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Contents

Manufacturing Science

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CHAPTER 1

Metal Cutting and Machine Tools

1.1 Metal Cutting

Machining is the process of removing unwanted material from workpiece. In machining the total energy required is summation of energy required in plastic deformation to break crystal structure and in overcoming the friction. And it is done with the help of cutting tool having cutting edges.

The cutting edges are developed as the lines of intersection of the three major surfaces - the rake surface and the two clearance surfaces. Thus, the total performance of any cutting tool depends on

1. The material of the tool.
2. The sharpness of the cutting edges.
3. The orientation angles of the planes that generate the cutting edges.

Therefore, the overall performance of cutting tools is governed almost equally by choice of the material and geometry of the cutting tools and by their way of application. Appropriate selection of tool geometry enables efficient and economic machining of any job. This requires thorough knowledge of cutting tool geometry.

Cutting tools are classified into :

1.1.1 Single point cutting tools

The tool terminating in a single point has been termed as single point cutting tools. It is made up of either high carbon steel, high speed steel or carbide bay.

- Its cutting edge is prepared by grinding.
- Its nose is given a small radius and it is never a sharp point because this imparts strength to the cutting edge.

  Example : Turning tools, shaping, planing and slotting tools and boring tools.

1.1.2 Multipoint Cutting tools

They have more than one cutting edge to remove excess material from the work piece.

Example : Milling cutter, Drills, Reamers, Broaches etc.

1.2 Terminology of Turning Tool

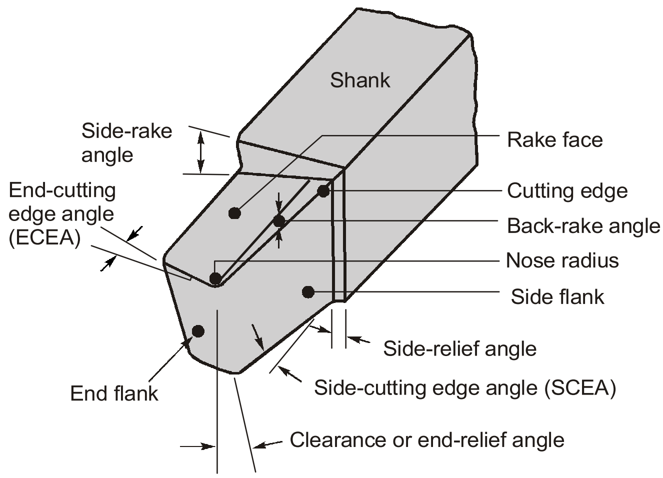

Fig. *Single point cutting tool*

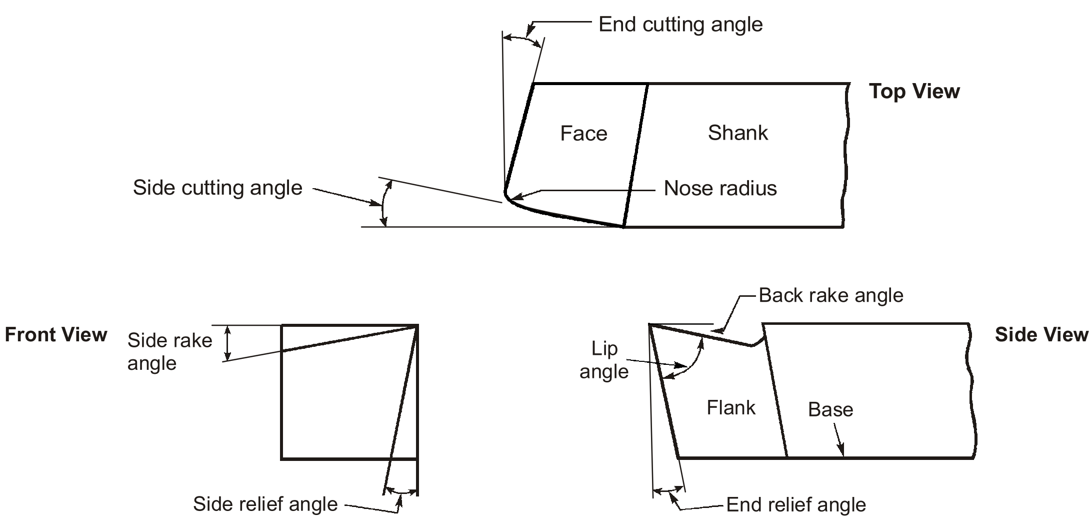

Fig. *Representation of various angles in different views of Single Point Cutting Tool*

1.2.1 Back Rake Angle (α_b)

It is the angle between the line parallel to the tool axis passing through the tip and the rake face and angle is measured in a plane perpendicular to the base and parallel to the length of tool. After plastic deformation chips flow over the rake face and heavy drag exists between chip and rake face. Due to this, temperature continues to develop and the maximum temperature will appear 2-3 mm away from the cutting edge. At high temperature carbon starts diffusing from the tool to the chip and as a result of that tool becomes weaker and weaker.

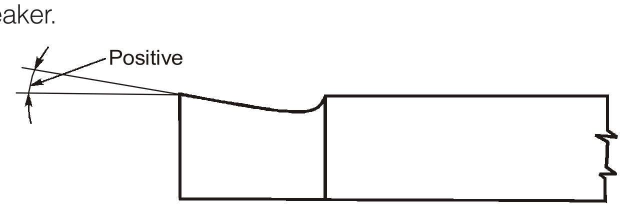

Fig. (a): *Positive Rake angle*

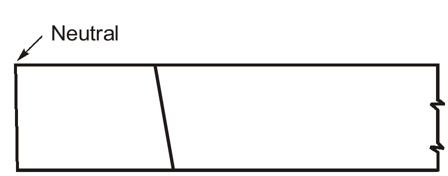

Fig. (b): *Neutral Rake angle*

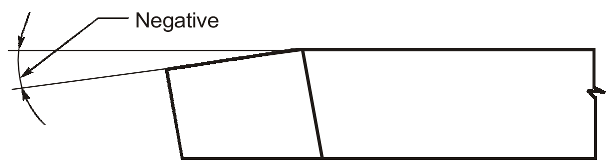

Fig. (c): *Negative rake angle*

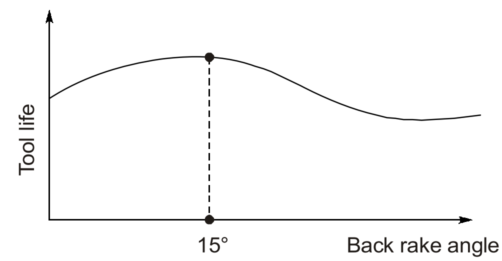

Fig. (d): *Tool life*

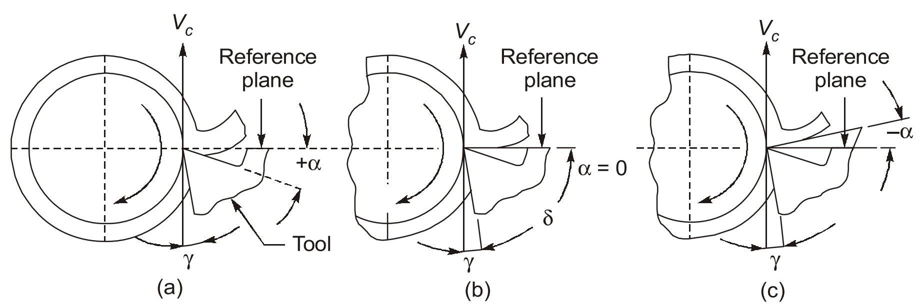

Fig. *Sign convention of tool rake angles*, (a) *Positive rake*, (b) *Zero rake*, (c) *Negative rake*.

The relative advantages of different types of rake angles are:

1. **Positive rake:** It helps reduce cutting force, thus cutting power requirement.
2. **Negative rake:** It increases strength and life of the cutting edge.
3. **Zero rake:** It simplifies design and manufacture (of form tools, etc.)

- Due to drag between chip and the tool, a portion of the tool will be carried away by the chip. This phenomenon is called diffusion wear.
- By increasing the back rake angle, chip flow will be easier, that is drag will decrease and hence the tool wear decreases, so initially by increasing back rake angle tool life increases.

  While machining stronger or brittle materials smaller rake angles are used for example machining brass zero rake angles are chosen.
- If tool material is brittle like ceramics and carbides negative rake angle have to be provided because we want tool be stronger.
- By providing the negative back rake angle, energy required to overcome the friction increases which increases the overall power requirement in machining but negative rake angles are required for tool stability because due to impact created by **payalite** tool may break.
- While machining of slots or keys ways the cutting tool may be given a negative back rake and positive side rake. For machining ductile material tool life increases by increasing back rake angle because of decrease in contact length between chip and tool over the rake face. But when this angle becomes more than a particular value lip angle of the tool decreases. This decreases the strength of tool hence tool life decreases.

1.2.2 Side Cutting Edge Angle (C_s)

- It is the angle between the side cutting edge and the line extending the shank. The angle is measured in a plane parallel to base.
- Width of the chip is the length of the cutting edge covered by the chips and it can be observed in the analysis that as side cutting edge angle increases chips become wider.

Uncut chip thickness is experienced by the side cutting edge in the perpendicular direction and by increasing the side cutting edge angle, chips become thinner.

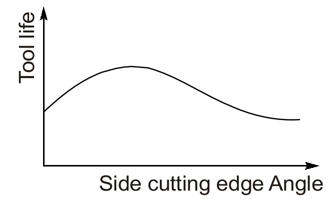

Fig. *Variation of tool life with respect to side cutting edge angle*

- Since the heat distributed over the larger area, peak temperature over the rake face will decrease. This will decrease, the tool wear and hence increase the tool life.
- Wider chips increases the friction force so by increasing the side cutting edge angle cutting force requirement is slightly increased. But since the heat is distributed over the large area peak temperature over the rake face will decrease. This will decrease, the tool wear and hence increases the tool life. Side cutting edge angle increases the possibility of chatter vibrations.
- For machining shoulders a small negative side cutting edge angle of 2° – 15° is given on tools. Normally the value of side cutting edge angle is 15° – 30°.

1.2.3 Side Rake Angle (5° - 15°) (α_s)

It is the angle between the rake face and the line passing through the tip perpendicular to the tool axis and the angle is measured in a plane perpendicular to the base. Normally this angle varies between 15° - 30°.

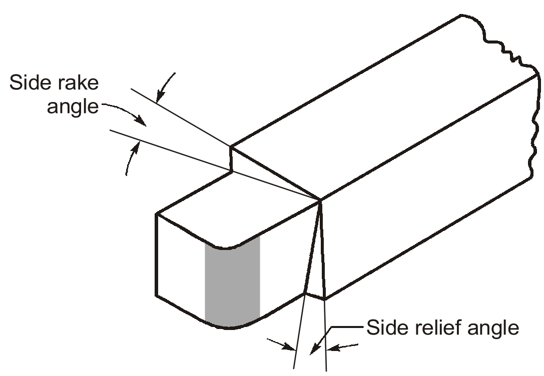

Fig. *Representation of Side Rake and Side Relief Angles*

1.2.4 Side Relief Angle (5° - 15°) (γ_s)

It is the angle between the side flank and the line passing through the tip perpendicular to the base and the angle measured in a plane perpendicular to the tool axis.

This angle varies in the range of 5°-15°. The work piece material which is going to be removed in the next revolution will try to hit the side flank due to elastic recovery of work piece material. To avoid this rubbing side relief angle is provided.

1.2.5 End Cutting Edge Angle (8° - 15°) (C_e)

It is the angle between the end cutting edge and the line passing through the tip perpendicular to the tool axis and the angle is measured in a plane parallel to the base.

At smaller values of the angle, large forces normal to the machine surfaces are produced and the tool may chatter. Side cutting edge angle is made zero for a distance slightly greater than the feed in order to decrease rough marks due to feed marks. The normal value of this angle is the range 8° – 15°.

1.2.6 End Relief Angle/ Clearance Angle (E_C)

It is the angle between the end flank and the line passing through the tip perpendicular to the base and angle is measured in plane parallel to the tool axis.

There will be some elastic recovery in the finished work and as a result of that it will try to rub the end flank while machining ductile material elastic recovery will be more so larger clearance angle has to be provided. Relief is provided to the side and end flanks in order to minimize physical interference or rubbing contact with the machine surface of work piece.

Smaller relief angles do not weaken the cutting edge as much as large relief angle.

1.3 Nose Radius and Its Effects

Proper tool nose radius improves machinability to some extent through

- increase in tool life by increasing mechanical strength and reducing temperature at the tool tip
- reduction of surface roughness,, $h_{max} = \frac{(f)^2}{8r}$. Proper edge radius ($r$) also often enhances strength and life of the cutting edge without much increase in cutting forces.

1.4 Tool Signature

1.4.1 ASA Tool Signature

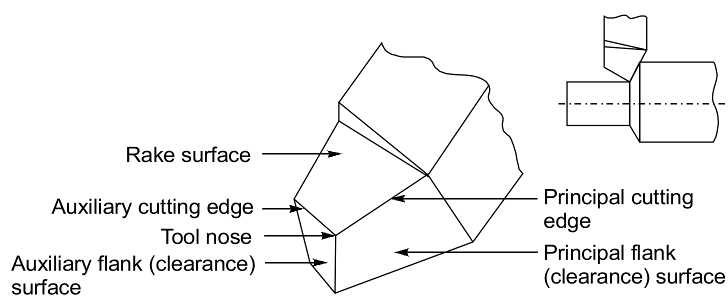

Fig. *Basic features of a single-point tool in the tool-in-hand system*

In the ASA system, the three planes of reference and the coordinates are chosen based on the configuration and axes of the machine tool concerned. Figure shows the planes and axes used for expressing tool geometry in ASA system in respect of turning operation.

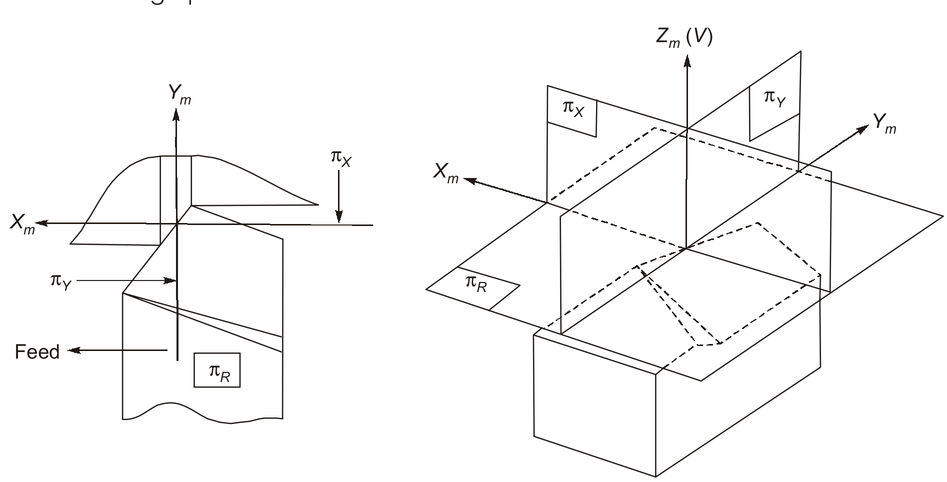

Fig. *Planes and axes used for visualizing and designating tool geometry in the ASA system*

Back rake angle → Side rake angle → End relief angle → Side relief angle → End cutting edge angle → Side cutting edge angle → Nose radius.

$\alpha_b \rightarrow \alpha_s \rightarrow \gamma_e \rightarrow \gamma_s \rightarrow C_e \rightarrow C_s \rightarrow R$

The planes of reference and the coordinates, used in the ASA system for tool geometry are $\pi_R - \pi_X - \pi_Y$ and $X_m - Y_m - Z_m$, respectively, where π_R is the reference plane, perpendicular to the velocity vector, $\vec{V}$ as shown in figure π_X is the machine longitudinal plane, perpendicular to π_R and taken in the direction of the assumed longitudinal feed and π_Y is the machine transverse plane, perpendicular to both π_R and π_X, that is, taken in the direction of cross feed. The axes X_m, Y_m and Z_m are taken in the direction of longitudinal feed, cross feed and cutting velocity vector, respectively.

1.4.2 Orthogonal Rake System (ORS)

Angle of inclination (i) → Orthogonal rake angle → (α) → Side relief angle (γ_s) → End relief angle (γ_e) → End cutting edge angle (C_e) → Approach angle (λ) where λ > 60° or λ = 90° – C_s → Nose radius

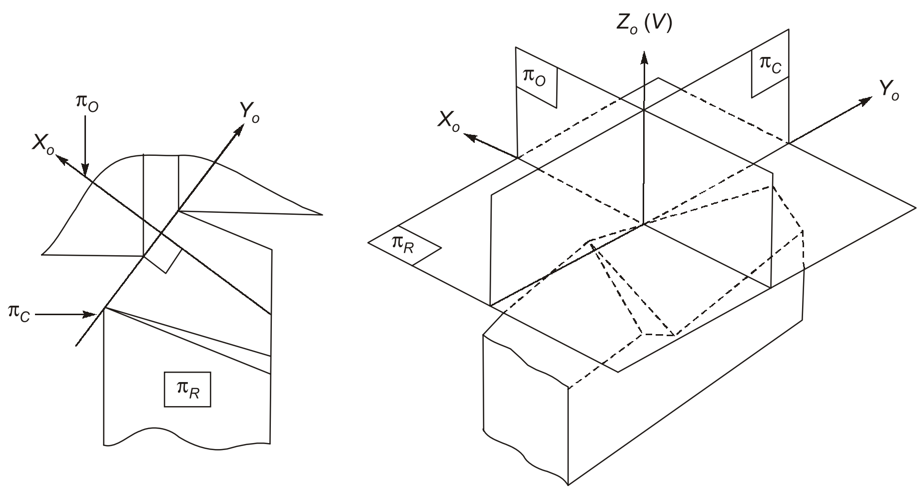

Fig. *Planes and axes used for visualizing tool geometry in the orhtogonal rake system* (ORS)

$i \rightarrow \alpha \rightarrow \gamma_s \rightarrow \gamma_e \rightarrow C_e \rightarrow \lambda \rightarrow R$

This system is also known as ISO – old system. The planes of reference and the co-ordinate axes used for expressing the tool angles in ORS are $\pi_R - \pi_C - \pi_O$ and $X_o - Y_o - Z_o$, respectively, which are taken in respect of the tool configuration as indicated in figure.

π_R is the reference plane, perpendicular to the velocity vector $\vec{V}_c$, π_C is the cutting plane perpendicular to π_R and taken along the principal cutting edge, and π_O is the orthogonal plane perpendicular to both π_R and π_C. Also, X_o is taken along the line of intersection of π_R and π_O, Y_o is taken along the line of intersection of π_R and π_C, and Z_o is taken along the velocity vector, that is, it is normal to both X_o and Y_o axes.

1.4.3 Surface Roughness (Turning)

- Ideal surface (Zero nose radius)
- Peak to valley roughness, $h = \dfrac{f}{\tan(SCEA) + \cot(ECEA)}$

Centre average value, $R_a = \frac{h}{4} = \frac{f}{4[\tan SCEA + \cot ECEA]}$

- Practical surface (with nose radius = R)

Peak to valley, $h = \frac{f^2}{8R}$ where, f - feed; R - Nose radius

1.5 Metal Cutting Process

There are two type of metal cutting process :

1.5.1 Orthogonal Cutting Process

- It is also known as two dimensional cutting process.
- The cutting edge is wider than the work piece width and extends beyond the work piece on either side. Also the width of the work piece is much greater than depth of cut.
- The chip generated flows on the rake face of tool with chip velocity will be perpendicular to the cutting edge.

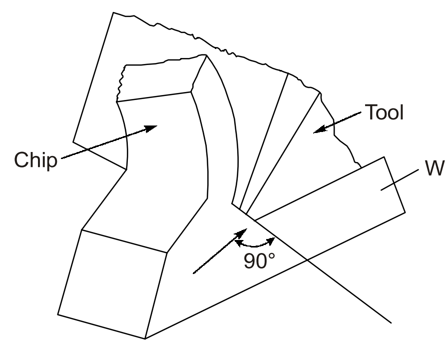

Fig. *Orthogonal Cutting Process*

1.5.2 Oblique Cutting Process

- It is also known as three dimensional cutting.
- This form of cutting occurs when the major cutting edge of the tool is presented to the work piece at angle acute to the direction of feed motion.

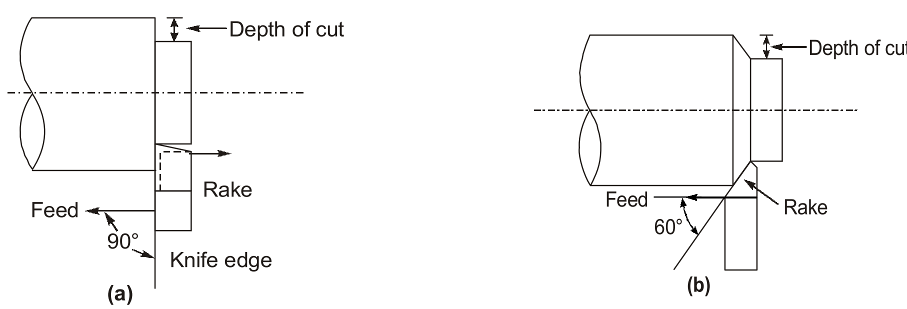

Fig. **(a)** *Orthogonal Turning Process* **(b)** *Oblique Cutting Process*

The majority of cutting operations involve tool shapes that are three dimensional (oblique). The basic difference between two dimensional and oblique cutting is shown in Figure. As we have seen in orthogonal turning the tool edge is perpendicular to the movement of the tool and the chip slides directly up the face of the tool.

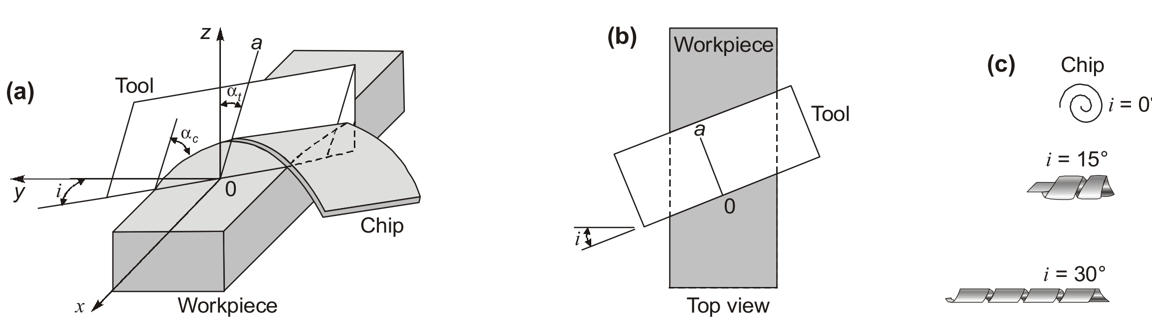

Fig. **(a)** *Schematic illustration of cutting with an oblique tool*
(b) *Top view showing the inclination angle* **(c)** *Types of chips produced with different inclination*

In oblique cutting, the cutting edge is at an angle, i called the inclination angle. The lateral direction of chip movement in oblique cutting. This situation is similar to an angled snowplow blade which throw the snow side ways.

The workpiece material approaches the tool at a velocity V and leaves the surface (as a chip) with velocity V_C and shear velocity is V_s.

Table: *Difference between Orthogonal and Oblique Cutting*

Orthogonal Cutting	Oblique Cutting
1. Chip flow in a direction perpendicular to the cutting edge.	1. Chip flow at an angle to cutting edge.
2. Chip get coiled in a spiral fashion.	2. Chip flow in any direction is in wide area thus less concentration of heat.
3. Tool life is less.	3. Tool life is more.
4. There are two component of forces (no radial force).	4. There are three component of force.
5. Surface finish is poor.	5. Surface finish is good.
6. It is used in slotting, parting, grooving, pipe cutting.	6. It is used in turning, milling, drilling, grinding.
7. Chip flow angle is zero.	7. Chip flow angle is more than zero.

1.6 Mechanism of Chip Formation

1.6.1 For Ductile Materials

The basic two mechanisms that accomplish chip formation are:

1. Yielding (Generally for ductile materials)
2. Brittle fracturing (For brittle material)

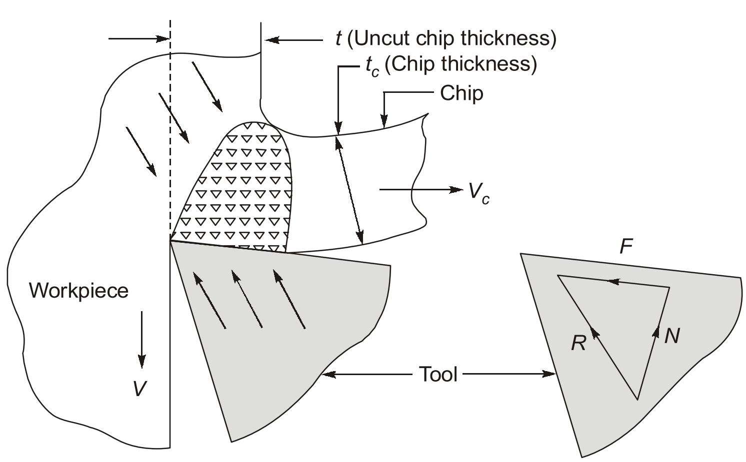

Fig. *Compression of work material (layer) ahead of the tool tip*

However, most of the engineering materials behave ductile in machining. During machining, the uncut layer of the work material just ahead of the cutting tool (edge) is subjected to almost all sided compression as indicated in figure. The force exerted by the tool on the chip arises in the form of normal force N and frictional force F.

Due to such compression, shear stress develops and grows within that compressed region, in different magnitude, in different directions. Whenever and wherever the value of the shear stress reaches or exceeds the shear strength of that work material in the deformation region, yielding or slip begins resulting in shear deformation in that region and initiating of separation in the form of a small crack along the plane of maximum shear stress in the case of brittle materials, the crack immediately propagates causing chip separation along irregular plane. However, 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.

1.6.2 For Brittle Materials

Turing 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. In the case of ductile materials, immediately yielding takes place at the crack tip which reduces the effect of stress concentration and prevents its propagation as crack.

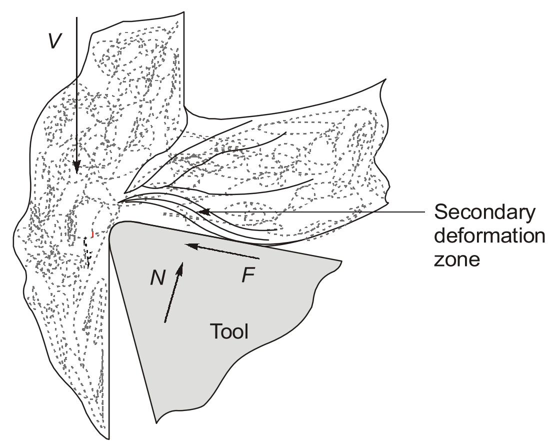

Fig. *Typical micro-view of a frozen turning chip*

However, in the case of brittle materials the initiated crack quickly propagates, under stressing action, and total separation of the chip takes place from the parent workpiece through the minimum resistance path as indicated in fig (a). Machining of brittle material produces discontinuous chips and mostly of irregular size and shape. The process of forming such chips is schematically shown in fig (b). Due to continuous motion of 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 as shown in fig (b).

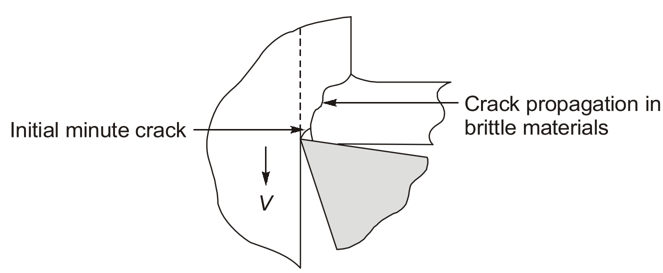

Fig. (a) *Development and propagation of crack causing chip separation*

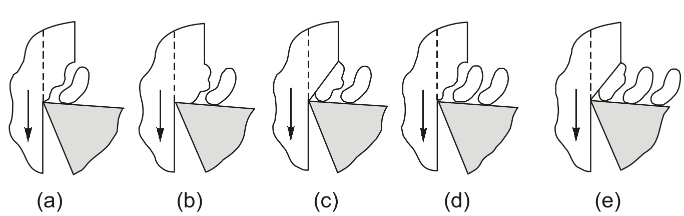

Fig. (c) *Schematic view of chip formation in machining brittle materials*
(a) Separation, (b) swelling, (c) further swelling, (d) separation again, (e) swelling again

3. **Spindle:** This rod-like component is rotated and axially moved along with the coaxially mounted drill to impart both cutting motion and feed motion to the tool.

Drilling machines of different sizes and configurations are used

1. Mainly for creating or enlarging straight cylindrical holes.
2. Occasionally for boring, counter boring, counter sinking, etc. .
3. Often for cutting internal threads in objects like nuts using suitable attachments.

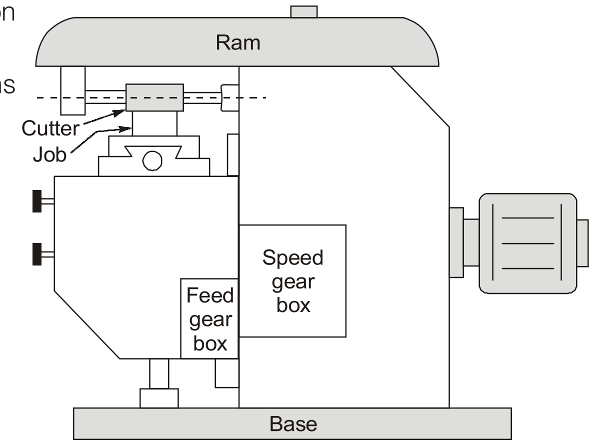

Fig. *Milling machine*

Milling Machine

The general configuration of typical knee type conventional milling machine with horizontal arbour is shown in figure. Its major parts are as follows:

1. Milling arbour to hold and rotate the cutter.

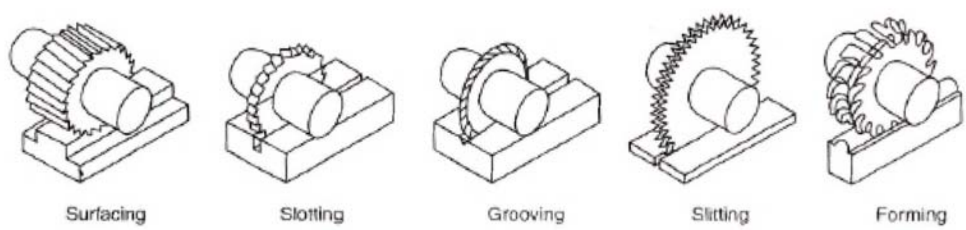

Fig. *Some common milling machine operations*

2. Ram to support the arbour.
3. Machine table on which job and job holding devices are mounted to provide the feed motions to the job.
4. Power drive with speed and feed gear boxes to provide power and motions to the tool-work.
5. Bed which moves vertically upward and downward and accommodates the various drive mechanisms.
6. Column with base which is the main structural body to support other parts.

Milling machines are also quite versatile and can do several operations such as:

1. Making fiat surfaces in different planes.
2. Grooving, slitting and parting.

Example 1.1 In a machining operation that approximates orthogonal cutting, the cutting tool has rake angle = 10°. The chip thickness before the cut t = 0.50 mm and the chip thickness after the cut t_c = 1.125 m. Calculate the shear plane angle and the shear strain in the operation.

Solution:

$$\text{The chip thickness ratio, } r = \frac{t}{t_c} = \frac{0.50}{1.125} = 0.44$$

$$\text{The shear plane angle, } \tan\phi = \frac{r\cos\alpha}{1-\sin\alpha} = \frac{0.444\cos 10°}{1-0.444\sin 10°} = 0.4738$$

or $\phi = \tan^{-1}(0.4738) = 25.35°$

The shear strain, $\gamma = \tan(\phi - \alpha) + \cot\phi = \tan(25.35° - 10) + \cot 25.35°$

$= 0.275 + 2.111 = 2.386$

Example 1.2 The cutting force and thrust force are measured during an orthogonal cutting operation: $F_c = 1559$ N and $F_t = 1271$ N. The width of the orthogonal cutting operation $b = 3.0$ mm. Based on data in example 1.1, determine the shear strength of the work material.

Solution:

Rake angle, $\alpha = 10°$, Shear plane angle, $\phi = 25.4°$. Shear force, $F_s = F_c \cos\phi - F_T \sin\phi$

$$F_s = 1559 \cos 25.35° - 1271 \sin 25.35° = 863 \text{ N}$$

$$\text{The shear plane area, } A_s = \frac{bt}{\sin\phi} = \frac{(0.5)(3.0)}{\sin 25.4} = 3.497 \text{ mm}^2$$

Thus the shear stress, which equals the shear strength of the work materials is:

$$\tau = \frac{F_s}{A_s} = \frac{863}{3.497} = 247 \text{ N/mm}^2 = 247 \text{ MPa}$$

Example 1.3 An orthogonal cutting operation is performed using a rake angle of 15°, chip thickness before the cut = 0.03 mm and width of cut = 2.54 mm. The chip thickness ratio is measured after the cut to be 0.55. Determine (a) the chip thickness after the cut, (b) shear angle, (c) friction angel, (d) coefficient of friction and (e) shear strain.

Solution:

Given: Rake angle, $\alpha = 15°$, Uncut chip thickness, $t = 0.30$ mm, Width of cut, $b = 2.54$ mm,

Chip thickness ratio = 0.55

As we know

(a) Chip thickness ratio, $r = \dfrac{t}{t_c} = 0.55$

$$\text{Chip thickness, } t_c = \frac{t}{r} = \frac{0.30}{0.55} = 0.545 \text{ mm}$$

(b) Shear angle (ϕ) $\tan\phi = \dfrac{r\cos\alpha}{1 - r\sin\alpha} = \dfrac{0.55\cos 15°}{1 - 0.55\sin 15°} = 0.61943$

$\phi = 31.775°$

(c) Friction angle (β)

as we know

$$2\phi + \beta - \alpha = 90°$$

$$2 \times 31.775° + \beta - 15° = 90°$$

$$\beta = 41.45°$$

(d) Coefficient of friction, $\mu = \tan\beta = \tan(41.45°) = 0.88$

(e) Shear strain (γ) as we know, $\gamma = \cot\phi + \tan(\phi - \alpha) = \cot(31.5°) + \tan(31.5° - 15°)$

$= 1.92$

Example 1.4 In a turning operation, spindle speed is set to provide a cutting speed of 1.8 m/s. The feed and depth of cut of cut are 0.30 mm and 12.6 mm, respectively. The tool rake angle is 8°. After the cut, the deformed chip thickness is measured to be 0.49 mm. Determine (a) shear plane