Metal Cutting and Machining

Prepared By:

Dr. Soumya Ranjan Parimanik

Guest Faculty

Department of Mechanical Engineering,

Government College of Engineering, Kalahandi

Dr. Ajit Kumar Pattanaik

Assistant Professor

Department of Mechanical Engineering,

Government College of Engineering, Kalahandi

Course Outcomes

CO1: Remembering (Knowledge): Recall tool geometry systems (ASA, ORS), types of tool wear, and fundamentals of chip formation.

CO2: Understanding (Comprehension): Explain the impact of tool geometry, cutting fluids, and variables on tool life and surface finish.

CO3: Applying (Application): Calculate tool life using Taylor’s equation and analyze cutting forces using dynamometers.

CO4: Analyzing (Analysis): Compare conventional and non-traditional machining processes (e.g., EDM, laser) based on efficiency, precision, and applications.

CO5: Creating (Synthesis): Design machining strategies for cost-effective production, integrating CNC and advanced processes for complex geometries.

Reference Books

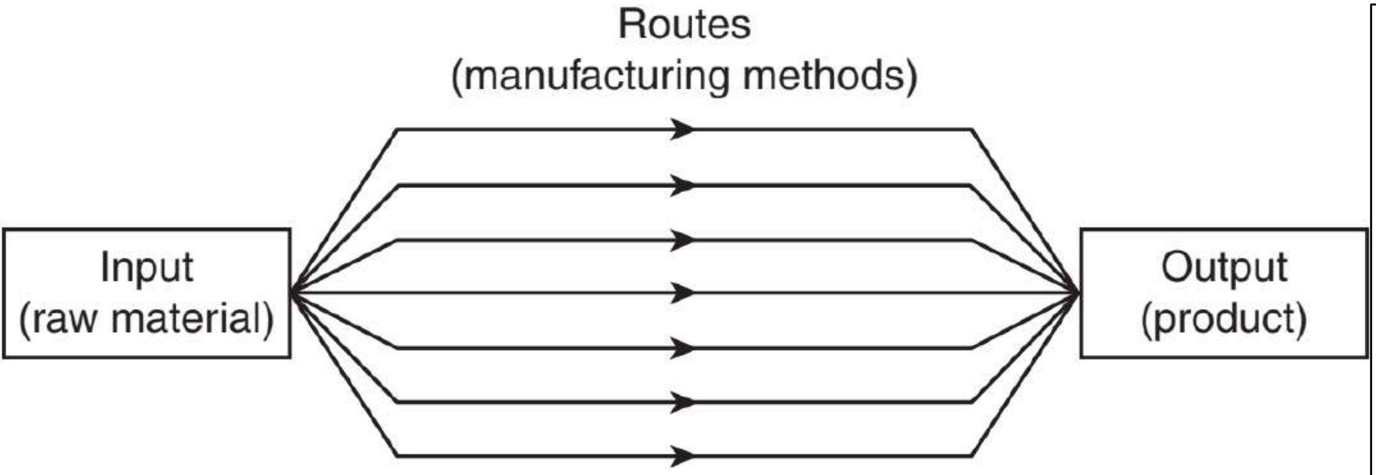
1. A Bhattacharryya, Metal Cutting, Theory and Practice, New Central Book Agency (p) Ltd, 1st Edition, 2022.
2. A B Chattopadhyay, Machining and Machining tool, Wiley Publisher, 2nd. Edition, 2021.
3. Sreeramulu Moinikunta, Production Technology, Volume 2, Wiley Publisher, 1st. Edition 2019.
4. P. K. Mishra, Nonconventional Machining, Narosa Publishing House, 2007.
5. Production Technology HMT, Tata McGraw Hill, 2001.
6. M. C. Shaw, Metal Cutting Principles, Second Edition, Oxford University Press, 2005.

Module – I

Syllabus

Geometry of cutting tools in ASA and ORS, Effect of Geometrical parameters on cutting force and surface finish, Mechanics of chip formation, Merchant's theory, Force relationship and velocity relationship, Cutting tool materials. Types of Tool Wear: Flank wear, Crater wear, Wear measurement, Temperature in metal Cutting, Cutting fluid and its effect.

Introduction

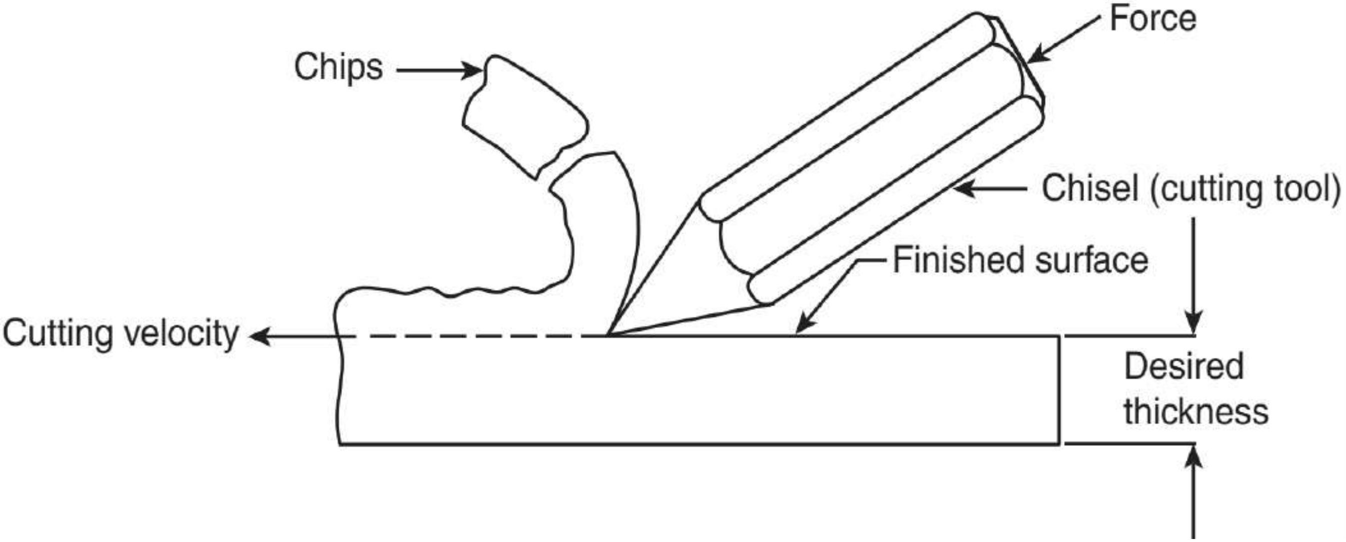


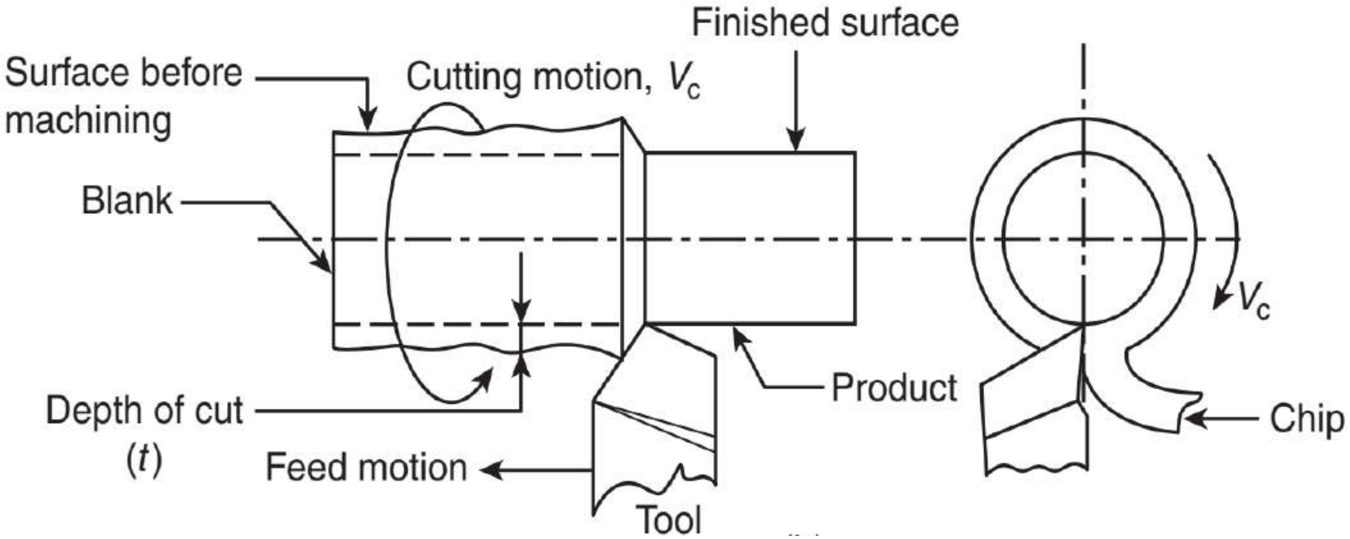
- **Manufacturing** is defined as a value addition process by which raw materials or objects, originally of low value due to inadequate material properties and poor or irregular size, shape and finish are converted into high-utility and high-value products with proper size, form, dimensions and finish, imparting some functional ability.

Purpose of machining: the engineering components are essentially finished to desired accuracy and surface finish by machining to enable the product

- Meet its functional requirements.
- Provide improved performance.
- Have longer service period.

Definition of machining: Machining is an essential finishing process by which jobs of desired dimensions and surface finish are produced by gradually removing the excess material from the performed blank in the form of chips with the help of cutting tool(s) moved past the work surface(s).





Principle of Machining:

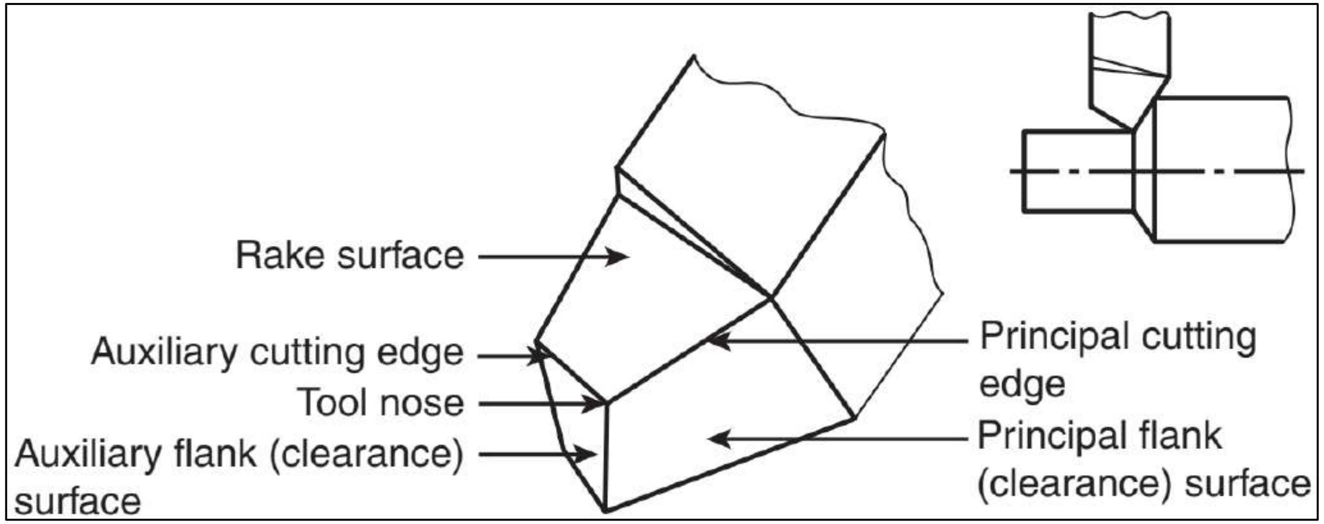
- Machining is basically a removal process.
- Layer is removed from the top surface of a specimen to make the surface smooth as well as to get the desired dimension.
- The excess material is gradually removed in the form of chips by relative motion of the tool and the workpiece.

GEOMETRY OF CUTTING TOOLS

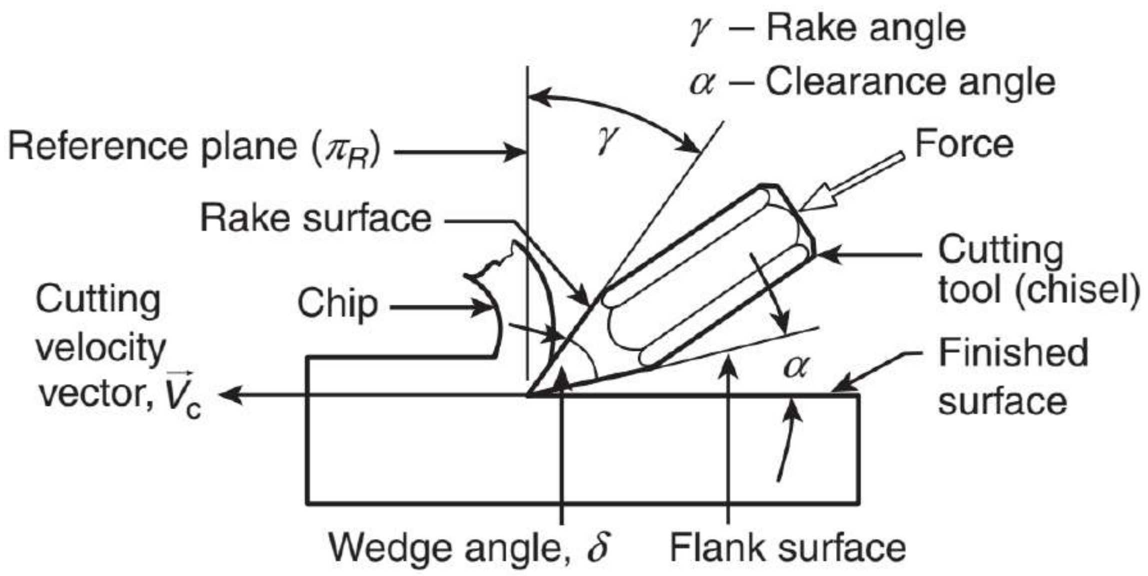
- The performance of any cutting tool depends on
  - The material of the tool.
  - The sharpness of the cutting edges.
  - The orientation angles of the planes that generate the cutting edges.
- Appropriate selection of tool geometry enables efficient and economic machining of any job.

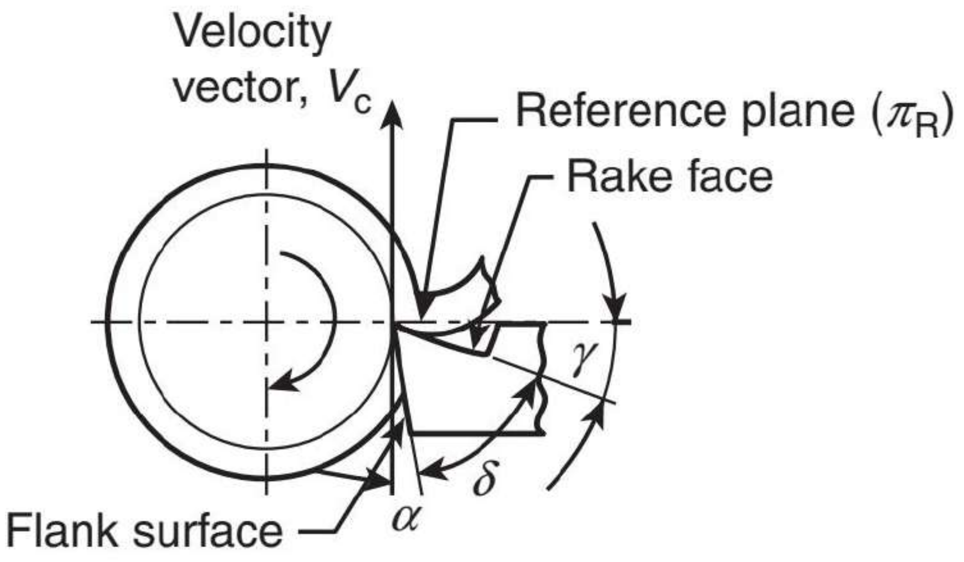
Classification of Cutting Tool according to Number of their Working Cutting Edges (Points)

- Single-point
  - Turning tools, Shaping, Planing and Slotting tools and Boring tools
- Double-point or Two-point
  - Drills
- Multipoint (More than two points)
  - Milling cutters, Broaching tools, Hobs, Gear shaping cutters,, Grinding wheels



- Tool geometry refers to some specific angles or slopes of the salient faces and edges of the tools at their cutting point.
- **Rake angle** and **clearance angle** are the most significant geometrical features of cutting tools.





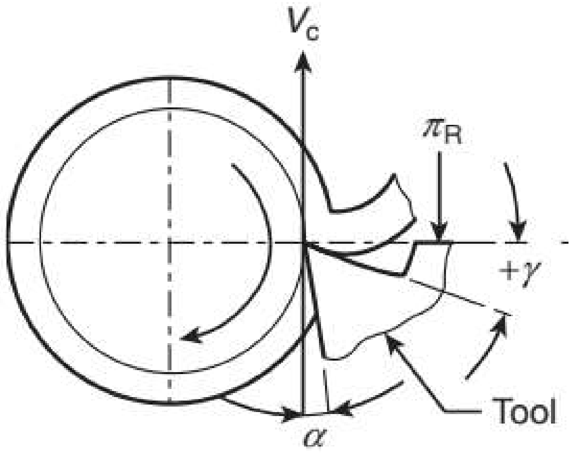
Rake Angle (γ): It is the angle of inclination of the cutting tool's rake surface from the reference plane, i.e., the plane perpendicular to the velocity vector, V_c. It is generally provided for ease of chip flow.

Clearance Angle (α): It is the angle of inclination of the clearance or flank surface of the tool from the finished surface or the cutting plane π_c.

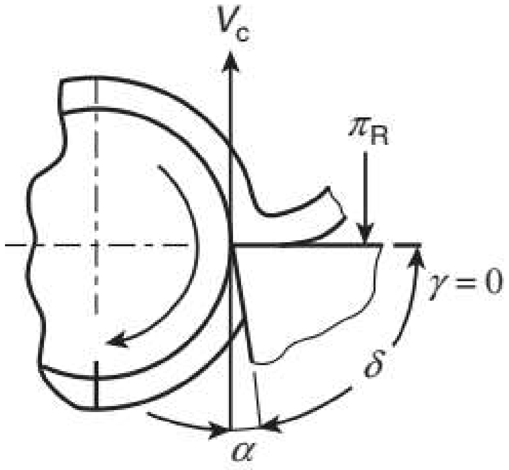
- Rake angle may be positive, negative or zero, however, clearance angle must be greater than zero. Also,

$$\gamma + \alpha + \delta = 90°$$

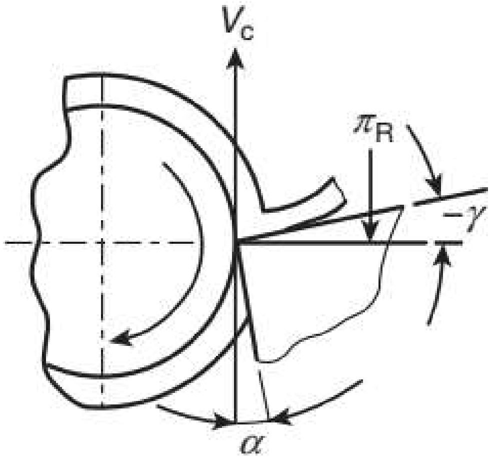
Where δ is wedge angle. This angle is provided for mechanical strength of the cutting edge.



Positive Rake
It helps reduce cutting force, thus cutting power requirement.



Negative Rake
It increases strength and life of the cutting edge



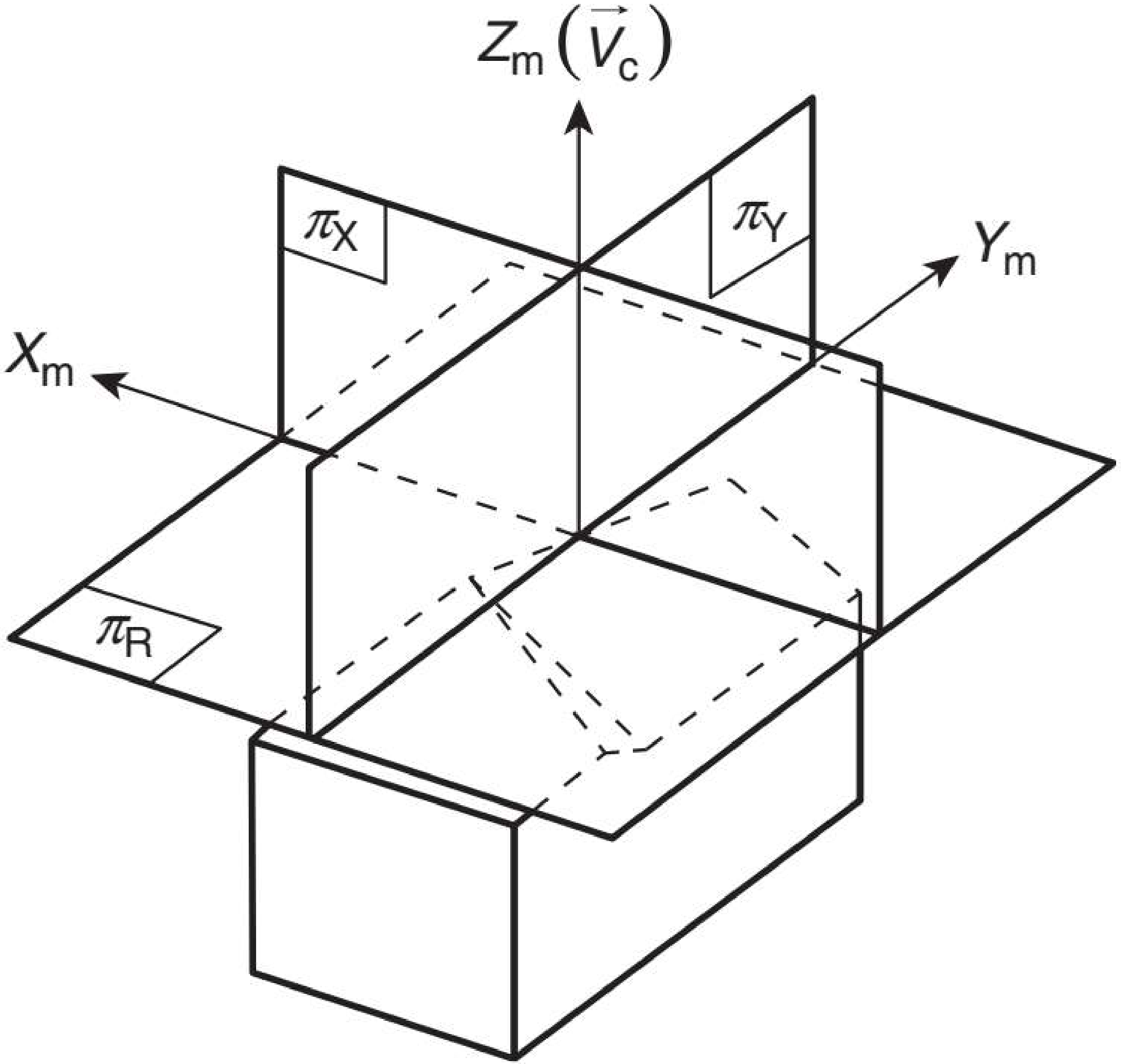
Zero Rake
It simplifies design and manufacture (of form tools, etc.)

- A clearance angle is provided to avoid rubbing of the too (flank) against the machined surface.
- It also reduces the loss of energy and damages to the tool and the job surface.
- It must be present and must be positive.
- Typical range: 3-15° (depending upon tool-work materials and type of machining operation)

SYSTEMS OF DESCRIPTION OF TOOL GEOMETRY

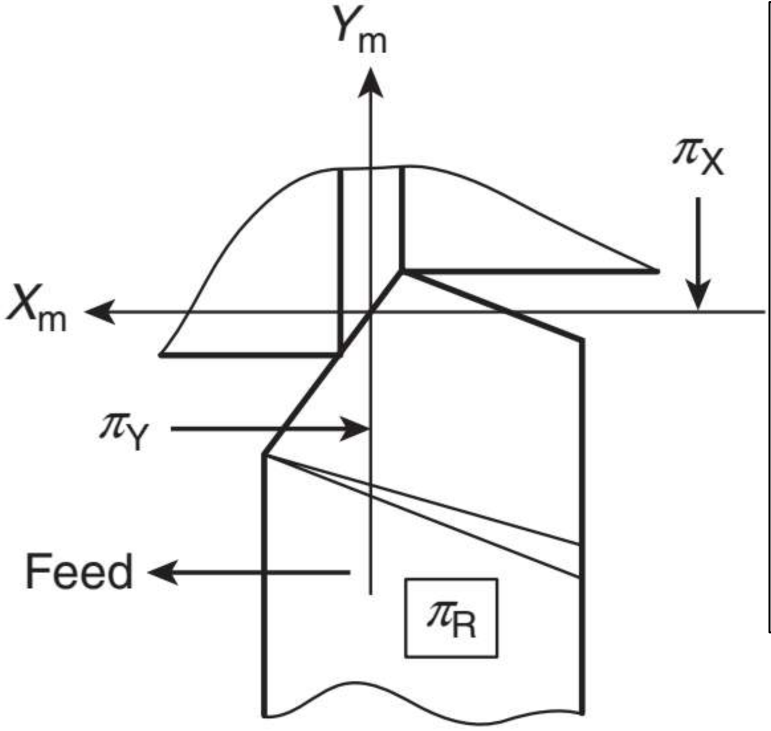
Designation of Tool Geometry in the ASA System

- **ASA** stands for **American Standard Association**.
- This system is a **machine reference system**.
- The geometry of the cutting tool refers to the angles or slopes of its salient working surfaces and cutting edges.
- Those angles are expressed w.r.t. some planes of reference.
- The planes of reference and the coordinates are chosen based on the configuration and axes of the machine tool concerned.



Planes of Reference: π_R-π_X-π_Y

Coordinates: X_m-Y_m-Z_m



π_R: Reference Plane, perpendicular to the velocity vector $\vec{V_c}$

π_X: Machine Longitudinal Plane, Perpendicular to π_R and taken in the direction of the assumed longitudinal feed

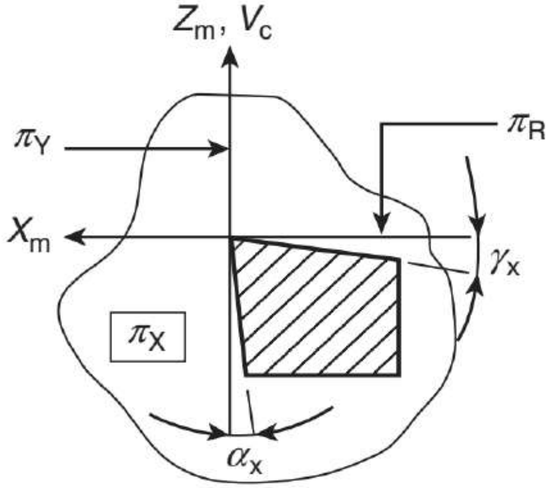
π_Y: Machine Transverse Plane, perpendicular to both π_R and π_X, taken in the direction of cross feed

Coordinates: X_m-Y_m-Z_m are taken in the direction of longitudinal feed, cross feed and cutting velocity vector, respectively.

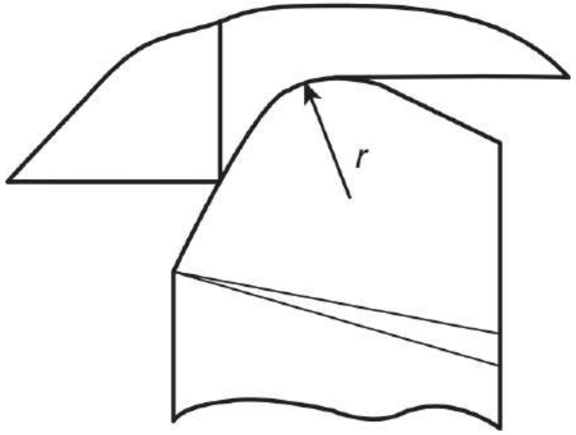
Designation

1-2-3-4-5-6-7

- **Rake Angle**
- **Clearance Angle**
- **Cutting Angle**
- **Nose Radius**



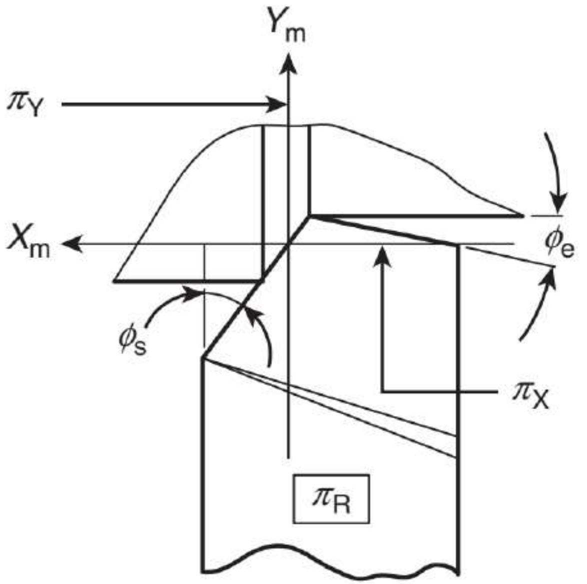
Section along π_X

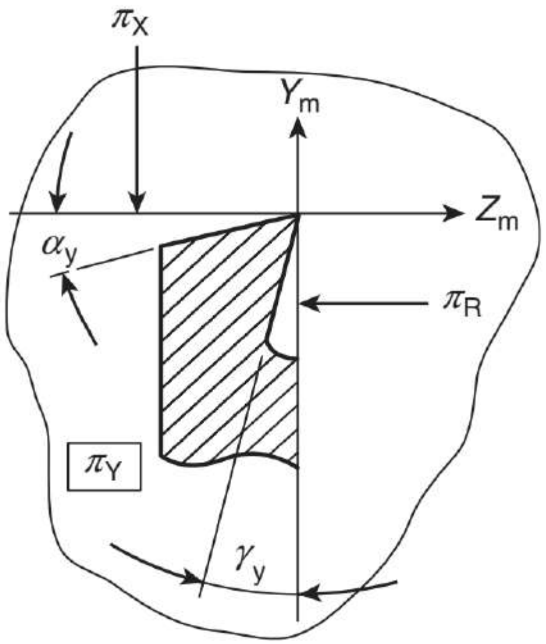


Nose radiusing

In ASA system, the geometry of single-point turning tool is designated as

$$\lambda_x, \lambda_y, \alpha_x, \alpha_y', \phi_e, \phi_s, r \text{ (inch)}$$





Section along π_Y

Ranke Angles

1. **Side (Axial) Rake (γ_X):** It is the angle of inclination of the rake surface from the reference plane (π_R) and is measured on the machine longitudinal plane (π_X).
2. **Back Rake (γ_Y):** It is the angle of inclination of the rake surface from the reference plane (π_R) and is measured on the machine transverse plane (π_Y).

Clearance Angle

1. **Side Clearance (α_x):** It is the angle of inclination of the principal flank from the machined surface (or $\vec{V_c}$) and is measured on the machine longitudinal plane (π_X).
2. **Back Clearance (α_y):** It is the angle of inclination of the principal flank from the machined surface (or $\vec{V_c}$) and is measured on the machine transverse plane (π_Y).
3. **Auxiliary Back Clearance (α_y'):** It is the angle of inclination of the auxiliary flank from $\vec{V_c}$ measured on the π_Y' plane, parallel to π_Y plane.

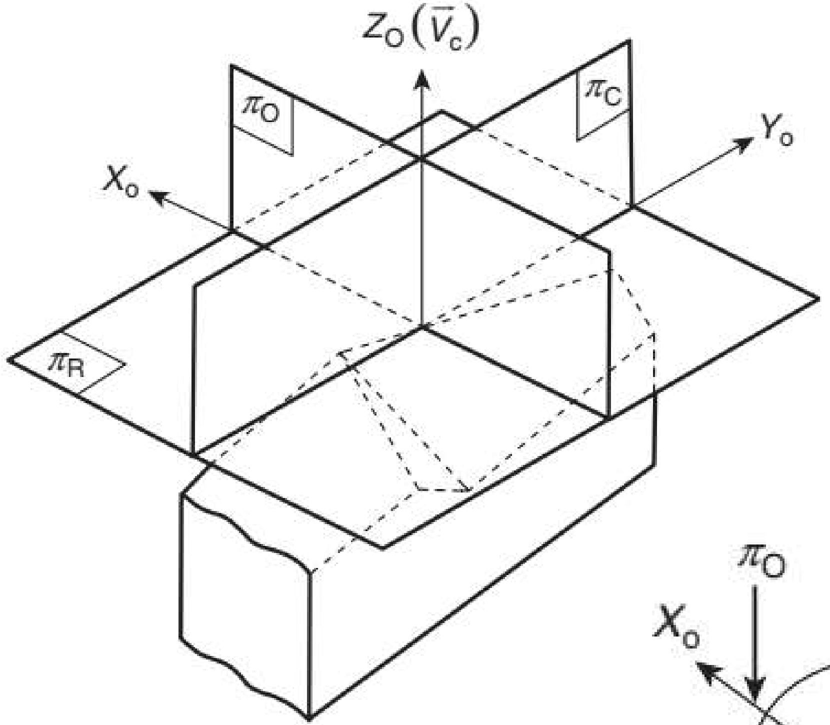
Cutting Angles

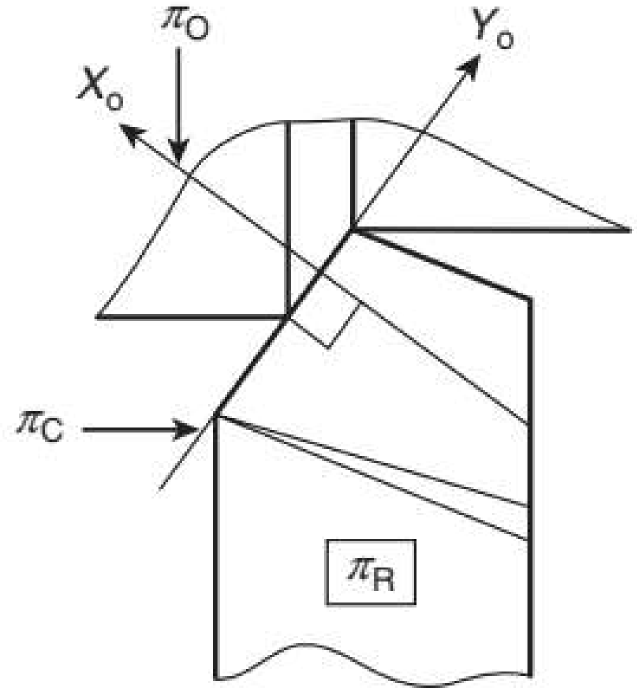
1. **Approach angle (ϕ_s):** It is the angle between the principal cutting edge (its projection on π_R) and π_Y, measured on π_R.
2. **End Cutting Edge angle (ϕ_e):** It is the angle between the end cutting edge (its projection on π_R) and π_X, measured on π_R.

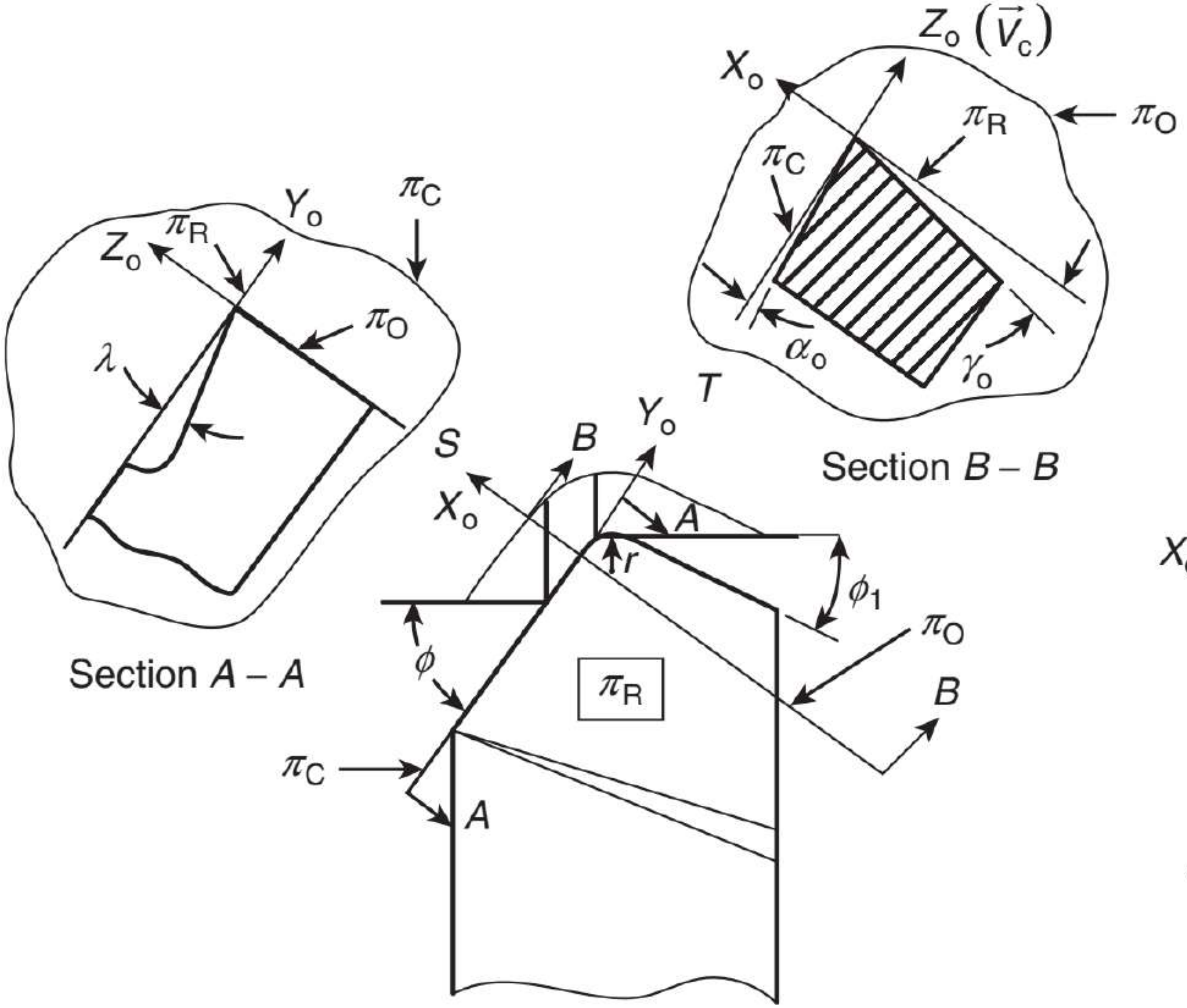
Nose Radius (r) (in inches): It is the radius of curvature of the tool tip, it provides strength to the tool nose and a better surface finish.

Designation of Tool Geometry in the ORS System

- **ORS** stands for **Orthogonal Rake System**.
- Also known as **ISO System** or **Tool Reference System**.
- **Planes:** π_R-π_C-π_O
- **Co-ordinates:** X_o-Y_o-Z_o
- All planes of reference and co-ordinates are taken in respect of the tool configuration.
- π_R is the reference plane, perpendicular to velocity vector $\overrightarrow{V_c}$.
- π_C is the cutting plane perpendicular to π_R and taken along the principal cutting edge.
- π_O is the orthogonal plane perpendicular to both π_R and π_C.
- X_o is taken along the line of interaction of π_R and π_O.
- Y_o is taken along the line of interaction of π_R and π_C.
- Z_o is taken along the velocity vector, that is, it is normal to X_o and Y_o.

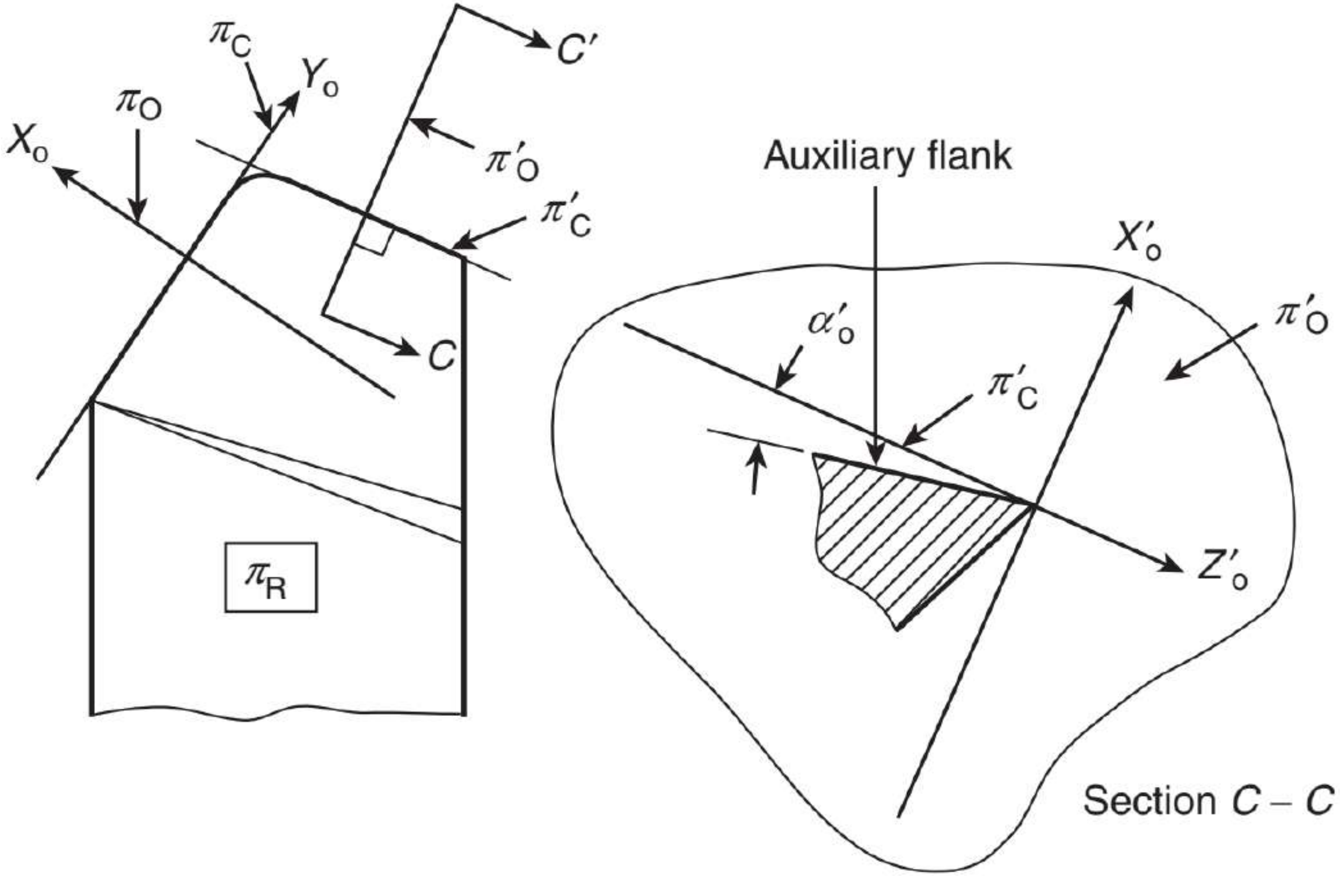






Cutting Tool Angles in ORS

Auxiliary orthogonal clearance (ORS)



The geometry of single-point turning tool is designated in ORS by:

$$\lambda, \gamma_o, \alpha_o, \alpha_o', \phi_1, \phi, r \text{ (mm)}$$

Ranke Angles

1. **Orthogonal Rake (γ_O):** It is the angle of inclination of the rake surface from the reference plane (π_R) and is measured on the orthogonal plane (π_O).
2. **Inclination Angle (λ):** It is the angle of inclination of the principal cutting edge from π_R and is measured on the cutting plane (π_C).

Clearance Angle

1. **Orthogonal Clearance of the Principal Flank (α_o):** It is the angle of inclination of the principal flank from π_C and is measured on π_O.
2. **Auxiliary Orthogonal Clearance (α_o'):** It is the angle of inclination of the auxiliary flank from the auxiliary cutting plane π_C' and is measured on the auxiliary orthogonal plane (π_O').

Cutting Angles

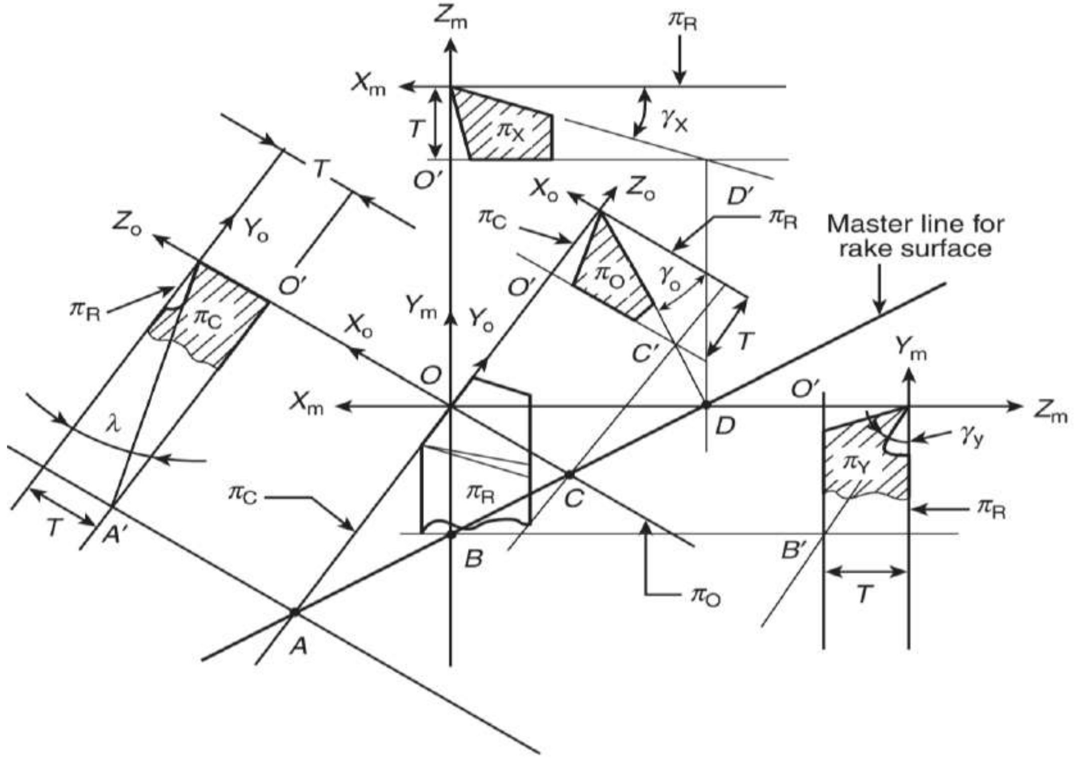
1. **Principal Cutting Edge Angle (ϕ):** It is the angle between π_C and the direction of assumed longitudinal feed or π_X, measured on π_R.
2. **Auxiliary Cutting Edge angle (ϕ_1):** It is the angle between π_C' and π_X, measured on π_R.

Nose Radius (r) (in mm): It is the radius of curvature of the tool tip.

CONVERSION OF TOOL ANGLES OF SINGLE POINT CUTTING TOOL

(By Graphical Method)

Conversion of Rake Angles



Master Line for Rake Surface (All rake angles are positive)

From the diagram, the intercepts become,

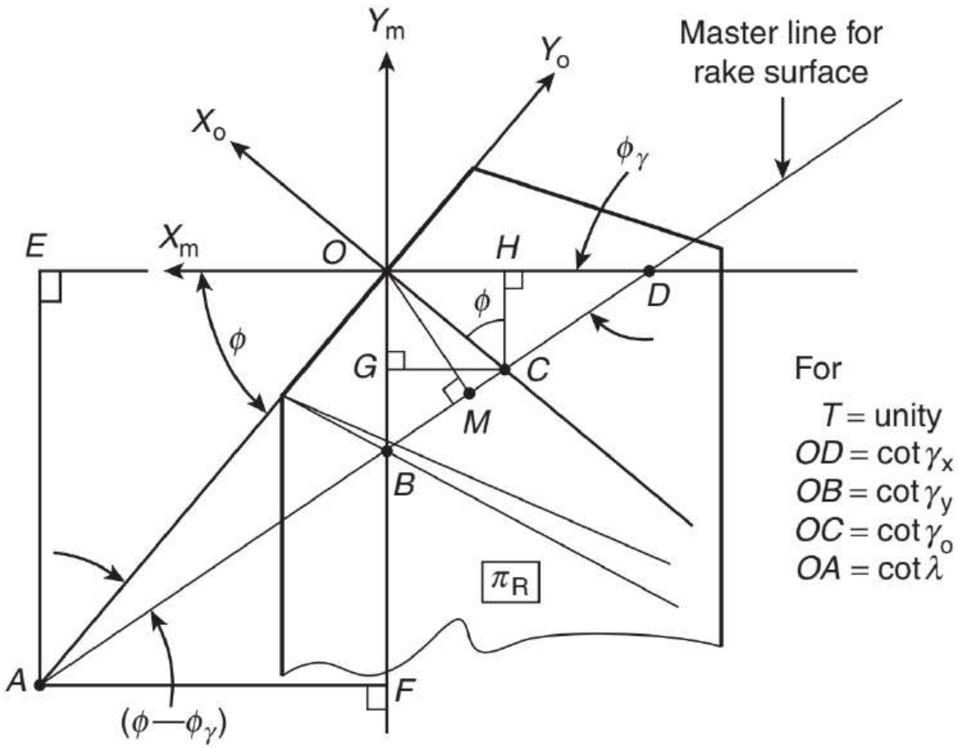
$$OD = T\cot\gamma_x$$
$$OB = T\cot\gamma_y$$

$$OC = T\cot\gamma_o$$
$$OA = T\cot\lambda$$

T= Thickness of the tool shank

- Graphical method uses **Master Line (ML)** to convert the tool angles for rake surface and clearance surface.
- The rake surface, when extended along the π_x, meets the bottom surface of the tool (parallel to π_R) at the point D′, that is, the point D in plain view.
- Similarly, when the same tool rake surface is extended along π_y, it meets the bottom surface of the tool at the point B′, that is, at B in the plain view.
- The straight line obtained by joining B and D is nothing but the line of interaction of the rake surface when extended with the tool's bottom surface, which is parallel to π_R.
- Hence, if the rake surface is extended in any direction, its meeting point with the bottom plane of the tool must be situated on the line of interaction, that is, BD.
- Thus, the points C and A that are obtained by extending the rake surface along π_o and π_c, respectively, upto the tool's bottom surface, will be situated on the line of interaction BD.
- This line of interaction, BD of the rake surface and a plane parallel to π_R is called the **master line of the rake surface**.

Conversion of Rake Angle from ASA to ORS



Conversion of Tool Rake Angle

To derive $\gamma_0 = f(\gamma_x, \gamma_y)$, consider

$$\Delta OBD = \Delta OBC + \Delta OCD$$

$$\Rightarrow \frac{1}{2}OB.OD = \frac{1}{2}OB.CG + \frac{1}{2}OD.CH$$

$$= \frac{1}{2}OB.OC\sin\phi + \frac{1}{2}OD.OC\cos\phi$$

Dividing both sides by $\frac{1}{2}OB.OC.OD$, we get

$$\frac{1}{OC} = \frac{1}{OD}\sin\phi + \frac{1}{OB}\cos\phi \Rightarrow \tan\gamma_o = \tan\gamma_x\sin\phi + \tan\gamma_y\cos\phi \quad \text{(Eq.1)}$$

Similarly, to derive λ as $f(\gamma_x, \gamma_y)$, consider

$$\Delta OBD = \Delta OAD - \Delta OAB$$

$$\Rightarrow \frac{1}{2}OB.OD = \frac{1}{2}OD.AE - \frac{1}{2}OB.AF = \frac{1}{2}OD.OA\sin\phi - \frac{1}{2}OB.OA\cos\phi$$

Dividing both sides by $\frac{1}{2}OA.OB.OD$, we get

$$1/_{OA} = 1/_{OB}\sin\phi - 1/_{OD}\cos\phi$$

$$\Rightarrow \tan\lambda = \tan\gamma_y\sin\phi - \tan\gamma_x\cos\phi \qquad \text{(Eq. 2)}$$

Eq. 1 and 2, if combined, can be expressed as

$$\begin{bmatrix} \tan\gamma_o \\ \tan\lambda \end{bmatrix} = \begin{bmatrix} \sin\phi & \cos\phi \\ -\cos\phi & \sin\phi \end{bmatrix} \begin{bmatrix} \tan\gamma_x \\ \tan\gamma_y \end{bmatrix} \qquad \text{(Eq. 3)}$$

$\begin{bmatrix} \sin\phi & \cos\phi \\ -\cos\phi & \sin\phi \end{bmatrix}$ is transformation matrix.

<u>Conversion of Rake Angle from ORS to ASA</u>

To derive γ_x and γ_y as function of γ_o and λ, Eq. (3) may be inversed to the form

$$\begin{bmatrix} \tan\gamma_x \\ \tan\gamma_y \end{bmatrix} = \begin{bmatrix} \sin\phi & -\cos\phi \\ \cos\phi & \sin\phi \end{bmatrix} \begin{bmatrix} \tan\gamma_o \\ \tan\lambda \end{bmatrix} \qquad \text{(Eq. 4)}$$

This leads to the relations

$$\tan\gamma_x = \tan\gamma_o \sin\phi - \tan\lambda\cos\phi \qquad \text{(Eq. 5)}$$

$$\tan\gamma_y = \tan\gamma_o \cos\phi + \tan\lambda\sin\phi \qquad \text{(Eq. 6)}$$

Effect of Geometrical Parameters on Cutting Force and Surface Finish

Parameters	Effect on Cutting Force	Effect of Surface Finish
Rake Angle	• Increasing the rake angle reduces the cutting force because the shear angle increases and the shear plane area decreases • A positive rake angle reduces the thrust force more significantly than the main cutting force • Negative rake angle increases both cutting force and thrust force but improves tool strength • Higher rake angle reduces the work done in deforming the chip, lowering power consumption • Very high rake angle reduces the tool wedge strength, which can increase vibration and indirectly raise force fluctuations • Negative rake tools used in heavy interrupted cuts show higher force due to increased friction and ploughing action	• Positive rake angle produces a smoother surface due to easier shearing action and reduced built up edge formation • Negative rake angle increases rubbing and ploughing, which can degrade surface finish • Very high positive rake weakens the cutting edge, leading to edge chipping and poor finish • Moderate positive rake gives the best balance between smooth cutting action and edge strength • Lower rake angle increases cutting temperature, which can promote built up edge and rough surface at low speeds

Parameters	Effect on Cutting Force	Effect of Surface Finish
Clearance Angle	• Clearance angle has a relatively small direct effect on cutting force • Very small clearance angle causes flank rubbing, which increases friction and slightly raises thrust force • Very large clearance angle weakens the cutting edge, making it prone to chipping under load • Adequate clearance angle reduces unnecessary rubbing forces between tool flank and workpiece	• Insufficient clearance angle causes flank face rubbing against the machined surface, resulting in burnished and rough surface • Excessive clearance angle reduces tool strength and can cause chatter, which worsens surface finish • Optimum clearance angle prevents flank wear and helps maintain consistent surface quality over the tool life • Flank wear caused by poor clearance angle progressively degrades finish as machining continues

Parameters	Effect on Cutting Force	Effect of Surface Finish
Cutting Edge Angle	• Decreasing the side cutting edge angle spreads the chip load over a longer cutting edge, reducing force concentration • Decreasing the side cutting edge angle increases the thrust or radial force component • Increasing the side cutting edge angle concentrates more load near the tool nose, increasing local stress • End cutting edge angle affects clearance between the trailing edge and the finished surface, influencing rubbing forces • Larger cutting edge angle can increase vibration tendency due to concentrated loading at the nose	• Smaller side cutting edge angle produces a thinner and wider chip, resulting in a smoother theoretical surface finish • Larger side cutting edge angle increases the theoretical roughness because the feed marks become deeper • Very small end cutting edge angle causes the trailing edge to rub against the finished surface, degrading finish • Very large end cutting edge angle weakens the tool nose, leading to nose wear and poor finish • Proper combination of side and end cutting edge angles minimizes feed mark height and improves surface quality

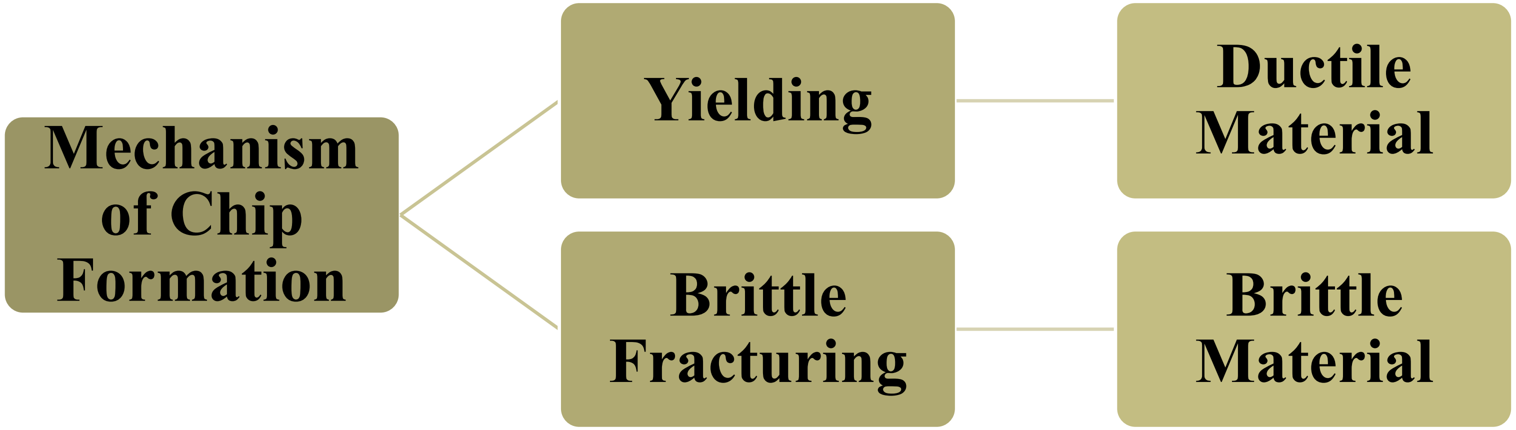
Parameters	Effect on Cutting Force	Effect of Surface Finish
Nose Radius	• Increasing the nose radius increases the thrust or radial force component • Larger nose radius increases the length of engaged cutting edge, which raises the tendency for chatter in less rigid setups • Larger nose radius increases heat generation due to greater contact length between tool and workpiece • Smaller nose radius concentrates force at a point, increasing local stress and risk of nose chipping • Nose radius selection is a balance between force distribution and vibration stability	• Increasing the nose radius significantly improves surface finish because it reduces the height of feed marks • Surface roughness decreases in proportion to the increase in nose radius for a given feed • Very large nose radius can cause chatter marks on the surface if the machine or workpiece lacks rigidity • Increasing feed has a much stronger negative effect on surface finish compared to nose radius, since feed affects roughness in a squared relationship while nose radius affects it linearly • Optimum nose radius gives the best surface finish without introducing vibration related defects

Parameters	Effect on Cutting Force	Effect of Surface Finish
Inclination Angle	• Increasing the inclination angle changes the direction of chip flow, which redistributes the force components between the cutting and radial directions • Positive inclination angle tends to reduce the effective cutting force in the feed direction due to a slicing type action rather than a direct push action • Positive inclination angle increases the radial force component, which can affect workpiece deflection in slender components • Negative inclination angle directs the chip toward the finished surface and tends to increase impact loading on the tool tip • Negative inclination angle is often used in interrupted cutting because it protects the tool tip from the initial shock of engagement, which alters the force distribution pattern • Inclination angle influences the point of first contact on the cutting edge, which affects how gradually the tool engages the workpiece and hence the smoothness of force application	• Positive inclination angle directs the chip away from the freshly machined surface, preventing chip recutting and scratching, which improves surface finish • Negative inclination angle can direct chips toward the finished surface, increasing the chance of surface damage from chip recutting • Gradual engagement created by inclination angle reduces impact and vibration marks on the surface • Proper inclination angle reduces surface damage caused by chip entanglement or chip contact with the machined surface • Inclination angle indirectly affects finish by controlling chip flow direction and chip disposal efficiency

Parameters	Effect on Cutting Force	Effect of Surface Finish
Approach Angle	• Decreasing the approach angle increases the effective width of cut and reduces the uncut chip thickness for a given feed, which spreads the cutting load over a longer edge • Decreasing the approach angle reduces the force concentrated on any single point of the cutting edge, improving tool life under similar force conditions • Decreasing the approach angle increases the radial or thrust force component, which raises the risk of workpiece deflection and chatter in slender or overhung workpieces • Increasing the approach angle toward ninety degrees concentrates force near the tool nose, increasing local stress and reducing edge engagement length • Approach angle influences the direction in which the resultant cutting force acts relative to the workpiece axis, affecting overall machine tool and workpiece rigidity requirements	• Decreasing the approach angle produces a thinner chip for the same feed, which reduces the height of feed marks and improves theoretical surface finish • Increasing the approach angle increases the theoretical surface roughness because the feed marks become taller and more pronounced • Very small approach angle can increase the tendency for chatter due to higher radial force, which may offset the finish benefit from thinner chip formation • Approach angle close to ninety degrees is often preferred for facing and square shoulder operations despite a slightly rougher theoretical finish, because it reduces radial force and deflection • Selection of approach angle for finishing operations always involves balancing theoretical roughness improvement against practical vibration and rigidity limitations

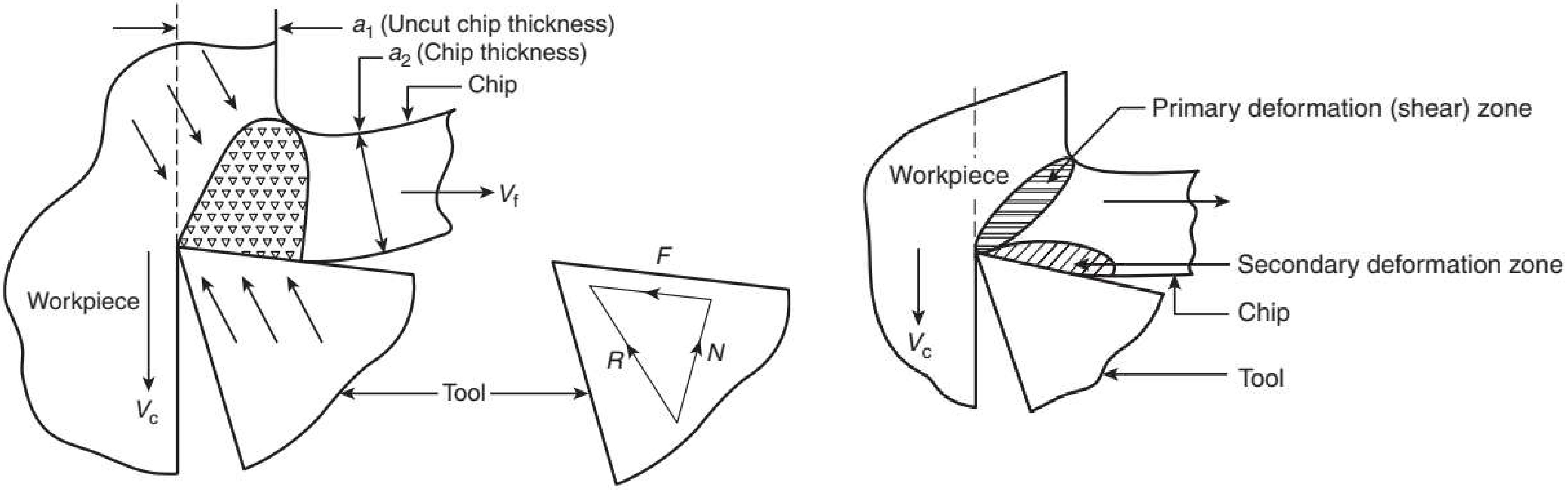
MECHANISM OF CHIP FORMATION IN MACHINING

- Machining is a process of material removal from the preformed blanks and is employed to provide desired shape and dimensions with higher accuracy and surface finish.
- In any machining, material is gradually removed in the form of chips.
- Almost all machining parameters play significant role on the pattern of the chips.
- The different patterns of the chip can indicate good machinability or poor machinability condition.
- Favourable chip can be obtained by proper selection of the machining conditions.
- Thorough knowledge of chip formation mechanism essentially required for assessment and improvement of machinability through proper selection and application of
  1. Cutting tool
  2. Cutting velocity, feed and depth of cut
  3. Cutting fluid
  4. Any special techniques

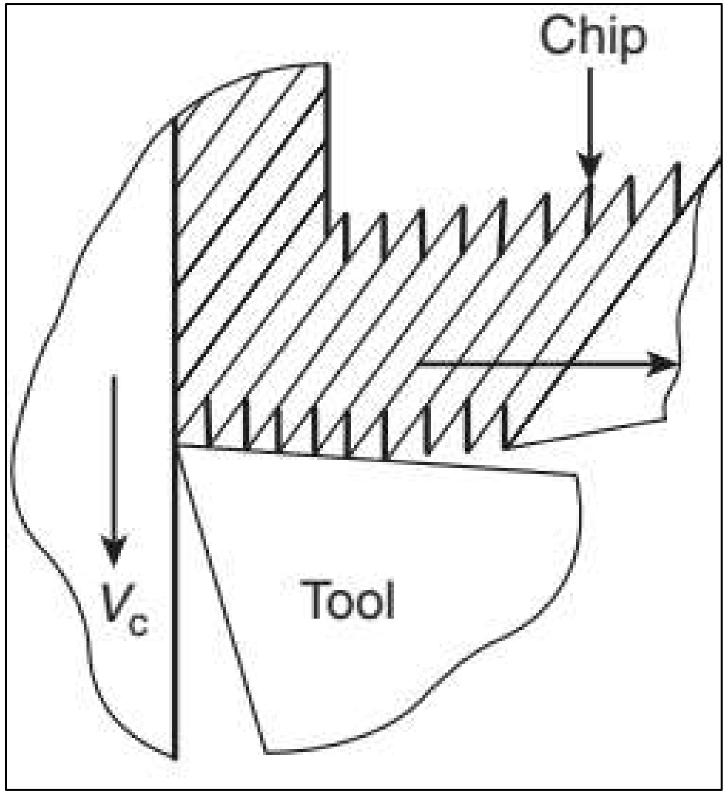


Chip Formation in Machining Ductile Materials

- During machining, the uncut layer of the work material just ahead of cutting too (edge) is subjected to almost all side compression.
- Due to such compression, shear stress develops and grows within that compressed region, in different magnitude, in different direction.

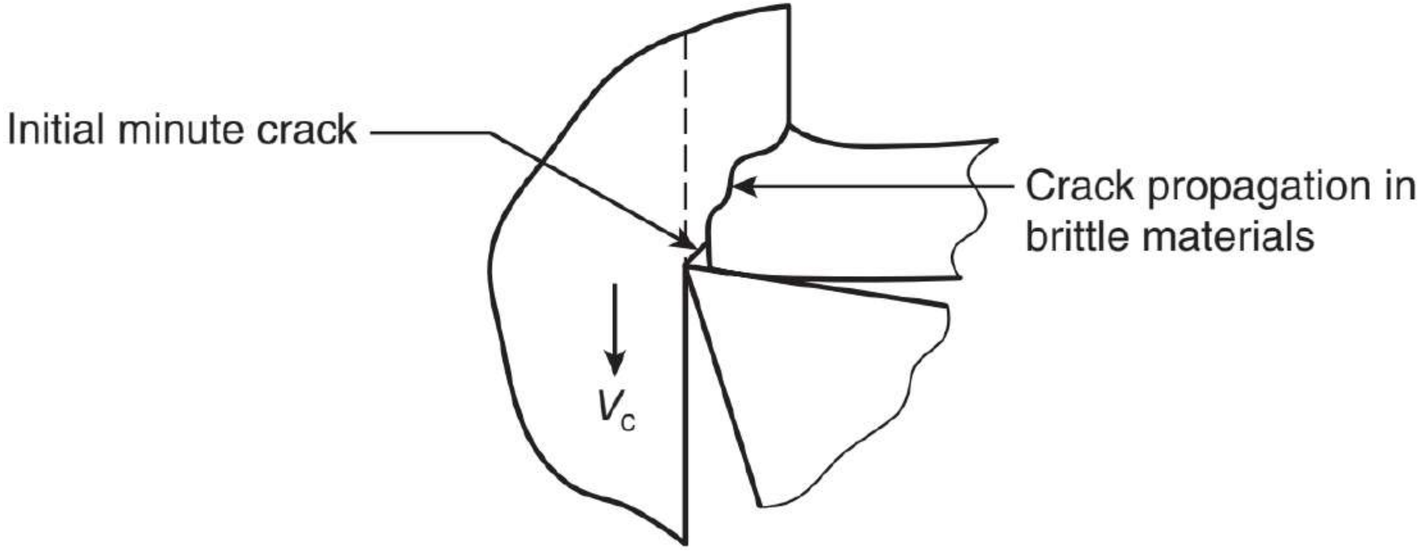


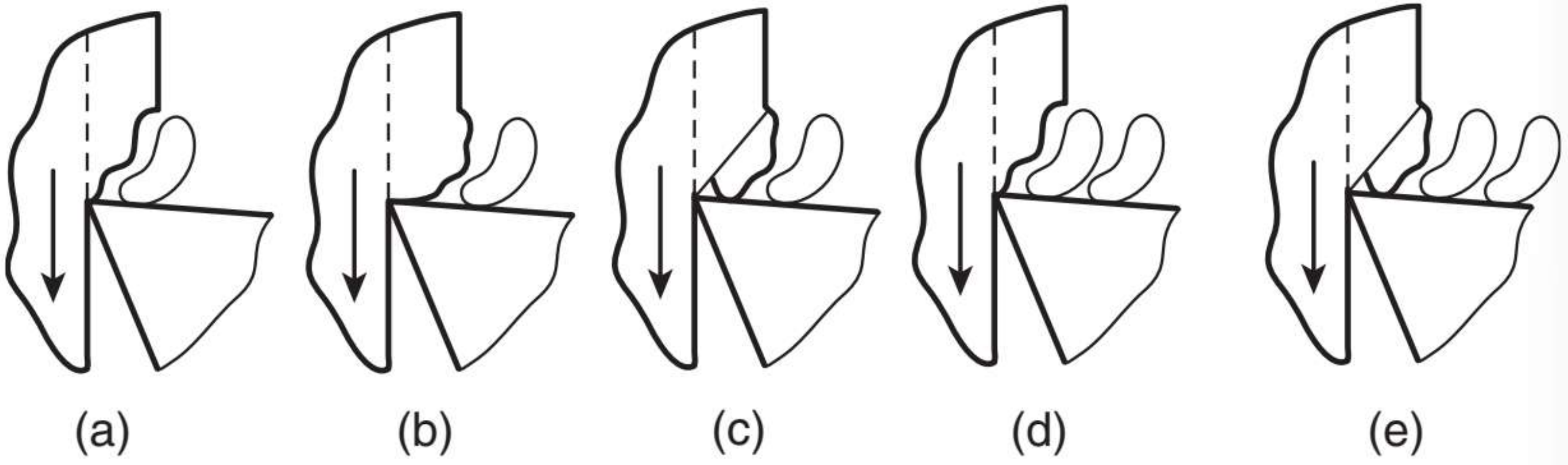
- When the value of the shear stress reaches or exceeds the shear strength of that work material in the deformation zone, yielding or slip begins resulting in shear deformation in that region and initiating of separation in the form of small crack along the plane of maximum shear stress.
- In case of brittle materials, the crack immediately propagates causing chip separation along irregular plane.
- In machining ductile materials, the forces causing the shear stresses in the region of the chip quickly diminish and finally disappear while that region moves along the tool rake surface towards and then goes beyond the point of chip-tool separation.
- As a result, the slip or shear stops propagating long before the total separation takes place.
- In the mean time, the succeeding portion of the work material starts undergoing compression followed by yielding and shear.
- This phenomenon repeats rapidly resulting in formation and removal of chips in thin layer.
- This phenomenon has been explained in a simple way by **Piispannen** using a card analogy.



Chip Formation in Machining Brittle Materials

- Dring machining, first a small crack develops at the tool tip due to wedging action of the cutting edge.
- At the sharp crack tip, stress concentration takes place.
- The initiated crack quickly propagates, under stress action, and total separation of the chip takes place from the parent workpiece through the minimum resistance path.
- Machining of brittle material produces discontinuous chips and mostly of irregular size and shape.





(a) Separation; (b) Swelling; (c) Further swelling; (d) Separation again; (e) Swelling Again

- Due to continuous motion of the uncut layer with V_c, the work material ahead is subjected to compression over the tool-face and starts swelling elastically.
- At the limiting state of stress a piece of material is separated out by fracture.
- Then the cycle repeats.

Chip Reduction Coefficient and Cutting Ratio

a_1= Uncut chip thickness (chip before cut), mm; a_2= Chip thickness (thickness of chip after cut), mm.

- The chip thickness becomes larger than the uncut chip thickness, because of
    1. Compression of the chip ahead of the tool.
    2. Frictional resistance to chip flow.
    3. Lamellar sliding of chip segments.
- The significant geometrical parameters involved in continuous chip formation are as follows:
    1. t= Depth of cut (mm); perpendicular penetration of the cutting tool tip in work surface.
    2. s_0= feed (mm/rev); axial travel of the tool per revolution of the job.
    3. b_1= width of the chip before cut (mm)
    4. b_2= width of the chip after cut (mm)
    5. A_1= cross section (area) of chip before cut (mm^2)

- The degree of thickening of the chip is expressed by

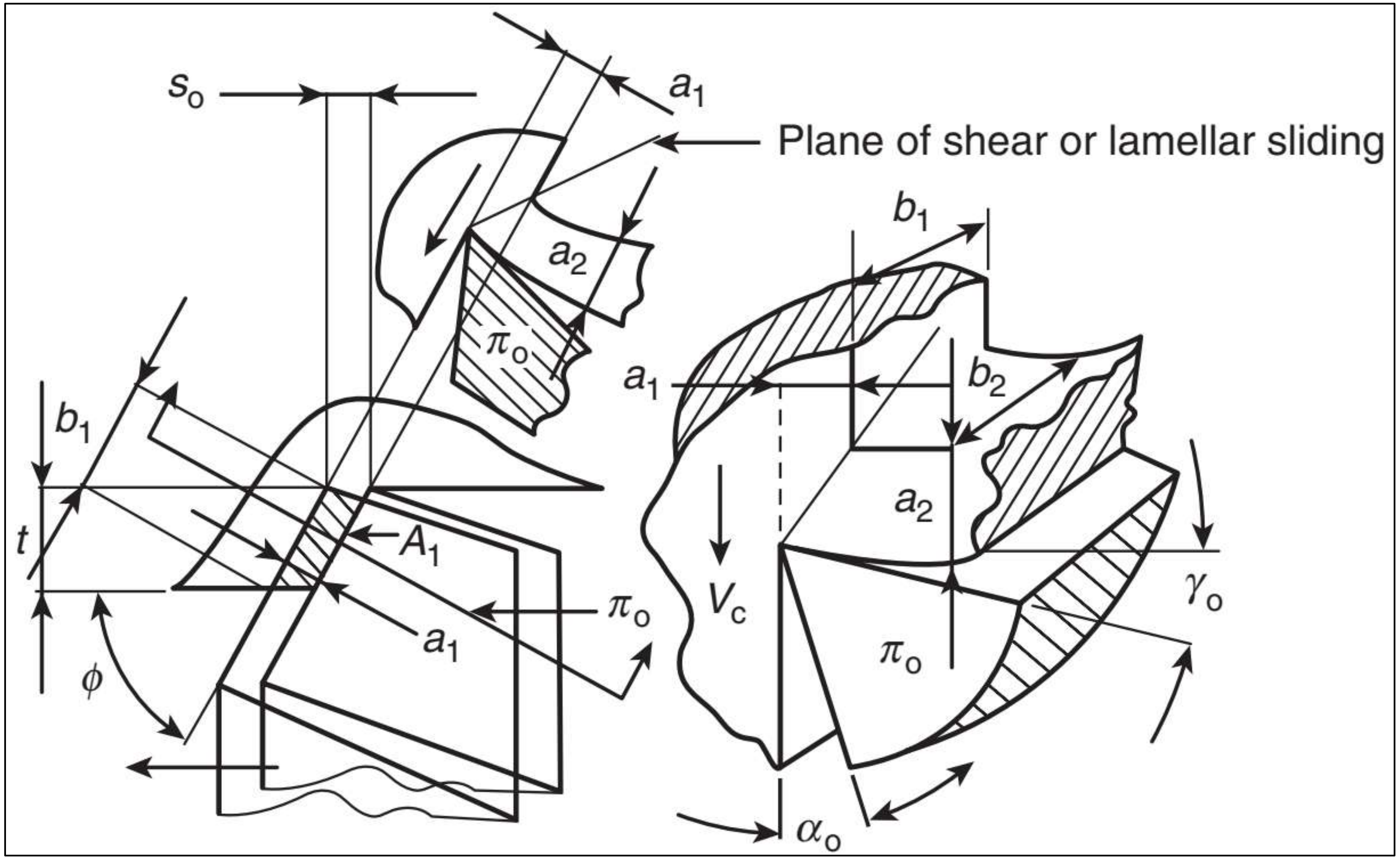
Chip Reduction Coefficient= $\zeta = \frac{a_2}{a_1} > 1.00$

$$a_1 = s_o \sin\phi$$

Where ϕ is the principal cutting edge angle.

- Larger value of $\zeta \Rightarrow$ more thickening $\Rightarrow$ more effort in terms of forces or energy is required for machining
- It is desirable to reduce the values of a_2 or ζ but without sacrificing MRR.
- Chip thickening can also be expressed as

$$Cutting\ Ratio\ (r_{cu}) = \frac{1}{\zeta} = \frac{a_1}{a_2}$$



- The ζ can also be expressed in terms of
  a. Total length of the chip before cut (L_1) and after cut (L_2).
  b. Cutting velocity V_c and chip velocity V_f.

Considering th total volume of chip produced in a given time, we can write

$$a_1 b_1 L_1 = a_2 b_2 L_2$$

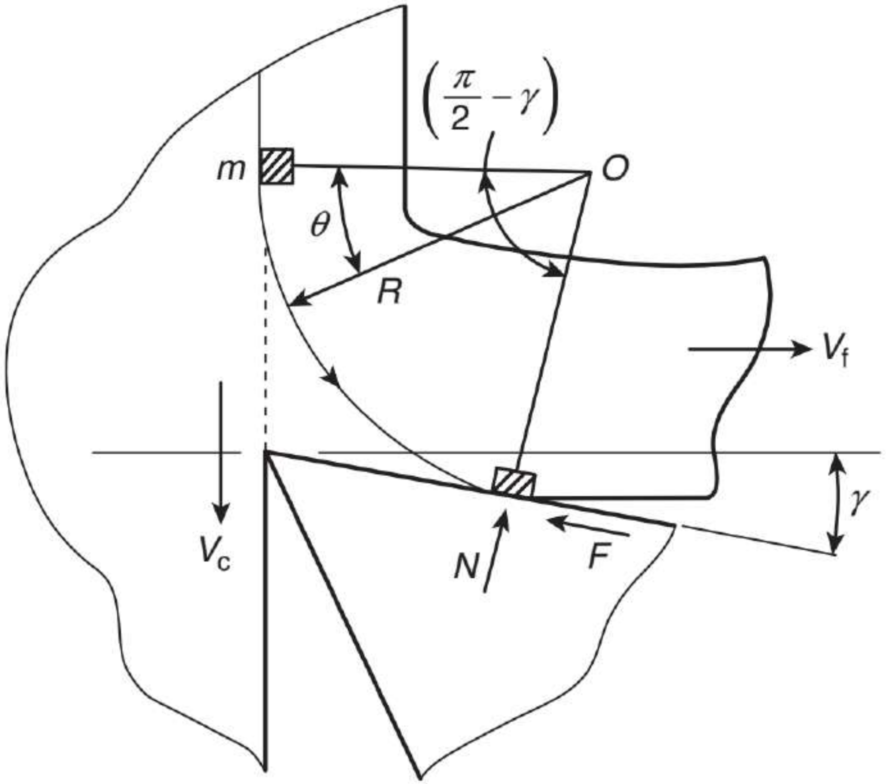
The width of the chip b generally does not change significantly during machining unless there is side flow in some adverse situation. So b_1=b_2

Hence, chip reduction coefficient ζ can be expressed as $\zeta = \frac{a_2}{a_1} = \frac{L_1}{L_2}$

Considering there is no change in material flow rate; $Q = (a_1 b_1)V_c = (a_2 b_2)V_f$

As b_1=b_2, the equation becomes; $\zeta = \frac{a_2}{a_1} = \frac{V_c}{V_f}$ ⇒ This equation reveals that chip velocity V_f will be lesser than the cutting velocity V_c.

The cutting ratio becomes; $r_{cu} = \frac{1}{\zeta} = \frac{V_f}{V_c}$



- The chip reduction coefficient ζ depends on the tool rake angle and the coefficient of friction μ at the chip-tool interface.
- Let us assume an elementary mass *m*, which is travelling with the chip in a circular path.
- The velocity of the mass gradually decreases from V_c to V_f due to friction force *F*.

  So, $F = -m\frac{dv}{dt}$ & $N = mv\frac{d\theta}{dt}$
- So, coefficient of friction becomes; $\mu = \frac{F}{N} = -\frac{dv}{vd\theta} \Rightarrow \frac{dv}{v} = -\mu d\theta$
- Integrating the equation we get, $\frac{V_c}{V_f} = e^{\mu[(\pi/2)-\gamma]} \Longrightarrow \zeta = e^{\mu[(\pi/2)-\gamma]}$
- $(\pi/2) - \gamma$ in the above equation is taken in radian.
- The value of chip reduction coefficient ζ can be reduced by

  1. Using tool having large positive rake.
  2. Reducing friction by using lubricant.

Shear Angle (β_o)

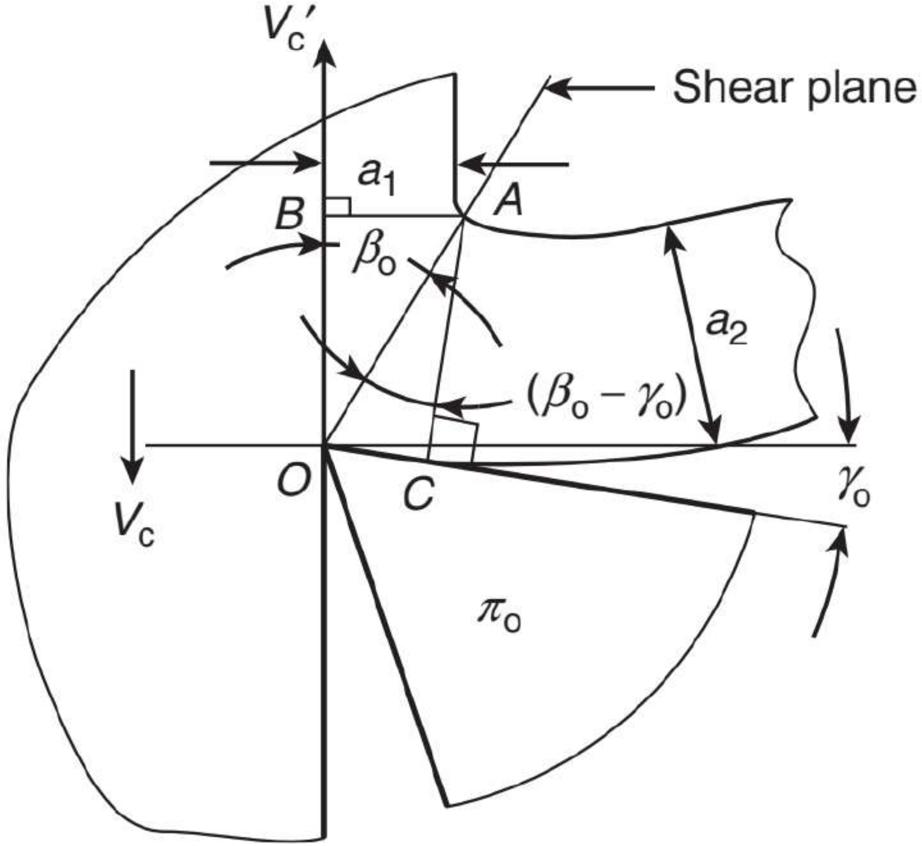
- The uncut chip layer while moving during machining at cutting velocity V_c almost abruptly changes its direction due to presence of the obstructing tool and undergoes thickening.
- The plane of separation of the thickened chip from the parent workpiece is known as **shear plane**.
- **Shear angle** can be defined as the angle of inclination of the shear plane from the direction of cutting velocity and is measured on orthogonal plane.
- The value of shear angle depends upon,
  1. Chip thickness before and after cut, (i.e., ζ)
  2. Rake angle γ_o (in orthogonal plane)
- From figure;

$$AC = a_2 = OA.\cos(\beta_o - \gamma_o)$$

$$AB = a_1 = OA.\sin\beta_o$$

- Dividing a_2 by a_1, we get

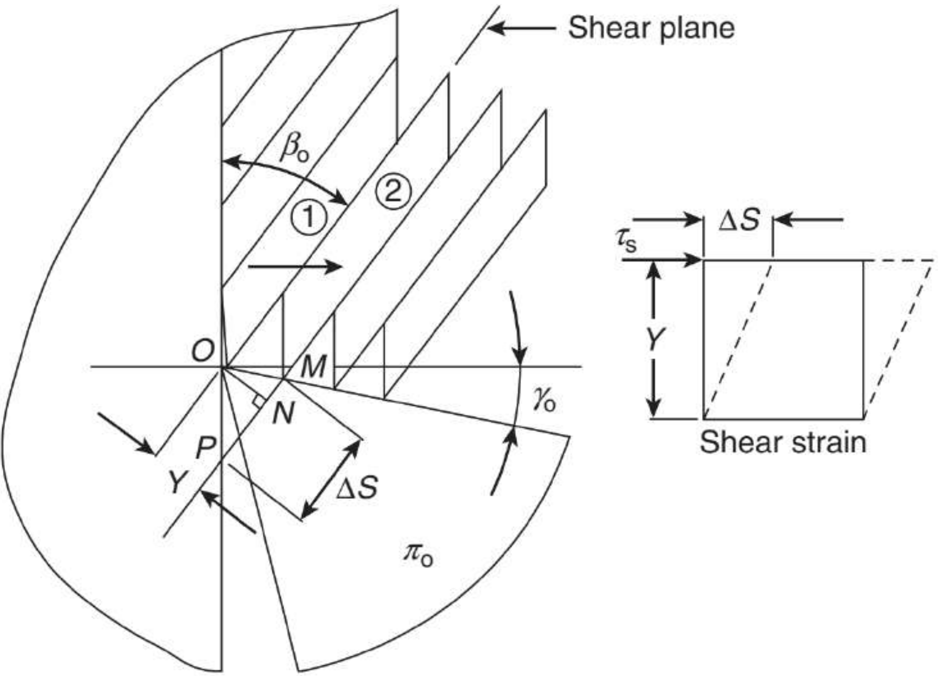
$$\frac{a_2}{a_1} = \zeta = \frac{\cos(\beta_o - \gamma_o)}{\sin\beta_o} \Longrightarrow \tan\beta_o = \frac{\cos\gamma_o}{\zeta - \sin\gamma_o} \Longrightarrow \tan\beta_o = \frac{r_{cu}\cos\gamma_o}{1 - r_{cu}\sin\gamma_o}$$



From the shear angle equations the following conclusions can be depicted:

- With increase in ζ, shear angle decreases and vice-versa.
- Shear angle increases both directly and indirectly with the increase in tool rake angle.
- Increase in shear angle means more favourable machining condition requiring lesser cutting force and specific energy.

Cutting Strain (ϵ)



- The magnitude of average strain, that develops along the shear plane due to machining action, is called **cutting strain** (shear).
- Due to presence of the tool as an obstruction, layer 1 has been shifted to position 2 by sliding along the shear plane.
- Cutting strain (average) is given by

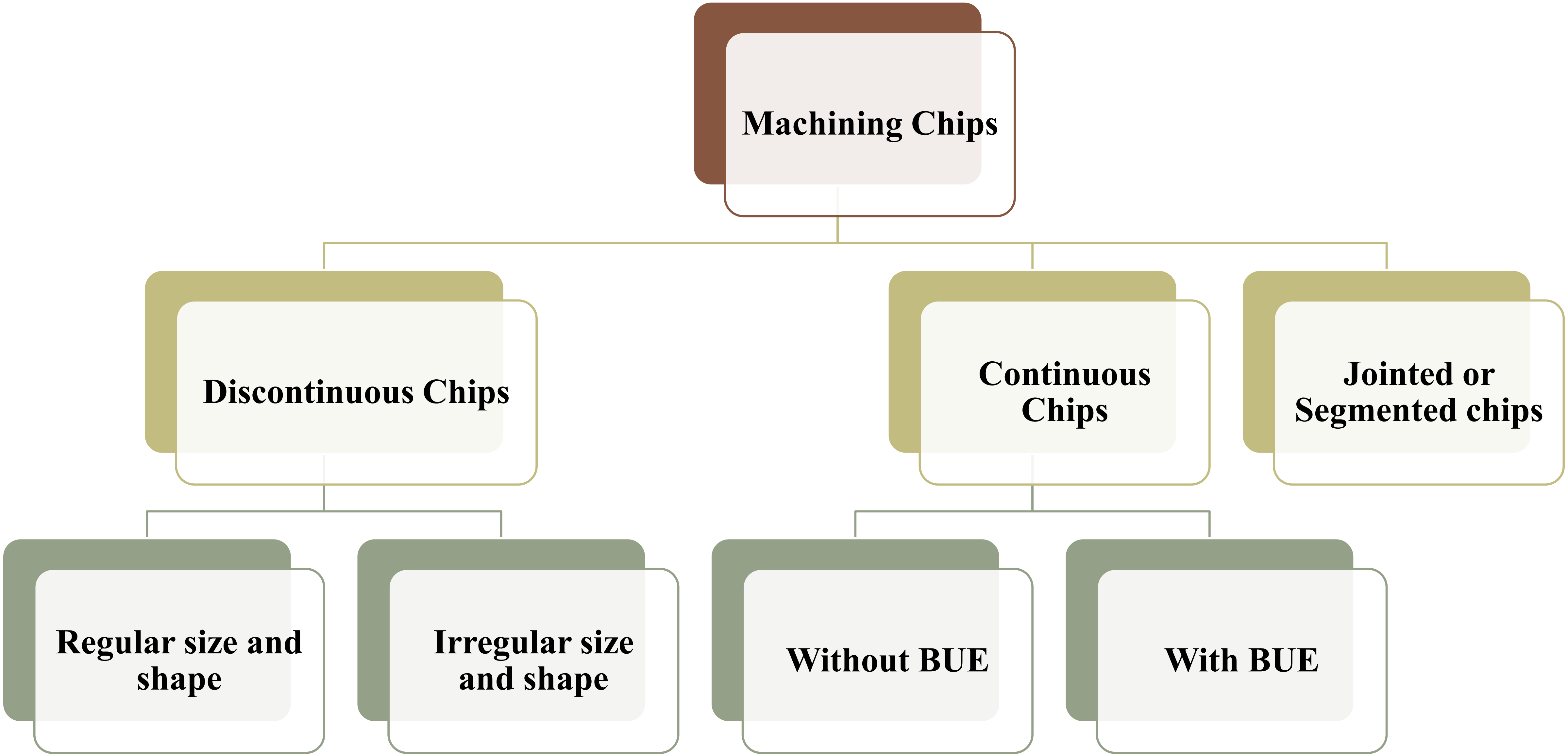
$$\epsilon = \frac{\Delta S}{Y} = \frac{PM}{ON} = \frac{PN + NM}{ON} = \frac{PN}{ON} + \frac{NM}{ON} \Rightarrow \epsilon = \cot \beta_o + \tan(\beta_o - \gamma_o)$$

- High cutting strain refers to unfavourable machining.

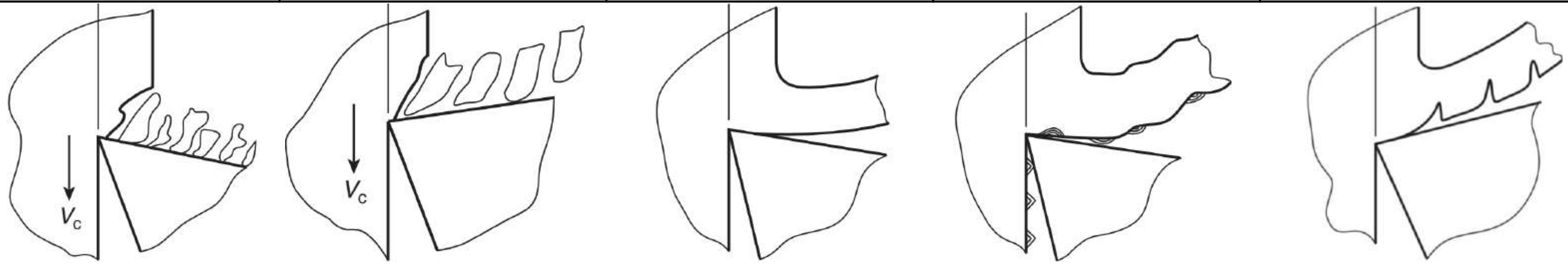
Classification of Machining Chips

Different types of chips of various shape, size, colour, etc. are produced by machining depends upon

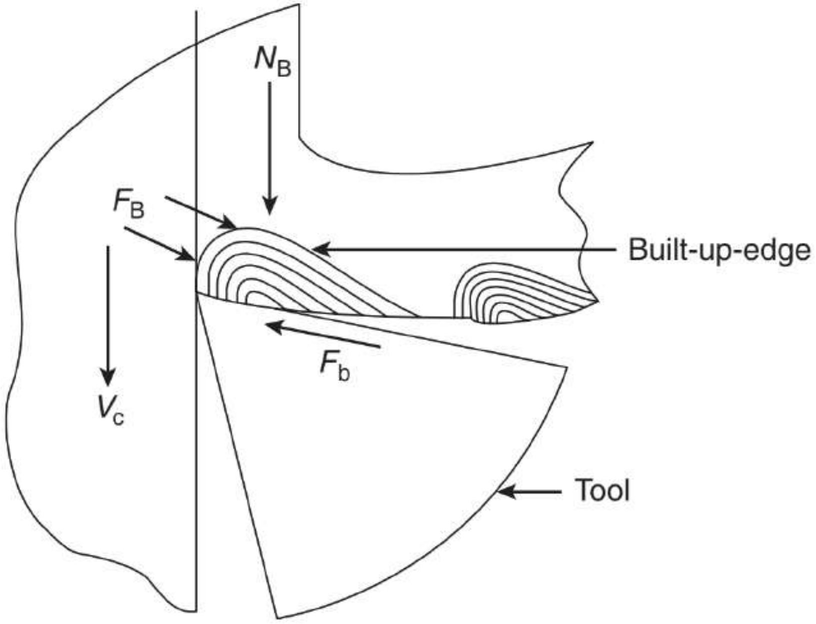
- **Type of cut (Continuous cut or intermittent cut)**
- **Work material (brittle or ductile)**
- **Cutting tool geometry (rake, cutting angles, etc.)**
- **Levels of cutting velocity and feed (low. Medium or high)**
- **Cutting fluid (type of fluid and method of application)**


Machining Chips
Discontinuous Chips
Continuous Chips
Jointed or Segmented chips
Regular size and shape
Irregular size and shape
Without BUE
With BUE

Conditions	Discontinuous Type Chips		Continuous Type Chips		Jointed or segmented type chips
	Irregular size and shape	Regular size and shape	Without BUE	With BUE	
Work Material	Brittle (grey cast iron)	Ductile but hard and work hardenable	Ductile	Ductile	Semi-ductile
Feed	Large	Large	Low	Medium or large	Medium to large
Tool Rake	Positive and small	Negative	Positive and large	Small	Negative
Cutting Fluid	Absent or inadequate	Absent or inadequate	Both cooling and lubricating	Inadequate or absent	Absent
Cutting Velocity	Low	Low	High	Medium	Low to medium

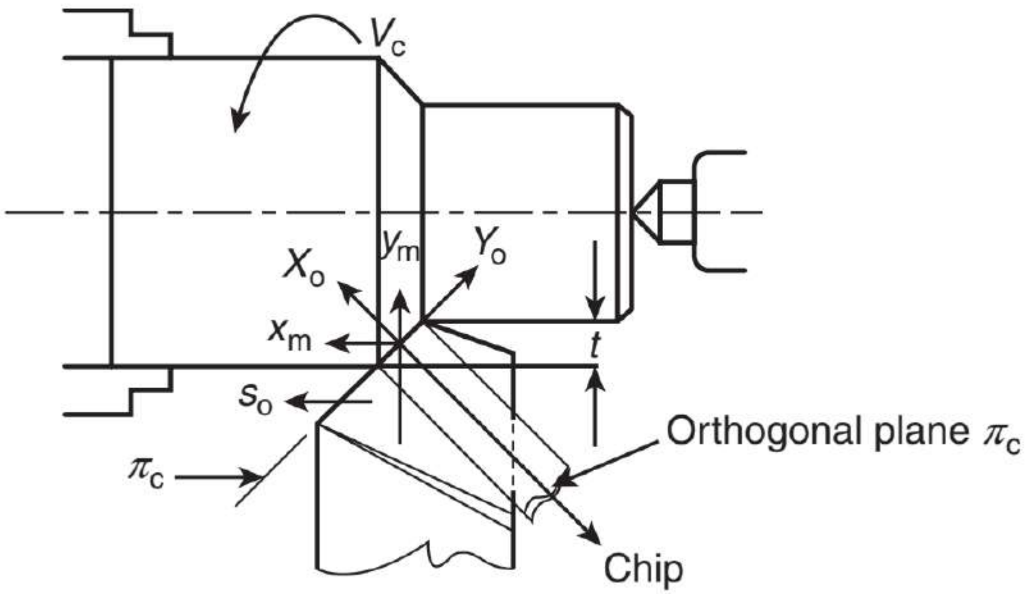


Built-up-Edge (BUE) Formation

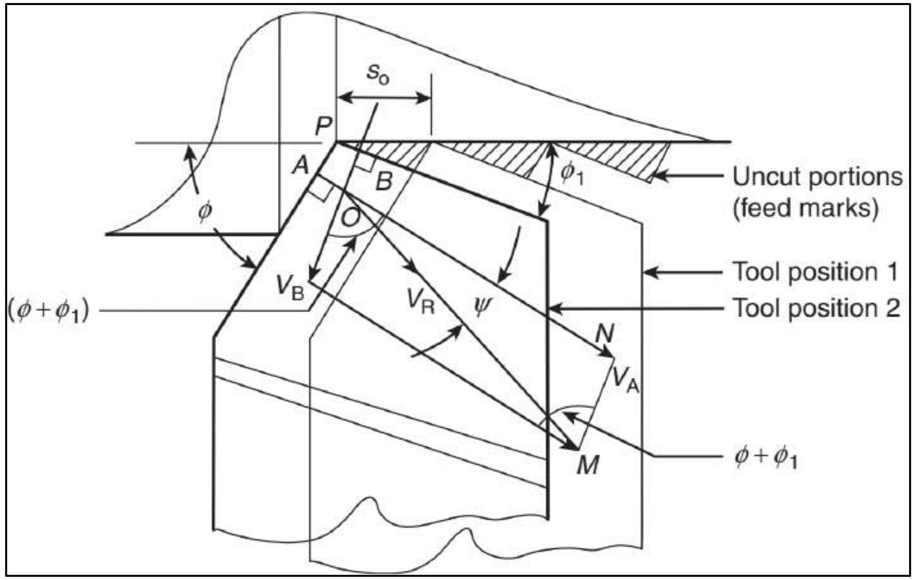


- In machining ductile materials with wide chip-tool contact length, lot of stress and temperature develop in the secondary deformation zone at chip-tool interface.
- Under such high stress and temperature in between two clean surfaces of metals, strong bonding may locally take place due to **adhesion** similar to welding.
- Such bonding will be encouraged and accelerated if the chip and tool materials have affinity or solubility.
- The weldment starts as an embryo at the most favourable location and then gradually grows.
- With the growth of BUE, the force F_B (Wedge Force) also gradually increases due to wedging action of the tool tip along with BUE formed on it.
- When ever the force F_B exceeds the bonding force F_b of the BUE, the BUE gets fractured or sheared off and carried away by the flowing chip.
- Then again BUE starts forming and growing. This goes on repeatedly.

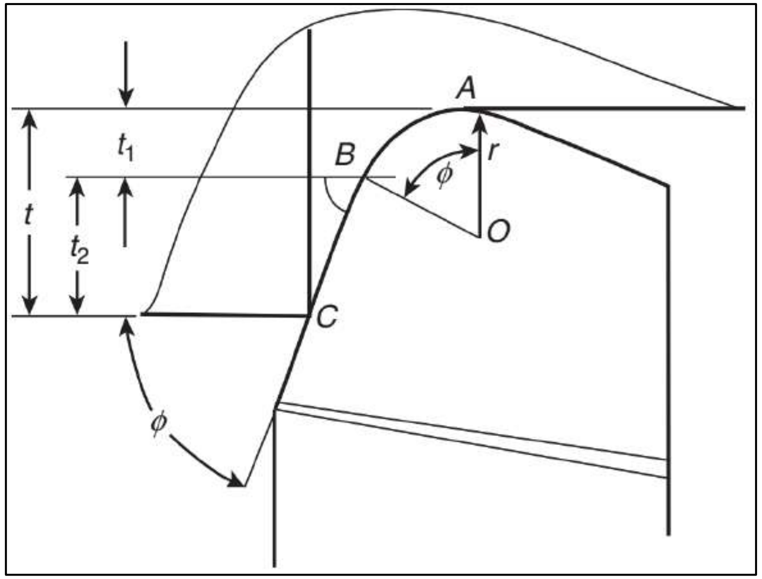
Orthogonal and Oblique Cutting



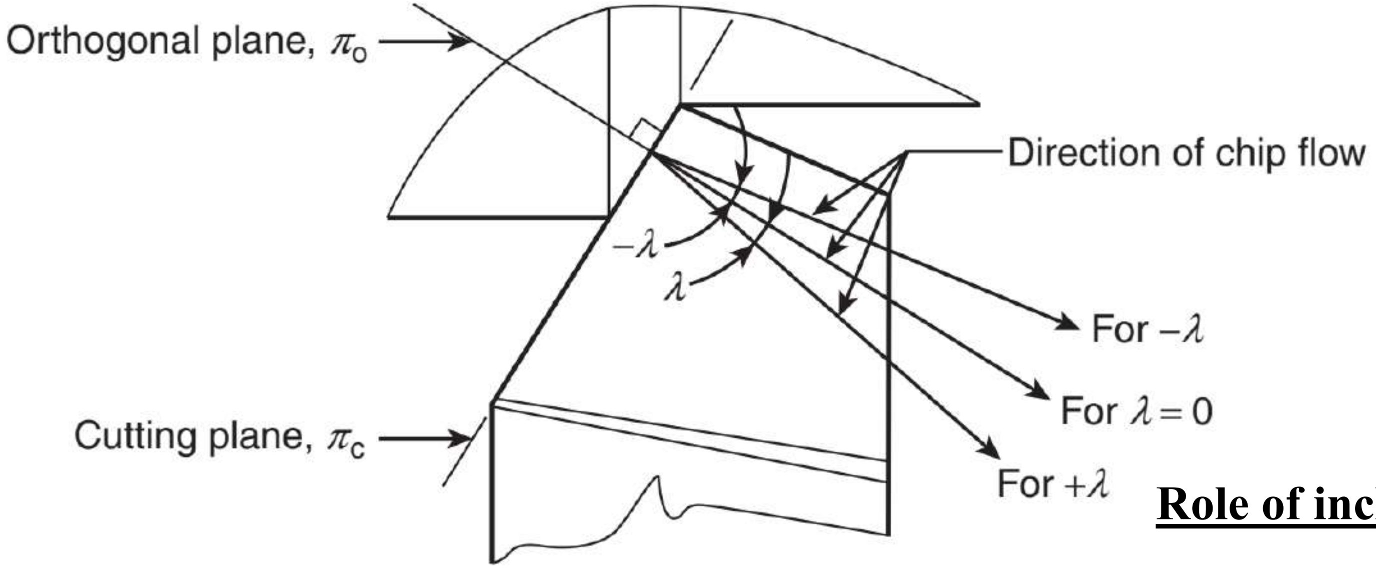
- In general, it is expected that in turning ductile material by a sharp tool, the continuous chip would flow over the tool's rake surface and in the direction apparently perpendicular to the principal cutting edge, that is, along orthogonal plane (which is normal to the cutting plane containing the principal cutting edge).
- Practically, the chip may not flow along the orthogonal plane due to several factors such as
  1. Restricted cutting effect (RCE)
  2. Presence of tool-nose radius (r)
  3. Presence of inclination angle ($\lambda \neq 0$)



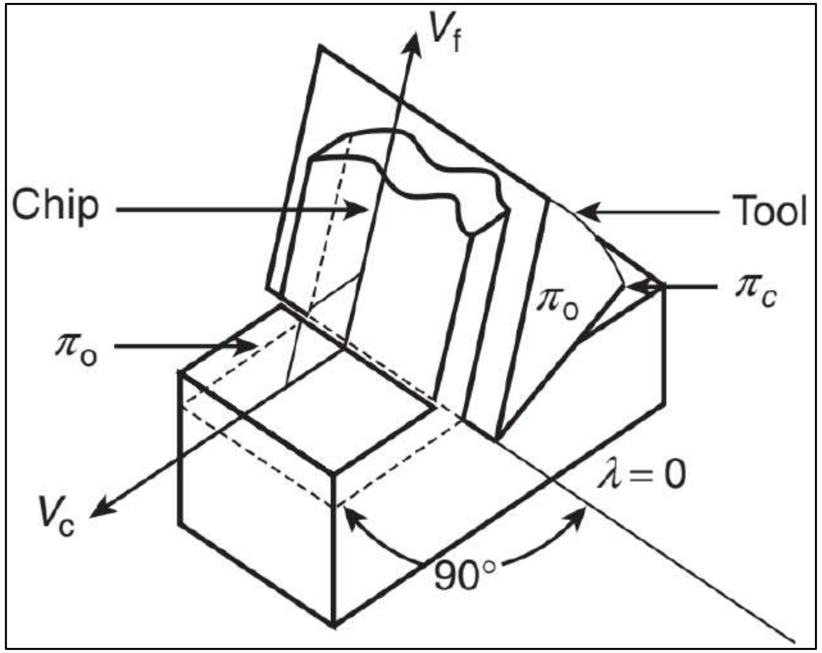
Chip flow deviation due to RCE



Variation of principal cutting edge angle along the nose of tool



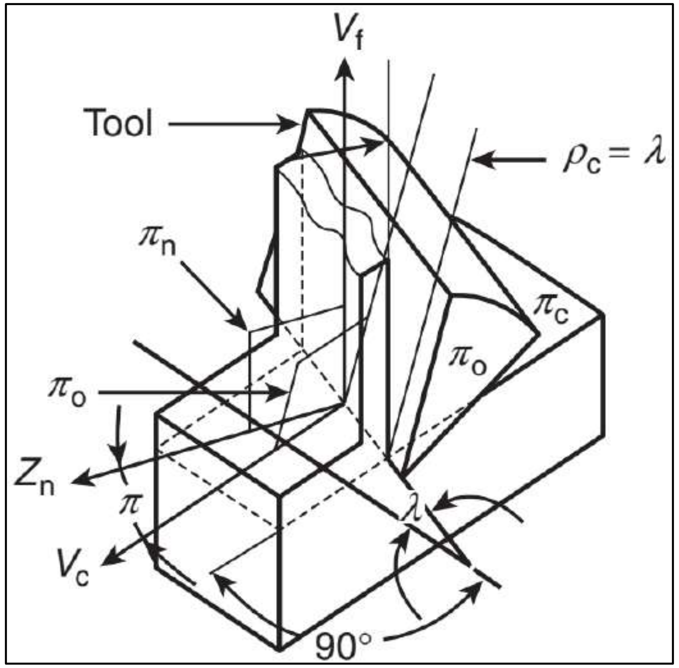
Role of inclination angle on chip flow direction

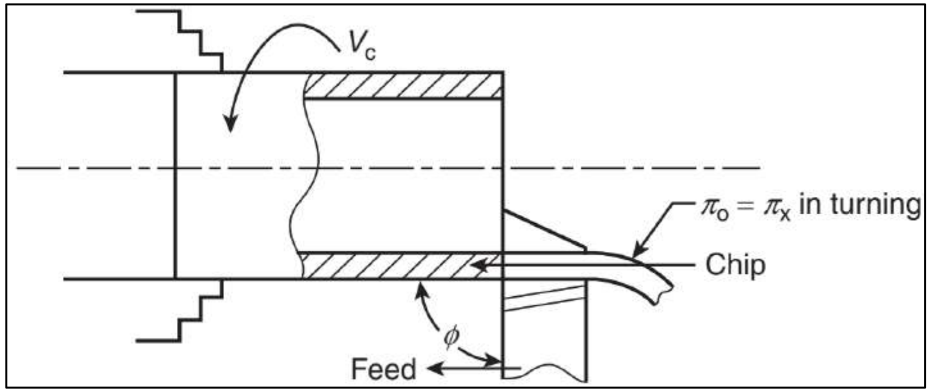


- Due to the presence of inclination angle (λ), there are different effects on the direction of the chip flow as following:
  1. **When λ=0**, the chip flows along the orthogonal plane ($\rho_c = 0$)
  2. **When λ≠0**, the chip flow is deviated from π_o and $\rho_c = \lambda$
- Here ρ_c is the chip flow deviation (from π_o) angle.

Cutting

Orthogonal Cutting	**chip flows along the orthogonal plane ($\rho_c = 0$)**
Oblique Cutting	**chip flow is deviated from π_o and $\rho_c \neq 0$**
Pure Orthogonal Cutting	**chip flow along π_o and ϕ=90°**



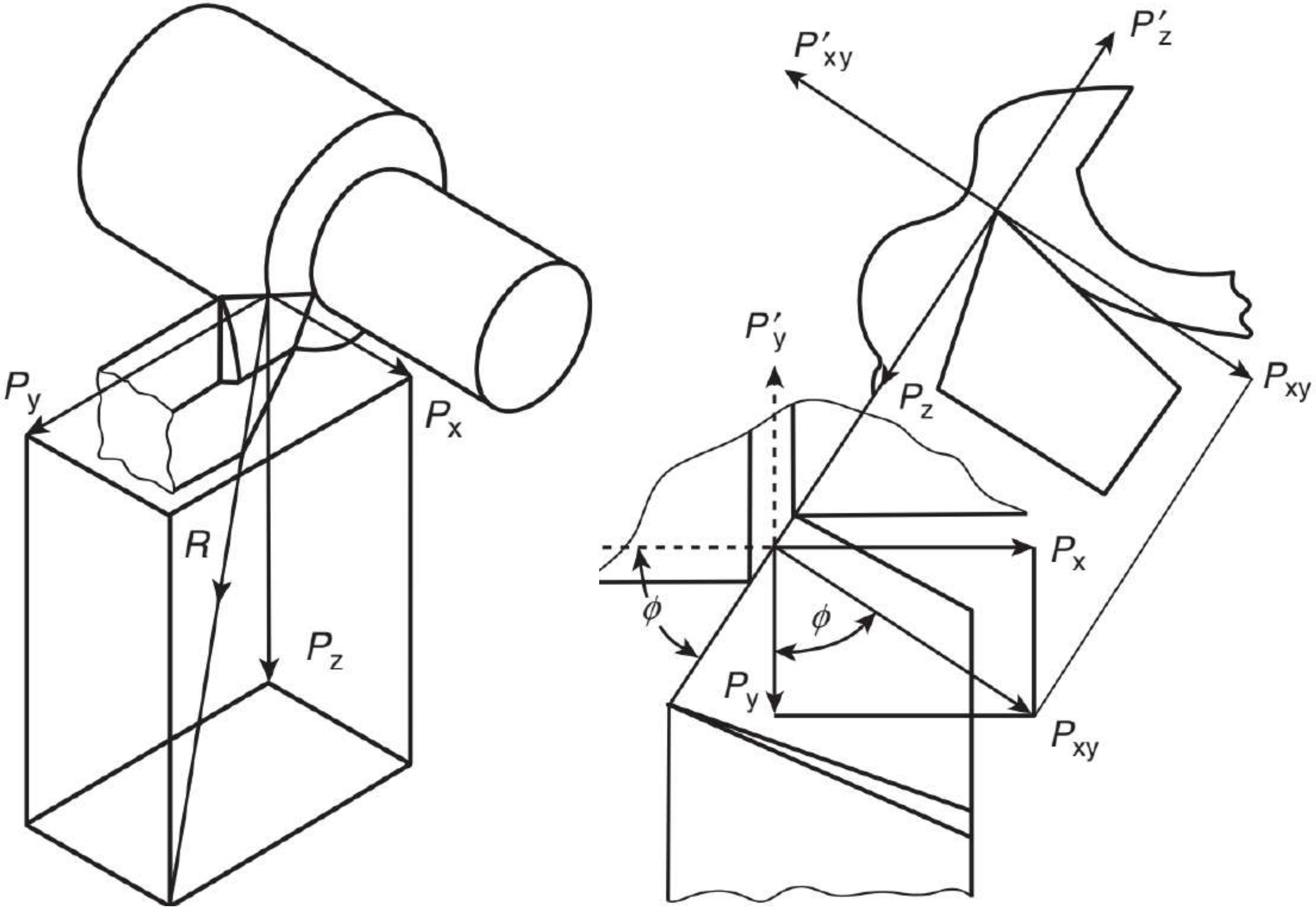


- **Pure orthogonal cutting:** A tubular job of uniform thickness is turned in a lathe by a turning tool of geometry λ=0 and ϕ=90°.

FORCE RELATION IN SINGLE POINT CUTTING TOOL

- The removal of materials by conventional machining requires a reasonable amount of mechanical energy to be expanded through the tool and the job to accomplish chip-separation by shearing or brittle fracture.
- So the forces develop and act on both the cutting tool and the workpiece at the cutting point.
- Attempts should be made to reduce the magnitude of the cutting forces as far as possible because large cutting forces not only cause increase in power and energy consumption but also affect the quality of the product as well as performance and life of the cutting tool and the machine tool.
- Therefore, mechanics of machining deals with:
  1. The cutting forces that are associated with machining.
  2. How to reduce the cutting forces without sacrificing productivity, by controlling the different machining parameters and the conditions of machining.
- Single-point cutting tools (turning, shaping, slotting, planing, boring, etc.) are characterized by having only one cutting force during machining. But that single force is resolved into three components in mutually orthogonal directions.

Cutting Forces in Turning



- The single resultant cutting force ***R*** is resolved into three components $\boldsymbol{P_x}$, $\boldsymbol{P_y}$ and $\boldsymbol{P_z}$.
- $\boldsymbol{P_x}$ acts along x-axis (axially).
- $\boldsymbol{P_y}$ acts along y-axis (radially).
- $\boldsymbol{P_z}$ acts along z-axis (tangentially).
- The components $\boldsymbol{P_x'}$, $\boldsymbol{P_y'}$, and $\boldsymbol{P_z'}$ are the corresponding reaction forces acting on the workpiece at its cutting point.
- The resultant force is resolved as

$$P_z + P_{xy} = R = R' = P'_z + P'_{xy}$$

$$P_x + P_y = P_{xy} = P'_{xy} = P'_x + P'_y$$

$$P_x = P_{xy} \sin\phi \text{ and } P_y = P_{xy} \cos\phi$$

- The significance of the cutting force components are
  1. **P_z:** It is called the main or major component. It is the largest in magnitude and is used for measuring cutting power consumption.
  2. **P_y:** Though relatively small in magnitude, it affects dimensional accuracy and induces vibration.
  3. **P_x:** It is least harmful and hence least significant.

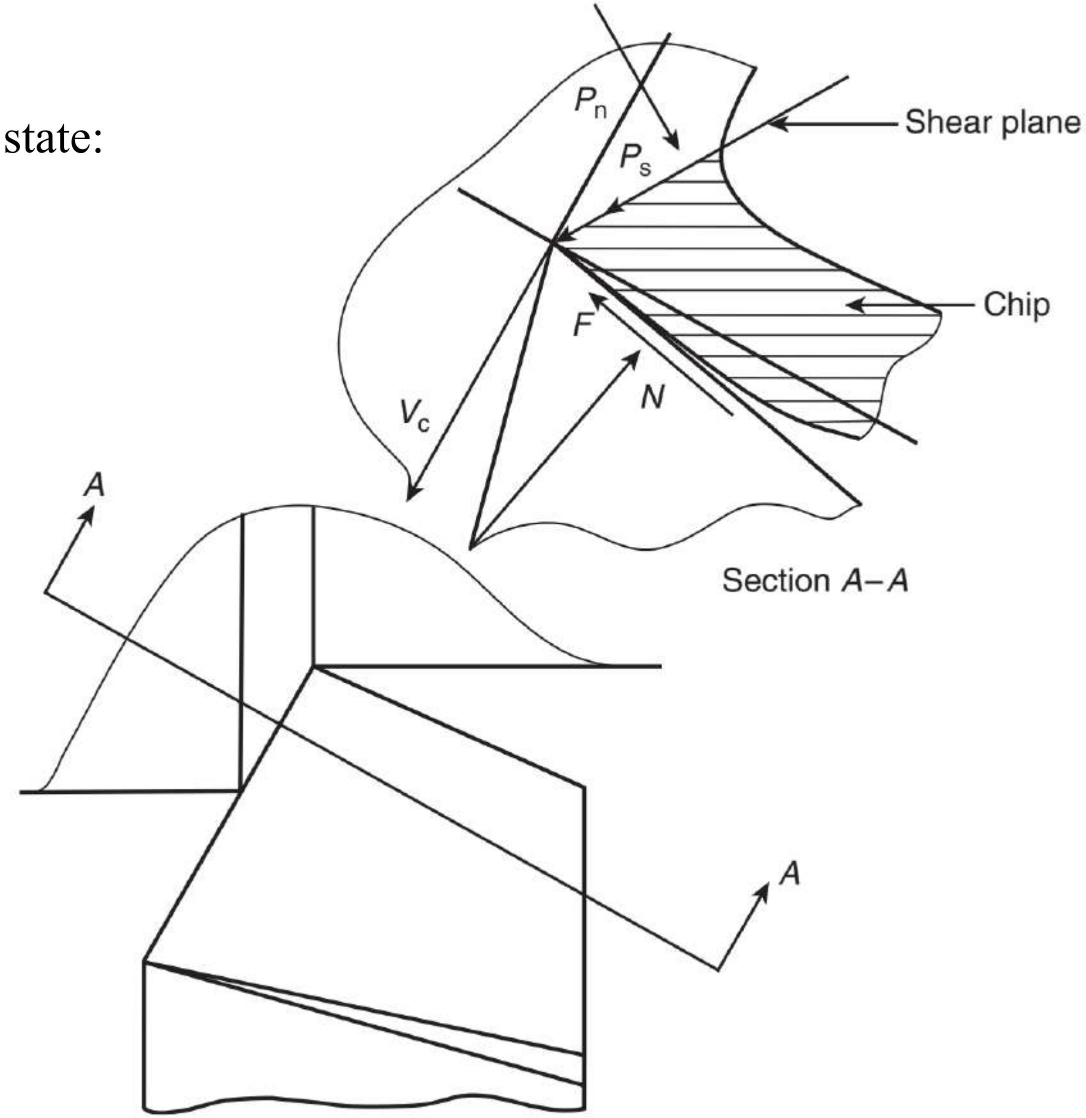
Purpose of Determination of Cutting Forces

- Assessment of cutting power consumption and selection of the power source while designing a machine tool.
- Structural design of the machine-fixture-tool system.
- Evaluation of the role of variation of the different machining parameters on cutting force.
- Study of the behaviour and machinability characteristics of any work material under given machining condition.
- Condition monitoring of the cutting tools and machine tool.

Cutting Forces Analysis for Machining by Single-Point Tools

- While machining any ductile material using a single-point cutting tool in ideal and stable conditions, smooth, uniform and continuous type chips are formed and come out at a constant speed.
- The chip segment is subjected to the following forces in its equilibrium state:

1. From the workpiece side
    a) **Shear force P_s** acting along the shear plane.
    b) **Force P_n** acting normal to the shear plane
2. From the tool side
    a) **Frictional force F** acting along the rake surface.
    b) **Normal force N** perpendicular to the rake surface.



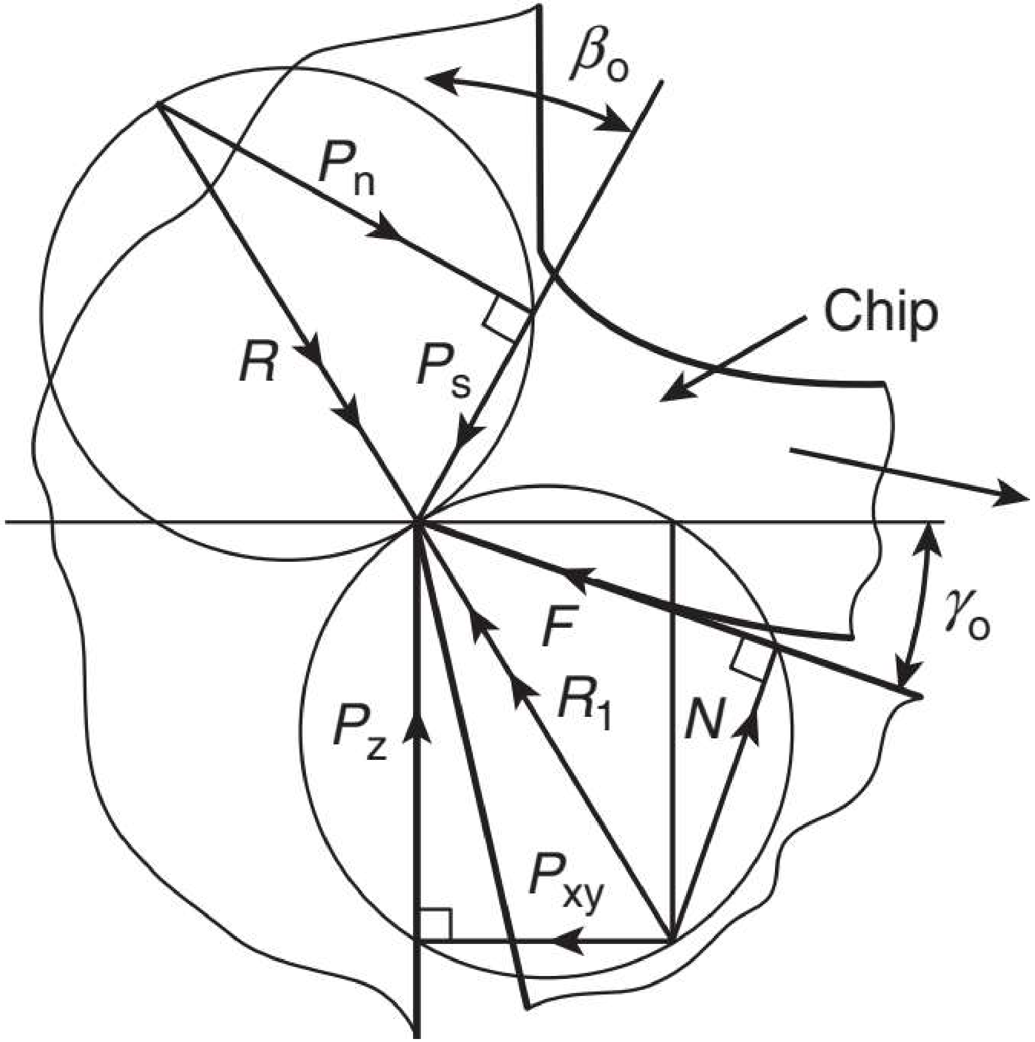
Force Analysis using Merchant's Circle Diagram (MCD)

- The display and inter-relationship of the different force components in continuous chip formation under orthogonal cutting is very easily visualized and established by a simple diagram called the **Merchant's circle diagram**.

Construction of MCD:

- In orthogonal cutting, the chip flows along the orthogonal plane π_o and the cutting force (resultant) and its major components P_z and P_{xy} remain in that plane.
- The forces acting on the chip segment are;
  - From the workpiece side:
    - *a)* P_s = Shear force which directly cause separation of the chip by shearing.
    - *b)* P_n = Force that acts normal to the shear plane.

    So, $\bar{P}_s + \bar{P}_n = \bar{R}$



Construction of MCD:

- From the tool side:

  a) F = Frictional force at the chip tool interface.

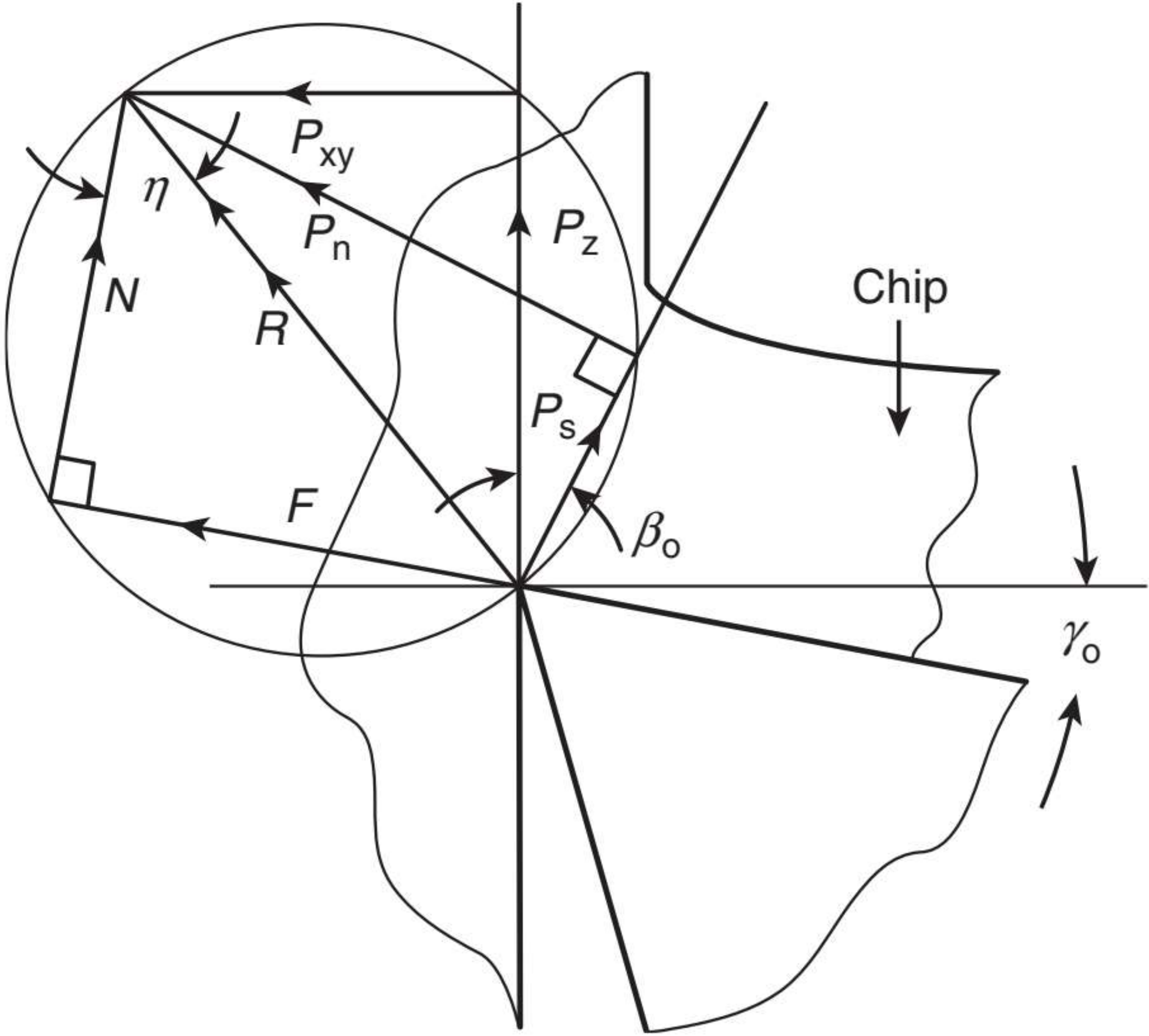
  b) N = Force that acts normal to the shear plane.

  So, $\bar{F} + \bar{N} = \bar{R}_1$

- The resultant forces R or R_1 can be resolved further as $\vec{R} = \vec{R}_1 = \vec{P}_z + \vec{P}_{xy}$
- So, it appears that; $\vec{P}_s + \vec{P}_n = \vec{R} = \vec{R}_1 = \vec{F} + \vec{N} = \vec{P}_z + \vec{P}_{xy}$
- It is to be noted that circles drawn using R and R_1 as diameter are identical.
- They contains pairs of resolved perpendicular components; P_s and P_n, F and N, P_z and P_{xy}
- Those two circles with their contents when combined into a single circle produce the MCD.
- MCD visualizes in it all the forces associated with the mechanics of formation of a machining chip and also the inter-relationships of those forces.

- The significance and important roles of the forces involved in chip formation as displayed in MCD are:

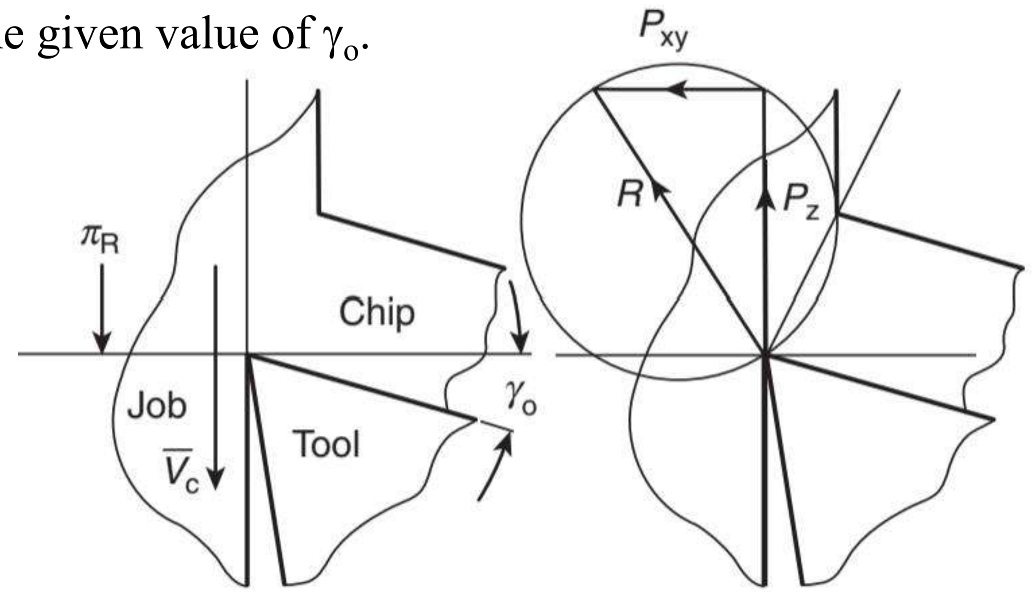
1. **P_s**:- It is the **shear force** which is mainly responsible for **chip-separation** from the parent body by shearing. It is used to **determine the dynamic yield strength** τ_s of the work material under the specific cutting condition.
2. **R**:- It is the **force to be induced into the workpiece at the cutting point** to provide the forces especially P_s which is required for shearing the chip out.
3. **R_1**:- It is the resultant force to be provided through the cutting edge to induce the force R in the workpiece.
4. **N** and **F**:- These are the components of R_1 and they act normal and along the rake surface.
5. **P_z**:- It is the **main cutting force component** used as the index of machinability and for evaluation of cutting power consumption.



- Suppose, in an orthogonal turning of a ductile rod of diameter D by a tool of known geometry (γ_o, ϕ, r, etc.) with given speed (N), feed (s_o) and depth of cut (t), the magnitude of the two cutting force components P_z and P_x are known by direct measurement.
- MCD helps determine the values of;
    1. Magnitude of the forces F, N, P_s and P_n.
    2. Apparent coefficient of friction μ_a at the chip-tool interface.
    3. Yield shear strength τ_s of the work material at that cutting condition.

Steps to Construct MCD

1. Draw the tool and the chip segment in the orthogonal plane π_o taking the given value of γ_o.
2. Determine P_{xy} using; $\boxed{P_x = Pxysin\phi}$
3. Select suitable scale for presenting P_z and P_{xy} in cm.
4. Draw P_z and P_{xy} along and normal to $\vec{V}_c$.
5. Draw the resultant (R) of P_z and P_{xy}.
6. Draw the circle (Merchant's circle) taking R as the diameter.

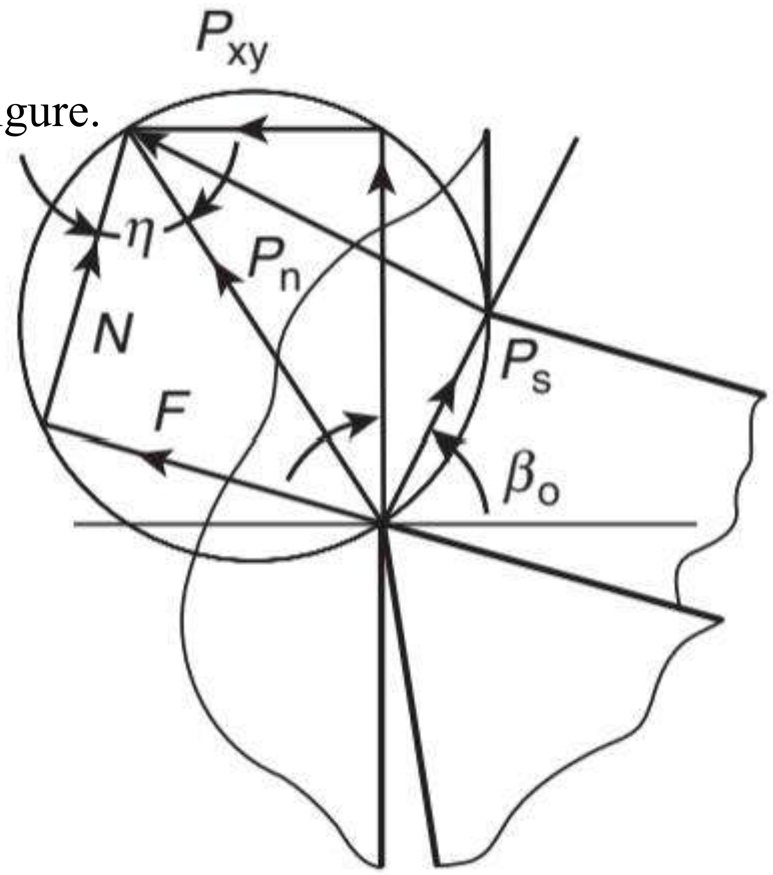


7. Obtain F and N as intercepts by extending the rake surface and then joining the tips of F and R.
8. Multiply those intercepts of F and N by the scale and get the values of F and N.

9. To determine the value of P_s (and P_n), the value of shear angle β_o is to be evaluated using; $\boxed{\tan\beta_o = \frac{\cos\gamma_o}{\zeta - \sin\gamma_o}}$

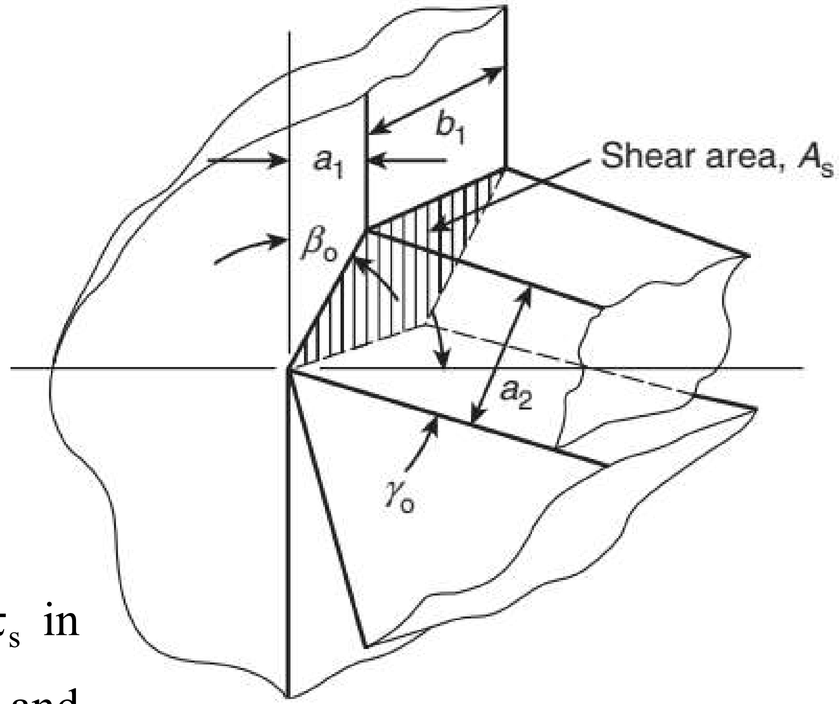
   where, $\zeta = \frac{a_2}{a_1} = \frac{a_2}{s_o \sin\phi}$

10. Draw the shear plane at an angle β_o and then draw the intercepts P_s and P_n in the same figure.
11. Obtain the value of P_s and P_n in N (Newton) using the scale.
12. Obtain the value of friction coefficient μ_a from the ratio $\mu_a = F/N$ and friction angle η from $\tan\eta = \mu_a$ or directly from the MCD drawn.



13. Obtain the value of dynamic yield shear strength τ_s of the work material in the given cutting condition using the simple relation $\tau_s = \frac{P_s}{A_s}$

Where, A_s is the shear area, given by $A_s = \frac{a_1 b_1}{\sin \beta_o} = \frac{t s_o}{\sin \beta_o}$



Development of Mathematical Expression for Cutting Forces Using MCD

- The magnitude of the forces F, N, P_s and P_n as well as the values of μ_a and τ_s in orthogonal cutting can be determined analytically also from the known values of P_z and P_{xy} using some equations only (without the direct use of MCD).
- But these equations are derived with the help of MCD.
- MCD also helps in developing mathematical expressions for analytical estimation of the cutting force components P_z and P_{xy} in orthogonal cutting.

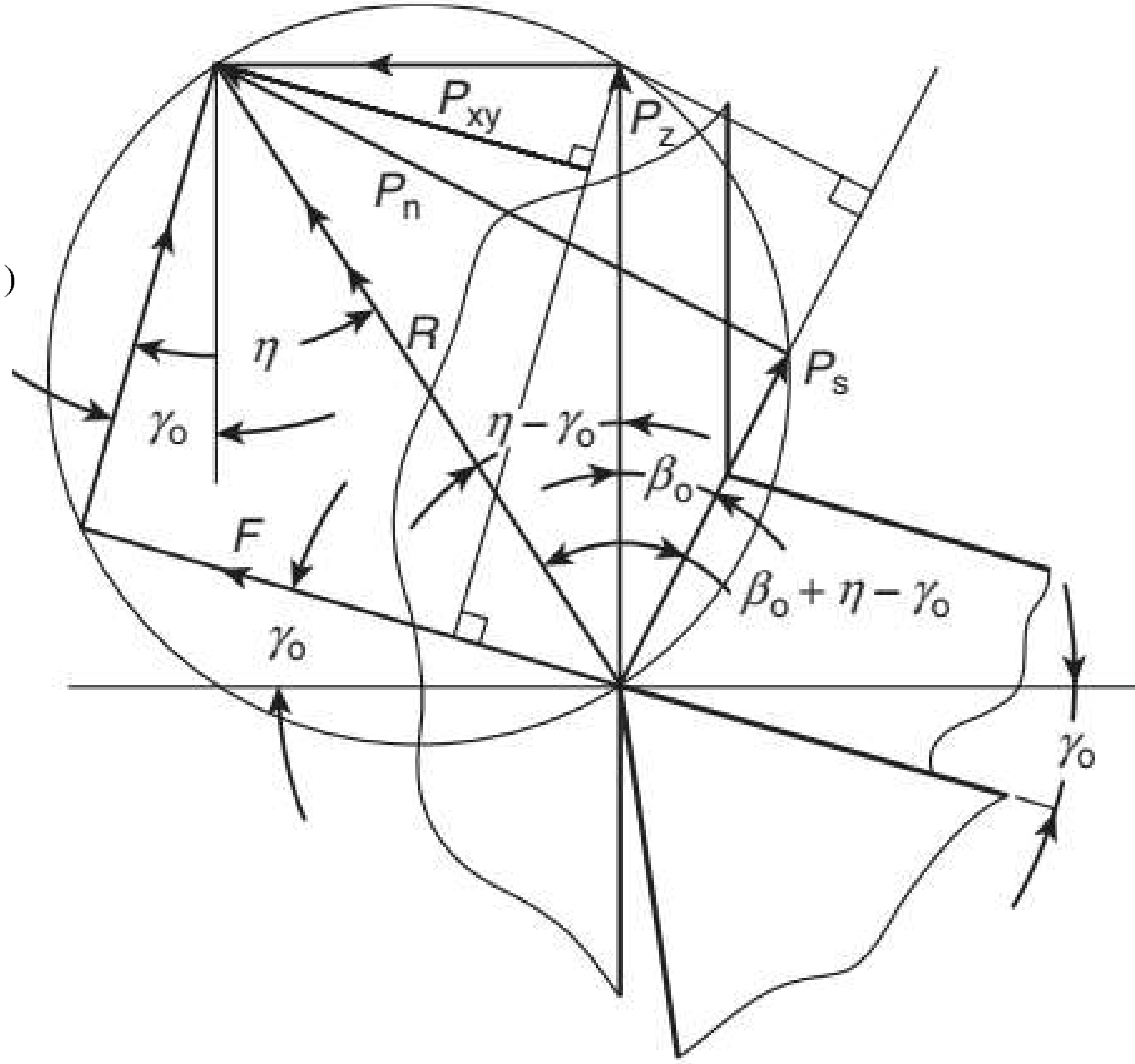
$$F = R\sin\eta = R\sin(\gamma_o + \eta - \gamma_o) = R\sin\gamma_o\cos(\eta-\gamma_o) + R\cos\gamma_o\sin(\eta-\gamma_o)$$
$$= R\cos(\eta-\gamma_o)\sin\gamma_o + R\sin(\eta-\gamma)\cos\gamma_o$$
$$\Rightarrow \boxed{F = P_z\sin\gamma_o + P_{xy}\cos\gamma_o}$$

$$N = R\cos\eta = R\cos(\gamma_o + \eta - \gamma_o) = R\cos\gamma_o\cos(\eta-\gamma_o) - R\sin\gamma_o\sin(\eta-\gamma_o)$$
$$= R\cos(\eta-\gamma_o)\cos\gamma_o - R\sin(\eta-\gamma)\sin\gamma_o$$
$$\Rightarrow \boxed{N = P_z\cos\gamma_o - P_{xy}\sin\gamma_o}$$

$$\mu_a = \frac{F}{N} = \frac{P_z sin\gamma_o + P_{xy} cos\gamma_o}{P_z cos\gamma_o - P_{xy} sin\gamma_o} \Rightarrow \boxed{\mu_a = \frac{P_z tan\gamma_o + P_{xy}}{P_z - P_{xy} tan\gamma_o}}$$

$$P_s = R\cos\left(\beta_o + \eta - \gamma_o\right) = R\cos\beta_o\cos(\eta-\gamma_o) - R\sin\beta_o\sin(\eta-\gamma_o)$$
$$= R\cos(\eta-\gamma_o)\cos\beta_o - R\sin(\eta-\gamma)\sin\beta_o$$
$$\Rightarrow \boxed{P_s = P_z\cos\beta_o - P_{xy}\sin\beta_o}$$

$$P_n = R\sin\left(\beta_o + \eta - \gamma_o\right) = R\sin\beta_o\cos(\eta-\gamma_o) + R\cos\beta_o\sin(\eta-\gamma_o)$$
$$= R\cos(\eta-\gamma_o)\sin\beta_o + R\sin(\eta-\gamma)\cos\beta_o$$
$$\Rightarrow \boxed{P_n = P_z\sin\beta_o + P_{xy}\cos\beta_o}$$



From MCD

$P_z = R\cos(\eta - \gamma_o)$

$P_s = R\cos(\beta_o + \eta - \gamma_o)$

So,

$$\frac{P_z}{P_s} = \frac{R\cos(\eta-\gamma_o)}{R\cos(\beta_o+\eta-\gamma_o)}$$

$$\Rightarrow P_z = \frac{P_s\cos(\eta-\gamma_o)}{\cos(\beta_o+\eta-\gamma_o)} = \frac{A_s\tau_s\cos(\eta-\gamma_o)}{\cos(\beta_o+\eta-\gamma_o)}$$

$$\Rightarrow \boxed{P_z = \frac{ts_o\tau_s\cos(\eta-\gamma_o)}{\sin\beta_o\cos(\beta_o+\eta-\gamma_o)}}$$

Angle Relation By Ernst & Merchant

- The **Minimum Energy Principle** states that "**During metal cutting, the shear plane angle adjusts itself such that the cutting process requires the minimum cutting energy or cutting force.**"
- In other words, the metal chooses the shear angle that makes the work done per unit volume of metal removed minimum.

Considering Minimum Energy Principle

$$\frac{dP_z}{d\beta_o} = 0 \Rightarrow \frac{d}{d\beta_o}\left[\frac{ts_o\tau_s\cos(\eta-\gamma_o)}{\sin\beta_o\cos(\beta_o+\eta-\gamma_o)}\right] = 0$$

$$\Rightarrow ts_o\tau_s\cos(\eta-\gamma_o)\frac{d}{d\beta_o}\left[\frac{1}{\sin\beta_o\cos(\beta_o+\eta-\gamma_o)}\right] = 0$$

$$\Rightarrow ts_o\tau_s\cos(\eta-\gamma_o)\frac{\cos(2\beta_o+\eta-\gamma_o)}{\sin^2\beta_o\cos^2(\beta_o+\eta-\gamma_o)} = 0$$

$$\Rightarrow \cos(2\beta_o+\eta-\gamma_o) = 0 = \frac{\pi}{2}$$

$$\Rightarrow \boxed{2\beta_o+\eta-\gamma_o = \frac{\pi}{2}} \Rightarrow \boxed{\beta_o = \frac{\pi}{4} - \frac{1}{2}(\eta-\gamma_o)}$$

Advantages of MCD

The major advantages of using MCD for cutting force analysis include

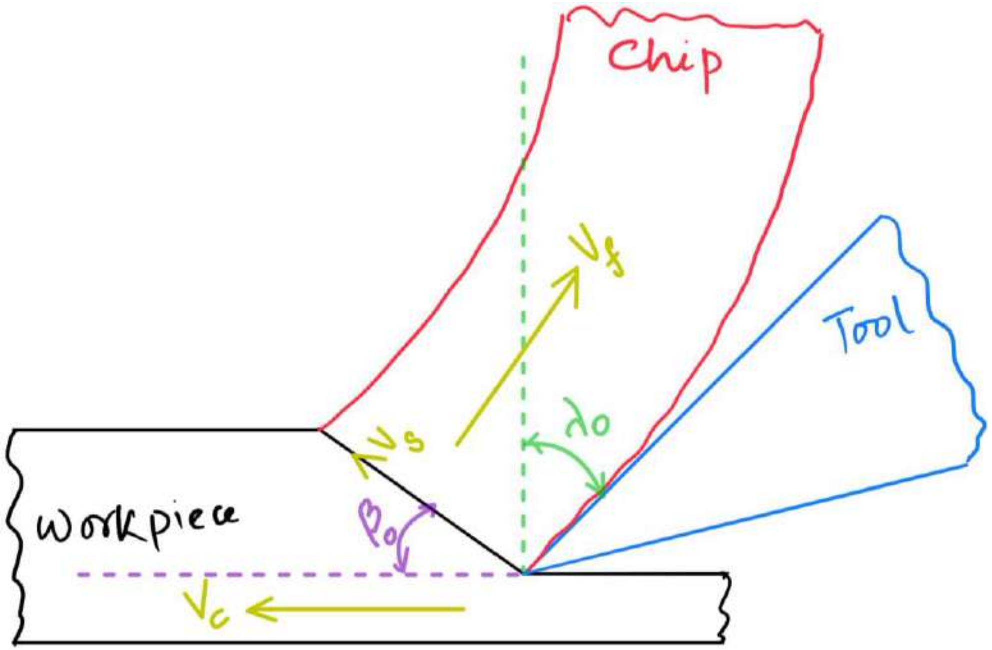
1. Easy, quick and reasonably accurate determination of magnitude and direction of the forces concerned from the known or predetermined values of a few forces.
2. Easy and quick evaluation of the following which are used to assess or indicate the machinability characteristics of the given tool–work combination.
   (a) Frictional force.
   (b) Apparent coefficient of friction occurring at the chip–tool interface.
   (c) Yield shear strength of the work material under any cutting condition.
3. Derivation of mathematical expressions for the different force components.

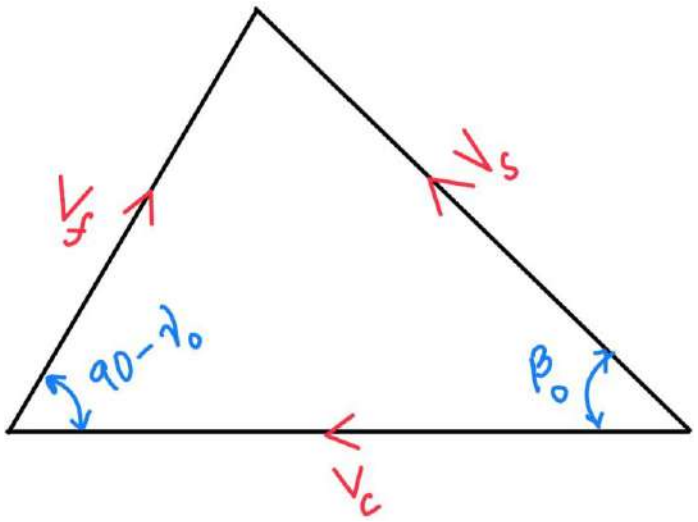
Limitations of MCD

The few limitations of MCD are

1. MCD is valid only for orthogonal cutting where all the forces are contained in the orthogonal plane.
2. The ratio F N/ gives only the apparent (not actual) coefficient of friction.
3. MCD is applicable where chip formation is based on single shear plane theory.
4. MCD is applicable only for smooth, continuous chip formation in stable condition.

Velocity Relation in Machining





V_c= Cutting Velocity

V_f= Chip flow velocity

V_s= Shear Velocity

γ_o= Orthogonal rake angle

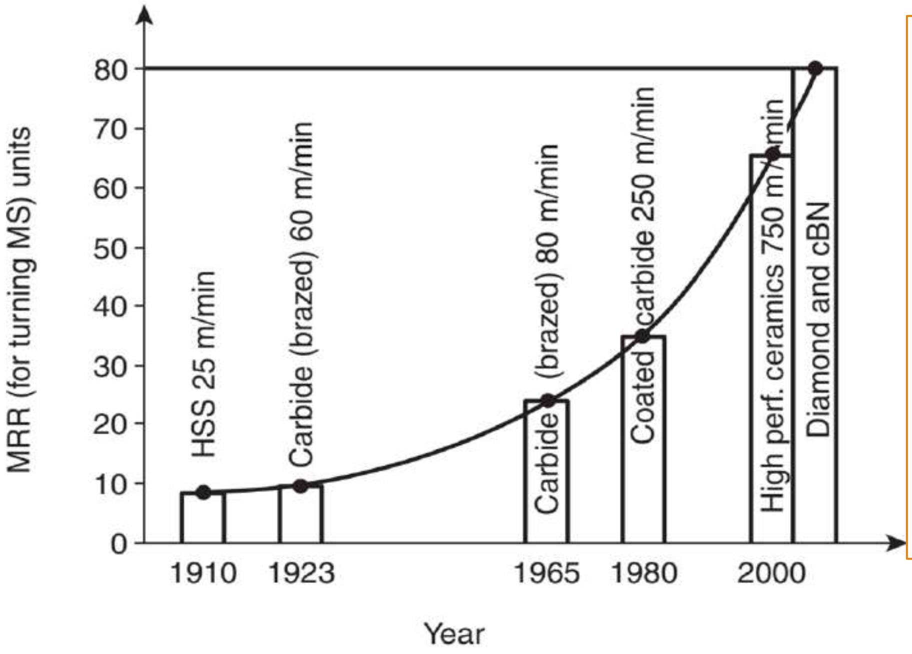
β_o= Shear angle

Applying sine rule of triangle (Lami's Theorem);

$$\frac{V_c}{\sin(90-(\beta_o-\gamma_o))} = \frac{V_s}{\sin(90-\gamma_o)} = \frac{V_f}{\sin(\beta_o)} \Rightarrow \boxed{\frac{V_c}{\cos(\beta_o-\gamma_o)} = \frac{V_s}{\cos\gamma_o} = \frac{V_f}{\sin(\beta_o)}}$$

Cutting Tool Materials

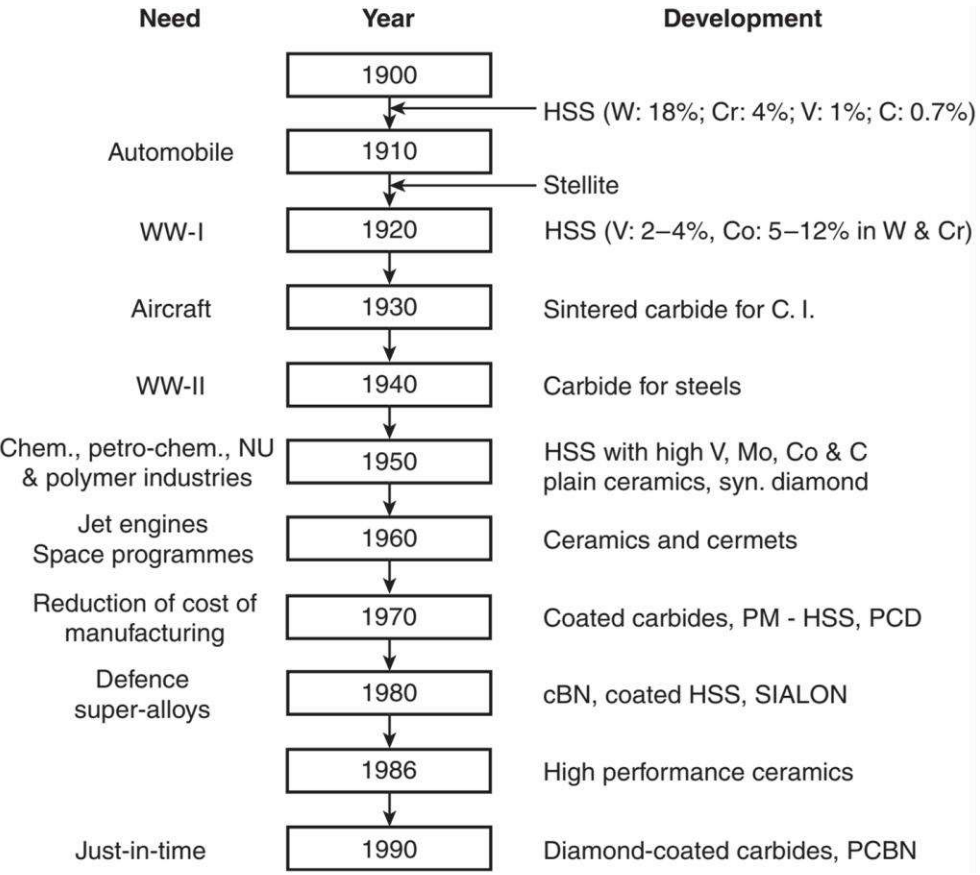
- Need for improvements in cutting tool materials and geometry
  1. To meet the **ever-growing demands** for enhanced productivity, high quality, and overall economy of machining.
  2. To enable effective and efficient machining of the so-called **difficult-to-machine exotic materials**, which are rapidly and widely becoming available with the progress of the industrial world.
  3. To accomplish **precision and ultra-precision machining** as per the demands of the day and the future.
  4. For **micro-machining**, as its demand is increasing.



- The service life and overall performance of cutting tools, for a given job, are governed by
  1. Material of the cutting tools.
  2. Geometry of the cutting tools.
  3. Proper selection and use of the cutting tools.
  4. The condition of machining and cutting fluid application.

Cutting Tool Materials Properties

- **High mechanical strength** to resist breakage of the tool or tool tip.
- **High hardness** to reduce abrasion wear.
- **High hot strength and hot hardness** to maintain the form stability of the cutting edges.
- **Adequate fracture toughness and transverse rupture strength** to reduce chipping and fracturing.
- **Enough fatigue strength** to withstand dynamic loading.
- **High chemical stability or inertness** against work material, atmospheric gases, and cutting fluid.
- **Reasonably high thermal conductivity** to reduce cutting temperature at the tool tip.
- **Resistance** to adhesion and diffusion to retard adhesion wear and the rapid diffusion wear.
- **High stiffness** to maintain the dimensional accuracy of the machined features.
- **Self-lubricity or lesser friction at the chip–tool interface** to resist the formation of a built-up edge.
- **Formability, availability and inexpensiveness**.



HSS = high-speed steel
PCD = polycrystalline diamond
cBN/PCBN = (polycrystalline) cubic boron nitride
SIALON = silicon–aluminium–oxynitride
C.I. = cast iron
PM-HSS = powder-metallurgy HSS.

- ❖ **1900 — General machining need**: High-speed steel (HSS) appears (≈W 18%, Cr 4%, V 1%, C 0.7%) → much higher cutting speeds than carbon steel.
- ❖ **1910 — Automobile boom**: Stellite (Co-based alloy) adopted → better hot-strength and wear resistance than early HSS.
- ❖ **1920 — WW-I productivity push**: Improved HSS (V 2–4%, Co 5–12% replacing some W/Cr) → greater "red-hardness" for faster, hotter cutting.
- ❖ **1930 — Aircraft manufacturing**: Sintered (cemented) carbides for cast iron (e.g., WC–Co) → big jump in speed and tool life.
- ❖ **1940 — WW-II manufacturing:** Carbide grades for steels (TiC/TaC additions, optimized binders) → reliable machining of alloy steels.
- ❖ **1950 — Chem/petrochem/nuclear/polymer industries**: Two tracks (i) Richer HSS (higher V, Mo, Co, C) for toughness + hot-hardness (ii) Plain ceramics and synthetic diamond emerge for extreme wear resistance on non-ferrous/abrasive cuts.
- ❖ **1960 — Jet engines & space programs**: Ceramics and cermets (ceramic–metal composites) → high-temperature capability and chemical inertness.
- ❖ **1970 — Cost-reduction era**: Coated carbides (TiC/TiN/Al_2O_3 etc.), PM-HSS (powder-metallurgy HSS with finer carbides), and PCD (polycrystalline diamond) → higher speed, longer life, lower cost per part.
- ❖ **1980 — Defence & superalloys**: cBN (cubic boron nitride) for hardened steels, coated HSS, and SIALON (Si–Al–O–N ceramics) for heat-resistant alloys.
- ❖ **1986 — High-performance ceramics**: Toughened/whisker-reinforced ceramics → improved strength and thermal-shock resistance.
- ❖ **1990 — Just-in-time manufacturing**: Diamond-coated carbides and PCBN (polycrystalline cBN) → very high productivity with consistent tool life.

Conventional Tool Materials

- HSS
- Stellite
- Sintered Tungsten Carbide
- Plain Ceramic

Advanced Tool Materials

- Coated Carbide
- Coronite
- Cermets

Other Tool Materials

- High Performance Ceramics
- Carbon Boron Nitride
- Diamond

High Speed Steel (HSS)

- First discovered in 1905.
- Basic composition: 18% W, 4%Cr, 1%V, 0.7%C, rest is Fe.
- Basic HSS can machine mild steel jobs at a speed of only 20-30 m/min under dry cut and 45 m/min with cutting fluid.

Composition and Types of popular HSS

Type	*C*	*W*	*Mo*	*Cr*	*V*	*Co*	*RC*
T – 1	0.70	18		4	1		
T – 4	0.75	18		4	1	5	
T – 6	0.80	20		4	2	12	
T – 2	0.80	6	5	4	2		64.7
T – 4	1.30	6	5	4	4		
M – 15	1.55	6	3	5	5	5	
M – 42	1.08	1.5	9.5	4	1.1	8	62.4

Where HSS is used?

- The tool geometry and mechanics of chip formation is complex, such as helical twist drills, reamer etc.
- Brittle tools such as carbides, ceramics, etc. are not suitable (under shock loading conditions).
- Costlier tools are not affordable.
- Machine tools are low-power, small and old.
- Tool is to be used a large number of times by re-sharpening.

How the effectiveness of HSS was improved?

- Refinement of microstructure.
- Addition of large amount of cobalt and vanadium to increase hot hardness and wear resistance, respectively.
- Manufactured by powder metallurgical process.
- Surface coating with heat and wear resistance materials like TiC, TiN etc. by CVD or PVD processes.

Stellite

- Cast alloy of Co (40-50%), Cr (27-32%), W (14-19%) and C (2%).
- Quite tough
- More heat and wear resistive than basic HSS
- Stellite as a cutting material become obsolete because of its poor grindability.

Sintered Tungsten Carbides

1. Straight or single carbide
2. Composite carbides
3. Mixed carbides

1. Straight or Single Carbide

- First produced using powder metallurgy by mixing, compacting and sintering 90-95% WC powder with cobalt.
- Hot, hard and wear resistant tungsten carbide grains are held by the binder Co which provides the necessary strength and toughness.
- Suitable for machining grey cast iron, brass, bronze, etc. which produces short discontinuous chips and at cutting velocities 2 to 3 times of those possible for HSS tools.

2. Composite Carbide

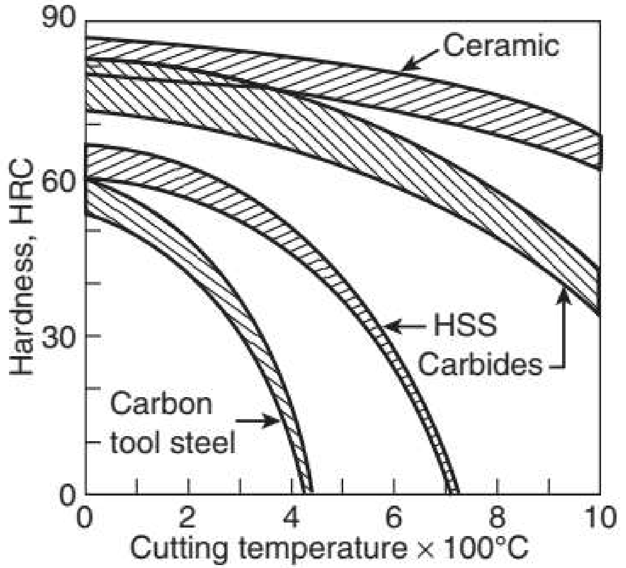
- Single carbide tools are not suitable for machining steel because of rapid growth of wear, caused by diffusion of cobalt and carbon from the tool to the chip due to continuous, intimate and wide bulk contact between the chip and the tool surfaces under high stress and temperature.
- Composite carbide tools are developed by adding a gamma phase (8-20% by volume) to the WC and Co mixture.
- The gamma phase is a mixture of TiC, TiN, TaC, etc. which are more diffusion resistant than WC due to their greater stability and lower wettability against steel.

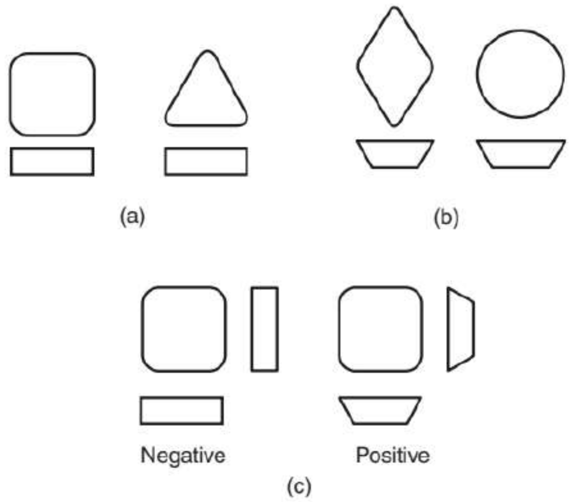
3. Mixed Carbide

- Titanium carbide (TiC) is not only more stable but also much harder than WC. Therefore, for machining ferritic steels that cause intensive diffusion and adhesion wear, a large quantity (5−25%) of TiC is added with WC and Co to produce another grade called mixed carbide.
- But increase in TiC content reduces the toughness of the tools.
- Therefore, for finishing with light cut but high speed, the harder grades containing upto 25% TiC are used, whereas for heavy roughing work at lower speeds, a lesser amount (5−10%) of TiC is suitable.

Plain Ceramics

- Ceramics have high compressive strength, chemical stability and hot hardness.
- Since 1950, ceramic tool inserts are produced using powder metallurgy method.
- Ceramics commonly used as cutting tool are Alumina (Al_2O_3) and Silicon Nitride (Si_3N_4).
- Alumina has higher hardness and chemical stability than silicon nitride.
- Silicon nitride is more thermally conductive, tougher and stronger, but difficult to process without hot pressing and reaction bonding.
- Plain ceramic tools are brittle in nature and hence had limited applications.
- The plain ceramic outperformed the then existing tool materials in applications like high speed machining of softer steels mainly for higher hot hardness.





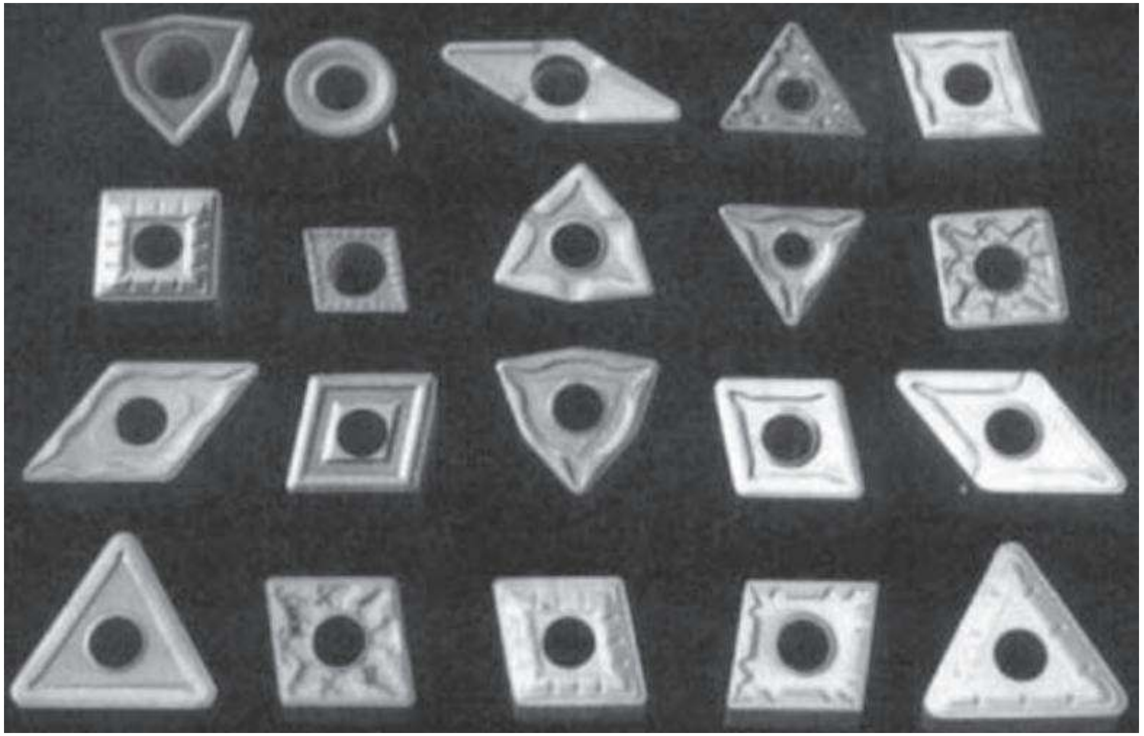
Carbide Inserts: (a) Square and Triangular; (b) Rhomboidal and Circular; (c) Negative and Positive

Types of Alumina base ceramic tool-bit

- **Plain alumina with traces of additives**
  - These white or pink sintered inserts are cold pressed and are used mainly for machining cast iron and similar materials at speeds of 200−250 m/min.
- **Alumina with or without additives**
  - These inserts are hot pressed, black in colour, hard and strong, and are used for machining steels and cast iron at speeds of 150−250 m/min.
- **Carbide ceramic (Al_2O_3 + 20% to 30% TiC)**
  - These inserts are cold or hot pressed, black in colour, quite strong and tough; used for machining hard cast irons and plain and alloy steels at 150 to 200 m/min.

Coated Carbide

- A thin but hard coating of single or multiple layers of more stable and heat- and wear-resistive materials like TiC, TiCN, TiOCN, TiN, Al_2O_3, etc. is provided on the tough carbide inserts (substrate) by processes such as CVD, PVD, etc. in a controlled environment.



- The bulk core or substrate provides the desired mechanical strength, bulk toughness and TRS as well as high thermal conductivity for reducing tool temperature.
- The coating on the surface of the substrates provides resistance to oxidation, corrosion, all types of tool wear, etc. as well as reduces friction at the chip-tool contact surfaces and thus enable prolonging tool life in machining both common and exotic materials.

Coronite

- The coronate is manufactured by appropriately combining HSS for strength and toughness and tungsten carbide (WC + Co) for heat and wear resistance.
- Microfine powder of TiCN is uniformly dispersed into the HSS-carbide matrix.
- The merits of coronite tools are as follows:
  1. Compared to HSS tools, coronite tools
     (a) Provide longer tool life.
     (b) Need lesser cutting forces.
     (c) Provide higher accuracy and surface finish.
  2. Compared to sintered carbide tools, coronite tools are
     (a) Stronger and tougher.
     (b) Can be easily sharpened and re-sharpened by grinding.
  3. Wide range of work materials can be reasonably machined by coronite tools.

Cermets

- Cermet = cer (ceramic) + met (metals)
- Possesses some of the unique properties of ceramics and also of metals.
- Favourable ceramics: TiC, TiN, TiCN, etc.
- Favourable metals: Ni, Co, Ni-Co, Ni-Mo, Fe, etc.
- In cermet inserts, fine grains of TiCN (in a phase of WC) are mixed with Ni-Co and Fe as a binder.
- The unique characteristic of cermets are:
  1. Harder, more chemically stable and wear-resistant compared to sintered carbides of both uncoated and coated types.
  2. Less tough, thermally conductive and shock-resistant compared to carbides.
  3. Weight% of binder varies within 10−20%.
  4. Cutting edge sharpness is retained longer than that in coated carbide inserts.
  5. 20−100% more productive than both uncoated and coated carbide tools.

High Performance Ceramics

Methods to improve quality and performamce of ceramic tools

Addition of an appropriate amount of suitable oxides such as Fe_2O_3, NiO, TiO_2, MnO_2, Cr_2O_3, etc.	Improved sinterability and densification.
Addition of TiC by 10-30%	Enhanced strength, toughness and thermal conductivity of alumina tools but reduced wear resistance
Introduction of silicon nitride (Si_3N_4) ceramic and Sialon ($Si_3N_4 + Al_2O_3$)	More resistance to fracturing by mechanical and thermal shocks
Hot pressing and sintering of an appropriate mix of Al_2O_3 and Si_3N_4 powder to form a composite ceramic SIALON	Very hot hard, tough and wear resistant.

Properties that led to development of high performance ceramic tools are;

1. Zirconia toughened alumina
2. Whisker reinforced ceramic
3. Metal toughened alumina

Examples of high performance ceramic are

1. Nitride ceramic reinforced by SiC whisker
2. Zirconia toughened alumina (ZTA) ceramic
3. Alumina ceramic reinforced by SiC whiskers
4. Metal (Silver)toughened alumina ceramic

Cubic Boron Nitride (cBN)

- Has extreme hardness next to that of diamond.
- For critical machining requirements, polycrystalline cubic boron nitride (PCBN) is used.
- PCBN is manufactured by consolidation of fine cBN particles under high pressure and temperature in the presence of Ni, Fe and cobalt as catalyst.
- The unique properties of PCBN tool inserts include
  1. Extreme hardness (next to diamond) and extreme abrasion resistance.
  2. Quite high fracture toughness (in between ceramic and WC).
  3. Retention of sharpness (form stability), hardness and fracture toughness at elevated cutting temperature.
  4. High thermal conductivity, low thermal expansion coefficient and thermal stability at temperatures upto 1400°C.
  5. High chemical stability even against irons and steels at high machining temperature.
- cBN or PCBN tools should not be used for machining soft and very ductile irons and steels, stainless steels and any Ni-based super-alloys.
- Possibility of high MRR and finish machining by PCBN enables dry and pollution-free machining.
- The performance of PCBN tools were further improved by proper cutting-edge preparation. The only limitation of PCBN tools is its very high cost.

Diamond

- Remarkable (highest) hardness.
- High speed machining, finishing critical components of various general or exotic materials.
- Different forms of diamond tools are

1. **Single crystal diamond:**
    - Natural or synthetic
    - Used where high precision or accuracy is required.
    - Effective machining of difficult-to-machine materials.
    - Drill bits for mining, oil exploration, etc.
    - Super abrasive wheels for critical grinding.
    - Finish machining of wire drawing and extrusion dies.

2. Poly crystalline diamond (PCD):

- Layer (0.5-1.5 mm) of randomly oriented diamond particles of fine grain size sintered with a suitable binder (usually cobalt) and then metallurgically bonded to a suitable substrate like cemented carbide insert.
- Excellent wear resistance, sharp cutting edge, generates little friction in the cut, high fracture strength, good thermal conductivity.
- Long tool life.
- Can be used in conventional and high speed machining of soft, non-ferrous materials (aluminium, magnesium, copper, etc.), advanced composites and metal-matrix composites, super-alloys and non-metallic materials.
- Not recommended for machining ferrous metal because of graphitization of diamond at elevated temperature.
- Limitations
  - ✓ High tool cot.
  - ✓ Presence of binder, cobalt, which reduces wear resistance and thermal stability.
  - ✓ Complex tool shapes like in-built chip breaker can not be made.
  - ✓ Size restriction, particularly in making very small diameter tools.

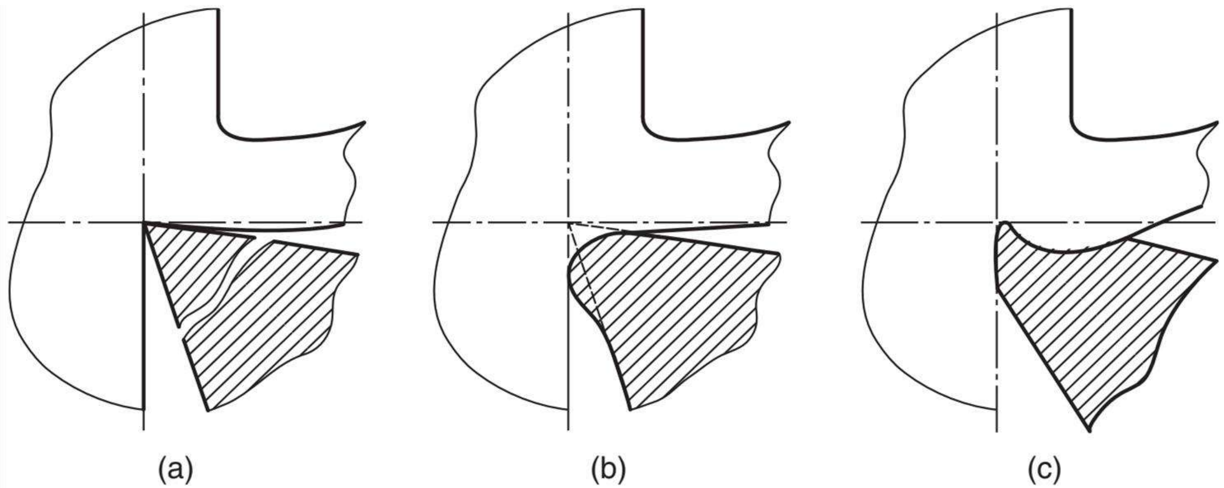
3. Diamond coated carbide tools:

- Thin (< 50 μm) films of diamond is directly deposited on the tool surface.
- Thick (> 200 μm) film is grown on an easy substrate and later brazed to the actual tool substrate, after which the primary substrate is removed by dissolving it or by other means.
- Applications: making inserts, drills, reamers, end mills, routers, etc.
- While cBN tools are feasible and viable for high speed machining of hard and strong steels and similar materials, diamond tools are extremely useful for machining stones, slates, glass, ceramics, composites, FRPs and non-ferrous metals, especially those which are sticky and BUE former such as pure aluminium and its alloys.
- cBN and diamond tools are also essentially used for ultra-precision as well as micro- and nano-machining.

Tool Wear

Smooth, safe, and economic machining necessitates

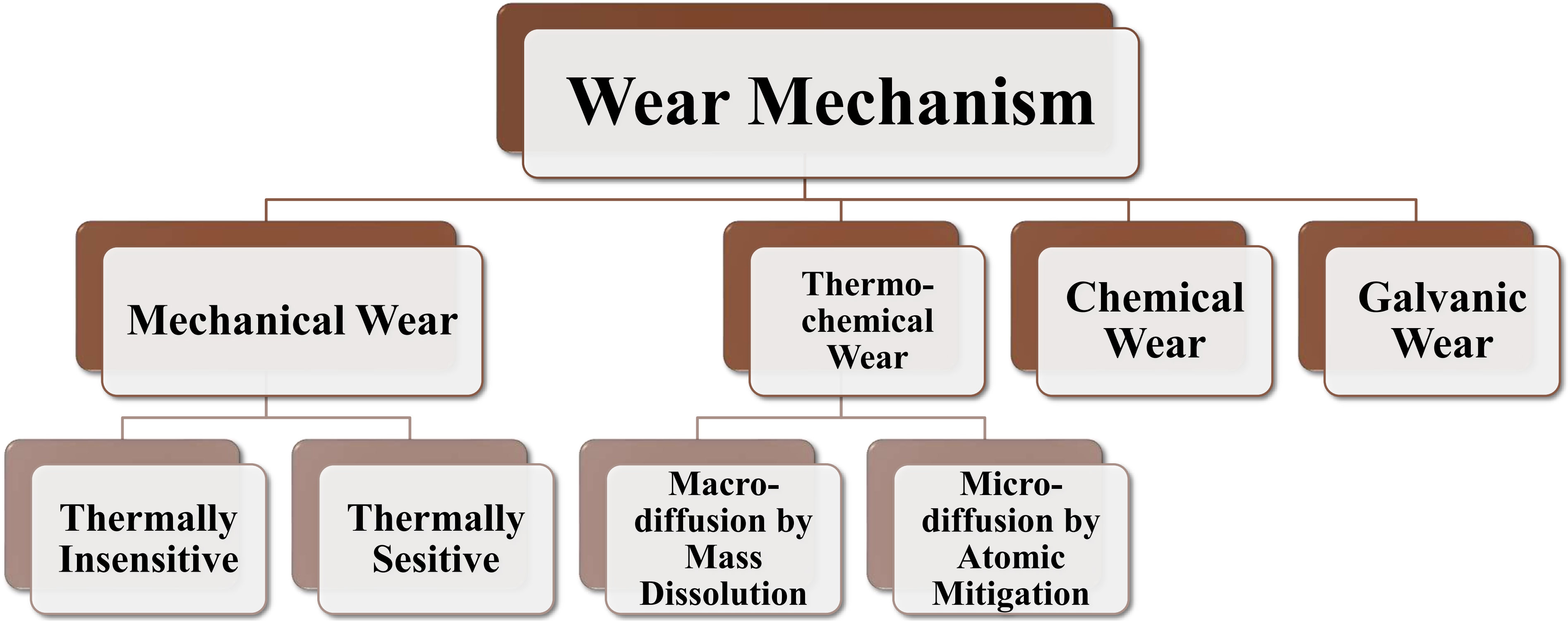
1. Prevention of premature, random, and catastrophic failure of the cutting tools.
2. Reduction of the rate of wear of tools to prolong their service life.



The cutting tools generally fail in the following modes

1. **Mechanical breakage** of the cutting tool at its cutting edges or tip due to intensive stresses and shocks. Such a mode of tool failure is random and catastrophic in nature and hence is highly harmful.
2. **Rapid dulling** of the tool tip or cutting edges of the tool by plastic deformation due to intensive stress and temperature. This mode of tool failure is also highly detrimental.
3. **Gradual wear** of the cutting tool at its working surfaces near the tool tip.

Wear: Failure of the cutting tool due to repeated operation and loss of material from the surfaces in sliding contact.


Wear Mechanism
Mechanical Wear
Thermo-chemical Wear
Chemical Wear
Galvanic Wear
Thermally Insensitive
Thermally Sesitive
Macro-diffusion by Mass Dissolution
Micro-diffusion by Atomic Mitigation

Thermally Insensitive Type

- Abrasion of high points of asperities at the tool surface
- Chipping at the sharp cutting edges
- Delamination
- Microfracturing

Thermally Sensitive Type

- Adhesion
- Thermal Fracturing
- Grain Pull out and Flaking

Abrasion by

- Attrition
- Scratching
- Ploughiong
- Fatigue Fracture

Thermo-Chemical (Diffusion) Wear

- Tool damage caused by atoms moving across the hot tool–chip interface, which removes or alters tool material and weakens it, speeding up wear.
- Two diffusion modes
  - ✓ ***Macro-diffusion (mass dissolution):*** bulk transfer of tool constituents into the chip/work.
  - ✓ ***Micro-diffusion (atomic migration):*** atom-by-atom movement across the interface.
- ***Mechanism***: Workpiece atoms (e.g., Fe) can diffuse into the tool, and tool atoms can diffuse out into the chip. This reduces bond strength/hardness in the tool material and accelerates wear (often as crater wear on the rake face).
- When diffusion wear becomes severe?
  - ➢ High chemical affinity / solid solubility between the tool and work materials.
  - ➢ Intimate, continuous chip–tool contact (large contact length, steady contact).
  - ➢ High interface temperature due to high cutting forces and high cutting speed.

Chemical wear

What it is: Material loss from chemical reactions at the hot tool–chip/flank interface (oxidation, chlorination/sulfurization from fluids, reaction with work metal or gases).

When it becomes significant:

- Tool material is chemically unstable against the work metal, cutting fluid additives, or atmospheric gases at cutting temperature.
- High speeds/temperatures, dry or reactive-fluid cutting; reactive alloys (Ti, Ni-base) are common culprits.

Typical signatures:

- Grooving wear along chip flow on the rake face.
- Aggravated notching at the depth-of-cut line.
- Smooth, discolored surfaces (oxide/reaction layers).

Galvanic wear

What it is:

Electrochemical dissolution caused by a galvanic couple between tool and work in the presence of an electrolyte film.

Conditions required:

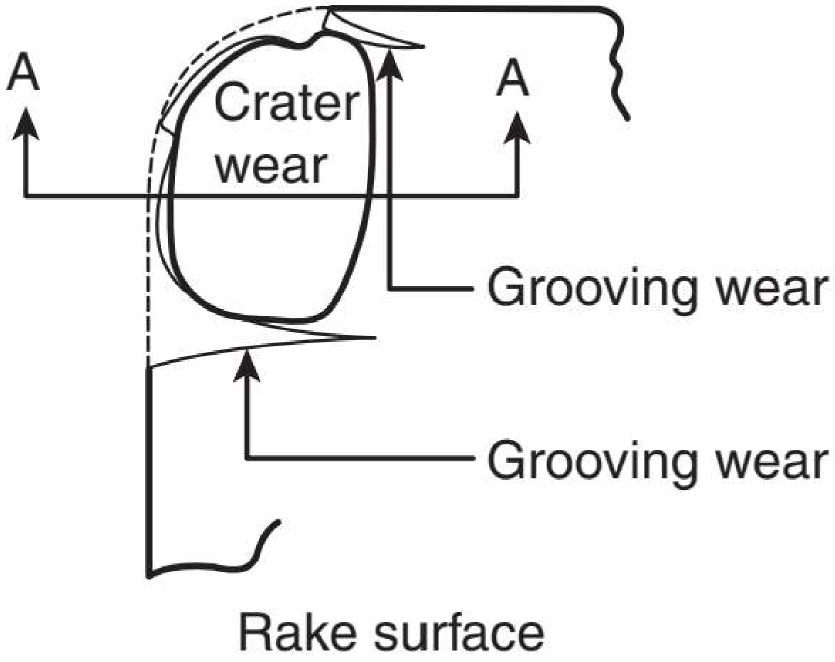
- Both tool and work are electrically conductive.
- Elevated temperature (accelerates electrochemistry, thins films).
- Cutting fluid acts as an electrolyte (water-based fluids, high ionic content).

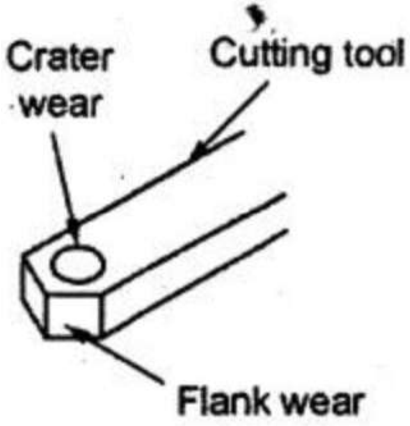
Typical signatures:

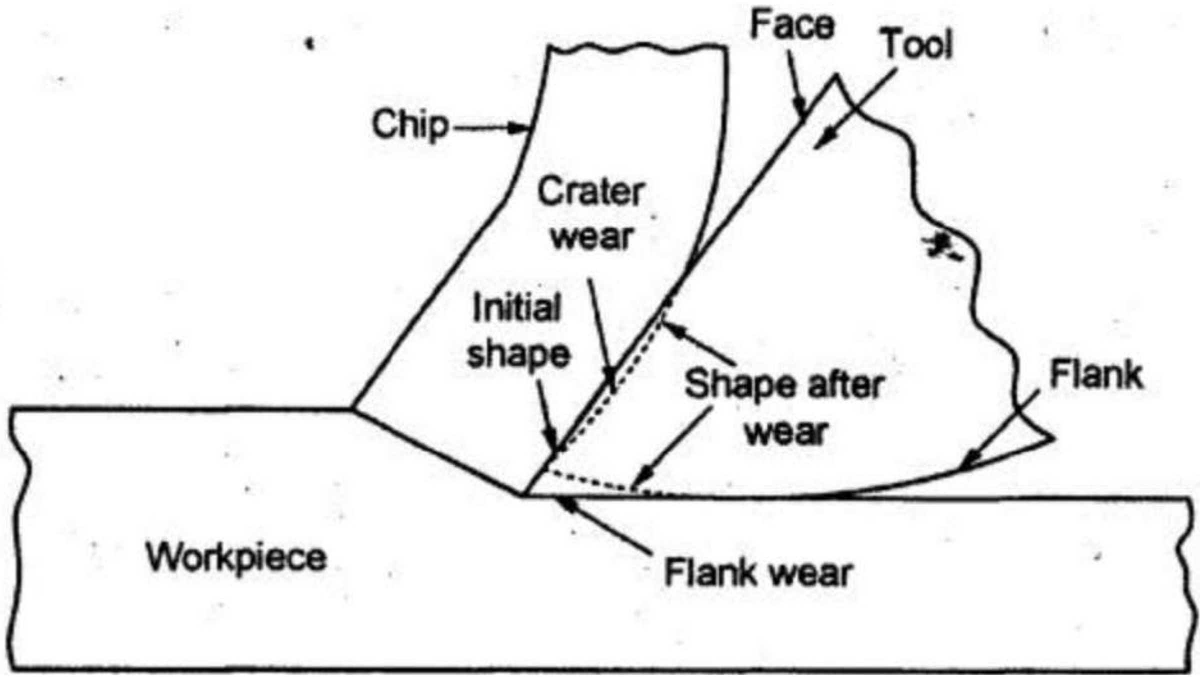
Slow, uniform material loss

Crater Wear

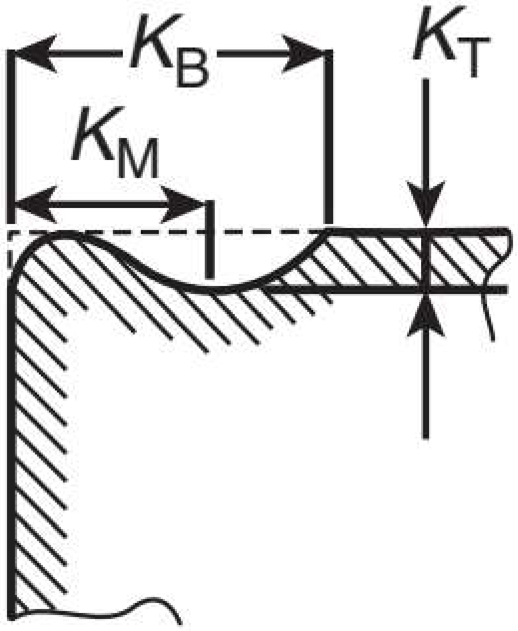
- **What is it? :** A cavity/“pond-like” depression on the rake face along the chip-flow path.
- **Primary mechanisms**
  - ***Abrasion***: hard workpiece carbides/inclusions scour the rake face.
  - ***Adhesion***: micro-welding to the chip, then tearing away tool material.
  - ***Diffusion***: atom exchange at high interface temperature (tool ↔ chip).
  - Also aided by: ***severe friction***, ***plastic deformation of the surface***, and ***grain pull-out***.

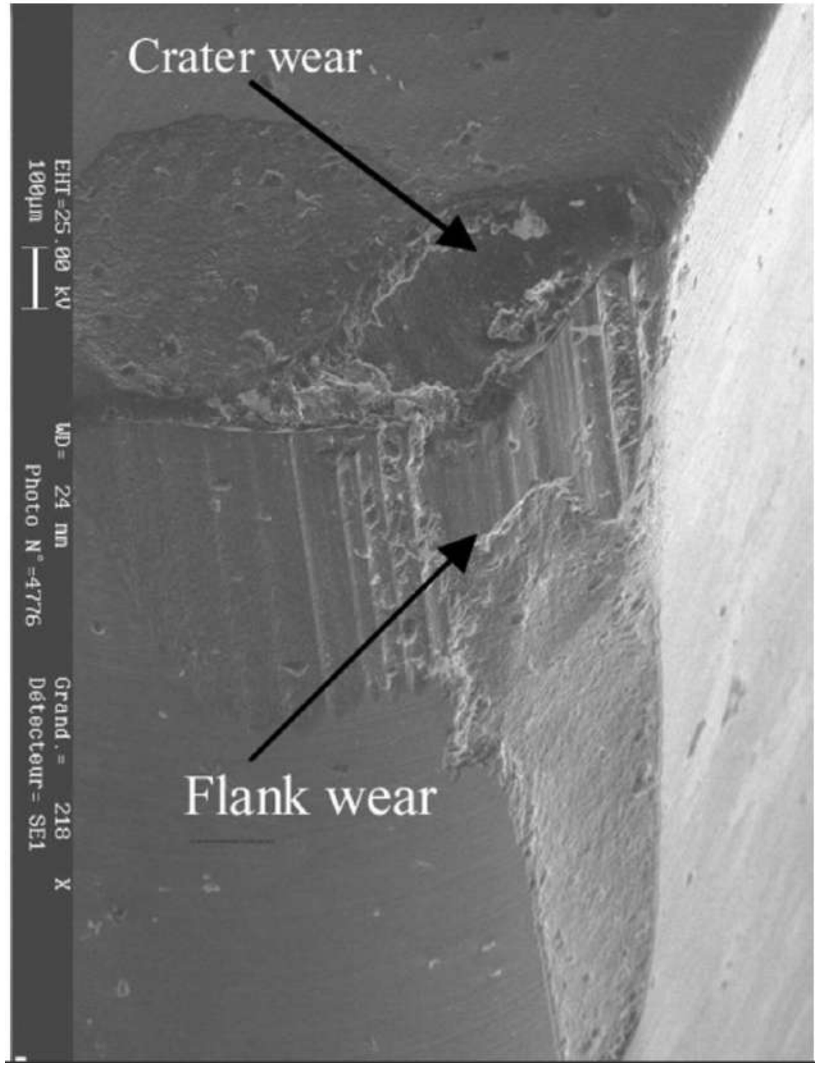






- **Where and when it forms**
  - In the chip–tool contact zone, typically where the temperature/pressure peak.
  - Prominent at high cutting speeds, long/continuous chips, reactive work metals, and inadequate cooling.
- **How it's measured**
  - K_T — crater depth (maximum penetration into the rake face).
  - K_B — crater width (extent of the worn cavity along the rake face).
  - K_M — location of crater maximum relative to the cutting edge.

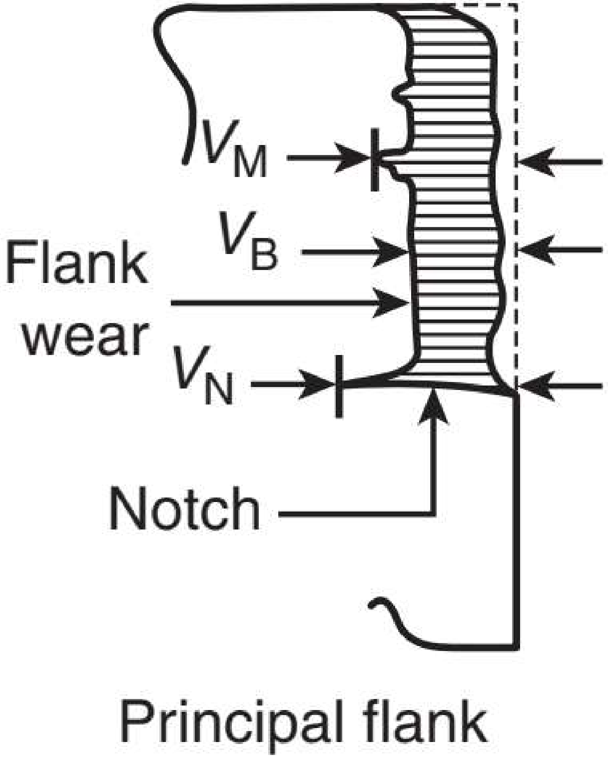


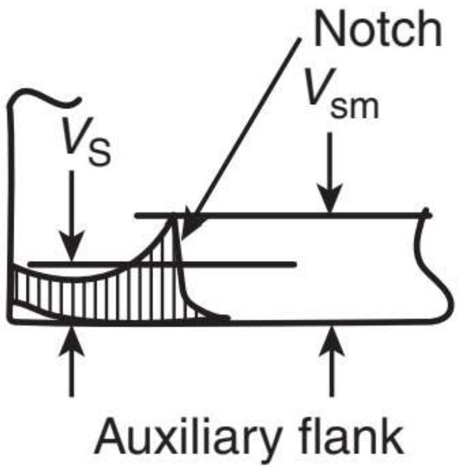


- **Why it matters**
  - Reduces effective rake angle; raises cutting forces/temperature.
  - Weakens the cutting edge, risking edge fracture.
  - Degrades surface finish and shortens tool life.
- **Typical indicators**: Smooth, polished cavity matching chip flow; sometimes discoloration (oxidation/diffusion).
- **Mitigation**
  - Lower cutting speed or optimize chip load; use efficient cooling/MQL.
  - Choose coated or more chemically inert tool materials (e.g., TiAlN, Al_2O_3, cermets/ceramics for suitable jobs).
  - Use chip breakers/rake geometry to shorten contact length and lower interface temperature.
  - Maintain correct coolant chemistry; avoid fluids that react with the tool/work pair.

Flank Wear

- **What & where**
  - Flank wear = material loss on the flank faces that rub the newly machined surface.
  - Principal flank wear occurs along the leading cutting edge; auxiliary flank wear occurs along the secondary (end) cutting edge.
- **Dominant mechanisms**
  - Abrasion by hard workpiece carbides/asperities (grooves parallel to cutting direction).
  - Adhesion → micro-welds tear out tool fragments.+ Diffusion at high speeds / dry cutting adds to wear.
- **How it's specified**
  - V_B — average width of wear land on the flank.
  - V_M — maximum width of the wear land (worst spot).





- **Progression**
  - Starts as a shiny, narrow wear land, grows uniformly with time (more uniform on the principal flank).
  - May show parallel abrasive striations; with heat/reactivity can show discoloration or micro-pitting.
  - Auxiliary flank behaves similarly but strongly affects side surface finish and can interact with notch wear at the depth-of-cut line.
- **When it accelerates**
  - High cutting speed and temperature, hard/abrasive work materials, inadequate coolant/filtration.
  - Incorrect tool geometry (too small clearance), low tool hardness/hot hardness, and poor coatings.
- **Why it matters**
  - Increases rubbing → higher cutting forces, heat, and power.
  - Degrades surface finish and dimensional accuracy (size drift).Leads to loss of edge support and eventual edge failure.

- **Typical tool-life criteria (rules of thumb)**
  - End the cut when $V_B \approx 0.3$ mm (finishing) or ≈ 0.6 mm (roughing); V_M limits may be slightly higher depending on standard/process.
- **Mitigation**
  - Use harder / hot-hard tool materials and coatings (TiAlN, Al_2O_3, etc.).
  - Optimize clearance/rake, apply coolant or MQL, and reduce speed if thermal wear dominates.
  - Improve filtration to remove abrasives; avoid reactive coolants for susceptible tool–work pairs.

Notching wear

- A deep and wide groove (V_N), called notching wear, is often found to develop on the principal flank at the outer end of the main cutting edge.
- Such a notch is caused mechanically by the sharp and hardened work surface in contact with the outer end of the main cutting edge.

Wear Measurement

Why wear must be monitored (effects on machinability)

- **Higher Cutting forces** due to edge dulling and flank rubbing.
- **Higher Power consumption**.
- **Dimensional errors** from tip wear + higher forces.
- **Odd sound & vibration** (chatter/instability).
- **Poor surface finish** (nose/auxiliary edge wear + vibration).

Common wear indices

- V_B: average **flank wear land** width (principal flank).
- V_M: **maximum** flank wear width (worst spot).
- V_N: **nose wear** (rounding/flattening at tool nose).
- V_S: **notch/side wear** at depth-of-cut line (aux. flank).
- K_T: **crater depth** on rake face (max penetration).
- K_M: **location** of crater max from cutting edge.

Monitoring modes

- **Off-line vs. on-line** (stop-and-inspect vs. continuous monitoring).
- **Online** proxies commonly include cutting power, forces, acoustic emission, vibration, and temperature (for trend tracking).

How wear is assessed (direct/off-line methods)

- **Loss of volume/weight**: very **crude**; suited to abrasives (grinding wheels, hones).
- **Groove/indentation** method: **approximate** depth from length difference inside vs. outside worn zone.
- **Low-mag optical microscopy**: **simple, common, effective** for $V_B/V_M/V_N/V_S$.
- **SEM examination**: **detailed** quantitative/qualitative study of mechanisms and microfeatures.
- **Profilometer/Talysurf**: precise **crater** profile/roughness measurement (K_T, K_B).
- **Radioactivity (tracer) method**: useful in complex cases but **rare** due to health/safety concerns.

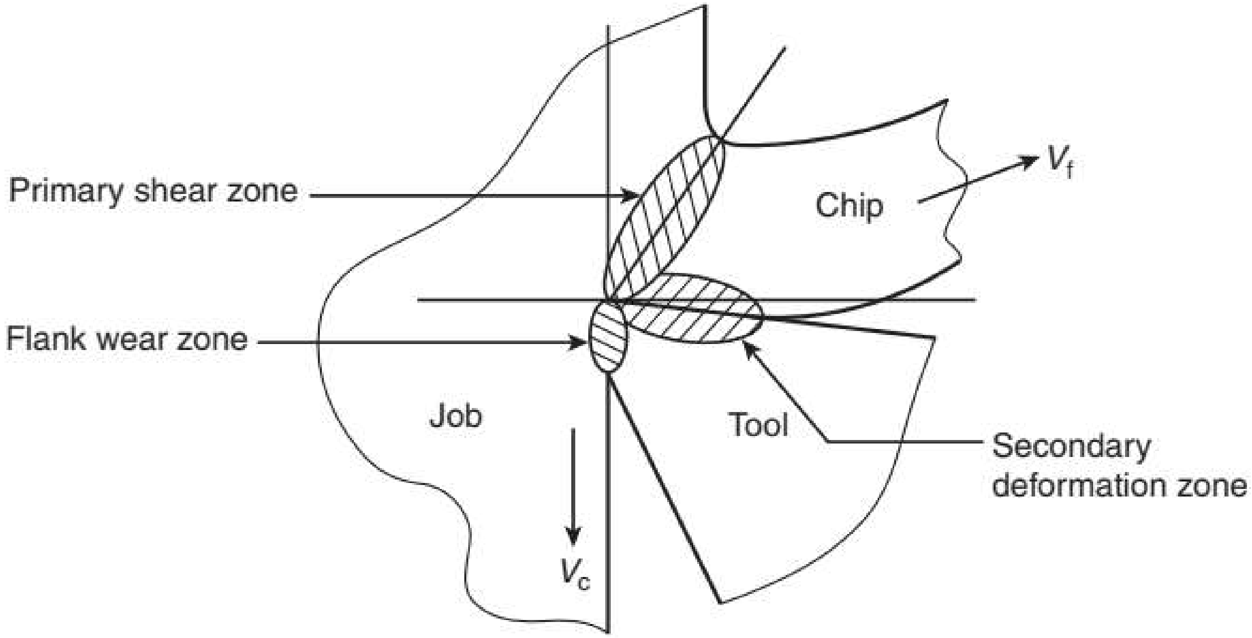
Off-line Wear Measurement Methods:

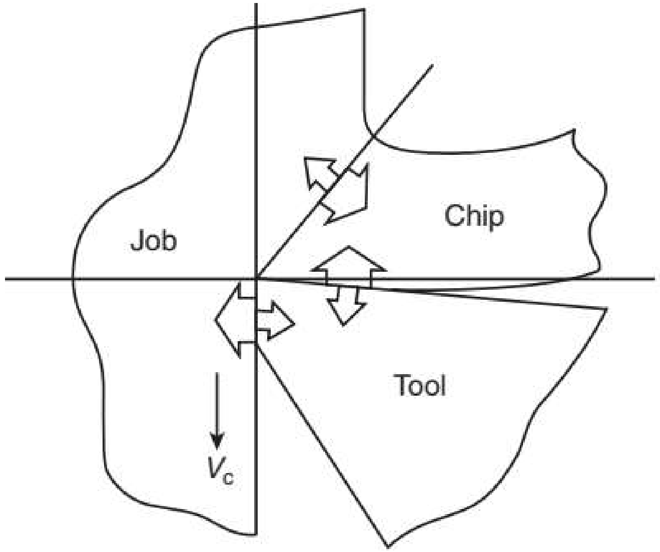
1. **From loss of volume or weight**: This method is crude and is applicable for grinding wheels, honing sticks, etc.
2. **By the grooving or indentation method**: In this approximate method, the depth of wear is determined from the difference in length of the grooves or indentations taken outside and inside the worn area.
3. **Using a low magnification optical microscope**: This method is quite simple but effective, and hence is very commonly used.
4. **Observing the worn zones under scanning electron microscope (SEM)**: This method is generally used for a detailed study, both quantitatively and qualitatively.
5. **Using a profilometer or a talysurf,** especially for crater wear.

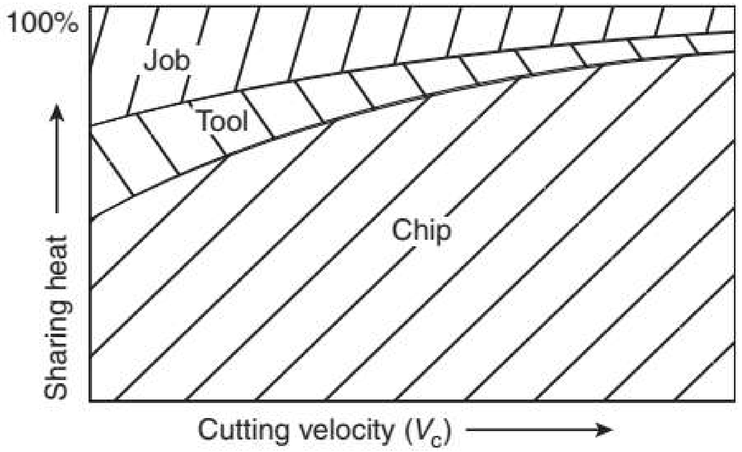
Temperature in Metal Cutting

Location of Heat Generation in Machining

1. **Primary shear zone** where the major part of the mechanical energy is converted into heat.
2. **Secondary deformation zone** covers the rake surface where further heat is generated due to rubbing at the chip–tool interface.
3. **Flank wear zone** where heat is also generated due to rubbing of the flank surfaces of the worn tool against the machined surface.







Effects of High Cutting Temperature on Product Quality

- Dimensional inaccuracy of the product due to thermal distortion as well as expansion and contraction during and after machining.
- Damage of the machined surface by oxidation, rapid corrosion, burning, etc.
- Development of tensile residual stresses and micro-cracks at the surfaces and sub-surfaces.

Effects of High Cutting Temperature on Cutting Tools

- Reduction of tool life by rapid tool wear.
- Rapid failure of the cutting edges and tool tip by plastic deformation if the tool material is not hot enough, hard enough, or strong enough.
- Thermal flaking and fracturing at the cutting edges due to thermal shocks.
- Built-up-edge (BUE) formation.

Possible Favourable Effects of High

- The high cutting temperature may also often help in **reducing the magnitude of the cutting forces and cutting power consumption** to some extent by **locally softening or reducing the yield shear strength of the work material** at the cutting zone.
- To attain and enhance this benefit, particularly while machining difficult-to-machine hot, strong, and heat-resistive materials, the work material in front of the tool is deliberately additionally heated externally.
- A special technique, called hot machining, is often favourably used to machine some inherently difficult-to-machine materials, such as Ni-base superalloys, Ni-hard steel, and Hadfield steel.

Methods of Measuring Cutting Temperature

- De-colourizing Agent
- Calorimetric Method
- Thermocouple
- Photocell
- Infrared Photographic Technique

Parameters Affecting the Cutting Temperature

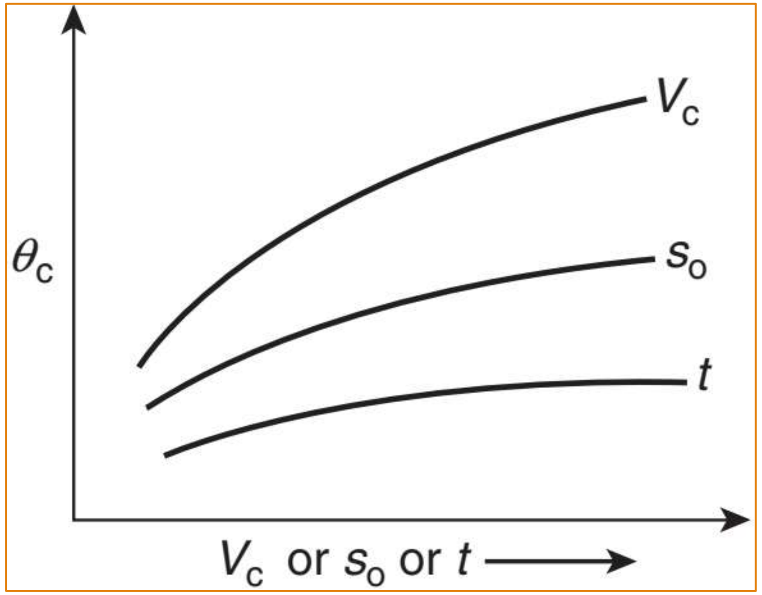
Work Material
- Specific Energy Requirement
- Ductility
- Thermal Properties (conductivity and diffusivity)

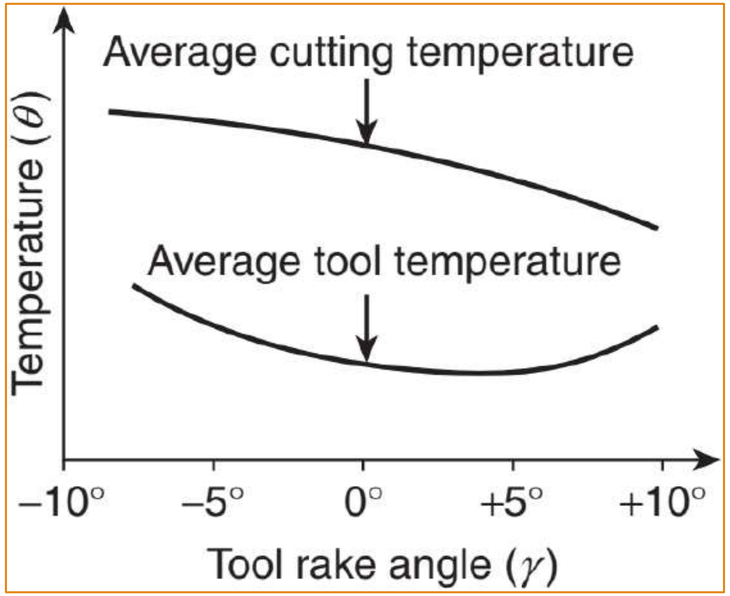
Cutting Tool Material
- Thermal Properties
- Chemical Stability
- Wear Resistance

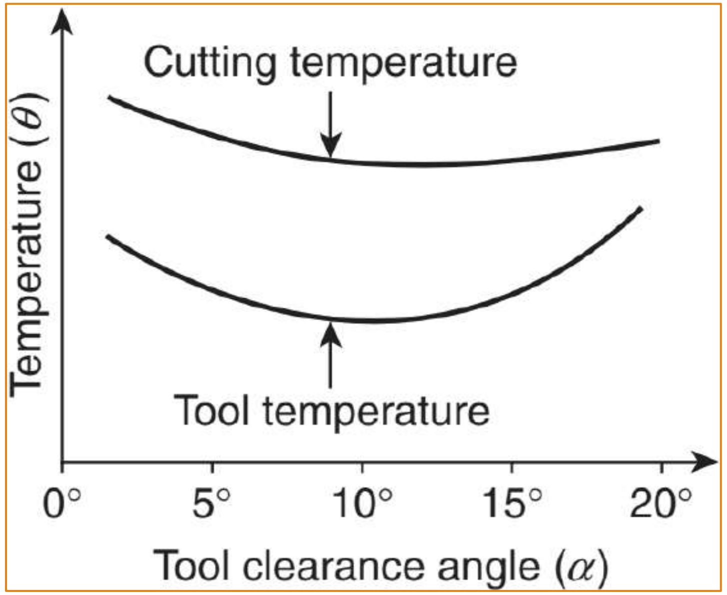
Process Parameters
- Cutting Velocity
- Feed Rate

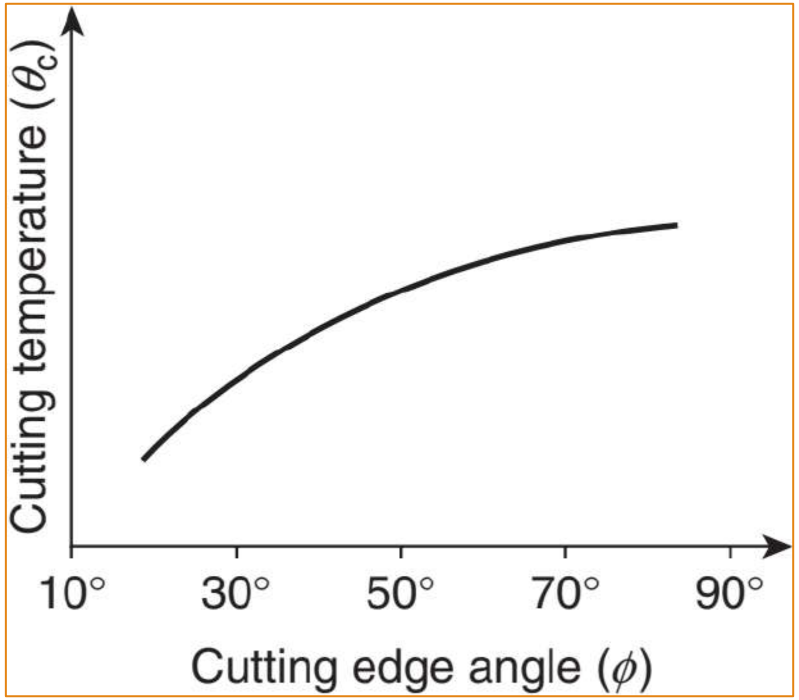
Tool Geometry
- Rake angle
- Cutting Edge Angles
- Clearance angle
- Nose Radius

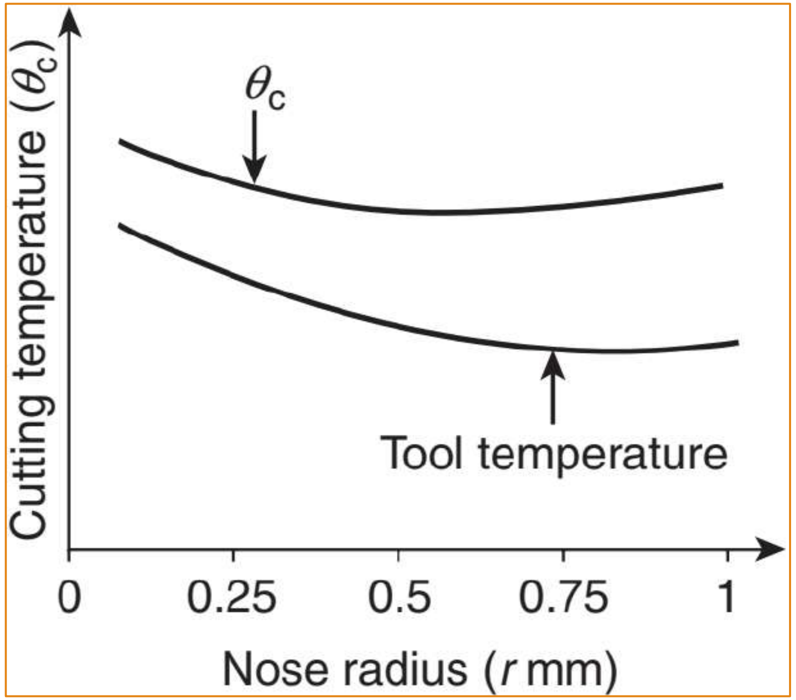
Environment
- Thermal Properties of the Cutting Fluid
- Lubrication Property
- Method of Application


θ_c
V_c
s_o
t
V_c or s_o or t


Temperature (θ)
Average cutting temperature
Average tool temperature
−10°
−5°
0°
+5°
+10°
Tool rake angle (γ)


Temperature (θ)
Cutting temperature
Tool temperature
0°
5°
10°
15°
20°
Tool clearance angle (α)


Cutting temperature (θ_c)
10°
30°
50°
70°
90°
Cutting edge angle (ϕ)


Cutting temperature (θ_c)
θ_c
Tool temperature
0
0.25
0.5
0.75
1
Nose radius (r mm)

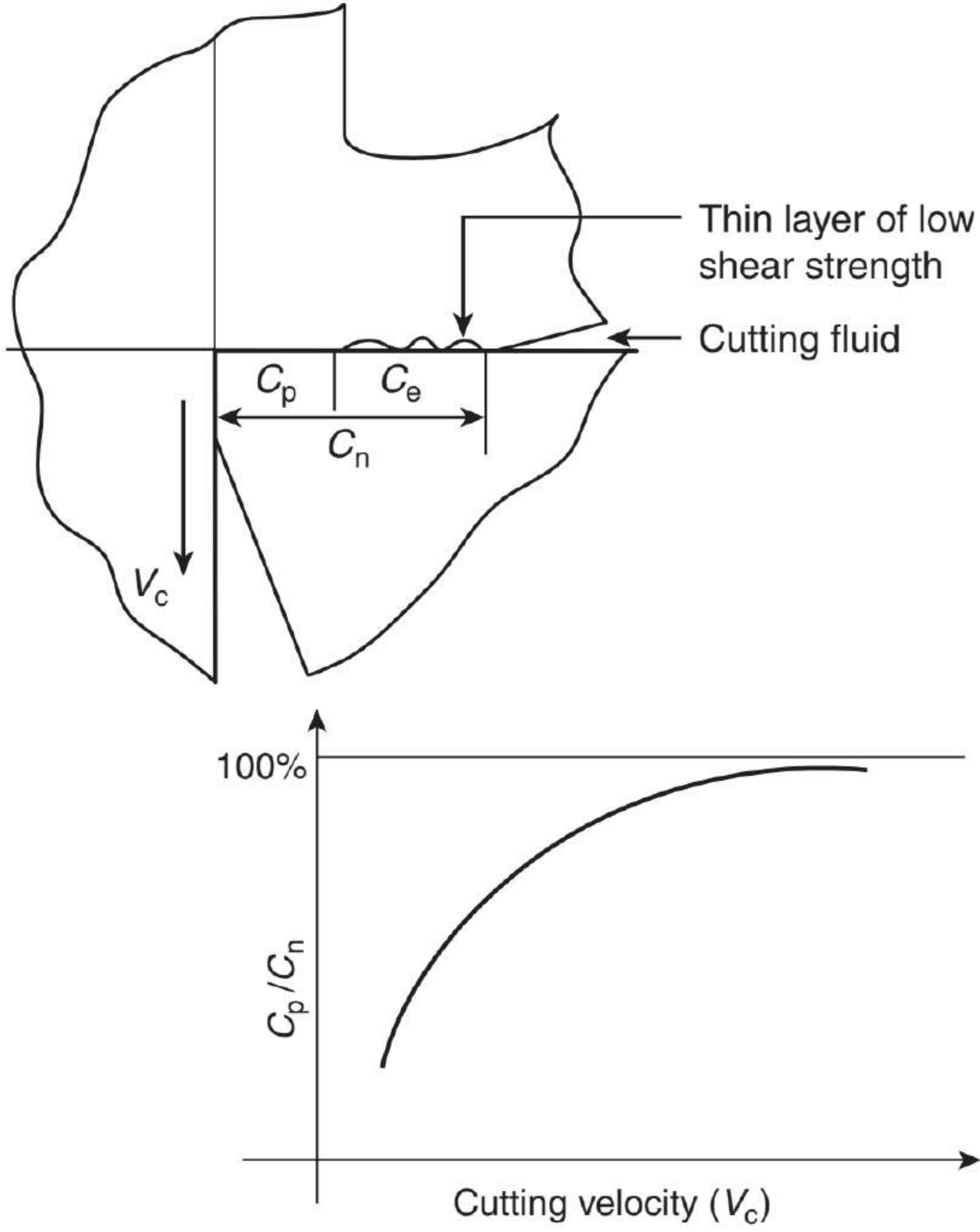
Application of Cutting Fluids in Machining

The basic purposes of cutting fluid application are:

1. **Cooling of the job and the tool** to reduce the detrimental effects of cutting temperature on the job and the tool.
2. **Lubrication at the chip–tool interface and the tool flanks** to reduce cutting forces and friction, and thus the amount of heat generation.
3. **Cleaning the machining zone** by washing away the chip particles and debris, which, if present, spoil the finished surface and accelerate damage to the cutting edges.
4. **Protection of the nascent finished surface** – a thin layer of the cutting fluid sticks to the machined surface and thus prevents its harmful contamination by gases like SO_2, O_2, H_2S, and N_xO_y present in the atmosphere.

Principle of Cutting Fluid Action

- The chip–tool contact zone usually comprises two parts, plastic or bulk contact zone and elastic contact zone.
- The cutting fluid cannot penetrate or reach the plastic contact zone (C_p) but enters in the elastic contact zone (C_e) by capillary effect.
- With the increase in cutting velocity, the fraction of plastic contact zone gradually increases and covers almost the entire chip–tool contact zone (C_n).
- Therefore, at high speed machining, the cutting fluid is not able to lubricate but cools the tool and the job only by bulk external cooling.



Properties of Cutting Fluid

For Cooling

- High Specific Heat
- Thermal Conductivity
- Film Co-efficient for heat transfer
- Spreading, Wetting ability

For Lubrication

- High Lubricity without gumming and foaming
- Wetting and Spreading
- High Film Boiling Point
- Friction Reduction even at High Pressure and Temperature

Chemical Stability

- Should be non-corrosive to the material

Less Volatility and High Flash Point

High Resistance to bacterial growth

Odourless and preferably colourless

Non-toxicity in both liquid and Gaseous Stages

Easy Availability and Low Cost

Types of Cutting Fluids and Their Selection

1. **Air blast or compressed air only**: Machining of some materials, like grey cast iron, becomes inconvenient or difficult if any cutting fluid is employed in liquid form. In such a case, only an air blast is recommended for cooling and cleaning.
2. **Water:** For its good wetting and spreading properties and very high specific heat, water is considered the best coolant and hence employed where cooling is most urgent.
3. **Soluble oil**: Water acts as the best coolant, but does not lubricate. Besides, the use of only water may impair the M-F-T-W system by rusting. So, oil containing an emulsifying agent and additive, such as EPA, together called a cutting compound, is mixed with water in a suitable ratio (1–2 parts in 20–50 parts). This milk-like white emulsion, called soluble oil, is very common and widely used in machining and grinding.
4. **Cutting oils**: Cutting oils are generally compounds of mineral oil to which the desired type and amount of vegetable, animal, or marine oils are added for improving spreading, **wetting**, and lubricating properties. As and when required, some EP additive is also mixed to reduce friction, adhesion, and BUE formation in heavy cuts.

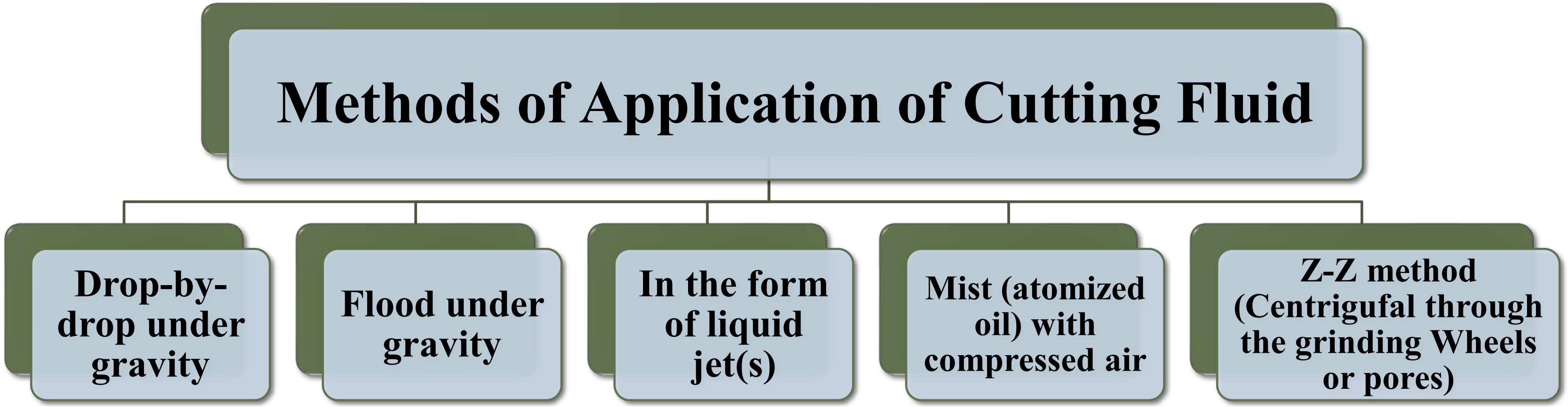
5. **Chemical fluids**: These are occasionally used water-based fluids, where some organic and/ or inorganic materials are dissolved in water to enable the desired cutting fluid action. There are two types of such cutting fluid:

   (a) **Chemically inactive type** – high in cooling, anti-rusting, and wetting properties, but less lubricating.

   (b) **Active (surface) type** – moderate cooling and lubricating.

6. **Solid or semi-solid lubricant:** Pastes, waxes, soaps, graphite, Moly-disulphide (MoS2) are also often used, either applied directly to the workpiece or as an impregnate in the tool to reduce friction and thus cutting forces, temperature, and tool wear.

7. **Cryogenic cutting fluid**: Extremely cold (cryogenic) fluids (often in the form of liquid or gas) like liquid CO2 or N2 are used in some special cases for effective cooling without creating much environmental pollution and health hazards.



Selection of Cutting Fluid

1. Grey cast iron:
   (a) Generally dry without any cutting fluid due to its self-lubricating property.
   (b) Air blast for cooling and flushing chips.
   (c) Soluble oil for cooling and flushing chips in high speed machining and grinding.
2. Steels:
   (a) If machined by HSS tools, soluble oil (1:20–30) for low carbon and alloy steel and neat oil with EPA for heavy cuts.
   (b) If machined by carbide tools, thinner soluble oil for low strength steel, thicker soluble oil (1:10–20) for stronger steels, straight sulphurized oil for heavy and low speed cuts and EP cutting oil for high alloy steel,
   (c) Often steels are machined dry by carbide tools for preventing thermal shocks.
3. Aluminium and its alloys:
   (a) Preferably machined dry.
   (b) Light soluble oil.
   (c) Straight neat oil or kerosene for stringent cuts.

4. Copper and its alloys:
   (a) Water-based fluids are generally used.
   (b) Oil with or without EPA for tougher grades of Cu-alloys.
5. Stainless steels and heat-resistant alloys:
   (a) High performance soluble oil or neat oil with high concentration with chlorinated EP additive.
6. Brittle ceramics and cermets (tools) should be used either under dry condition or light neat oil in case of fine finishing.
7. Grinding at high speed needs cooling by soluble oil (1:50–100).
8. For finish grinding of metals and alloys low viscosity neat oil is also used.