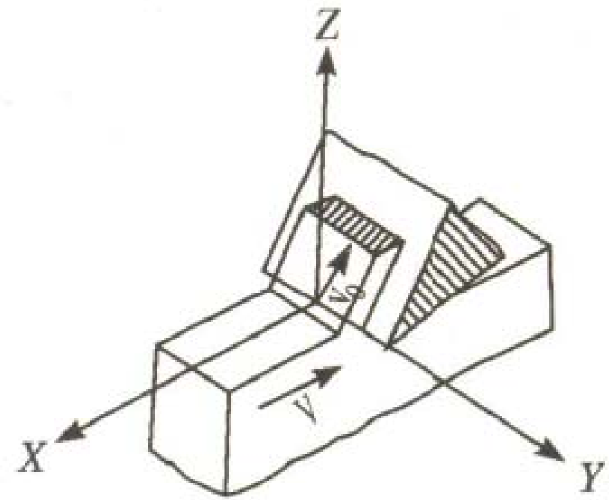




Chip thickness ratio ‘r’ = t1/t2 ?

Types of cutting





Wedge shape tool – constrained to relative motion of the workpeice to form a chip.

Orthogonal cutting – where i = 0 and cutting edge is perpendicular to cutting velocity
Oblique cutting – 3D cutting and i is inclinde

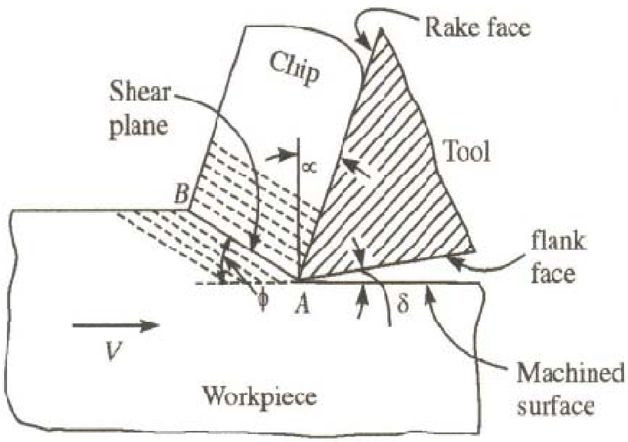
Difference between

- Orthogonal cutting
  - Cutting edge of the tool is perpendicular to the direction cutting velocity
  - Cutting edge is wider than the workpiece width – plain strain condition – flow is confined to the x,z plane
  - Chip flows on the rake face with velocity perpendicular to the cutting edge
  - Cutting forces act along X and Z directions only
- Oblique cutting
  - Cutting edge of the tool is inclined at an angle I with the normal to the cutting velocity
  - Chip flows on the rake face at an angle equal to I
  - Cutting edge extends beyond the width of workpiece
  - Cutting forces act along all directions

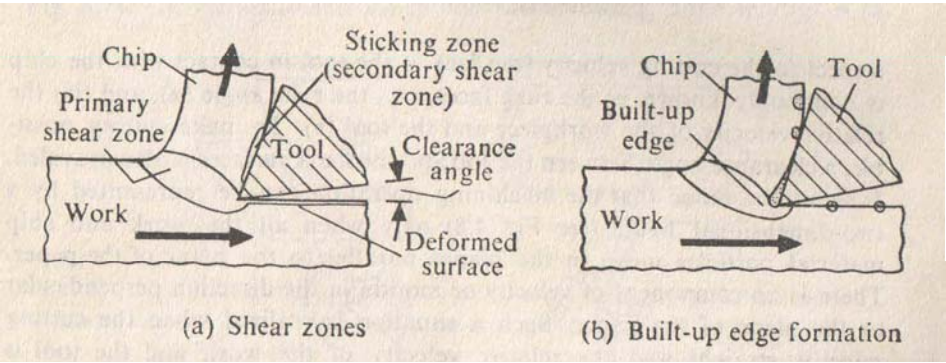
Types of chips

- Depending upon the work material , cutting conditions, three basic types

•Relative motion between tool and workpiece – compression at cutting edge – plastic state.
•Plastic flow on rake surface
•Shearing action of the work material



- Continuous chip
- Continuous chip with built-up edge
- Discontinuous chip

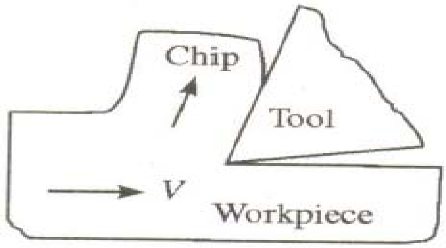


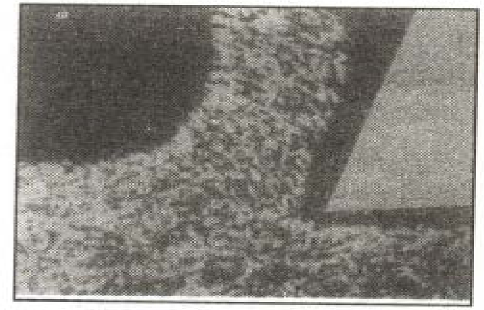
(a) Shear zones (b) Built-up edge formation

Types of chips

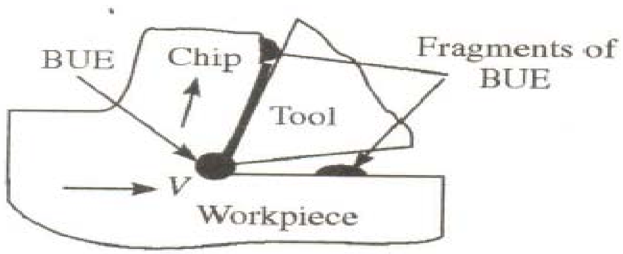
- Continuous chip with Built-up edge
  - Under certain conditions temperature and pressure at tool chip interface is high –
  - sliding – rupture(strain hardening and thermal softening) from the chip takes place
  - High resistance at tool-chip interface – protecting layer removed
  - Affinity for welding
  - Starting growing – build – up edge
  - Growth is high – unstable
  - Move along the chip
  - Move with the machined surface
  - Forms only at critical speed

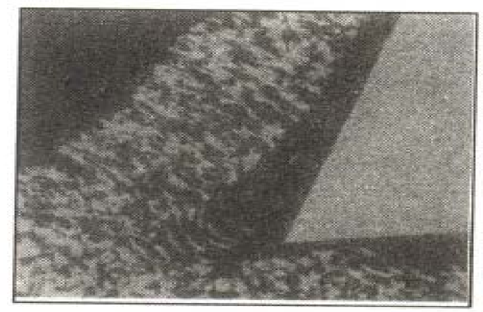
Types of chips



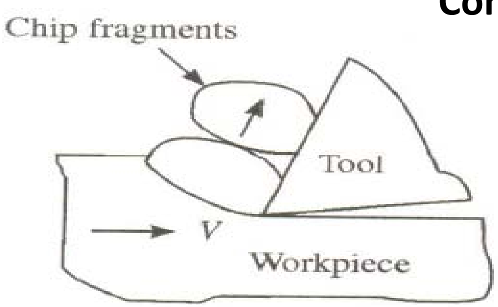


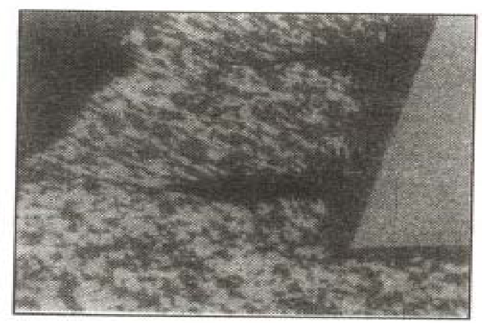
(a) **Continuous chip,**





Continuous chip with built-up-edge





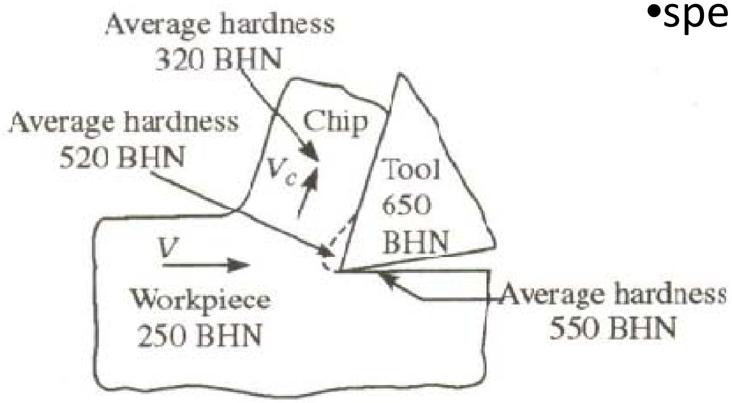
(c)

Discontinuous chip

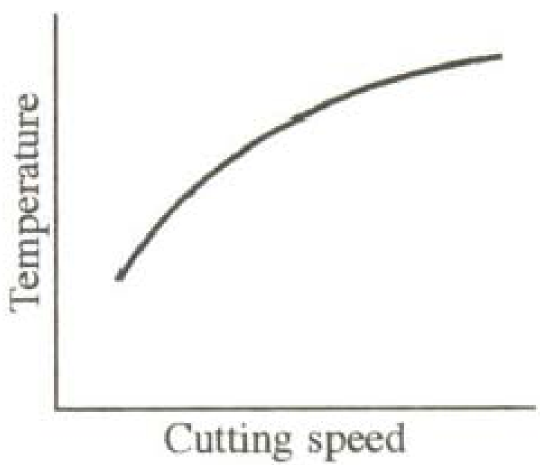
Formation of chip and its factors

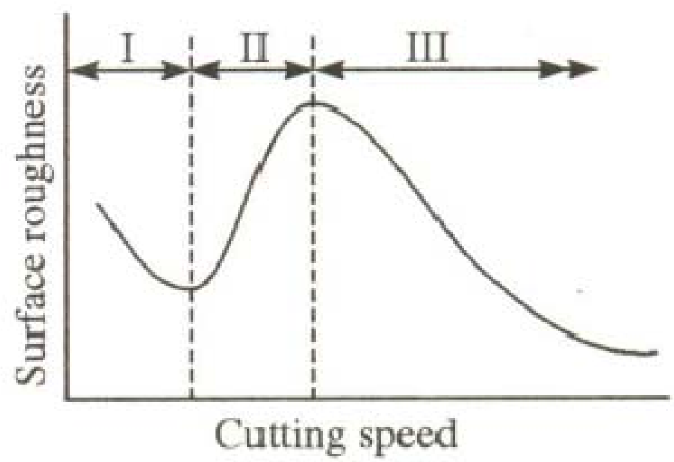
Factors	*Type of chip*		
	Continuous	*Continuous with B.U.E*	*Discontinuous*
Material	Ductile	Ductile	Brittle
Tool :			
Rake angle	Large	Small	Small
Cutting edge	Sharp	Dull	–
Cutting condition:			
Speed	High	Low	Low
Feed	Low	High	High
Friction	Low	High	–
Cutting fluid	Efficient	Poor	–

Type of chips



- speed - recrystalization temperature
  - Above recrystal temp – strain-hardening is neglected
  - Low recrystal temp – strain hardening is high
  - Same – BUE is formed





Influence of cutting speed and Roughness

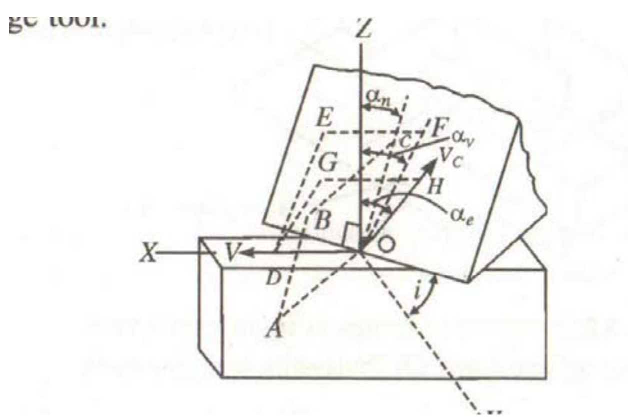
- Region 1 – Ra is poor, discontinuous chip, as speed increases Ra improves from discontinuous to semi discontinuous
- Region 2 – BUE is formed and continuous till recrystalization temperature
- Region 3 - Continuous chips with out BUE so good Ra

Tool Geometry

- Cutting process is influenced by the inclination of the cutting edge and orientation of rake and flank face.
- Orientation define we need reference plane and axes.
- Important – rake face inclination

Rake angle can be measured in

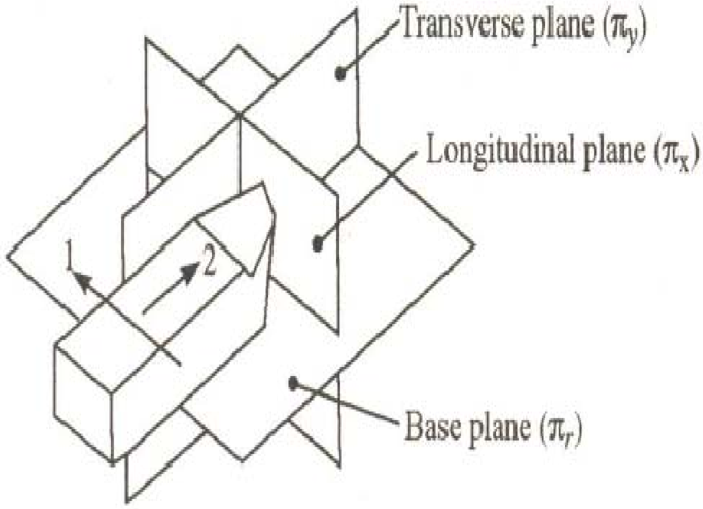
- A plane normal to the cutting edge and perpendicular to the plane containing cutting edge – OABC
- A plane parallel to the cutting velocity vector and perpendicular to the plane containing the cutting edge – ODEF
- A plane containing the cutting velocity and chip velocity – ODGH as shown in fig



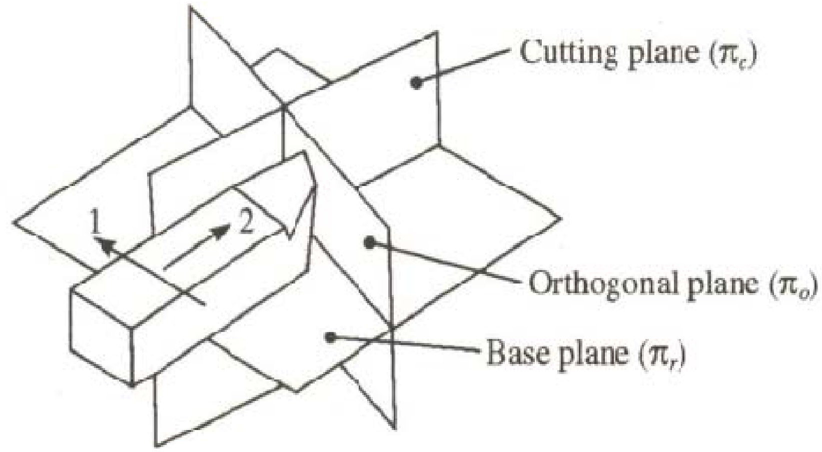
Single edge cutting tool

- In oblique cutting, three different values of rake angle is obtained
- They are normal rake, velocity rake and effective rake.
- More cutting edges are involved the cutting tool becomes very complex
- Different system are followed
  - **ASA/Co-ordinate system**
  - **Continental/Orthogonal system - German**
  - **Maximum rake system/British**
  - **Normal rake system/International**

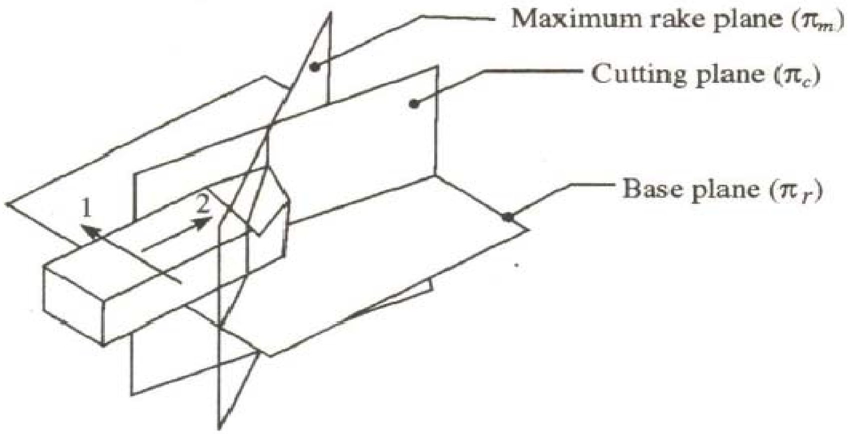
Reference planes



Reference planes in co-ordinate system



Reference planes in orthogonal system
(1) Longitudinal (2) transfer feed directions



Reference planes in normal rake systems
(1) Longitudinal (2) Transverse feed directions

Third plane is in the direction of the Max slope of the rake face

Normal rake system

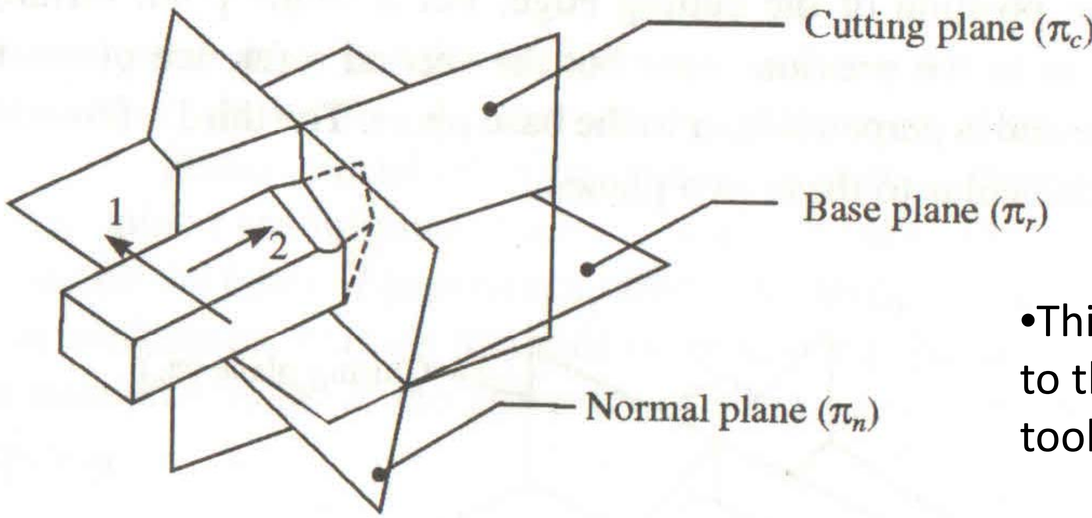
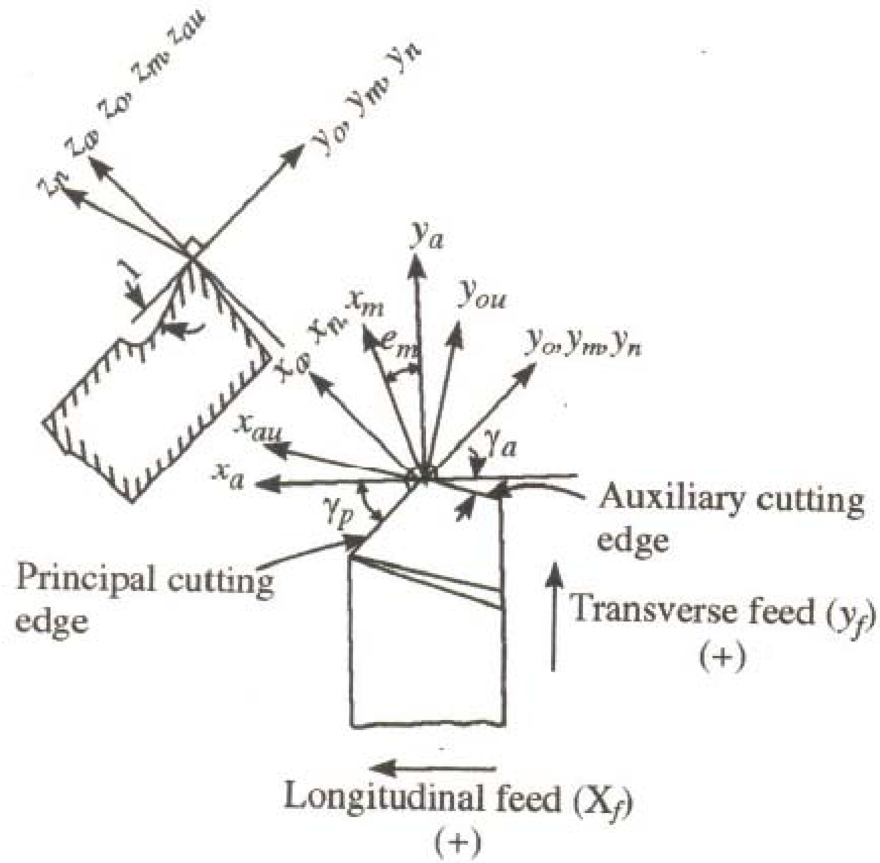


Fig. 3.2 (*d*) Reference planes in normal rake systems
(1) Longitudinal (2) Transverse feed directions

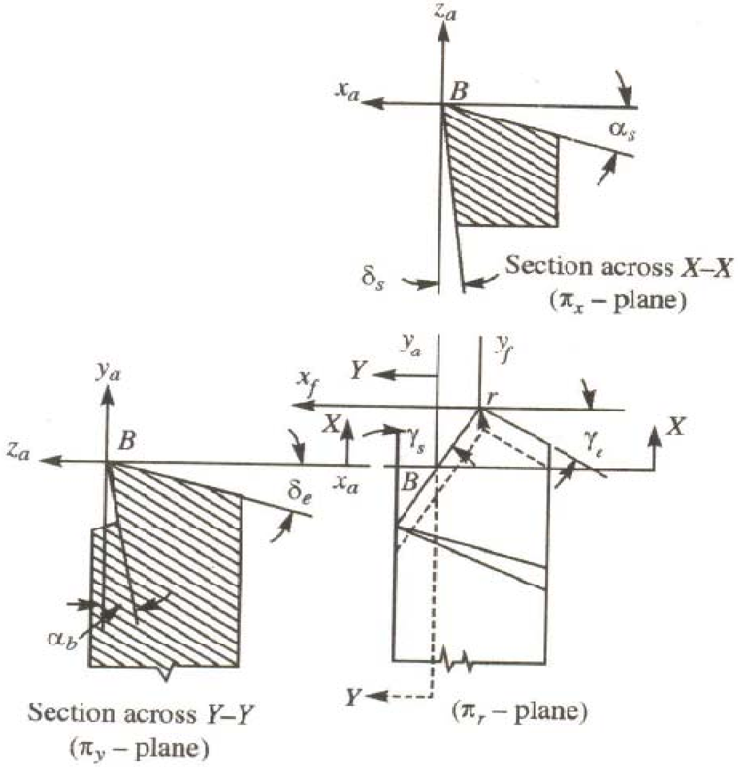
- Third plane is perpendicular to the cutting edge of the tool

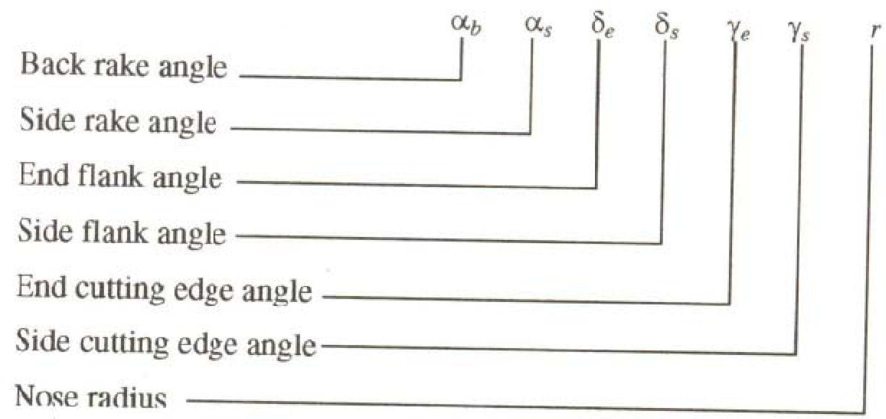
System of axes



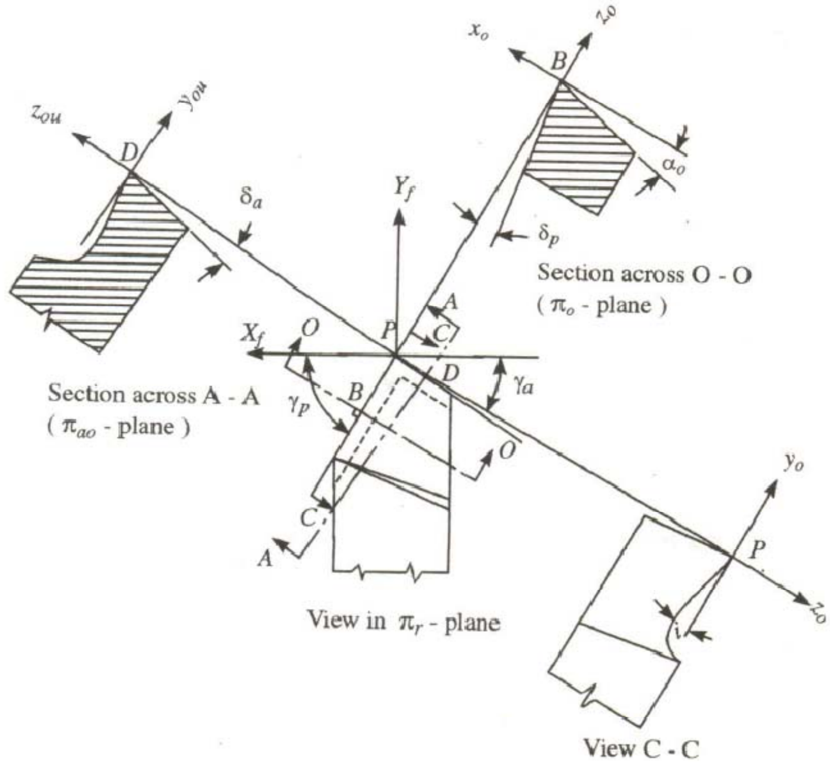
- These are not the cartesian co-ordinate axes but traces of the reference plane.
- The auxiliary cutting edge and auxiliary flank angles are also shown

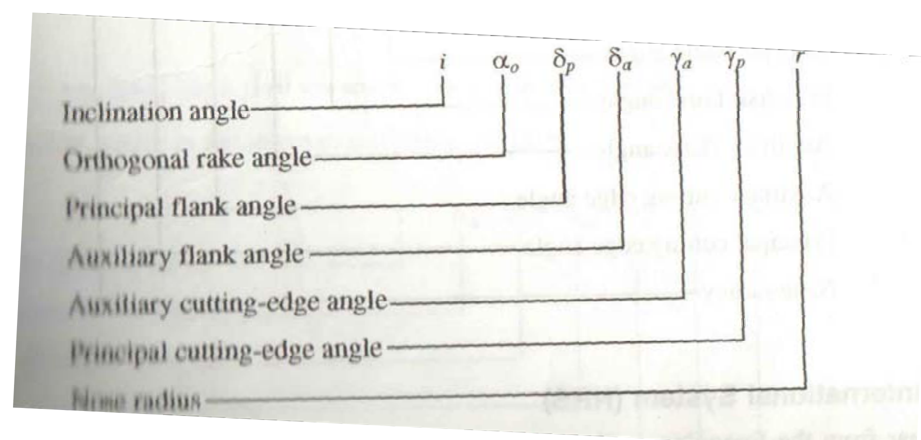
ASA/Co-ordinate system

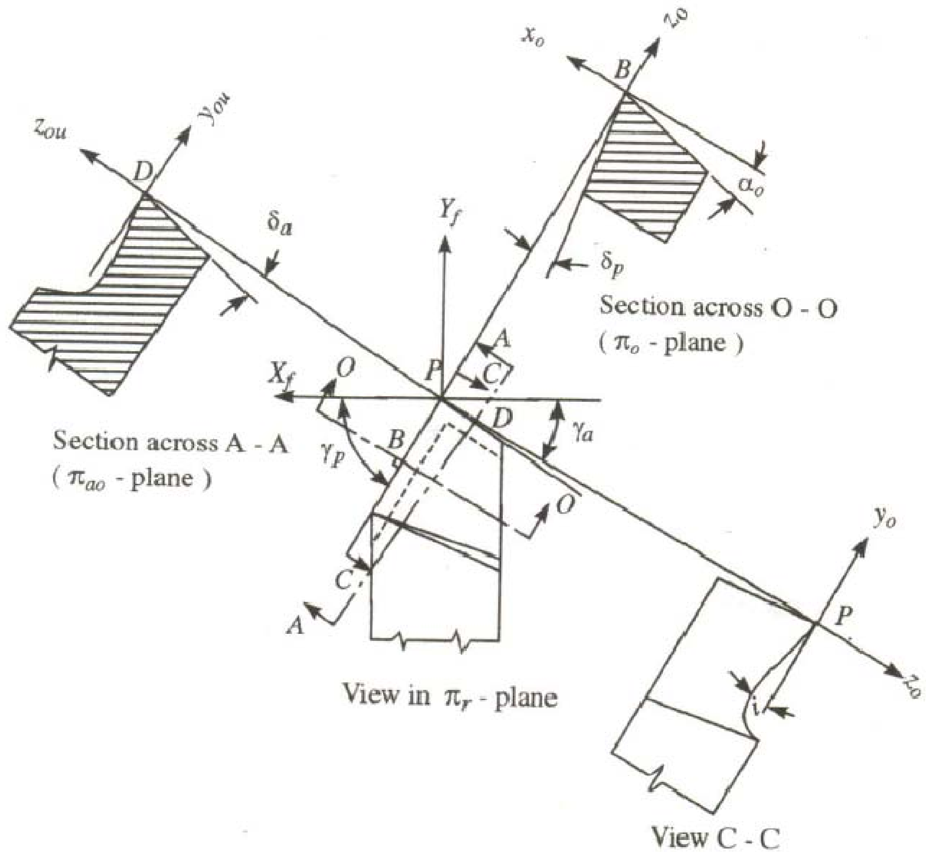




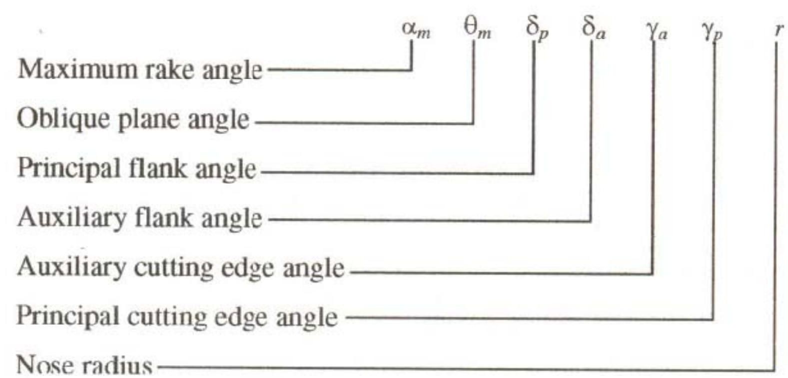
Singlegdnt tod specification in Continental system (ORS)

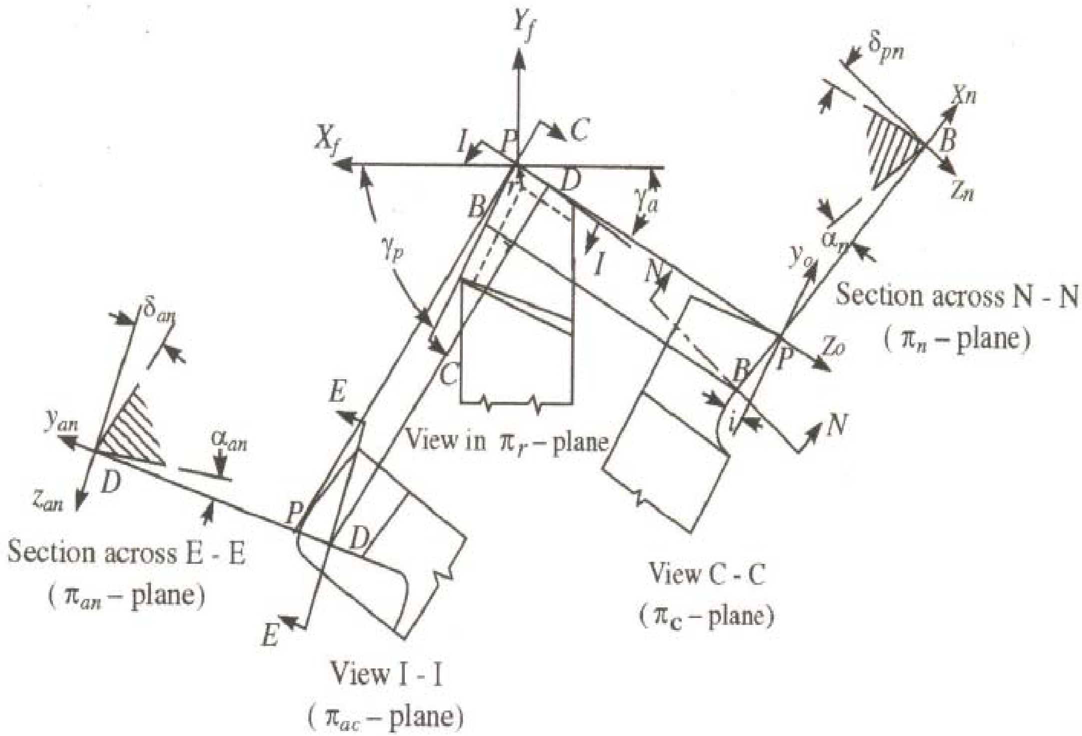




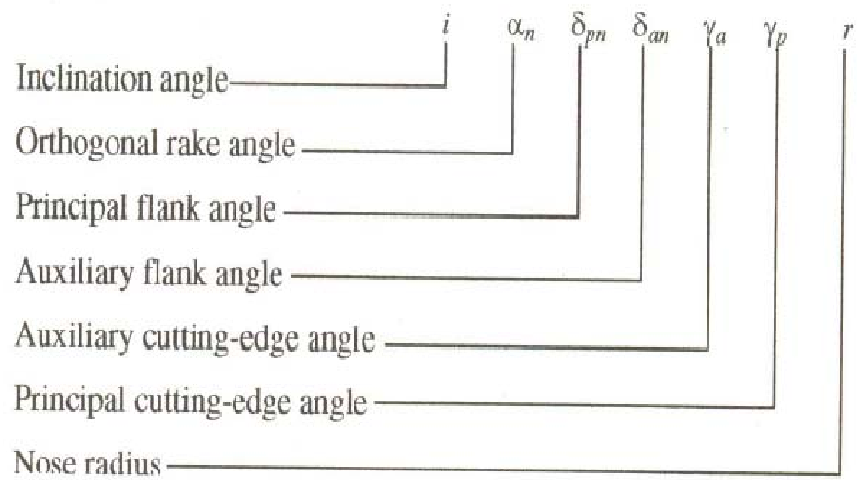


Single-point tool specification in British system (MRS)

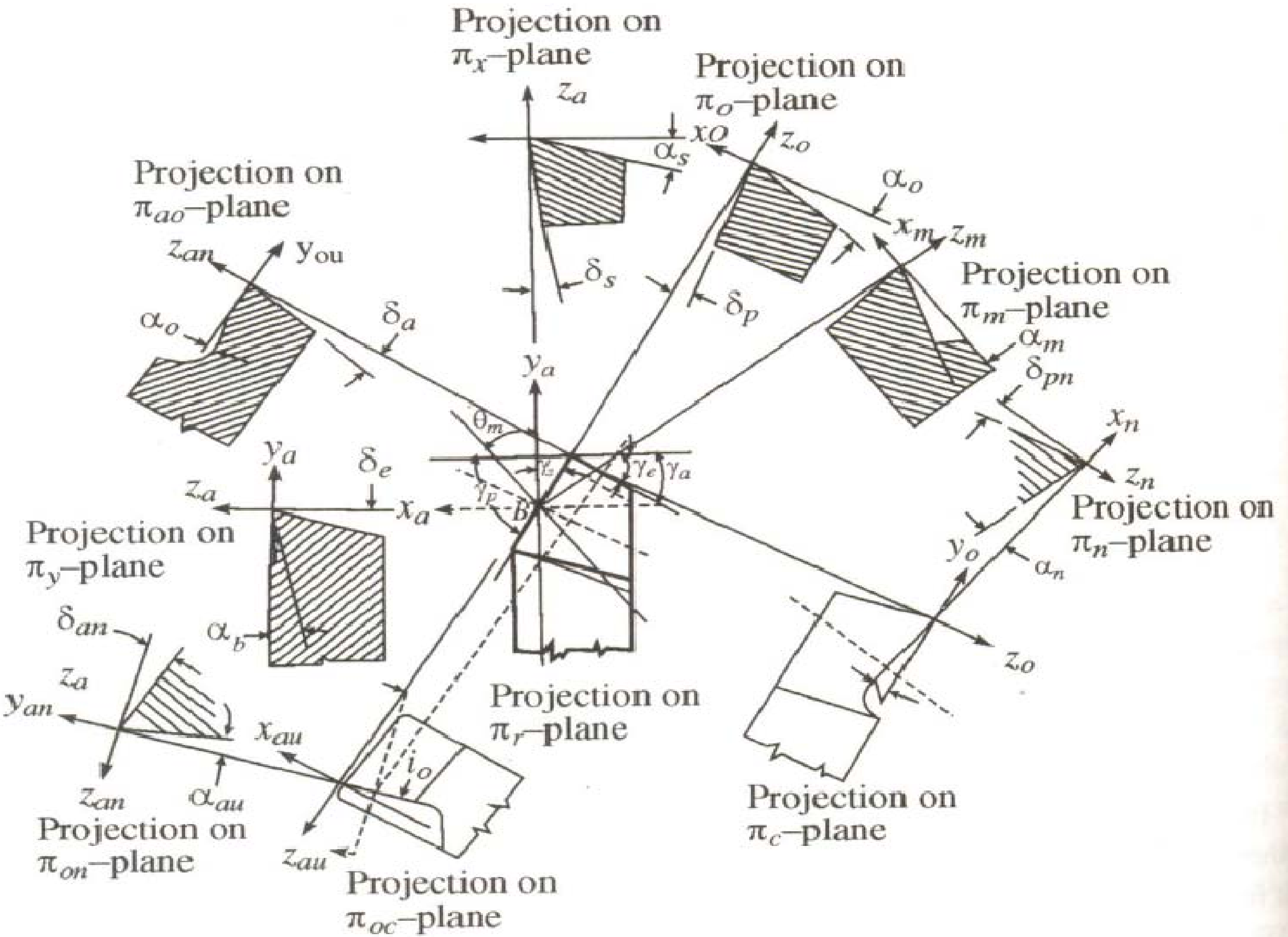




Single-point tool specification in International system (NRS)



Single-point tool specification in American continental system (MRS)



Different nomenclature systems

Table 3.1 Different Nomenclature Systems for Single-point Tools

Tool Section	*American System*	*Continental System*	*British System*	*International System*
Rake face	α_b, α_s	i, α_o	α_m, θ_m	i, α_n
Flank face	δ_e, δ_s	δ_a, δ_p	δ_a, δ_p	δ_{an}, δ_{pn}
Cutting edge	γ_e, γ_s	γ_a, γ_p	γ_a, γ_p	γ_a, γ_p
Nose radius	r	r	r	r

Table 3.2 Sequence of Tool Angles in Different Systems

Systems	*Specifications*
American (ASA)	$\alpha_b - \alpha_s - \delta_e - \delta_s - \gamma_e - \gamma_s - r$
Continental (ORS)	$i - \alpha_o - \delta_p - \delta_a - \gamma_a - \gamma_p - r$
British (MRS)	$\alpha_m - \theta_m - \delta_p - \delta_a - \gamma_a - \gamma_p - r$
International (NRS)	$i - \alpha_n - \delta_{pn} - \delta_{an} - \gamma_a - \gamma_p - r$

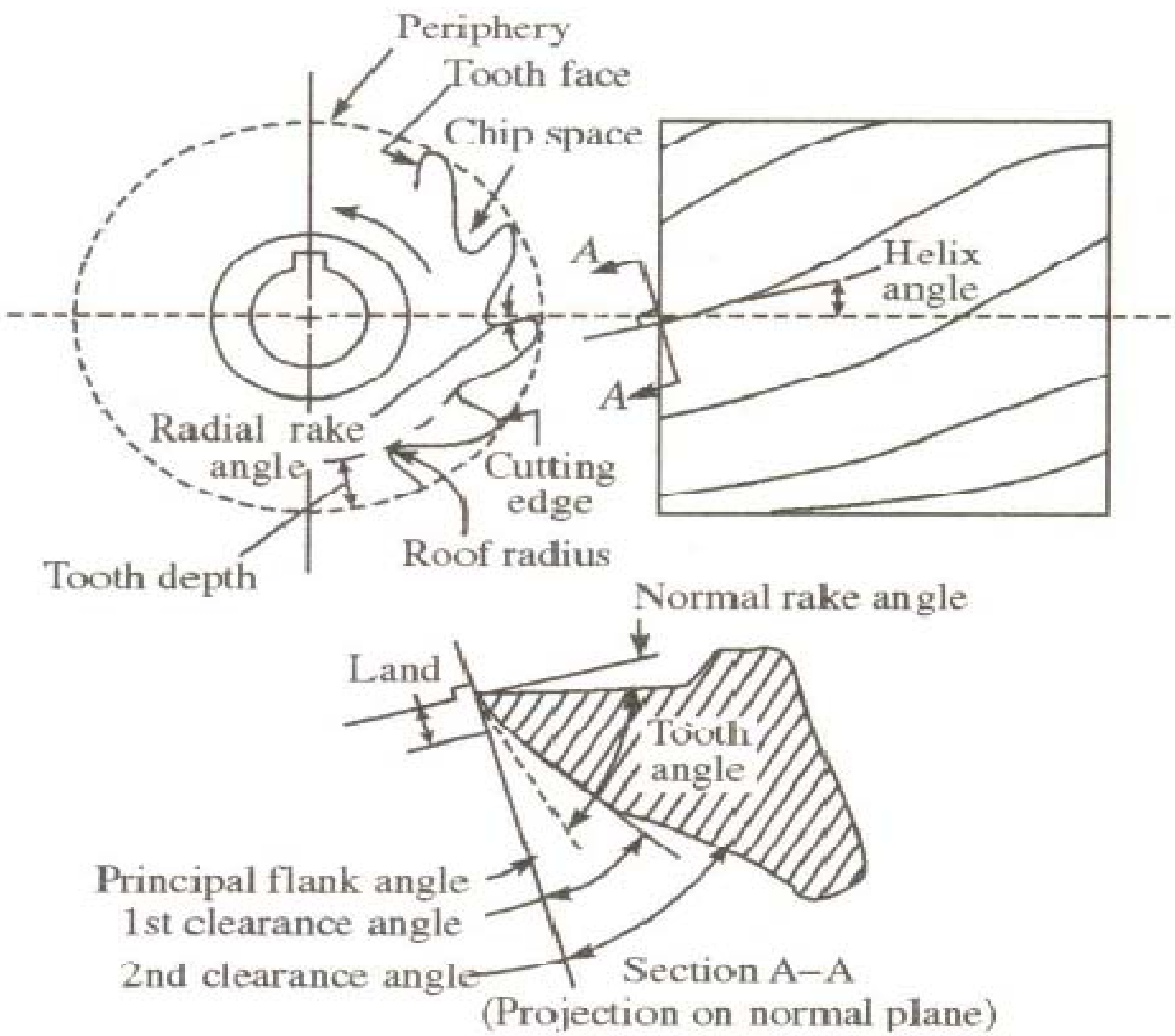
Selection of tool angles

- With zero inclination chip flows parallel to the work surface – chip disposal problem
- With inclination angle – chip flows – Cutting force, power and Ra is good
- Large – small rake angle
- Flank angle
- End Cutting-edge angles – provided clear the cutting edge from the machined surface and reduce tool chatter. Too large an angle, weak tool and affect heat conduction.
- Side cutting edge affects tool life

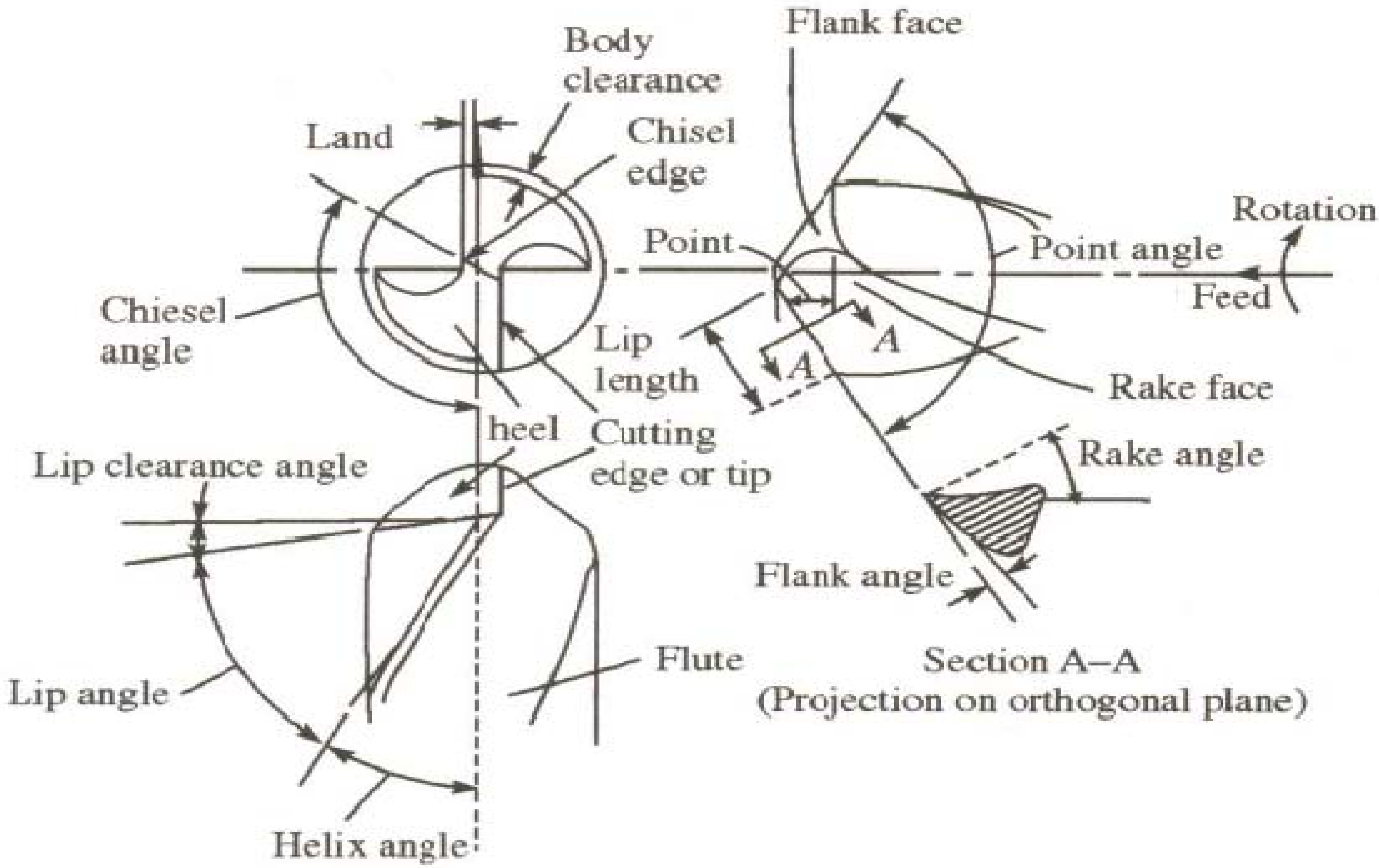
Table 3.3 Typical Tool Angles in ASA Specifications for Single-Point Turning Tools

Workpiece material	*Tool material*	*Tool angles (degrees)*					
		α_b	α_s	δ_e	δ_s	γ_e	γ_s
Mild steel	1. HSS	8	10	5	5	15	15
	2. Cemented carbide						
	(*i*) Brazed	0	6	5	5	15	15
	(*ii*) Throw-away	–5	–5	5	5	15	15
Cast iron	1. HSS	5	8	5	5	15	15
	2. Cemented carbide						
	(*i*) Brazed	0	6	5	5	15	15
	(*ii*) Throw-away	–5	–5	5	5	15	15
Aluminium alloys	1. HSS	20	15	12	10	5	5
	2. Cemented carbide						
	(*i*) Brazed	3	15	5	5	15	15
	(*ii*) Throw-away	0	5	5	5	15	15
Stainless steel	1. HSS	0	10	5	5	15	15
	2. Cemented carbide						
	(*i*) Brazed	0	6	5	5	15	15
	(*ii*) Throw away	–5	–5	5	5	15	15
Tool steel	1. HSS	–3	10	5	5	15	15
	2. Cemented carbide						
	(*i*) Brazed	0	–5	5	5	15	15
	(*ii*) Throw away	–5	–5	5	5	15	15

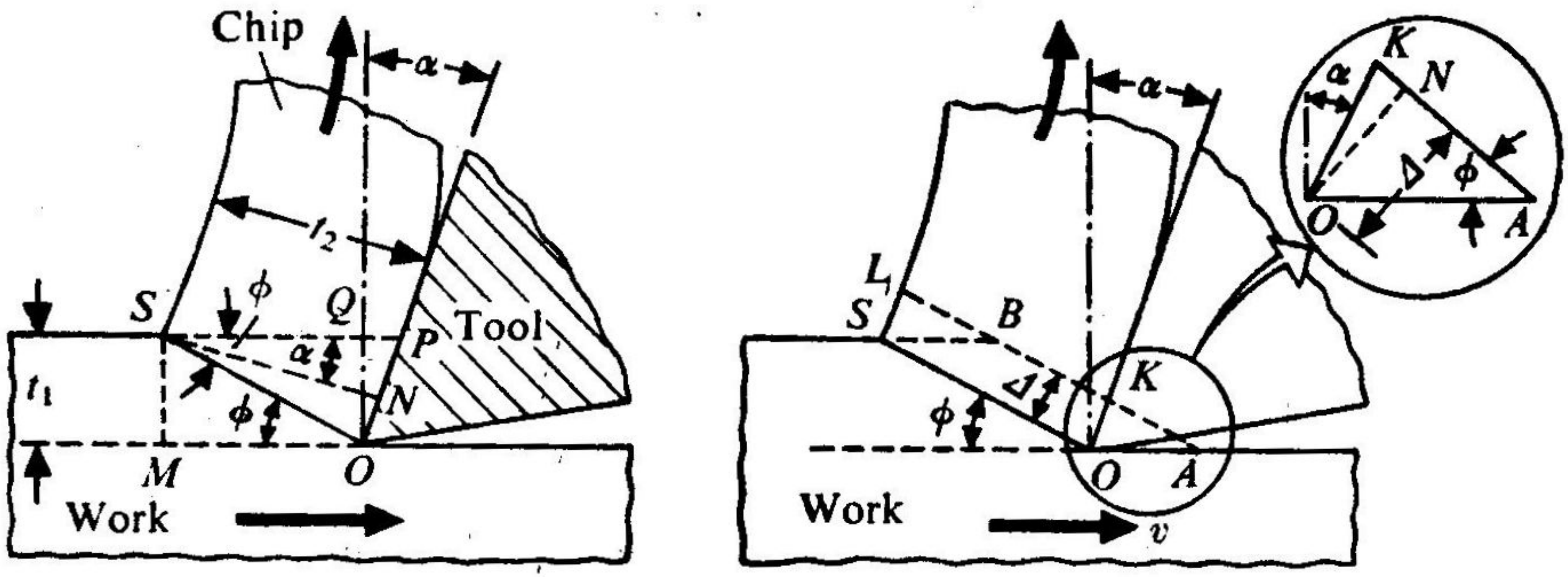
Geometry of helical milling cutter



Geometry of twist drill



Features of Orthogonal Chip Formation



(a) Geometry of orthogonal chip formation

(b) Determination of shear strain

Fig. 12: **Features of orthogonal chip formation.**

$$\angle PSN = \angle POQ = \alpha$$

$$\angle NSO = \angle PSO - \angle PSN = \varphi - \alpha$$

$$OS = \frac{SN}{Cos(\varphi - \alpha)} = \frac{t_2}{Cos(\varphi - \alpha)}$$

$$= \frac{SM}{Sin\ \varphi} = \frac{t_1}{Sin\ \varphi}$$

$$\frac{t_1}{t_2} = \frac{Sin\ \varphi}{Cos\ (\varphi - \alpha)} = r \tag{4.1}$$

r = Cutting Ratio

$$\tan \varphi = \frac{r\ Cos\ \alpha}{1 - r\ Sin\ \alpha} \tag{4.2}$$

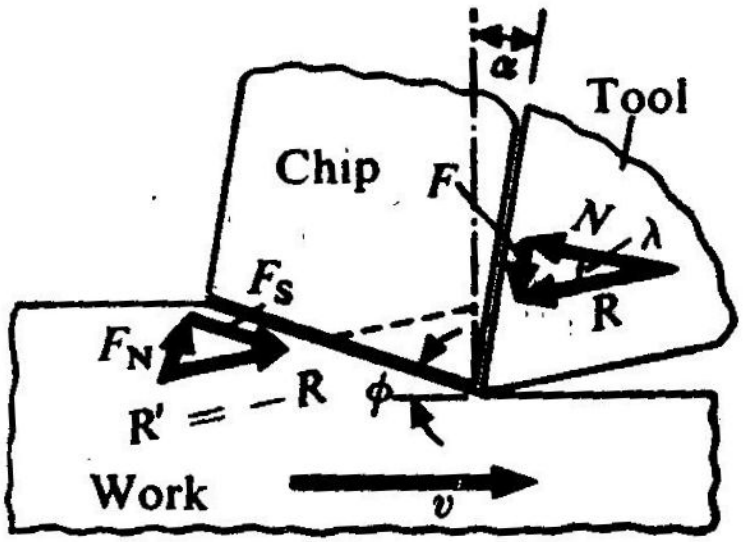
$$\frac{\pi}{2} + \alpha = \angle OKA + \varphi$$

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

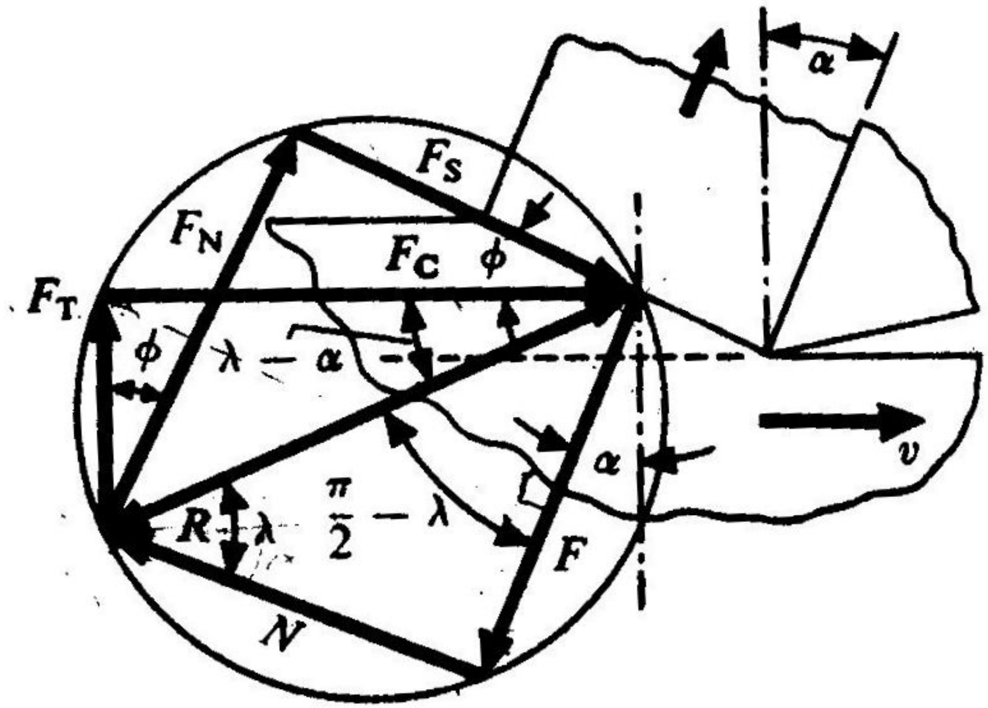
$$\gamma = \frac{AK}{\Delta} = \frac{AN + NK}{ON} = Cot\ \varphi + \tan \angle KON$$

$$\gamma = Cot\ \varphi + \tan(\varphi - \alpha) \tag{4.3}$$

Mechanics of Chip Formation



(a) Equilibrium of chip



(b) Merchant's circle diagram

Fig. 13: Forces in chip formation.

Express *Fc in Fs and Fn*

Ft in Fn and Fs

F in Fc and Ft

N in Fc and Ft

Fs in Fc and Ft

Fn in Fc and Ft

R in F and angles

Fc in R and friction and rake angles

Ft in R and friction and rake angles

$$\frac{F}{N} = \mu \qquad (4.4)$$

$$\mu = \tan\lambda \qquad (4.5)$$

$$F_C = F_S \, Cos\, \varphi + F_N \, Sin\, \varphi \qquad (4.6a)$$

$$F_T = F_N \, Cos\, \varphi - F_S \, Sin\, \varphi \qquad (4.6b)$$

$$F = F_C \, Sin\, \alpha + F_T \, Cos\, \alpha \qquad (4.7a)$$

$$N = F_C \, Cos\, \alpha - F_T \, Sin\, \alpha \qquad (4.7b)$$

$$F_S = F_C \, Cos\, \varphi - F_T \, Sin\, \varphi \qquad (4.8a)$$

$$F_N = F_C \, Sin\, \varphi + F_T \, Cos\, \varphi \qquad (4.8b)$$

$$R = \frac{F_S}{Cos\,(\varphi + \lambda - \alpha)} \qquad (4.9)$$

$$F_C = R \, Cos\,(\lambda - \alpha) \qquad (4.10a)$$

$$F_T = R \, Sin\,(\lambda - \alpha) \qquad (4.10b)$$

$$\mu = \frac{F}{N} = \frac{F_C \, Sin\, \alpha + F_T \, Cos\, \alpha}{F_C \, Cos\, \alpha - F_T \, Sin\, \alpha} \tag{4.11}$$

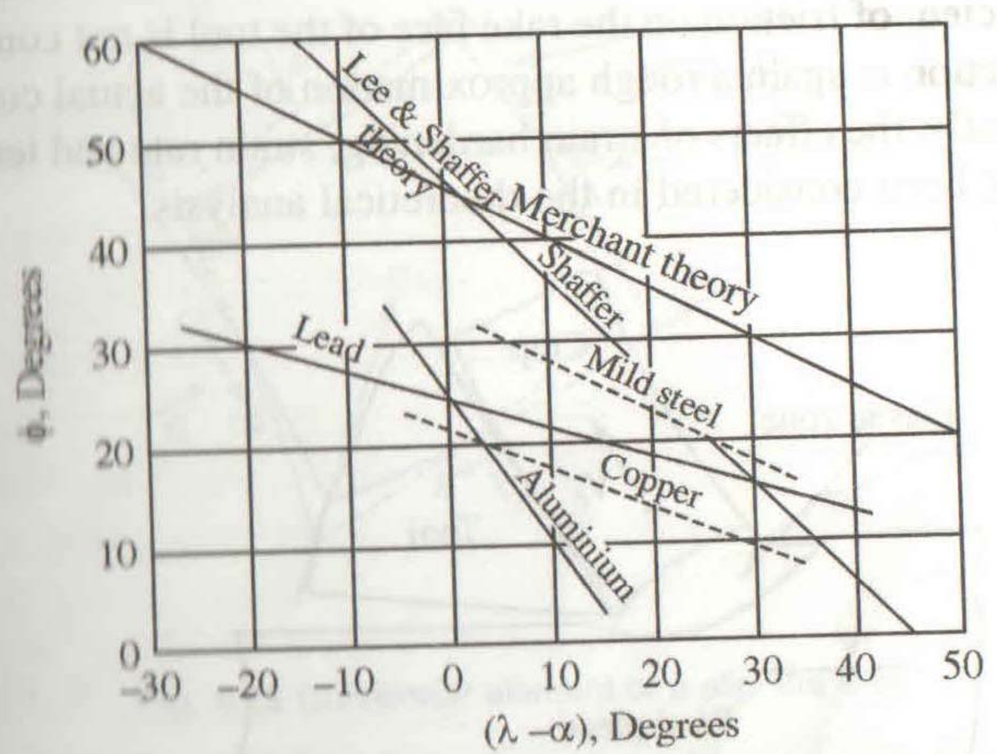
$$F_S = \frac{w \, t_1 \, \tau_S}{Sin\, \varphi} \tag{4.12}$$

$$F_C = \frac{F_S \, Cos\, (\lambda - \alpha)}{Cos\, (\varphi + \lambda - \alpha)}$$

$$F_C = w \, t_1 \, \tau_S \, Cos\, (\lambda - \alpha) \left[\frac{1}{Sin\, \varphi \, Cos\, (\varphi + \lambda - \alpha)} \right] \tag{4.13}$$

$$W = F_C \, v = v \, w \, t_1 \tau_S \, Cos\, (\lambda - \alpha) \left[\frac{1}{Sin\, \varphi \, Cos\, (\varphi + \lambda - \alpha)} \right] \tag{4.14}$$

$$W\, (\varphi) = \frac{Constant}{Sin\, \varphi \, Cos\, (\varphi + \lambda - \alpha)}$$


Lee & Shaffer theory
Merchant theory
Shaffer
Lead
Mild steel
Copper
Aluminium
ϕ, Degrees
(λ −α), Degrees
60
50
40
30
20
10
0
−30
−20
−10
0
10
20
30
40
50

$W(\varphi)$ will be minimum when the denominator is maximum. Differentiating the denominator with respect to φ and equating it to zero.

$$Cos\,\varphi\, Cos\,(\varphi + \lambda - \alpha) - Sin\,\varphi\, Sin\,(\varphi + \lambda - \alpha) = 0$$

$$Cos\,(2\,\varphi + \lambda - \alpha) = 0$$

$$2\,\varphi + \lambda - \alpha = \frac{\pi}{2} \tag{4.15}$$

Using equation (4.15) in equation (4.13), we get

$$F_C = \frac{2\,w\,t_1\,\tau_S\,Cos\,(\lambda - \alpha)}{1 - Sin\,(\lambda - \alpha)} \tag{4.16}$$

τ_S can be expressed as

In reality shear stress is not completely independent of normal stress

$$\tau_S = \tau_{S_0} + k_1\,\sigma \tag{4.17}$$

During machining, σ is given by

Where σ = normal stress acting on the shear plane

$$\sigma = \frac{F_N}{w\,t_1 / Sin\,\varphi}$$

So, the shear stress τ_S can be expressed as

$$\tau_S = \tau_{S_0} + k_1 \frac{F_N}{w\, t_1 / \sin\varphi}$$

From the circle diagram (Fig. 13 b), we can write

$$\frac{F_N}{F_S} = \tan(\varphi + \lambda - \alpha)$$

$$F_N = F_S \tan(\varphi + \lambda - \alpha)$$

Using this in the expression for τ_S and writing τ_S in terms of F_S, we get

$$\frac{F_S}{w\, t_1 / \sin\varphi} = \tau_{S_0} + k_1 \frac{F_S \tan(\varphi + \lambda - \alpha)}{w\, t_1 / \sin\varphi}$$

$$\frac{F_S}{w\, t_1 / \sin\varphi}\left[1 - k_1 \tan(\varphi + \lambda - \alpha)\right] = \tau_{S_0}$$

$$F_S = \frac{w\, t_1\, \tau_{s_0}}{Sin\,\varphi\,[1 - k_1 \tan(\varphi + \lambda - \alpha)]}$$

Using equation (4.9) and (4.10 a) along with the foregoing equation, we obtain

$$F_C = \frac{w\, t_1\, \tau_{s_0} Cos(\lambda - \alpha)}{Sin\,\varphi\,[Cos(\varphi + \lambda - \alpha) - k_1\, Sin\,(\varphi + \lambda - \alpha)]} \qquad (4.18)$$

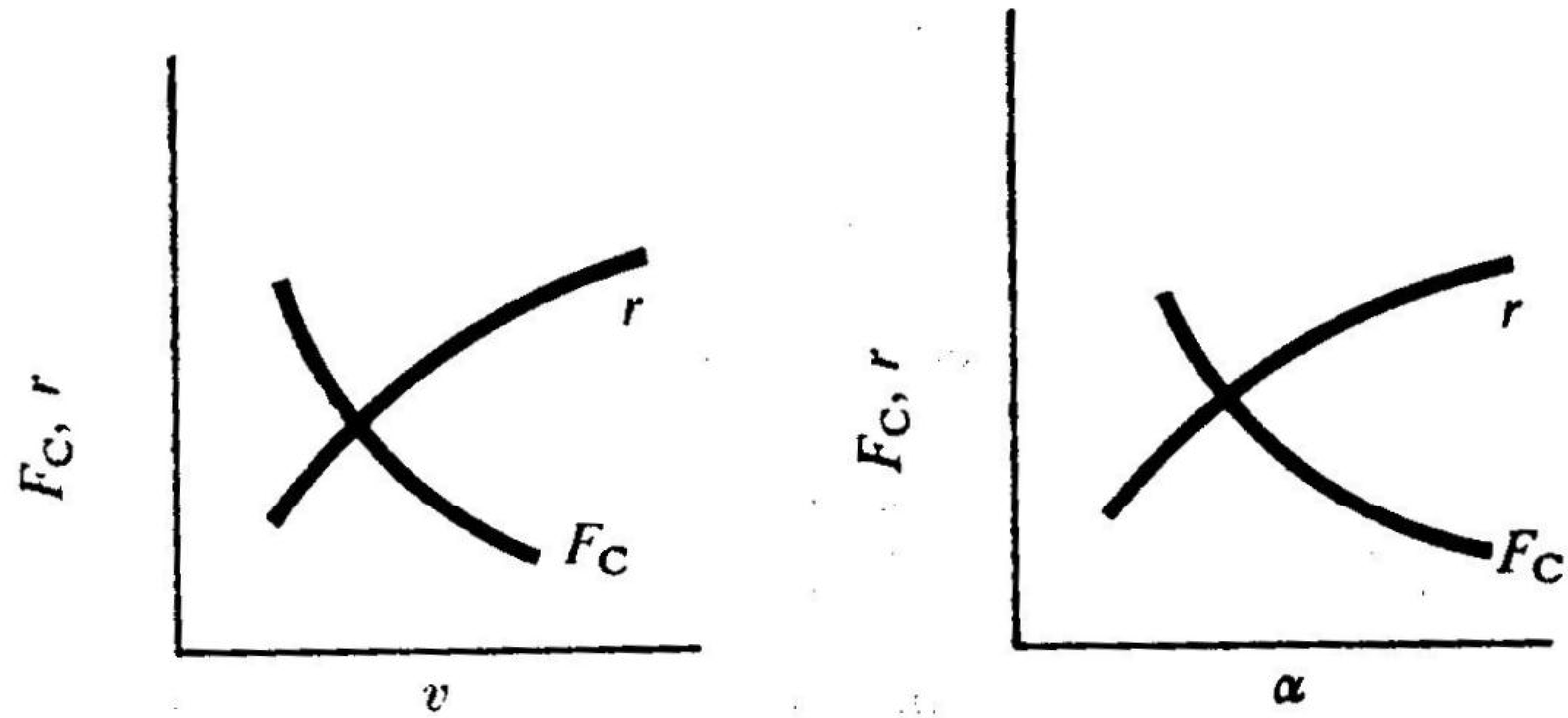
Now, applying the principle of minimum energy consumption, we finally get

$$2\varphi + \lambda - \alpha = C_m \qquad (4.19)$$

Where $C_m = Cot^{-1} k_1$ and is constant for the work material. C_m is sometimes called the machining constant.

It is clear α increases ϕ increases and μ increases ϕ decreases
As the cutting speed increases, μ decerases and so Fc too

Effect of Cutting Parameters on Chip Formation



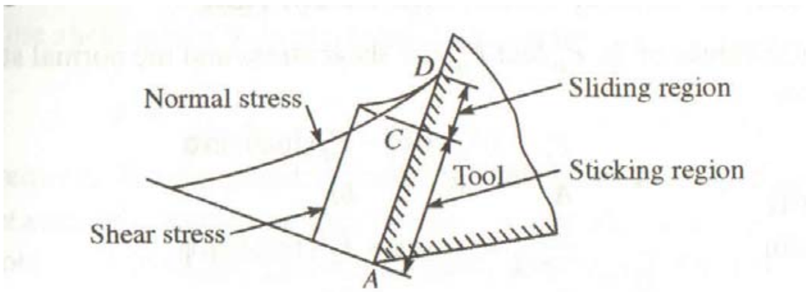
(a) Effect of v on F_C and r (b) Effect of α on F_C and r

Fig. 15: Effect of cutting parameters on chip formation.

During an orthogonal machining operation on mild steel, the results obtained are uncut thickness = 0.25 mm, chip thickness = 0.75 mm, w = 2.5 mm, rake angle is zero and Cutting force = 950 N and thrust force = 475 N.

Determine the co-efficient of friction
Determine the ultimate shear stress of the work material

Determination of co-efficient of friction



- The distribution of shear and normal stress on the rake face is not uniform.
- Tip to C, normal stress is high so sticking friction is high
- C to D, curling – sliding friction
- When normal force is small, F is proportional to normal load. Independent of apparent area. Elastic – plastic region.
- When normal force is high, plastic deformation at sliding interface so friction force is independent of normal load

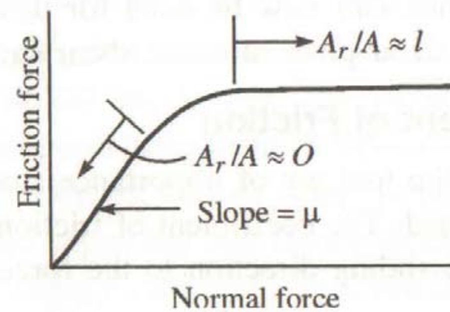


Fig. 4.3 Variation of friction force with normal force

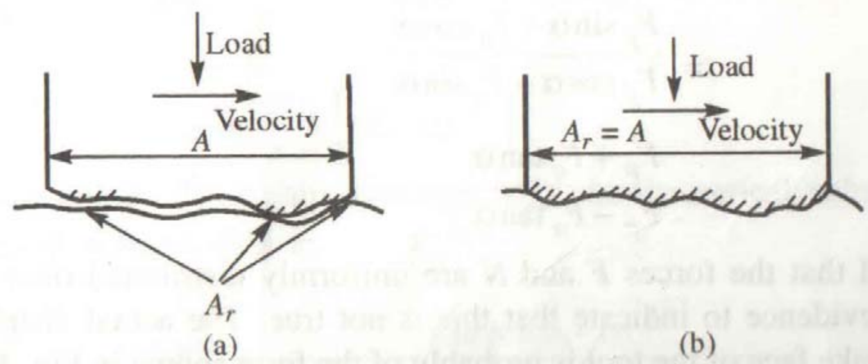
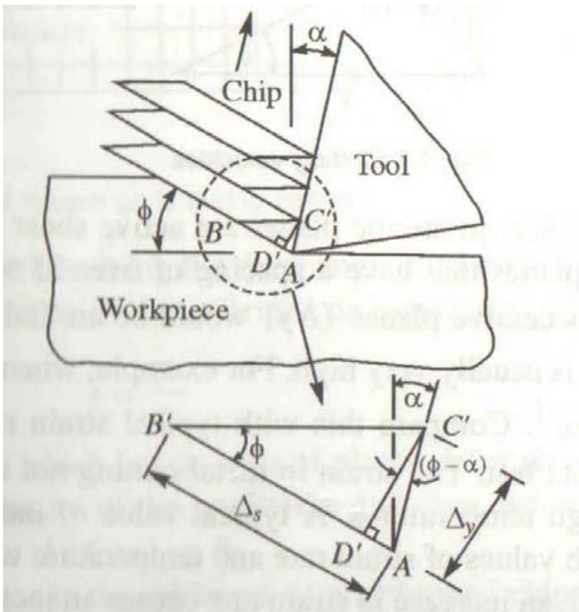


Fig. 4.4 Contact between mating surfaces in dry friction

Strain rate calculation :



$$\dot{\gamma} = \left(\frac{\Delta s}{\Delta t}\right) \cdot \frac{1}{\Delta y} = \frac{Vs}{\Delta y}$$

$$\dot{\gamma} = \frac{\cos\alpha}{\cos(\phi - \alpha)} \cdot \frac{V}{\Delta y}$$

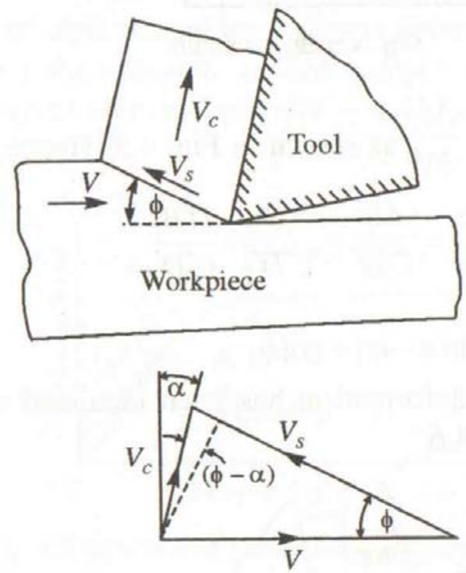


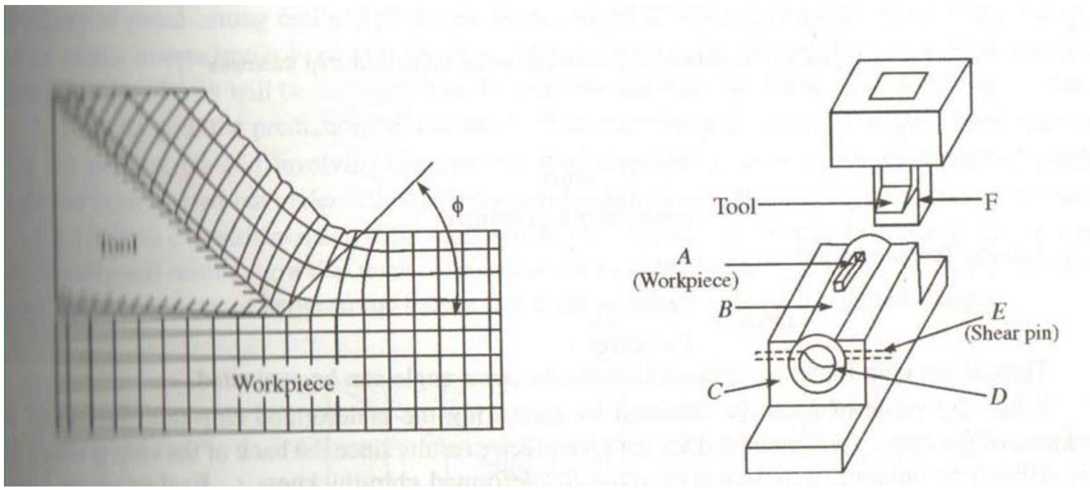
Fig. 4.7 Cutting velocities

- Strain rate = ((delta S)/(delta y))*(1/(delta t))
- Strain rate can be expressed in shear velocity
- Need for velocity diagram

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

Measurement of Shear angle

- Direct Method
- Indirect Method



Step 1 : determine r ; ltb = (ltb) of chip we calculate tc
Step 2 : AB = t/sin (ϕ) = tc/cos (ϕ-α) we get ϕ

Alternative method
Weight of the chip = $\rho l_c t_c b_c = \rho ltb$

Machining Constant

Table : 2 Machining constant C_m (degrees)

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

Shear Angle Relationships

Table : 3 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 $W = F_C v$ (4.20)

Specific Energy $U_C = \dfrac{F_C}{w\, t_1}$ (4.21 a)

$W = U_C Q$ (4.21 b)

$U_C = U_0 \tilde{t}_1^{-0.4}$ (4.22)

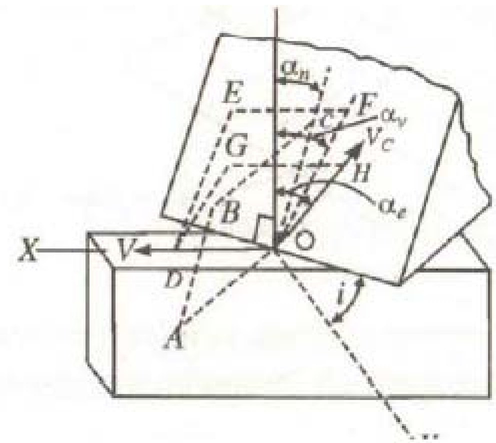
$\tilde{t}_1$ = Uncut thickness, mm

Q = Volume rate of material removal

Table : 4 Values of U_0 for various materials

Material	Hardness BHN	Hardness R_C	U_0 (J/mm^3)
Steel	85–200		1.4
		35–40	1.6
		40–50	1.9
		50–55	2.4
		55–58	4.0
Stainless steel	135–275		1.4
		30–45	1.6
Cast iron	110–190		0.8
	190–320		1.6
Al alloys	30–150		0.35
Copper		$80R_B$	1.2
Copper alloys		$10–80R_B$	0.8
		$80–100R_B$	1.2

Mechanics of oblique cutting



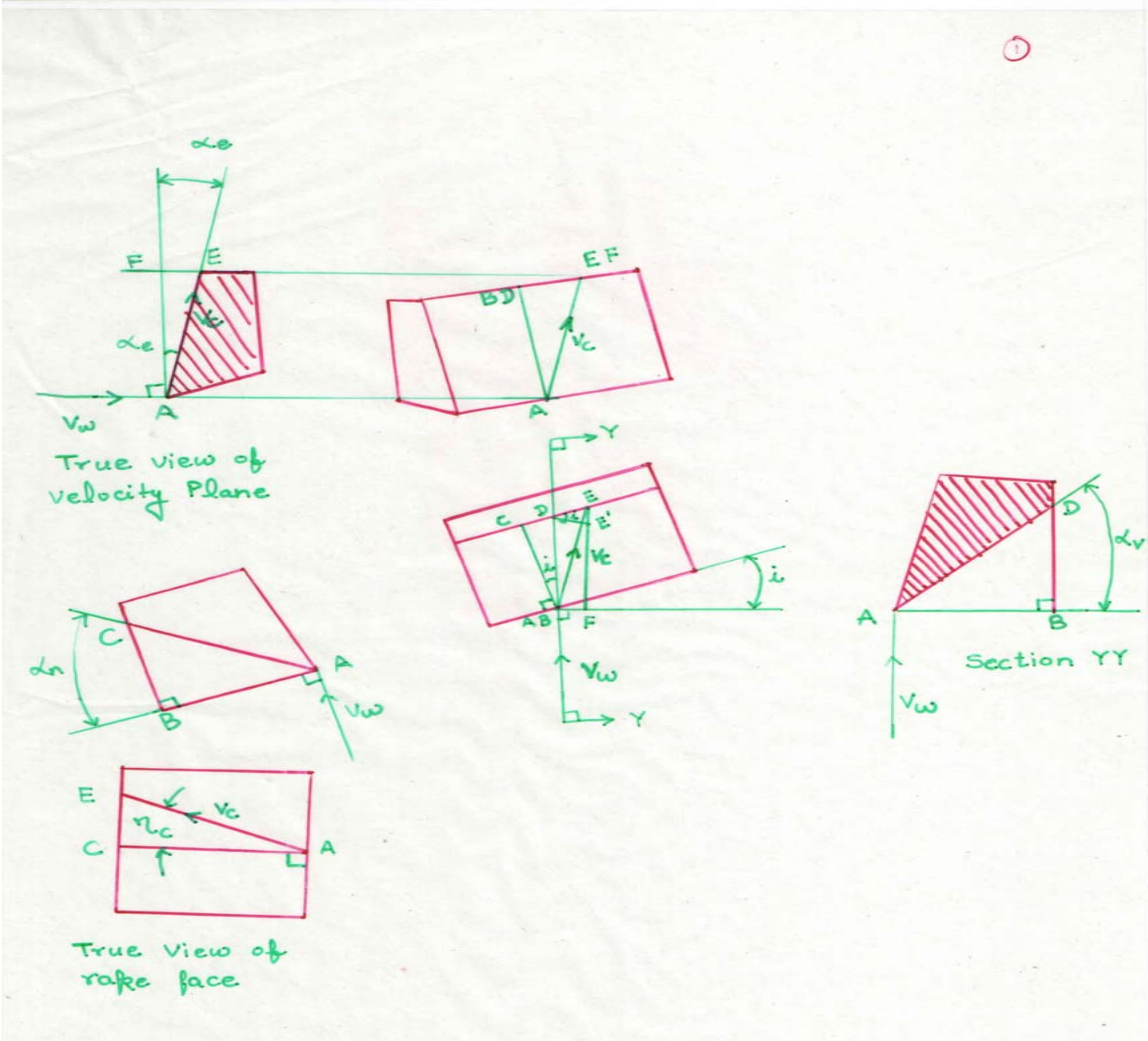
When cutting edge inclined by I, then following rake angle comes into existence

1. Normal rake angle
2. Velocity rake angle
3. Effective rake angle

Because of this two shear angle

1. Normal shear angle – angle from shear plane to plane containing the newly formed work surface measured in a plane normal to cutting edge
2. Effective shear angle – angle is measured in the plane containing the cutting velocity and chip velocity vector

Relationship between different rake angles and inclination



(2)

1) $$\tan \alpha_v = \frac{BD}{AB} = \frac{CB}{AB} \cdot \frac{BD}{CB}$$

$$= \tan\alpha_n \cdot \frac{1}{\frac{CB}{BD}}$$

$$\tan\alpha_v = \frac{\tan\alpha_n}{\cos i}$$

2) $$\sin\alpha_e = \frac{FE}{AE}$$

$$= \frac{FE' + EE'}{AE} = \frac{BD + EE'}{AE}$$

$$= \frac{(BD + DE \sin i)}{(AE)}$$

$$= \frac{BD \; (BD + DE \sin i)}{BD \; (AE)} \; *$$

$$= \frac{BD^2 + BD \cdot DE \sin i}{BD \cdot AE}$$

$$= \frac{BD^2 + DE \cdot CD}{BD \cdot AE}$$

$$= \frac{CD^2 + CB^2 + DE \cdot CD}{BD \cdot AE}$$

$$= \frac{CD(CD + DE) + CB^2}{BD \cdot AE}$$

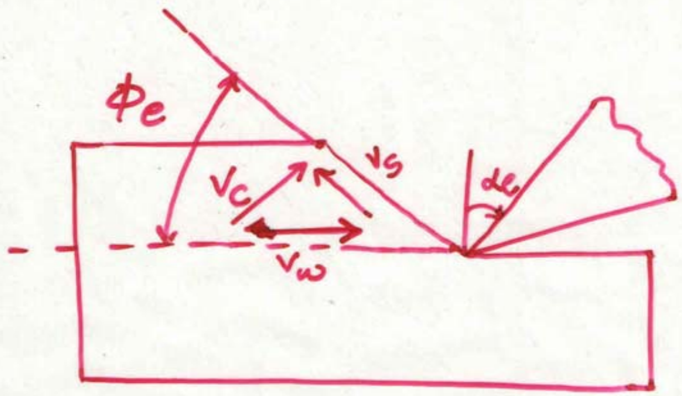
$$= \frac{CD(CD + DE)}{DB \cdot AE} + \frac{CB^2}{DB \cdot AE}$$

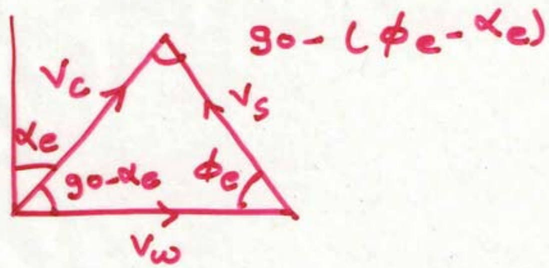
$$= \frac{CD}{DB} \cdot \frac{CE}{EA} + \frac{CB}{DB} \cdot \frac{CB}{EA}$$

$$= \frac{CD}{DB} \cdot \frac{CE}{EA} + \frac{CB}{DB} \cdot \frac{CA}{AB} \cdot \frac{CB}{CA} \; *$$

$$\sin\alpha_e = \sin i \, \sin \eta_c + \cos i \, \cos \eta_c \, \sin\alpha_n$$

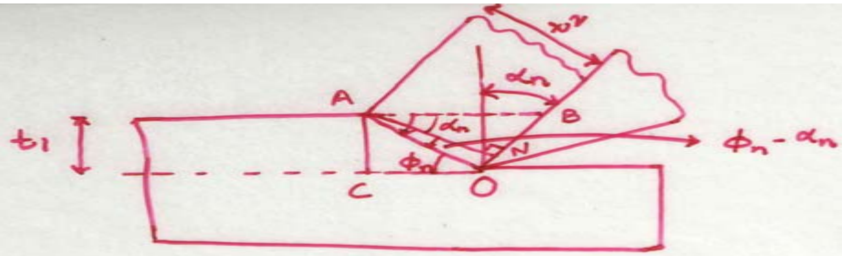
Velocity Relationship :- Sine rule.





$$\frac{V_s}{\sin(90-\alpha_e)} = \frac{V_c}{\sin\phi_e} = \frac{V_w}{\sin(90-(\phi_e-\alpha_e))}$$

$$\frac{V_s}{\cos\alpha_e} = \frac{V_c}{\sin\phi_e} = \frac{V_w}{\cos(\phi_e-\alpha_e)}$$



$$AC = t_1$$

$$AN = t_2$$

$$r = \frac{t_1}{t_2} = \frac{AC}{AN} \qquad \text{— (1)}$$

$$\cos(\phi_n - \alpha_n) = \frac{AN}{OA} = \frac{t_2}{OA}$$

$$t_2 = OA \cos(\phi_n - \alpha_n) \qquad \text{— (2)}$$

$$\sin\phi_n = \frac{AC}{OA} = \frac{t_1}{OA}$$

$$t_1 = OA \sin\phi_n \qquad \text{— (3)}$$

$$r = \frac{AC}{AN} = \frac{t_1}{t_2} = \frac{OA \sin\phi_n}{OA \cos(\phi_n - \alpha_n)}$$

$$r = \frac{\sin\phi_n}{\cos(\phi_n - \alpha_n)}$$

$$\frac{1}{r} = \frac{\cos(\phi_n - \alpha_n)}{\sin\phi_n}$$

$$= \frac{\cos\phi_n \cos\alpha_n + \sin\phi_n \sin\alpha_n}{\sin\phi_n}$$

$$= \frac{\cos\alpha_n + \tan\phi_n \sin\alpha_n}{\tan\phi_n}$$

$$\tan\phi_n = r\cos\alpha_n + r\tan\phi_n \sin\alpha_n$$

$$\tan\phi_n (1 - r\sin\alpha_n) = r\cos\alpha_n$$

$$\tan\phi_n = \frac{r\cos\alpha_n}{1 - r\sin\alpha_n}$$

Heat Generation and Cutting Tool Temperature

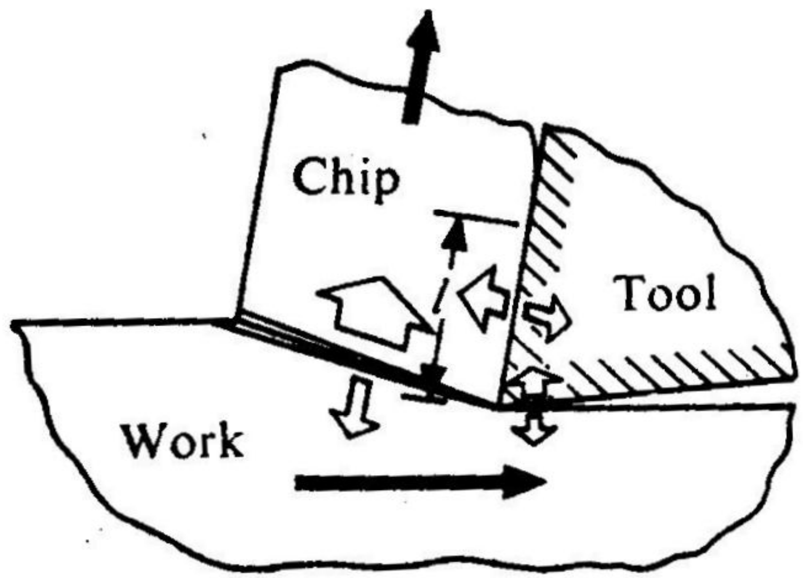


Fig. : 16 Generation and distribution of heat during machining.

Total rate of heat generation $W = W_P + W_S$ (4.23)

W_P = Rate of heat generation in primary zone

W_S = Rate of heat generation in secondary zone

$$W = F_C\, v$$

$$W_S = F\, v_c = F\, r\, v \tag{4.24}$$

v_c = Chip Velocity

From relations (4.24) and (4.25),

$$W_P = F_C\, v - F\, r\, v \tag{4.25}$$

When a material particle moves across the primary deformation zone, the temperature rise is given by

$$\theta_P = \frac{(1-\Lambda)W_P}{\rho c v t_1 w} \tag{4.26}$$

Where

Λ = Fraction of primary heat which goes to the workpiece

ρ = Density of the material

c = Specific heat of the material

t_1, w = Uncut thickness, width of cut respectively

It has been found that Λ is a function of the shear angle φ and a nondimensional quantity

$$\Theta = \frac{\rho c v t_1}{k} \tag{4.27}$$

k = Thermal conductivity of the material

For a wide range of work materials and machining conditions

$$\Lambda = 0.15\, ln\left(\frac{27.5}{\Theta\, tan\varphi}\right) \tag{4.28}$$

The maximum temperature rise θ_S when the material particle passes through the secondary deformation zone along the rake face of the tool can be approximately expressed as

$$\theta_S \approx 1.13\sqrt{\frac{\Theta t_2}{l}}\left(\frac{W_S}{\rho c v w t_1}\right) \tag{4.29a}$$

Where l is the length of contact between the tool and the chip

The corresponding average temperature rise

$$\theta_{S_{av}} = \frac{W_S}{\rho c v w t_1} \tag{4.29b}$$

It has been found that

$$\frac{l}{t_2} = [1 + \tan(\varphi - \alpha)]$$

Using this relation in equation (4.29a), we obtain

$$\theta_S = 1.13\sqrt{\frac{1}{\rho c v t_1 k[1 + \tan(\varphi - \alpha)]}\frac{W_S}{w}} \tag{4.29c}$$

The final temperature is given as

$$\theta = \theta_0 + \theta_P + \theta_S \tag{4.29d}$$

Where θ_0 is the initial temperature of the workpiece. This maximum temperature is Along the rake face of the tool.

Variation of Temperature with Cutting Speed

$$\theta_{OV} \propto U_C\sqrt{\frac{vt_1}{k\rho c}} \tag{4.30}$$

θ_{OV} = Overall temperature rise and U_C = Specific energy

Cutting Parameters: Workpiece Material – SAE B 1113 Steel

Tool – K2S WC

Rake Angle - 20^0

Uncut thickness – 0.06 mm

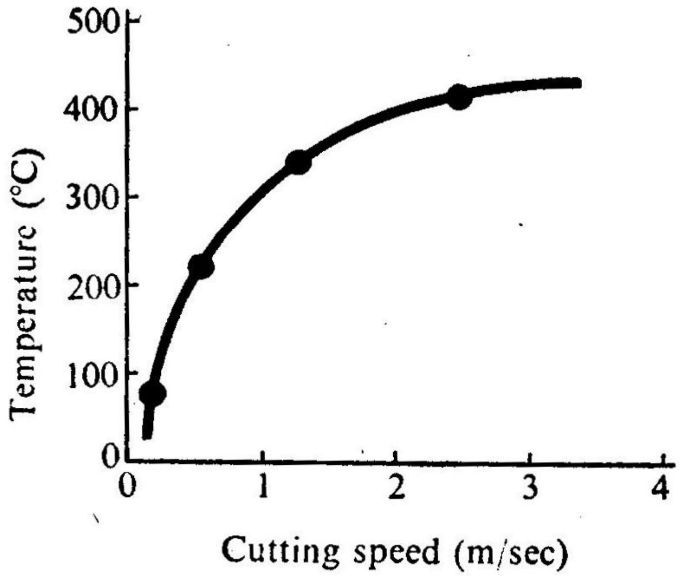
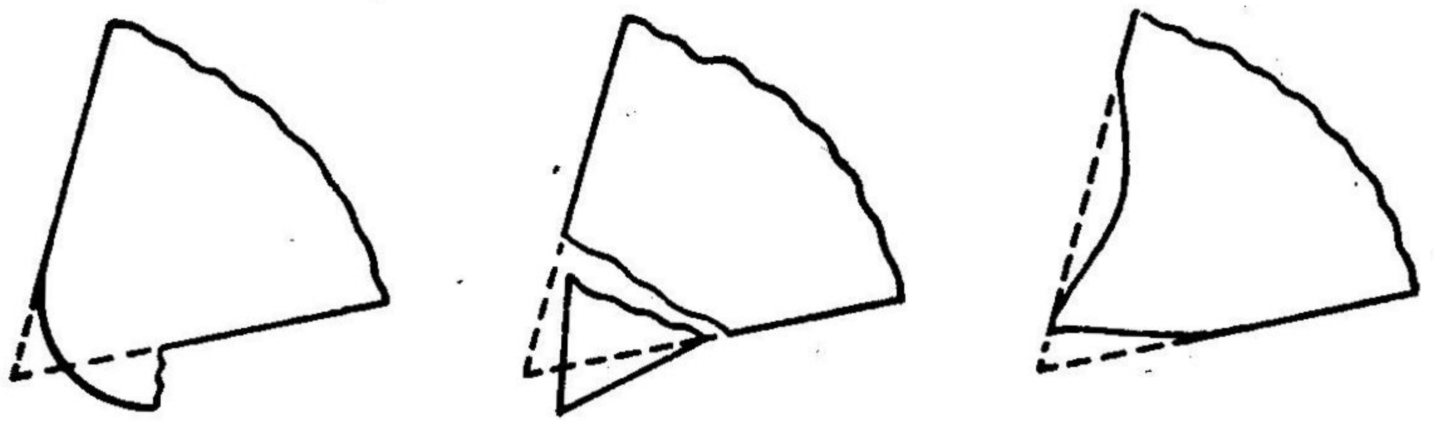


Fig. 4.17 Variation of temperature with cutting speed. (After Shaw, M.C., Metal Cutting Princi[illegible] IT Press, Cambridge, Massachus : 17 57.)

The overall interface temperature rise is Proportional to the square root of the Cutting speed

Failure of Cutting Tool and Tool Wear

- Plastic deformation of the tool due to high temperature and large stress
- Mechanical breakage of the tool due to large force and insufficient strength and toughness
- Blunting of the cutting edge of the tool through a process of gradual wear



(a) Plastic deformation (b) Mechanical breakage (c) Failure through gradual wear

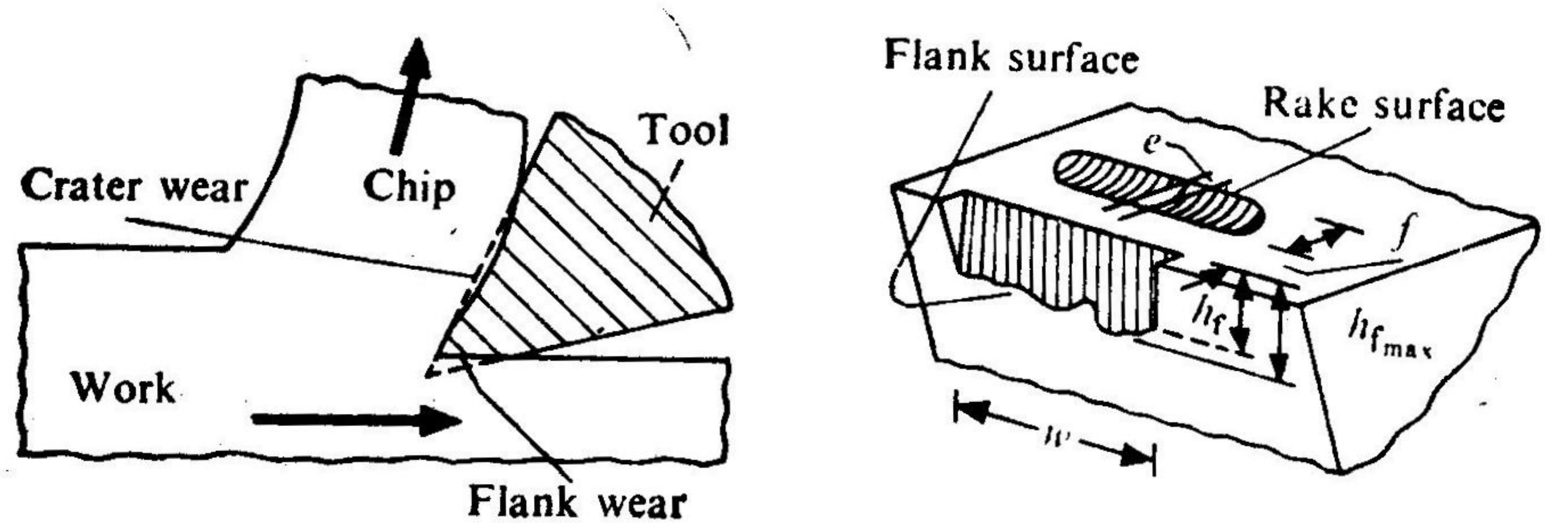
Fig. : 18 Modes of cutting tool failure.

Crater and Flank Wear

Wear takes place

- on the rake surface where the chip flows over the tool

- on the flank surface where rubbing between the work and the tool occurs



(a) Crater and flank wear

(b) Details of crater and flank wear

Fig. : 19 Wear of cutting tools.

Tool Wear various mechanism

Adhesion Wear : Surface mating - welding of tool and workpiece material
Small wear particles – attritious wear
Large wear particles – galling

Abrasion wear : surface asperities plough a series of grooves
Basic condition – particles must be harder than the surface.
This wear rate through this is process depends on hardness, elastic properties
And the geometry of the mating surfaces.

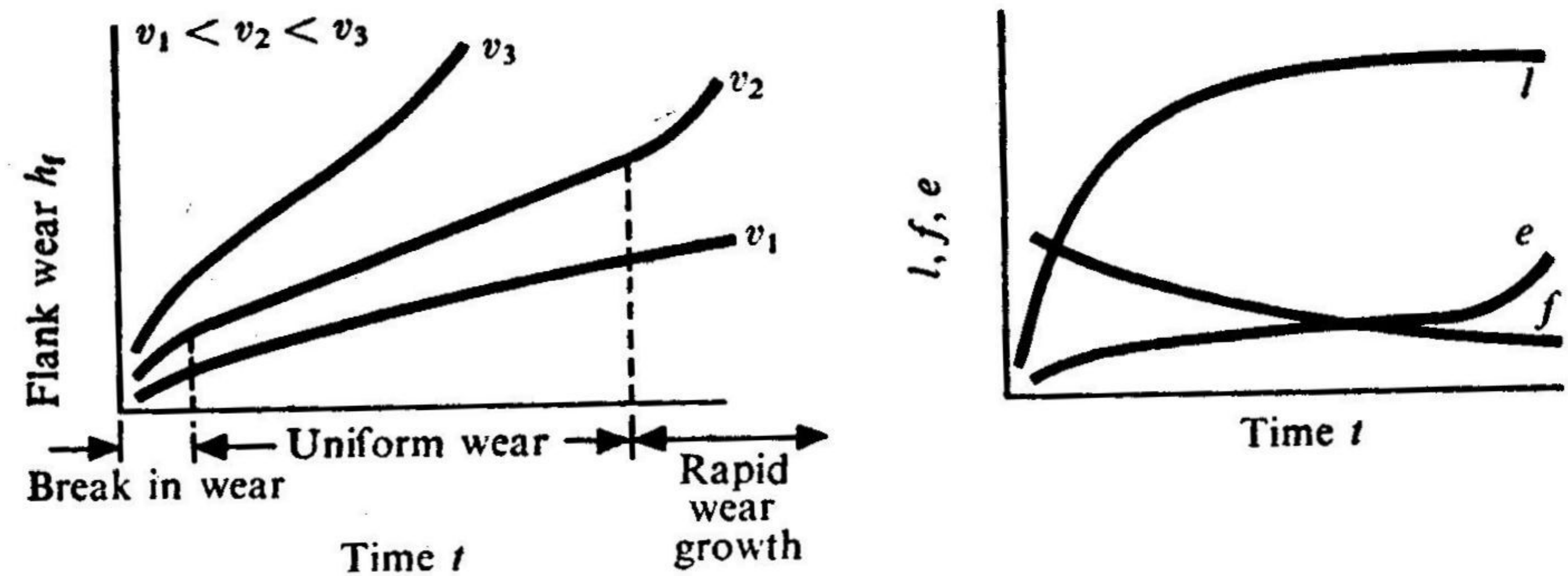
Diffusion : Two surfaces in close contact, atom from one transfer to other by diffusion
Changes the physical properties like hardness, toughness, etc.
Diffusion rate is temperature dependent so depends on sliding rate
Amount of material transfer is time of contact and inverse of sliding speed

Growth of Tool Wear

Flank Wear – Abrasion and adhesion

Crater Wear - Diffusion

Break in wear – sharp cutting edge is quickly broken, wear rate high, contact starts from zero and normal pressure is high to cause sub-surface plastic flow.



(a) Flank wear growth

(b) Growth of crater wear parameters

Fig. : 20 **Growth of tool wear.**

Cutting Tool Materials

Condition of Hardness Ratio (Proposed by T.N. Loladze)

$$1.35 = \left[\frac{H_{tool}}{H_{work}}\right]_{modified} < 1.5 \qquad (4.31)$$

Table : 5 Performance of various tool/work combinations

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 treated steel	Steel 65γ	1.45	≈ 1	No successful machining possible

Variables affecting tool life

- Cutting conditions
- tool geometry
- tool material
- work material
- cutting fluid

Properties of tool material

1. Hot hardness
2. Toughness
3. Thermal conductivity and specific heat should be high
4. Co-efficient of friction between the workpiece and tool

Tool list

1. Carbon tool steel
2. High Speed steel
3. Cemented carbide – WC-Co with other ingradients like TaC, TiC, etc
4. Ceramic oxide
5. Ceramic Non oxide
6. Coatings – Single and multi layer
7. Diamond

Cutting Speed for Various Tools

Table : 8 Cutting speed for various tools

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

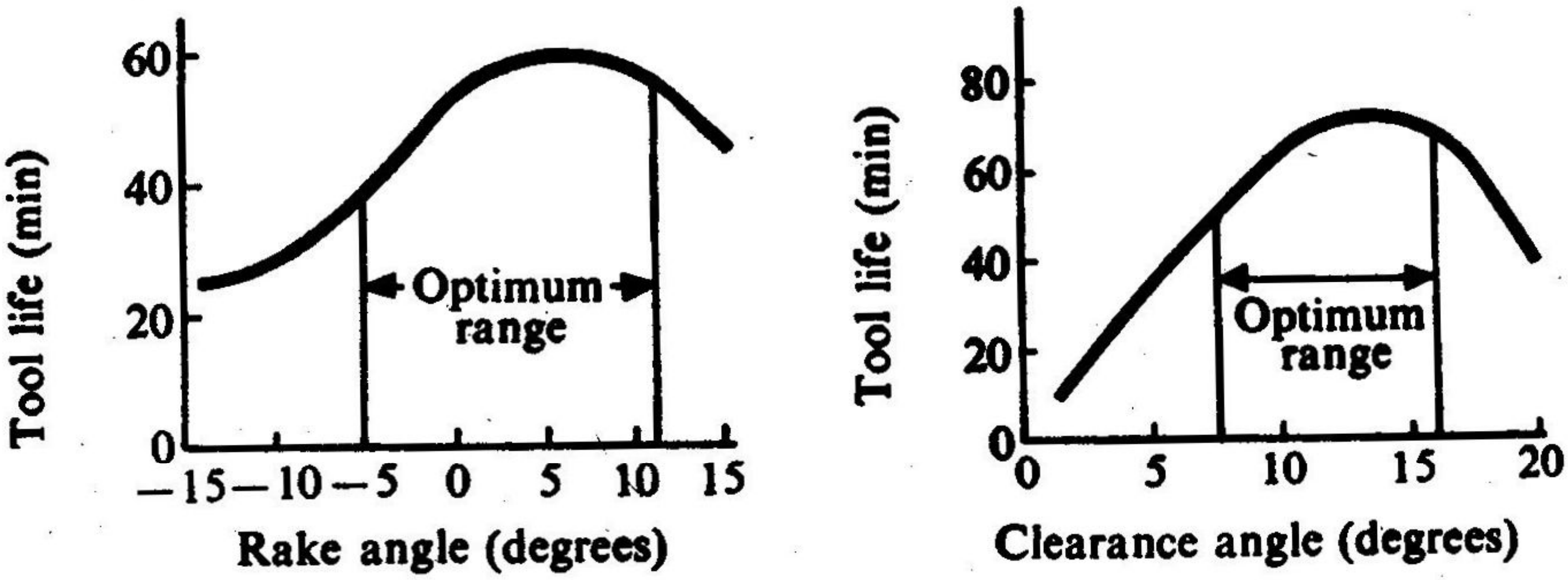
Tool life and machinability

Machinability – ease for machining

Major for criteria

- Machining forces and power consumption
- Surface finish
- Tool Life – flank wear 0.3 mm or flank wear max 0.6 mm
- Velocity has a direct influence on flank wear
- $VT^n = C$
- n,C= depends on tool, w/p, tool geometry and cutting condition
- $T = C'/(V^{1/n} f^{1/m} d^{1/o})$

Dependence of Tool Life on Tool Geometry



(a) Effect of rake angle (b) Effect of clearance angle

Work material: mild steel; tool material, cemented carbide; cutting speed, 100 m/min; uncut thickness, 0.13 mm; width of cut, 8 mm

Fig. : 24 Dependence of tool life on tool geometry.

Cutting fluids

Ways in which cutting fluid affects machining

- Cooling down of chip-tool-work zone be carrying away generated heat
- Reducing the coefficient of friction a chip-tool interface
- Reducing thermal distortion caused by temperature gradient
- Washing of chip
- Protecting from corrosion

Ideal cutting fluid

- Large specific heat and thermal conductivity
- Low viscosity and small molecular size
- Suitable reactive constituent
- Nonpoisonous
- Inexpensive

Types of cutting fluids

- Water based
- Mineral oil

Cutting Fluids

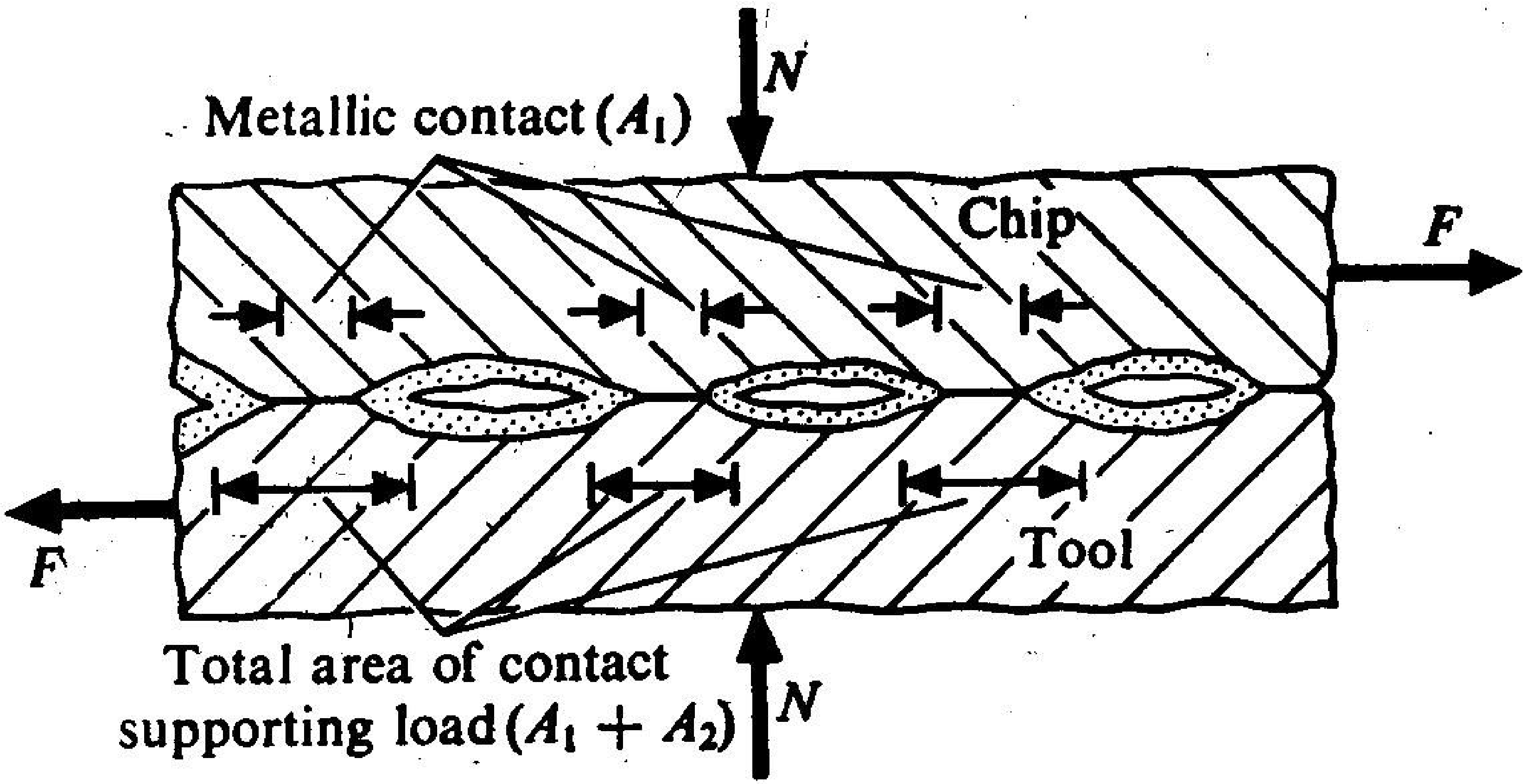
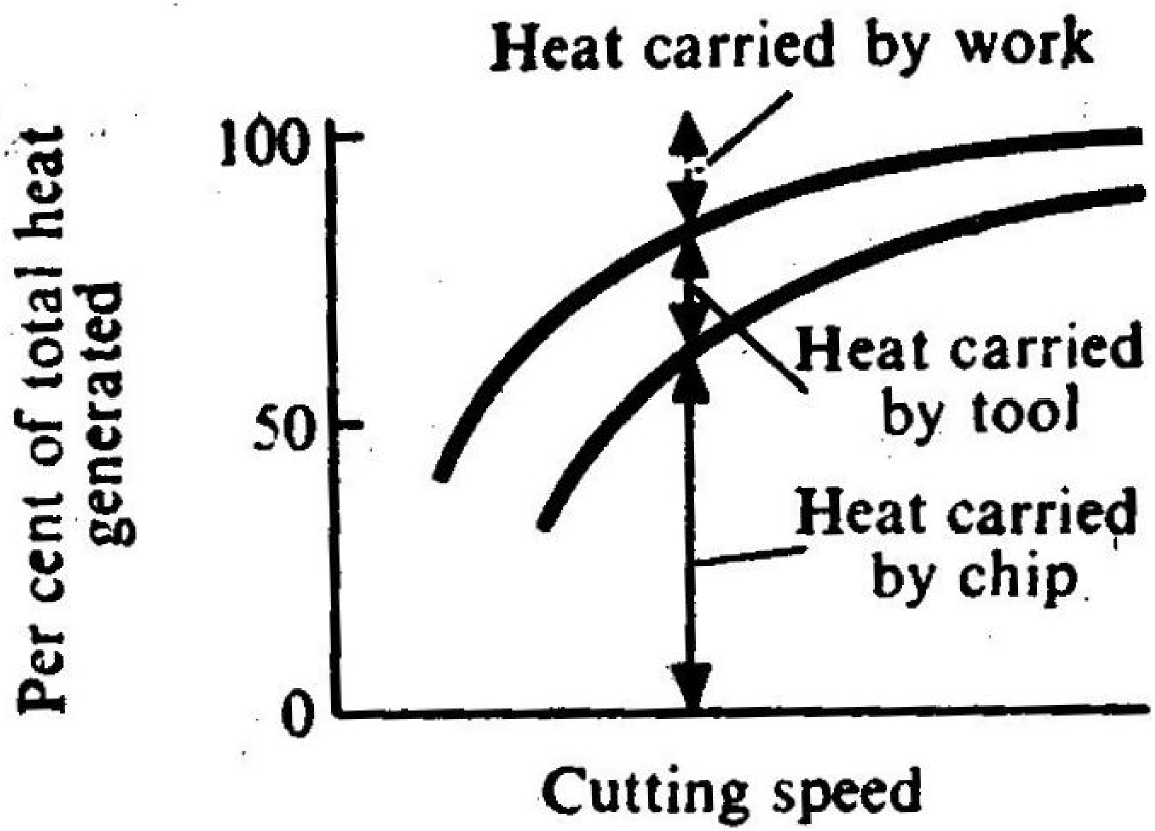


Fig. : 29 · **Effect of cutting fluid on chip-tool interface bonding.**

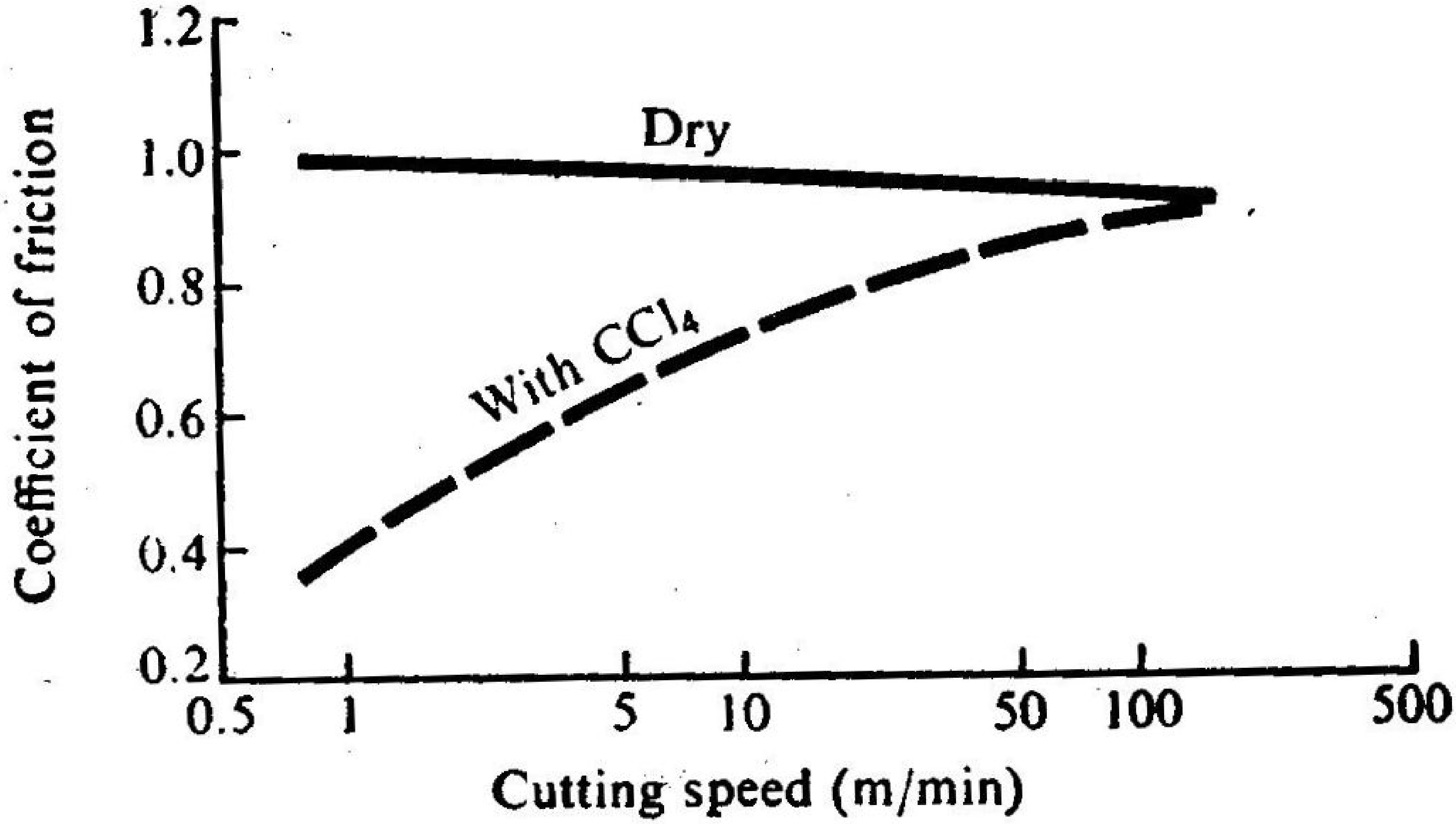
Change in per cent Heat Distribution with Speed



(a) Change in per cent heat distribution with speed

Fig.: 30 Role of Cutting Speed

Dependence of Coefficient of Friction on Speed



(b) Dependence of coefficient of friction on speed when machining copper

Fig. : 30 Role of cutting speed.

Effect of Cutting Environment

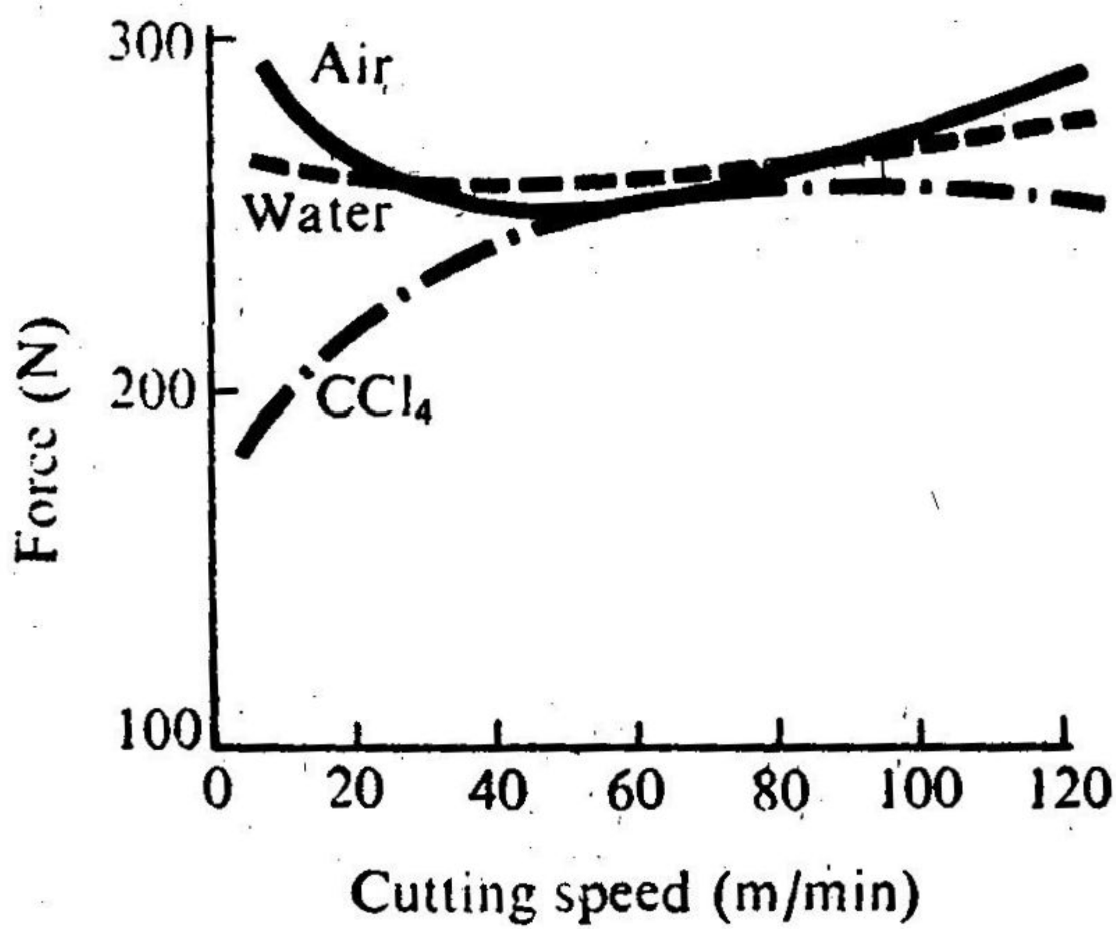


Fig. : 31 Effect of cutting environment when machining steel.