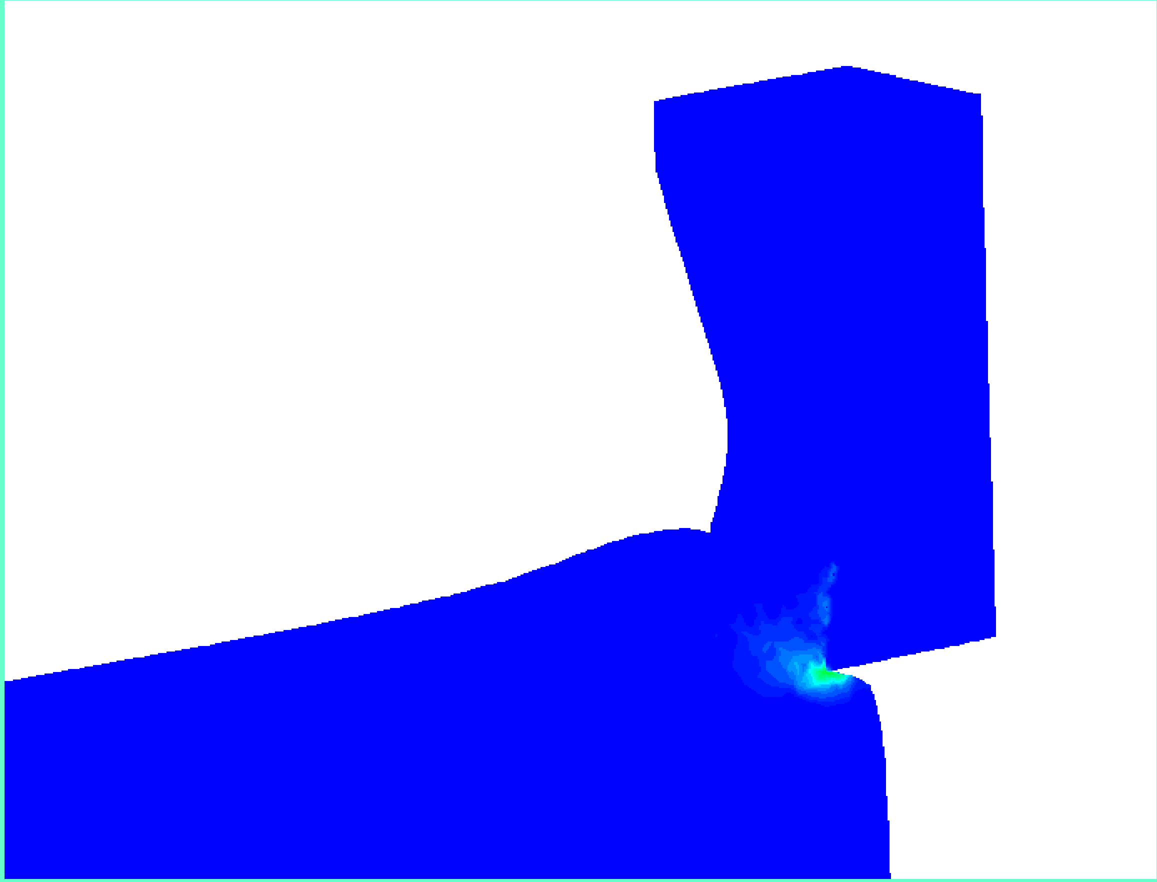
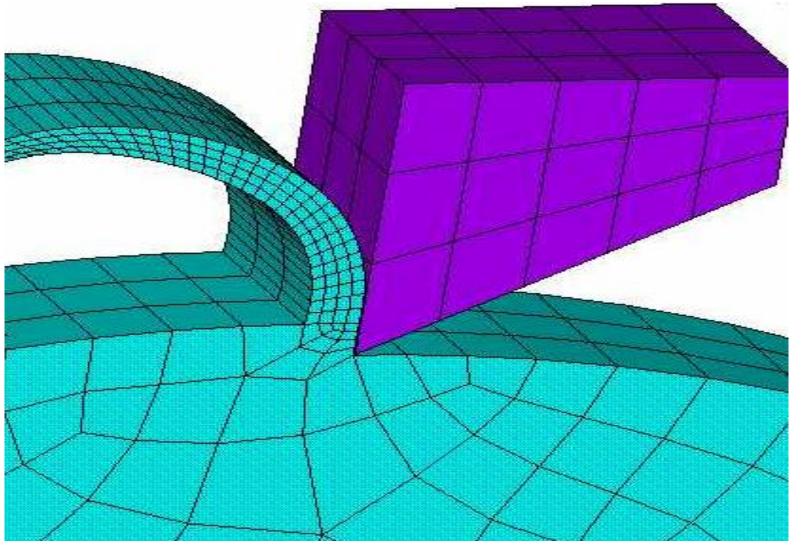
LECTURE-02: THEORY OF METAL CUTTING





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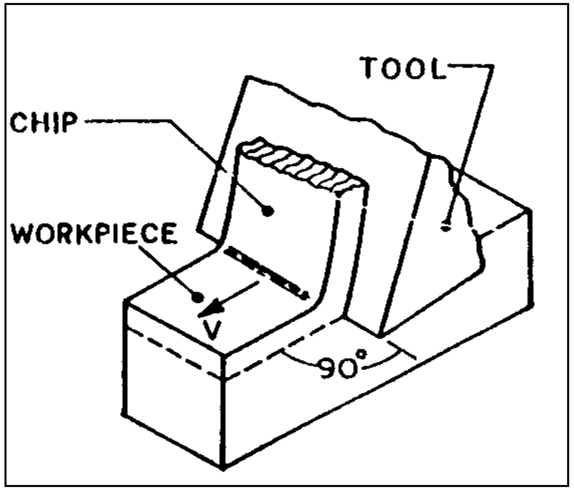
Introduction

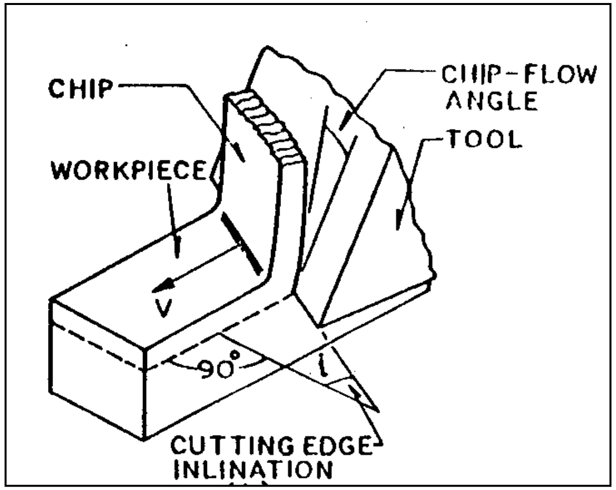
- Production or manufacturing of any object is a value addition process by which raw material of low utility and value due to its irregular size, shape and finish is converted into a high utility and valued product with definite size, shape and finish imparting some desired functionability.
- Machining is an essential process of semi-finishing and often finishing by which jobs of desired shape and dimensions are produced by removing extra material from the preformed blanks in the form of chips with the help of cutting tools moved past the work surfaces in machine tools.
- The chips are separated from the workpiece by means of a cutting tool that possesses a very high hardness compared with that of the workpiece, as well as certain geometrical characteristics that depend upon the conditions of the cutting operation.
- Among all of the manufacturing methods, metal cutting, commonly called machining; is perhaps the most important. Forgings and castings are subjected to subsequent machining operations to acquire the precise dimensions and surface finish required. Also, products can sometimes be manufactured by machining stock materials like bars, plates, or structural sections.

Methods of Machining

- In the metal cutting operation, the tool is wedge-shaped and has a straight cutting edge. Basically, there are two methods of metal cutting, depending upon the arrangement of the cutting edge with respect to the direction of relative work-tool motion:
    - Orthogonal cutting or two dimensional cutting
    - Oblique cutting or three dimensioning cutting



Orthogonal Machining



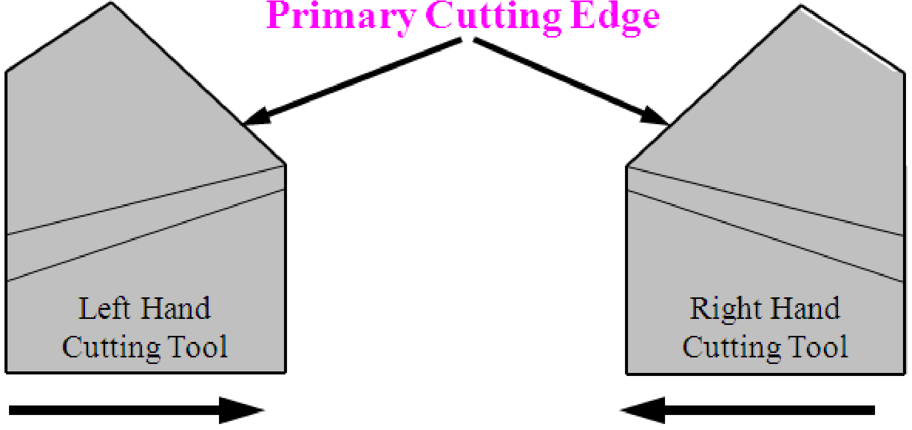
Oblique Machining

- Orthogonal Cutting or Two Dimensional Cutting
  - The cutting edge of the tool remains at 90^0 to the direction of feed
  - The chip flows in a direction normal to the cutting edge of the tool
  - The cutting edge of the tool has zero inclination with the normal to the feed
  - The chip flows along the plane of the tool face. Therefore, it makes no angle with the normal (in the plane of the tool face) to the cutting.
  - The shear force acts on a smaller area, so shear force per unit area is more.
  - The tool life is smaller than obtained in oblique cutting
  - There are two mutually perpendicular components of cutting forces on the tool
  - The cutting edge is bigger than the width of cut.

- Oblique Cutting or Three Dimensioning Cutting
  - Cutting edge of the tool remains inclined at an acute angle to the direction of feed
  - The direction of the chip flow is not normal to the cutting edge.
  - Cutting edge is inclined at an angle inclination angle (λ) to the normal to the feed.
  - The chip flows at an angle shear angle (β) to the normal to the cutting edge.
  - The shear force acts on a larger area, hence the shear force per area is smaller
  - The tool life is higher than obtained in orthogonal cutting
  - There are three mutually perpendicular components of cutting forces on the tool
  - The cutting edge is smaller than the width of cut.

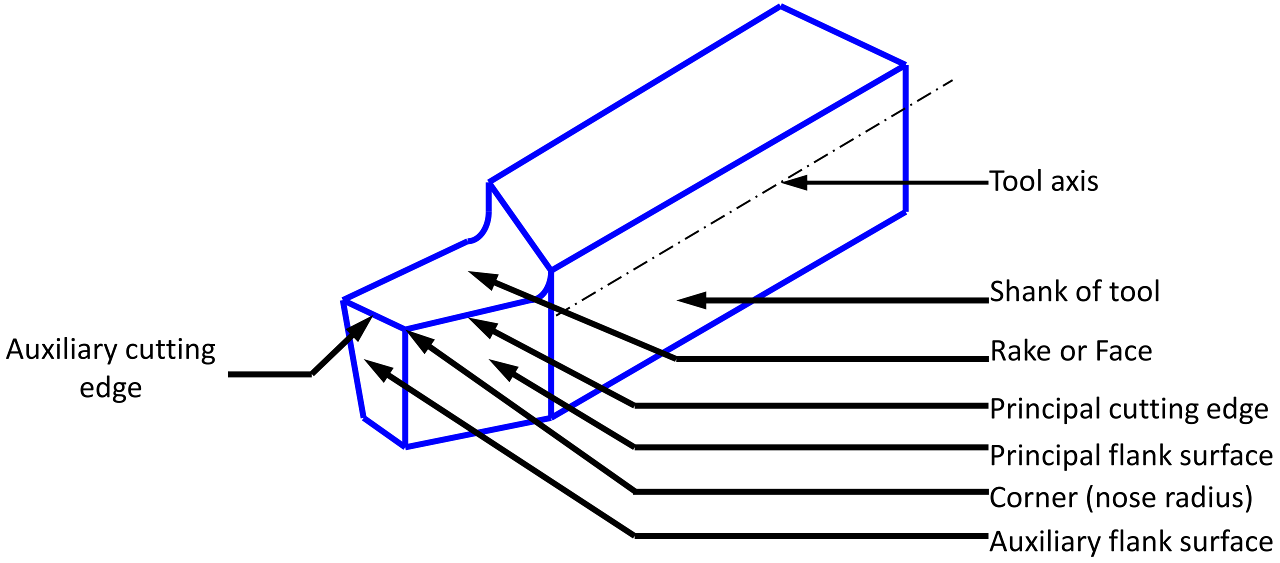
Cutting Tool Geometry

- Cutting tool is device with which a material could be cut to the desired size, shape or finish. So a cutting tool must have at least a sharp edge. There are two types of cutting tool.
  - The tool having only one cutting edge is called single point cutting tools. For example shaper tools, lathe tools, planer tools, etc.
  - The tool having more than one cutting edge is called multipoint cutting tools. For example drills, milling cutters, broaches, grinding wheel honing tool etc.
  - A single point cutting tool may be either right or left hand cut tool depending on the direction of feed.

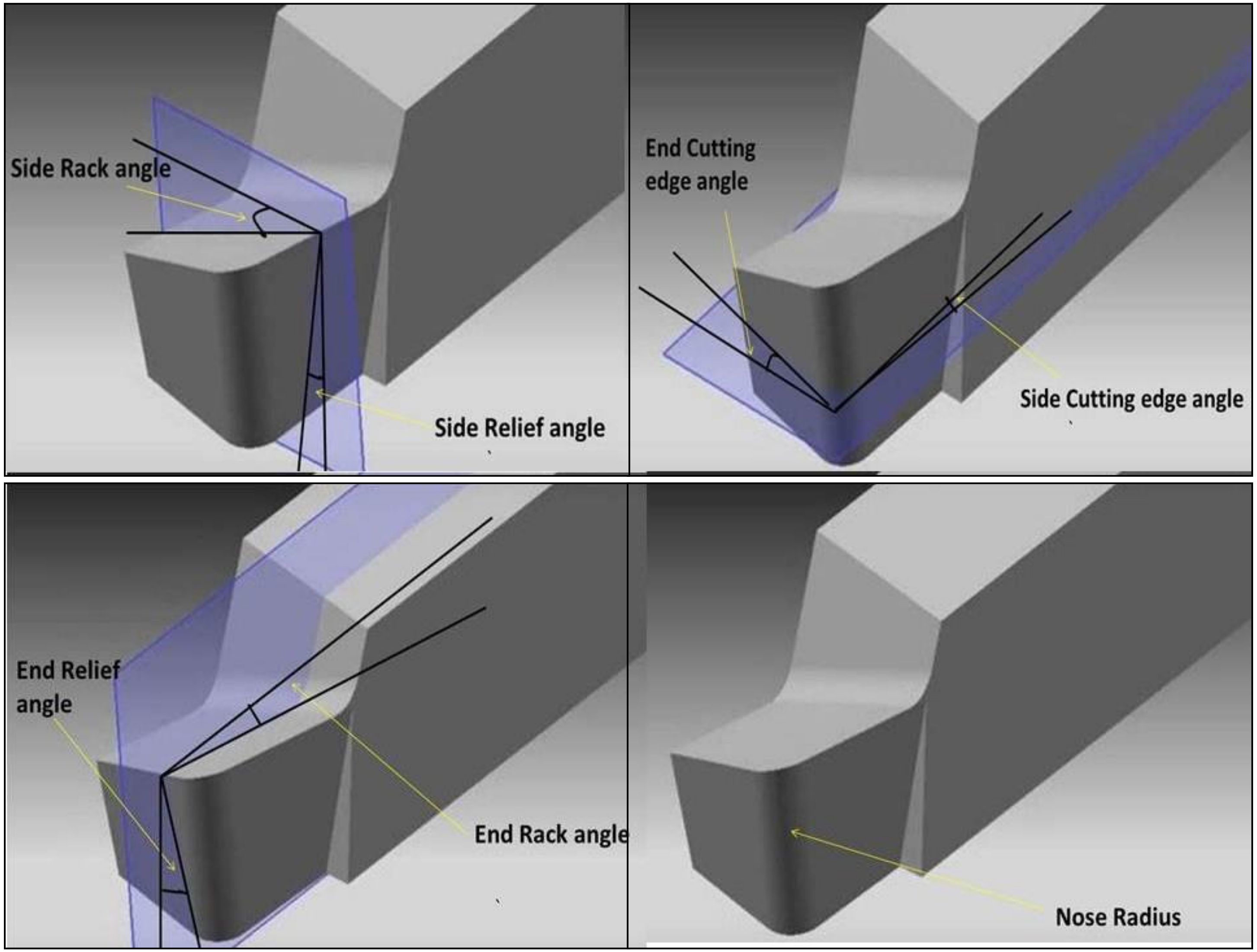


Cutting Tool Nomenclature

- The geometry of a cutting tool consists of the following elements: face or rake surface, flank, cutting edges and the corner (nose radius). Face or rake is the surface of the cutting tool along which the chips flow out. Flank surfaces are those facing the work piece. There are two flank surfaces, principal and auxiliary flank surfaces. Principal cutting edge performs the major portion of cutting and is formed by the intersecting line of the face with the principal flank surface. Auxiliary cutting edge (often called end cutting edge) is formed by the intersection of the rake surface with the auxiliary flank surface. Corner or cutting point is the meeting point of the principal cutting edge with the auxiliary cutting edge.



Single Point Cutting Tool



Side cutting edge angle	(φ_s)
End cutting edge angle	(φ_e)
End or back rake angle	(γ_y)
End or back relief angle	(α_y)
Side rake angle	(γ_x)
Side relief angle	(α_x)
Nose radius	(r)

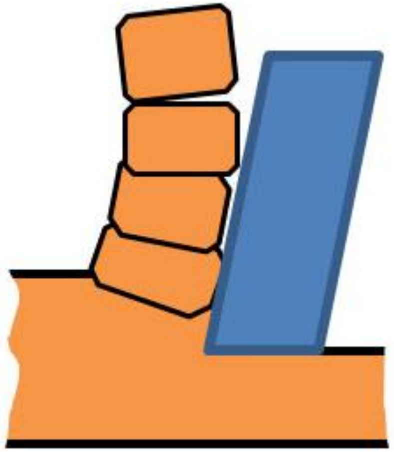
- Side cutting edge angle (φ_s): The side cutting-edge angle is usually referred to as the lead angle. It is the angle enclosed between the side cutting edge and the longitudinal direction of the tool. The value of this angle varies between 0° and 90°, depending upon the machinability, rigidity, and, sometimes, the shape of the workpiece. Usually, the recommended value for the lead angle should range between 15° and 30°.
- End cutting edge angle (φ_e): The end cutting-edge angle serves to eliminate rubbing between the end cutting edge and the machined surface of the workpiece. Although this angle takes values in the range of 5° to 30°, commonly recommended values are 8° to 15°.
- Side relief angle (α_x) and End relief angle (α_y): Side and end clearance angles serve to eliminate rubbing between the workpiece and the side and end flank, respectively. Usually, the value of each of these angles ranges between 5° and 15°.
- Side rake angle (γ_x) and Back rake angle (γ_y) : Back and side rake angles determine the direction of flow of the chips onto the face of the tool. Rake angles can be positive, negative, or zero. Its value usually varies between 0° and 15°.
- Nose radius (r): Nose radius is favorable to long tool life and good surface finish. There is an improvement in surface finish and permissible cutting speed as nose radius is increased from zero value.

Chip Formation

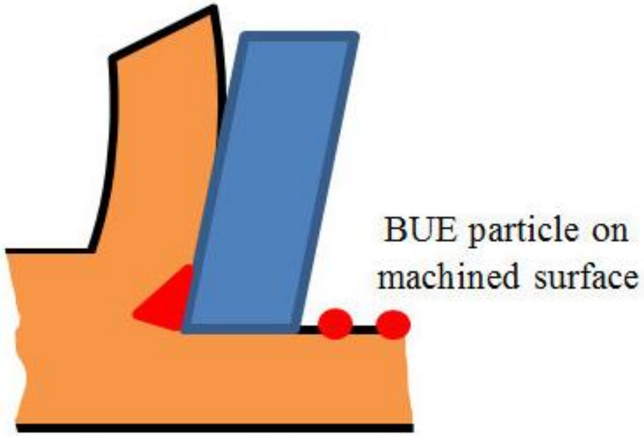
- Every Machining operation involves the formation of chips. The nature of which differs from operation to operation, properties of work piece material and the cutting condition.
- Chips are formed due to cutting tool, which is harder and more wearer-resistant than the work piece and the force and power to overcome the resistance of work material. The chip is formed by the deformation of the metal lying ahead of the cutting edge by a process of shear. Four main categories of chips are:
  - Discontinuous Chips
  - Continuous or Ribbon Type Chips
  - Continuous Chip with Built-up-Edge (BUE)
  - Serrated Chips
- Discontinuous chips: These chips are small segments, which adhere loosely to each other. They are formed when the amount of deformation to which chips undergo is limited by repeated fracturing. Hard and brittle materials will produce such chips.

- Continuous or Ribbon type chips: In continuous chip formation, the pressure of the work piece builds until the material fails by slip along the plane. The inside on the chip displays steps produced by the intermittent slip, but the outside is very smooth. It has its elements bonded together in the form of long coils and is formed by the continuous plastic deformation of material without fracture ahead of the cutting edge of the tool and is followed by the smooth flow of chip up the tool face.
- Continuous chip with BUE: This type of chip is very similar to that of continuous type, with the difference that it is not as smooth as the previous one. This type of chip is associated with poor surface finish, but protects the cutting edge from wear due to movement of chips and the action of heat causing the increase in tool life.
- Serrated chips: These chips are semicontinuous in the sense that they possess a saw-tooth appearance that is produced by a cyclical chip formation of alternating high shear strain followed by low shear strain. This chip is most closely associated with certain difficult-to-machine metals such as titanium alloys, nickel-base and austenitic stainless steels when they are machined at higher cutting speeds.

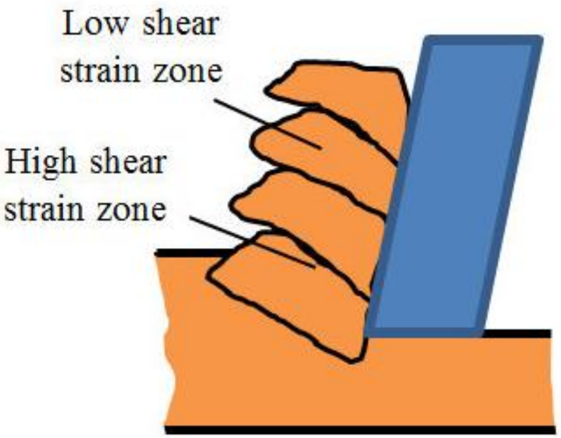
Continuous chip



Discontinuous chip



Continuous chip with BUE

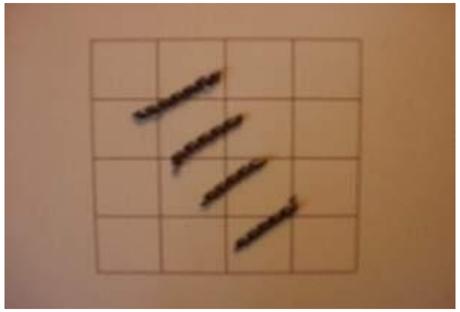


Serrated chip

Actual Chip Forms and Classifications


C-type and ε-type broken chips

Short helical broken chips




Medium helical broken chips

Long helical broken chips

Desired

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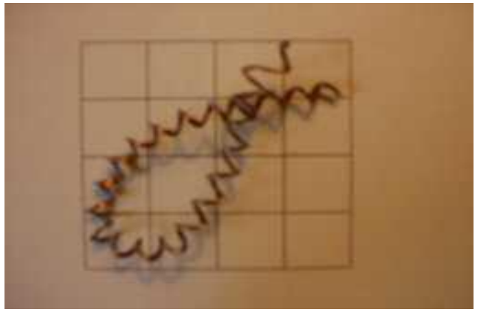
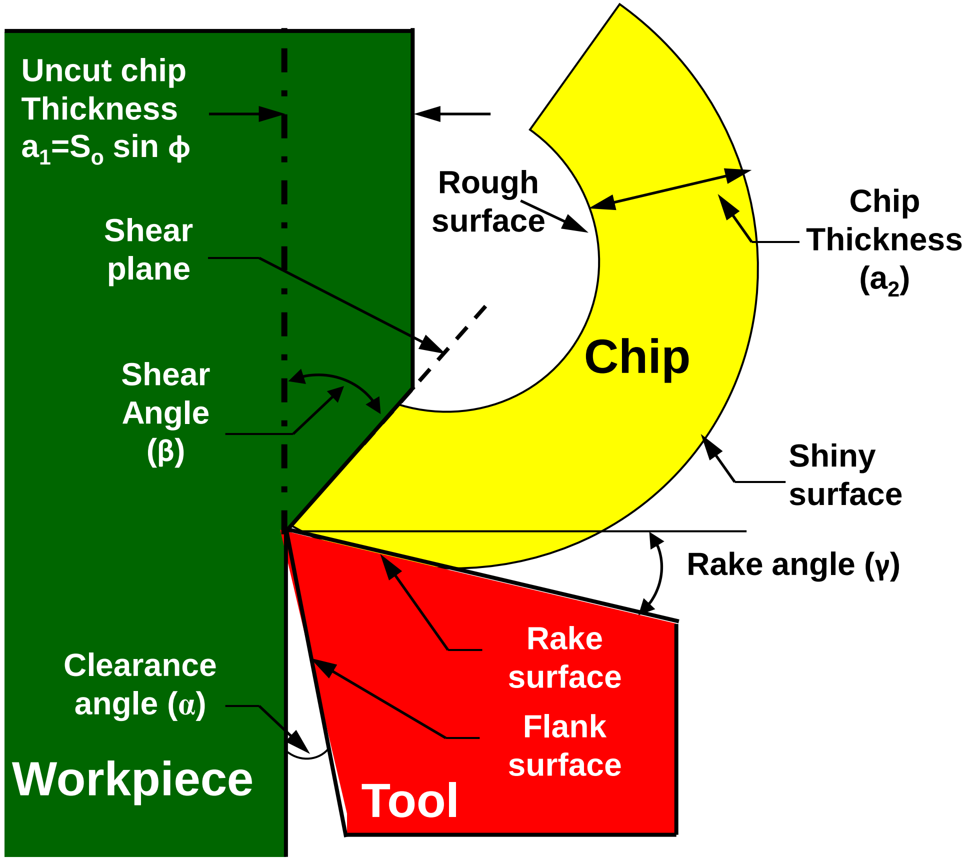
Not Desired

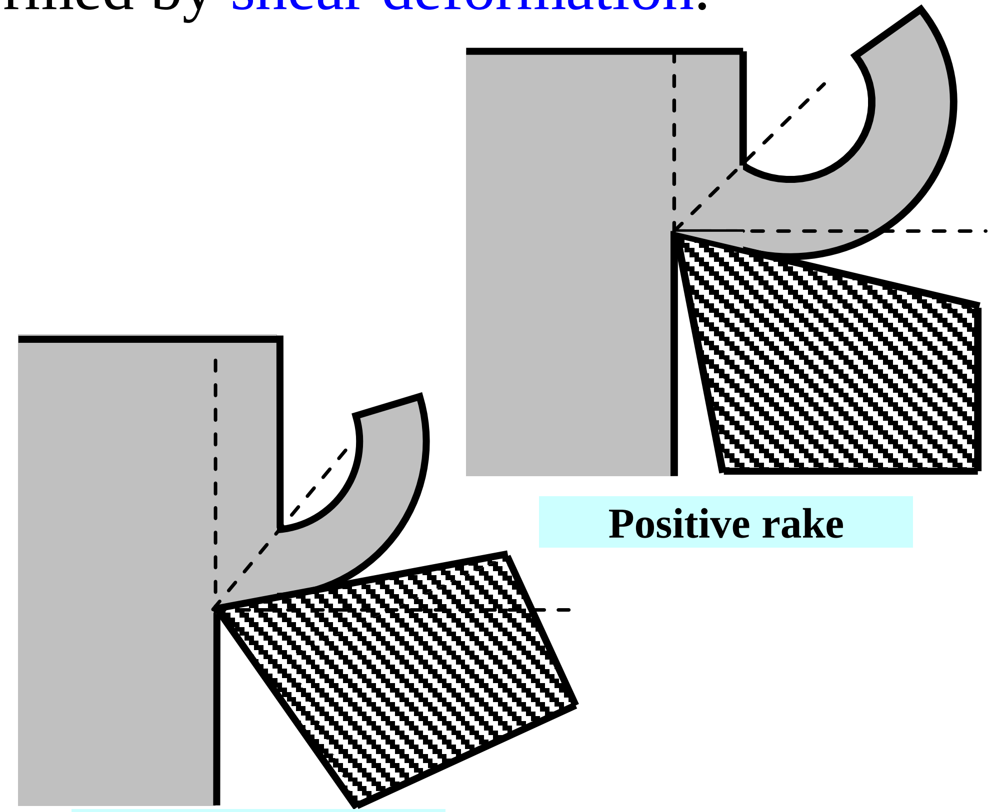

Long helical unbroken chips

Long and snarled unbroken chips

Chip Formation in Metal Machining

- Since the practical machining is complex we use orthogonal cutting model to explain the mechanics.In this model we used wedge shaped tool. As the tool forced into the material the chip is formed by shear deformation.





Positive rake

Negative rake

Chip Reduction Coefficient (ξ)

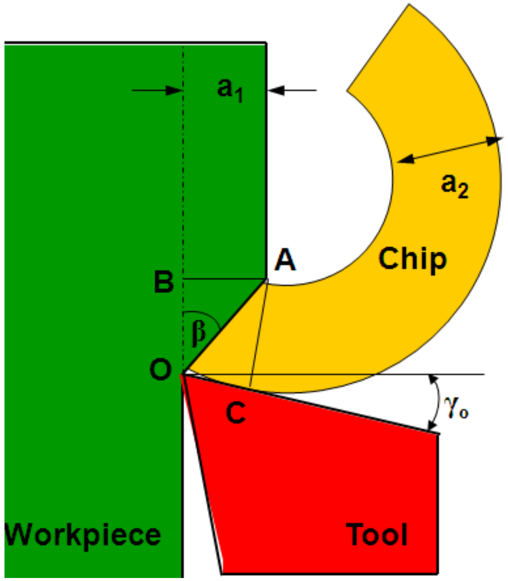
- Chip reduction coefficient (ξ) is defined as the ratio of chip thickness (a_2) to the uncut chip thickness (a_1). This factor, ξ, is an index of the degree of deformation involved in chip formation process during which the thickness of layer increases and the length shrinks. In the USA, the inverse of ξ is denoted by r_c and is known as cutting ratio. The following Figure shows the formation of flat chips under orthogonal cutting conditions. From the geometry of the following Figure.

$$\xi = \frac{a_2}{a_1} = \frac{AC}{AB} = \frac{OA\cos(\beta-\gamma)}{OA\sin\beta} = \frac{\cos\beta\cos\gamma + \sin\beta\sin\gamma}{\sin\beta}$$

$$= \frac{\cos\gamma}{\tan\beta} + \sin\gamma$$

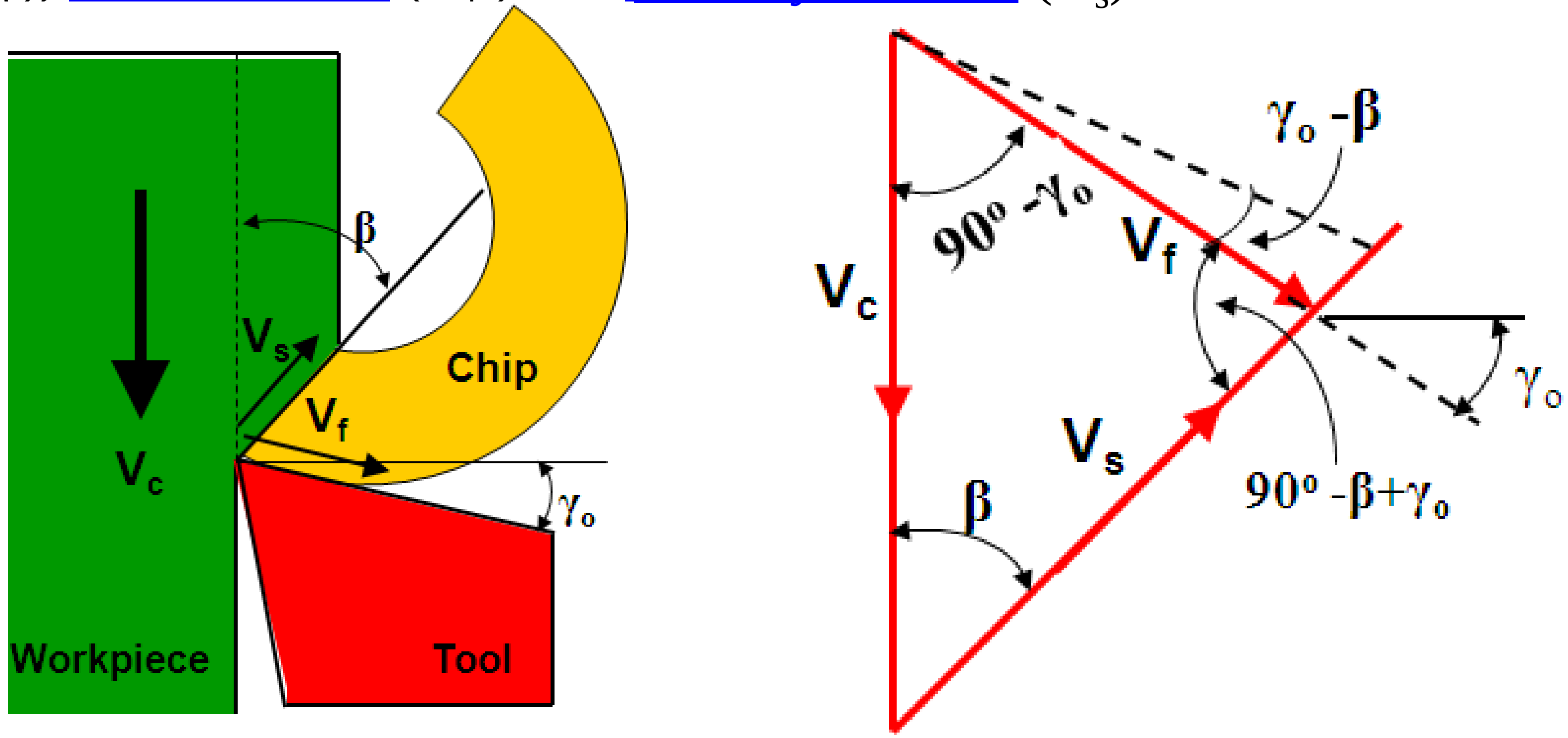
$$\therefore \tan\beta = \frac{\cos\gamma}{\xi - \sin\gamma}$$

$$\beta = \tan^{-1}\left(\frac{\cos\gamma}{\xi - \sin\gamma}\right) \text{ Shear angle}$$



Velocity Relationships

- The following Figure shows the velocity relation in metal cutting. As the tool advances, the metal gets cut and chip is formed. The chip glides over the rake surface of the tool. With the advancement of the tool, the shear plane also moves. There are three velocities of interest in the cutting process which include Cutting velocity (V_c), Flow velocity (V_f) and Velocity of shear (V_s).



- According to principles of kinematics, these three velocities, i.e. their vectors must form a closed velocity diagram. The vector sum of the cutting velocity, V_c, and the shear velocity, V_s, is equal to chip velocity, V_f. Thus,

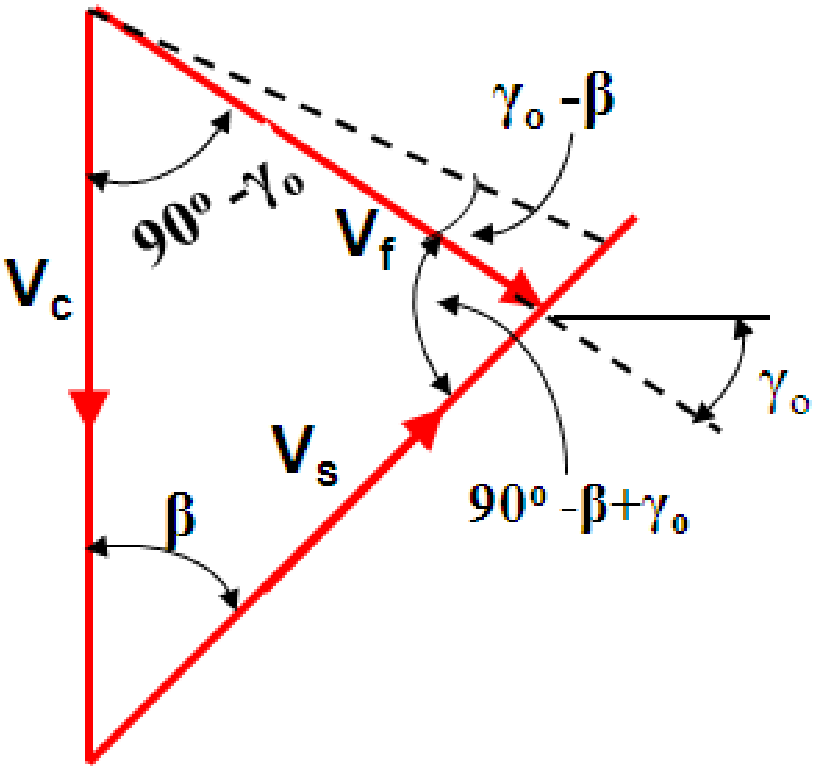
$$\overline{V}_f = \overline{V}_c + \overline{V}_s$$

$$\frac{V_s}{\sin(90^o-\gamma_o)} = \frac{V_c}{\sin\left[90^o-(\beta-\gamma_o)\right]} = \frac{V_f}{\sin\beta}$$

$$V_f = V_c\frac{\sin\beta}{\sin[90^0-(\beta-\gamma_o)]} = \frac{V_c\sin\beta}{\cos(\beta-\gamma_o)}$$

$$= \frac{V_c}{\xi}$$

$$\xi = \frac{V_c}{V_f}$$



- Kronenberg derived an interesting relation for chip reduction coefficient (ξ) which is of considerable physical significance. Considering the motion of any chip particle as shown in the following Figure to which principles of momentum change are applied:

$$F = -m\frac{dv}{dt} \text{ and } N = m\omega^2 r = mv\frac{d\theta}{dt} \;\Rightarrow\; \mu = \frac{F}{N}$$

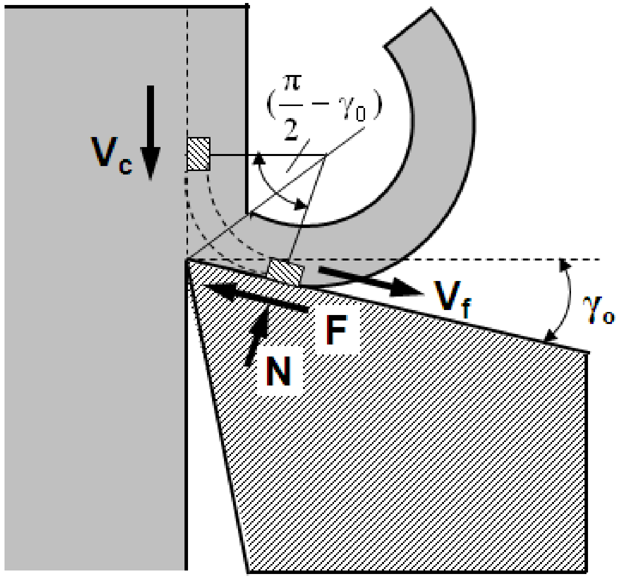
$$= -\frac{dv}{v\ d\theta}$$

$$-\frac{dv}{v} = \mu\ d\theta \;\Rightarrow\; \int_{V_c}^{V_f} -\frac{dv}{v} = \int_{0}^{(\frac{\pi}{2}-\gamma_o)} \mu d\theta$$

$$-\ln\left(\frac{V_f}{V_c}\right) = \mu\left(\frac{\pi}{2} - \gamma_o\right)$$

$$\frac{V_c}{V_f} = e^{\mu\left(\frac{\pi}{2}-\gamma_o\right)}$$

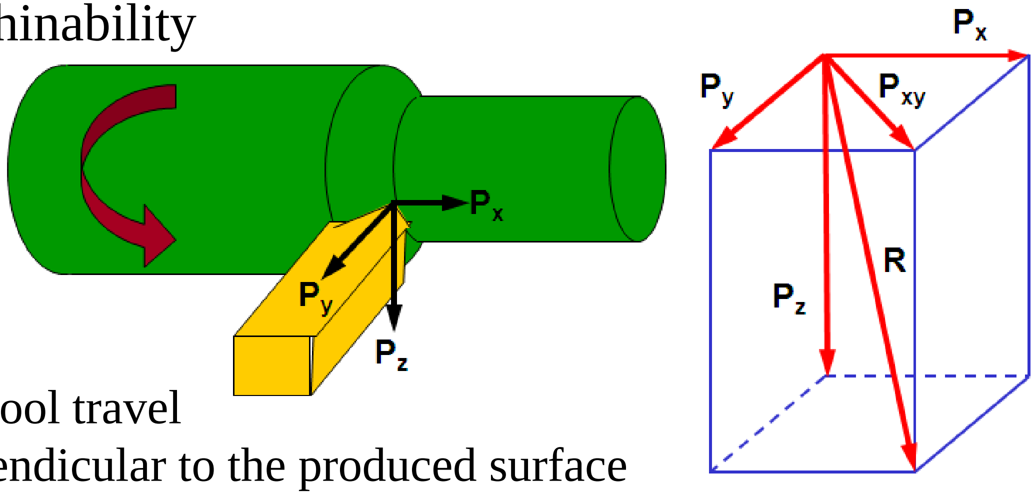
$$\Rightarrow \xi = e^{\mu\left(\frac{\pi}{2}-\gamma_o\right)}$$



This equation demonstrates that the chip reduction coefficient and chip flow velocity is dependant on the frictional aspects at the interface as well as the orthogonal rake angle (γ_0). If γ_0 is increased, chip reduction coefficient decreases.

Mechanics of Metal Cutting

- The force acting on a cutting tool during the process of metal cutting are the fundamental importance in the design of cutting tools. The determination of cutting forces necessary for deformation the work material is essential for several important requirements:
    - to estimate the power requirements of a machine tool
    - to estimate the straining actions that must be resisted by the machine tool components, bearings, jigs and fixtures
    - to evaluate the role of various parameters in cutting forces
    - to evaluate the performance of any new work material, tool material, environment, techniques etc. with respect to machinability



P_x = **Feed force** in the direction of the tool travel

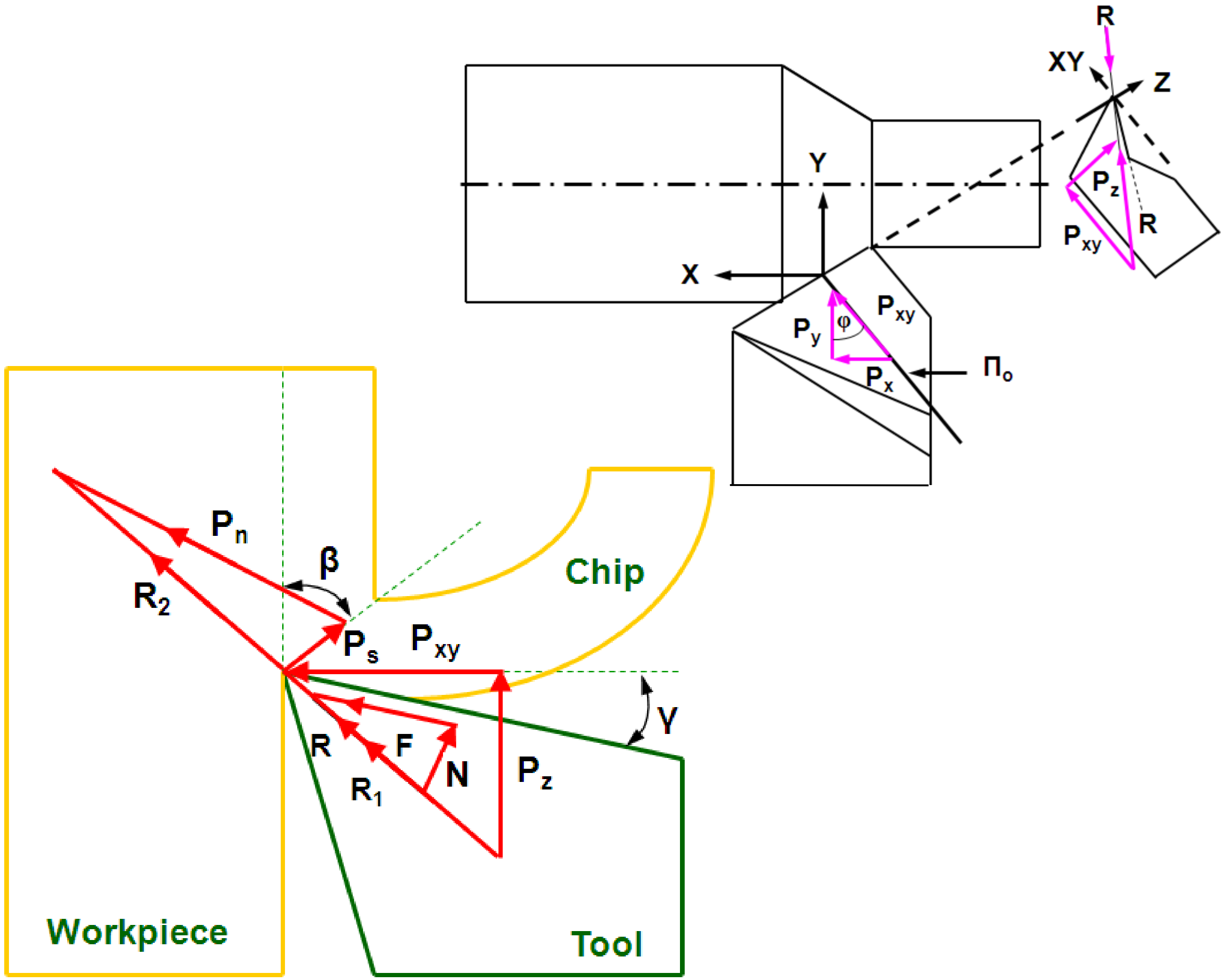
P_y = **Thrust force** in the direction perpendicular to the produced surface

P_z = **Cutting force** or **main force** acting in the direction of the cutting velocity.

$$P_x = P_{xy}\sin\varphi ....\ ....[1\ ]$$

$$P_y = P_{xy}\cos\varphi ....\ ....[2]$$

Several forces can be defined relative to the orthogonal cutting model. Based on these forces, shear stress, coefficient of friction, and certain other relationships can be defined.



Merchant Circle Diagram (MCD)

- The following relationships suggest a circle representation of forces as done by Merchant and indicated in the following Figure.

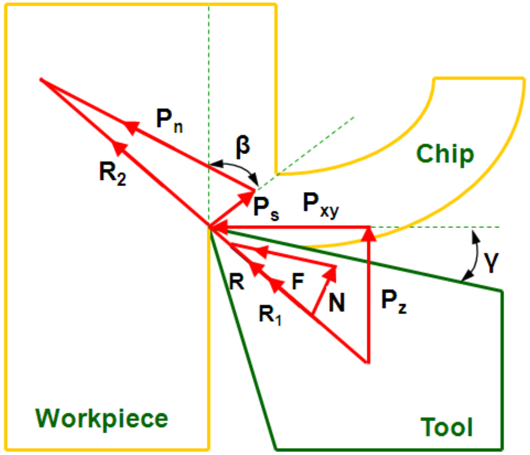
$$\overline{R} = \overline{F} + \overline{N} = \overline{P}_s + \overline{P}_n = \overline{P}_z + \overline{P}_{xy} \text{.........}[3]$$

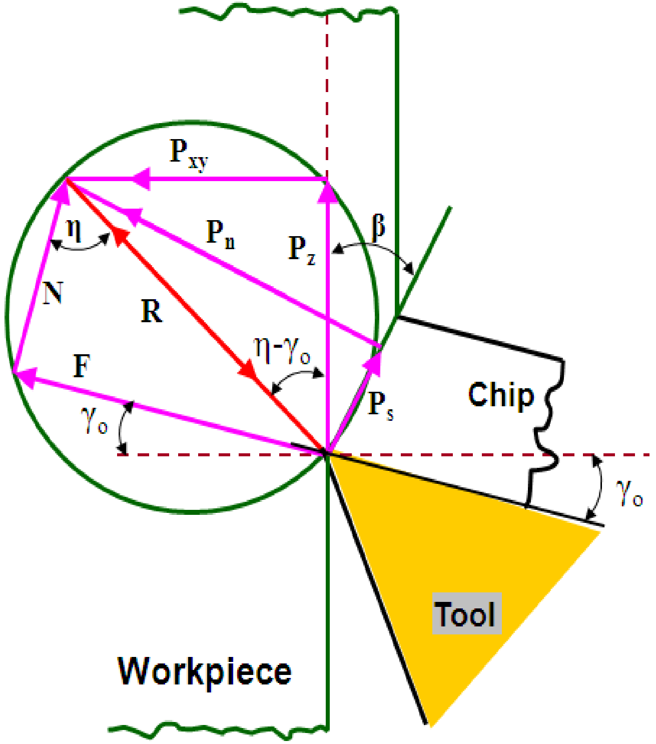
$$F = P_z \sin\gamma_o + P_{xy}\cos\gamma_o \text{......... ....}.[4]$$

$$N = P_z \cos\gamma_o - P_{xy}\sin\gamma_o \text{......... ....}[5]$$

$$P_s = P_z \cos\beta - P_{xy}\sin\beta \text{........ ....}[6]$$

$$P_n = P_z \sin\beta + P_{xy}\cos\beta \text{........ ....}[7]$$





From Equation [4] and [5]

$$\mu = \frac{F}{N} = \frac{P_z \sin\gamma_o + P_{xy}\cos\gamma_o}{P_z\cos\gamma_o - P_{xy}\sin\gamma_o} = \tan\eta \text{.....}[8]$$

Where,

μ = kinetic coefficient of friction

η = mean angle of friction at the rake surface

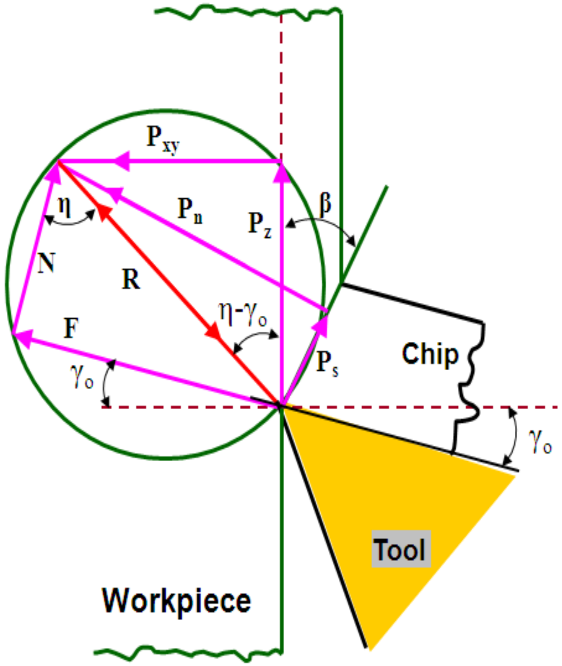
From the geometry of force relations of MCD circle

$$P_z = R\cos(\eta-\gamma_0)\ldots\ldots\ldots\ldots\ldots[9]$$

$$P_s = R\cos(\beta+\eta-\gamma_0)\ldots\ldots\ldots\ldots[10]$$

Fron Equation [9] and [10] $P_z = P_s\left[\dfrac{\cos(\eta-\gamma_0)}{\cos(\beta+\eta-\gamma_o)}\right]\ldots\ldots\ldots\ldots[11]$

Based on the shear force, the shear stress (τ_s) which acts along the shear plane between the work and the chip is:



$\tau_s = \dfrac{P_s}{A_s}$,where As $=$ area of the shear plane $= \dfrac{S_o t}{\sin\beta} \Rightarrow \tau_s = \dfrac{P_s\sin\beta}{S_o\ t}\ldots\ldots\ldots\ldots[12]$

From Equation [11]and [12]

$$P_z = \tau_s S_0 t\left[\frac{\cos(\eta-\gamma_0)}{\sin\beta\ \cos(\beta+\eta-\gamma_o)}\right]\ldots\ldots\ldots[13]$$

Similarly,

$$P_{xy} = \tau_s S_0 t\left[\frac{\sin(\eta-\gamma_0)}{\sin\beta\ \cos(\beta+\eta-\gamma_o)}\right]\ldots\ldots[14]$$

$$\frac{P_{xy}}{P_z} = \tan(\eta-\gamma_0)$$

Ernst-Merchant Theory

- Ernst and Merchant extended their analysis and studied the relationship between the shear angle and the cutting conditions. They suggested that the shear angle always takes the value that reduces the total energy consumed in cutting to a minimum. Because the total work done in cutting is dependent upon and is a direct function of the component P_z of the cutting force, they developed an expression for P_z in terms of β and the constant properties of the workpiece material. Condition for maximum cutting force (P_z) from Equation [13]

$$\frac{dP_z}{d\beta} = 0, \text{or}, \frac{dP_z}{d\beta} = \frac{d}{d\beta}\left[\frac{\tau_s S_0 t}{\sin\beta} \cdot \frac{\cos(\eta-\gamma_0)}{\cos(\beta+\eta-\gamma_o)}\right] = 0$$

$$\tau_s S_0 t\cos(\eta-\gamma_0)\left[\frac{\cos\beta\cos(\beta+\eta-\gamma_0)-\sin\beta\sin(\beta+\eta-\gamma_0)}{\{\sin\beta\cos(\beta+\eta-\gamma_0\}^2}\right] = 0$$

$$\cos\beta \times \cos(\beta+\eta-\gamma_0) - \sin\beta \times \sin(\beta+\eta-\gamma_0) = 0, \text{or} \cos(\beta+\beta+\eta-\gamma_0) = 0 = \cos\left(\frac{\pi}{2}\right)$$

$$\beta = \frac{\pi}{4} - \frac{\eta}{2} + \frac{\gamma_0}{2} \ldots\ldots\ldots\ldots\ldots\ldots [15]$$

Combining Equation [13] and [15],

$$P_z = 2\tau_s S_0 t\cot\beta$$

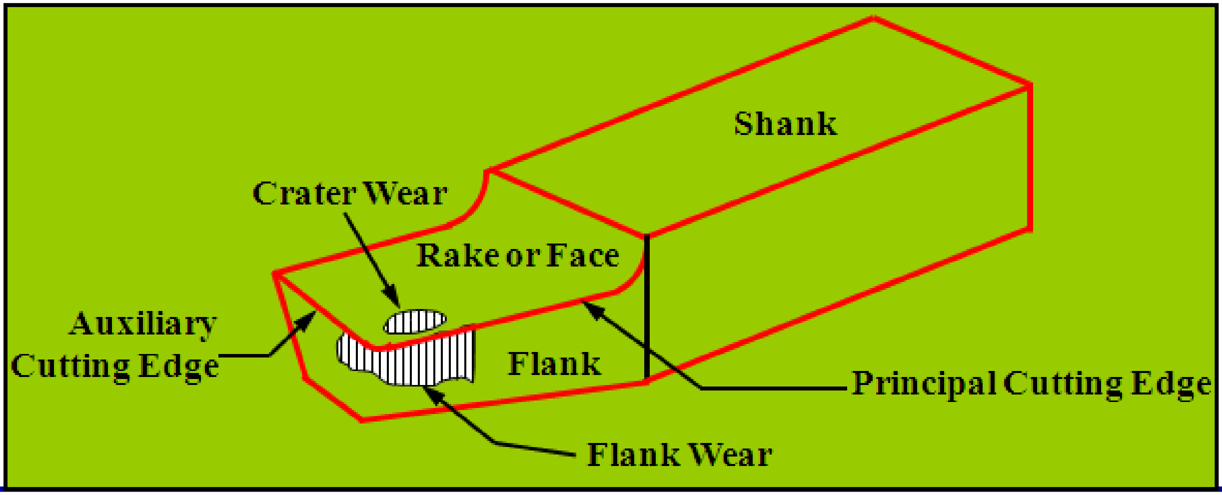
- Problem-01: While turning a metal rod of diameter 150 mm at speed of 560 rpm, feed of 0.32 mm/rev and 4.0 mm depth of cut by a tool having tool rake angle 12^o and principal cutting edge angle 60^o. It was noted that P_z = 1000 N, P_y =200 N and chip thickness, a_2 = 0.80 mm. Determine co-efficient of friction and dynamic yield shear strength.

- Problem-02: A mild steel rod of 150 mm diameter is turned on a lathe at a speed of 340 rpm, feed of 0.24 mm/rev and 2.5 mm depth of cut by a tool having tool rake angle 20^o and principal cutting edge angle 60^o.It is found by the dynamometer that the main cutting force = 800 N and feed force = 400 N. The value of chip reduction coefficient is 3.5. Calculate the coefficient of friction, shear plane angle, and dynamic yield shear strength.

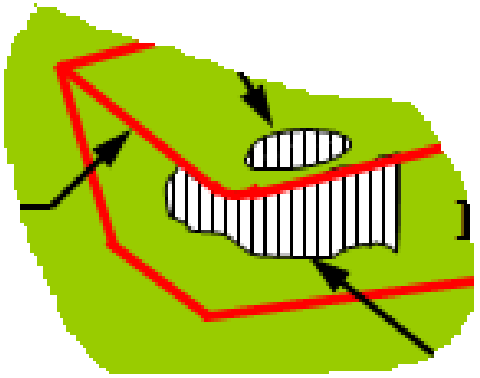
- Problem-03: SAE 133 cold rolled steel rod of 150 mm diameter is turned at a speed of 450 rpm, feed of 0.24 mm/rev. and 2 mm depth of cut by a tool having rake angle 6^o and principal cutting edge angle 60^o. It was noted that the magnitudes of the tangential component and the axial component of the cutting force 1050 N and 450 N respectively and the value of chip reduction coefficient is 1.8. Using MCD, determine the values of μ, P_s and P_n.

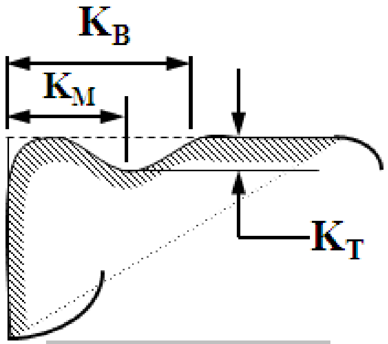
Tool Wear

- Productivity and economy of manufacturing by machining are significantly affected by life of the cutting tools. Cutting tools may fail by brittle fracture, plastic deformation or gradual wear. Turning carbide inserts having enough strength, toughness and hot hardness generally fail by gradual wears.
- With the progress of machining the tools attain crater wear at the rake surface and flank wear at the clearance surfaces, as schematically shown in following Figure (next slide) due to continuous interaction and rubbing with the chips and the work surfaces respectively. Among the aforesaid wears, the principal flank wear is the most important because it raises the cutting forces and the related problems.

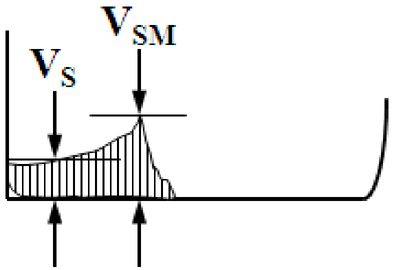


Features of Wear of Turning Tool



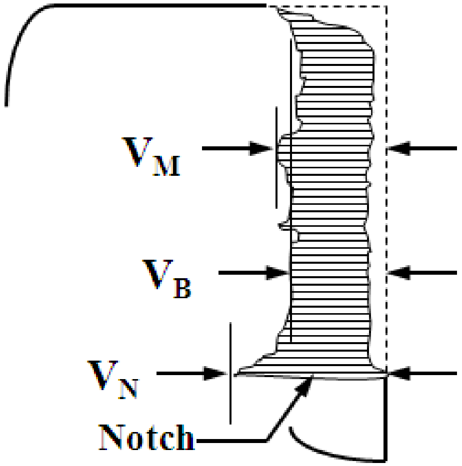


Section A-A

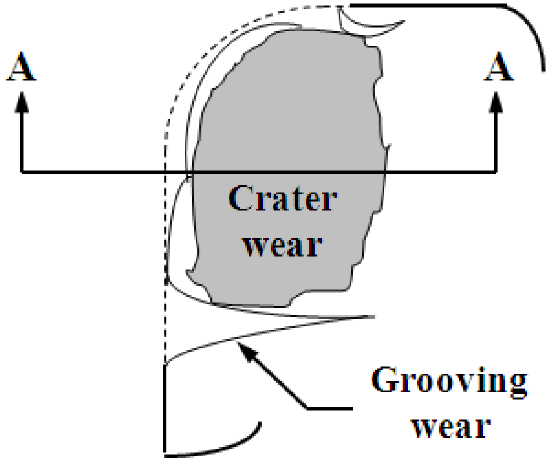


Auxiliary Flank

V_B = Average flank wear
V_N = Flank notch wear
V_M = Maximum flank wear
V_S = Average auxiliary flank wear
V_{SM} = Maximum auxiliary flank wear
K_T = Crater depth
K_M = Distance from center of crater
K_B = Crater width



Principal Flank



Rake Surface

- The life of the tools, which ultimately fail by systematic gradual wear, is generally assessed at least for R&D work, by the average value of the principal flank wear (V_B), which aggravates cutting forces and temperature and may induce vibration with progress of machining. The pattern and extent of wear of the auxiliary flank (V_S) affects surface finish and dimensional accuracy of the machined parts.
- However, tool rejection criteria for finishing operation were employed in this investigation. The values established in accordance with ISO Standard 3685 for tool life testing. A cutting tool was rejected and further machining stopped based on one or a combination of **rejection criteria**:

Average Flank Wear	≥	0.3 mm
Maximum Flank Wear	≥	0.4 mm
Nose Wear	≥	0.3 mm
Notching at the depth of cut line	≥	0.6 mm
Average surface roughness value	≥	1.6 μm
Excessive chipping (flanking) or catastrophic fracture of cutting edge.		

Mechanism of Tool Wear

- In general there are seven basic types of wear that affect a cutting tool:
  - Abrasion: Mechanical wearing, hard particles in workpiece removes small portions of the tool, that cause flank and crater wear. This is the dominant cause of flank wear.
  - Adhesion: Two metals contact under high pressure and temperature that cause welding between the materials.
  - Diffusion: Atoms on the boundry of workpiece and tool changes place. This is the principle cause for crater wear.
  - Chemical Reactions: The high temperatures and clean surfaces at the chip-tool interface in machining at high speeds can result in chemical reactions, in particular, oxidation, on the rake surface of the tool. The oxidized layer, being softer than the parent tool material, is sheared away, exposing new material to sustain the reaction process.
  - Plastic Deformation: Cutting forces acting on the cutting edge at high temperature cause the edge to deform plastically. This cause flank wear.

Cutting Tool Materials Properties

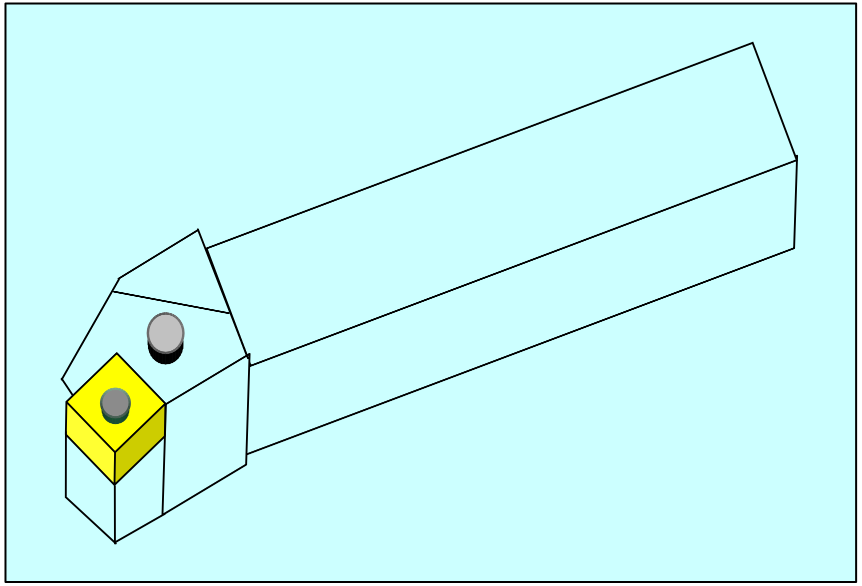
- A good type of tool material should possess certain desired properties such as
  - The material must remain harder than the work material at elevated operating temperature.
  - The material must withstand excessive wear even though the relative hardness of the tool-work materials changes.
  - The frictional coefficient at the chip-tool interface must remain low for minimum wear and reasonable surface finish.
  - The material must be sufficiently tough to withstand the shocks of intermittent cutting; if not reinforcement must be provided.
  - The tool material should also possess high thermal conductivity for quickly removing heat from the chip-tool interface, have a low coefficient of thermal expansion, not be distorted after heat treatment, be easy to regrind and also easy to weld to the tool holder

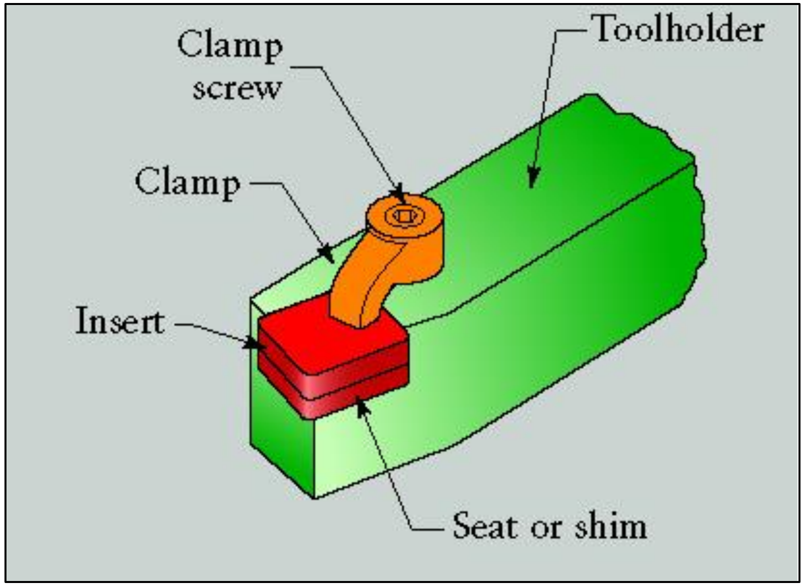
Cutting Tool Materials

- Carbon Tool Steels
  - Medium alloy steels
  - Poor properties above 200^{O}C and inexpensive
  - Uses: Taps and core drills for machining soft materials and wood working tools
- High Speed Steels (HSS)
  - Hot hardness is quite high, so the HSS cutting tools retain the cutting ability upto 600^{O}C
  - Wear resistance is high and hardenability is good
  - Uses: Drills, milling cutters, taps, lathe cutting tool, gear hobs etc. are made of HSS.
- Carbides: A hard material made of compacted binary compounds of carbon and heavy metals, used to make tools that cut metal.
  - Made using powder metallurgy and usually used as an insert
- Ceramics
  - High abrasion and high hot hardness
  - Not good for interrupted cutting
  - Requires dry, or constant profuse cutting fluids

Methods of attaching inserts to tool shanks

- All carbides, when finished, are extremely brittle and weak in their resistance to it impact and shock loading. Due to this, vibrations are very harmful for carbide tools. The machine tools should be rigid, faster and more powerful. Low feeds, low speeds and chatter are harmful. Due to the high cost of carbide tool materials and other factors, cemented carbides are used in the form of inserts or tips which are brazed or clamped to a steel shank as shown in the following Figure.





Types of Cutting Fluids

- Cutting fluids are used in metal machining for a variety of reasons such as improving tool life, reducing workpiece thermal deformation, improving surface finish and flushing away chips from the cutting zone. Practically all cutting fluids presently in use fall into one of four categories:
  - Straight oils
  - Soluble oils
  - Semi-synthetic fluids
  - Synthetic fluids
- Straight oils are non-emulsifiable and are used in machining operations in an undiluted form. They are composed of a base mineral or petroleum oil and often contain polar lubricants such as fats, vegetable oils and esters as well as extreme pressure additives such as Chlorine, Sulphur and Phosphorus. Straight oils provide the best lubrication and the poorest cooling characteristics among cutting fluids.

- Soluble oil fluids form an emulsion when mixed with water. The concentrate consists of a base mineral oil and emulsifiers to help produce a stable emulsion. They are used in a diluted form (usual concentration 3 to 10%) and provide good lubrication and heat transfer performance. They are widely used in industry and are the least expensive among all cutting fluids.
- Semi-synthetic fluids are essentially combination of synthetic and soluble oil fluids and have characteristics common to both types. The cost and heat transfer performance of semi-synthetic fluids lie between those of soluble oil fluids and synthetic fluid.
- Synthetic fluids contain no petroleum or mineral oil base and instead are formulated from alkaline inorganic and organic compounds along with additives for corrosion inhibition. They are generally used in a diluted form (usual concentration 3 to 10%). Synthetic fluids often provide the best cooling performance among all cutting fluids.

Properties of Cutting Fluid

- A good type of cutting fluid should possess certain desired properties such as:
  - Good cooling capacity and lubricating qualities
  - Rust resistance and stability- for long life
  - Resistance to rancidity and foaming
  - Non-toxic
  - Transparent-to allow the operator to see the work clearly during machining
  - Relatively low viscosity-to permit the chips and dirt to settle quickly
  - Nonflammable-to avoid burning easily and should be non-combustible
  - Ability to disposed in an environmentally responsible way.
  - In addition, it should not smoke excessively, form gummy deposit which may cause machine slide to become sticky, or clog the circulating system.