# METAL CUTTING & TOOL DESIGN

**Course Objective**

The following are the course objective of the MCTD course: -

1. To learn the mechanics of forces in orthogonal cutting and merchant circle.
2. To compare the behaviour of machining of different materials through Ernst & Merchant theory and explain the effect of heat generation on mechanical properties of tool and work material during metal cutting.
3. To analyze the maintainability, tool wear, and infer the mechanism of grinding.
4. To illustrate the principles of designing of single-point cutting tool, multi-point cutting tool, jig and fixtures.

# Unit- 1

## Lecture-1 Introduction to MCTD

### L 1.1 Metal Cutting

**Metal Cutting and Tool Design (MCTD) subject is the combination of two subjects, first is *Metal Cutting* and second is *Tool Design*.**

First, we start with Metal cutting.

- **Metal cutting is a material removal process in which a sharp cutting tool is used to mechanically cut away material so that the desired part geometry remains.**
- Most common application: to shape metal parts.
- Machining is the most versatile and accurate of all manufacturing processes in its capability to produce a diversity of part geometries and geometric features'
- **Machining Processes – Turning, Boring, Milling, Drilling, Shaping, Planing, Broaching, etc.**
- *Casting can also produce a variety of shapes, but it lacks the precision and accuracy of machining*

### L 1.1 Quiz

Which of the following manufacturing process is the part of the metal cutting?

1. Casting Process
2. Forging Process
3. Turning Process
4. Drawing Process

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### L 1.2 BASIC ELEMENTS OF MACHINING

The basic elements of all machining operations are the following:

- **Workpiece**
- **Tool**
- **Chip**

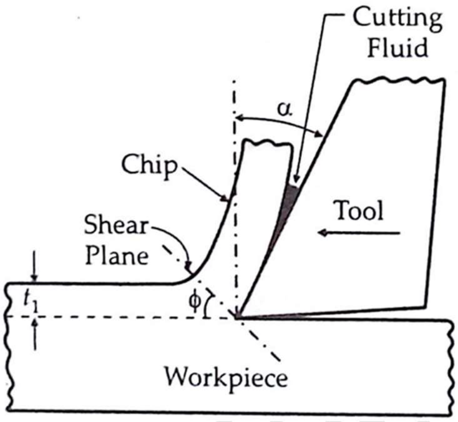

Fig.1.1 Basic element of machining

Fig. 1.1 shows the basic element of machining, which represent the cutting action of a tool in 2D or Orthogonal cutting. For providing the cutting action, relative motion between the tool and the workpiece is necessary. This relative motion can be provided by either keeping the workpiece stationary and moving the tool or vice-versa. The workpiece provided the parent metal, from which the unwanted metal is removed by the cutting action of the tool to obtain the predetermined shape and size of the component.

### L 1.2 Quiz

Is the Chip, Tool and workpiece are basic elements of all type of machining process?

- Yes
- No

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## Lecture-2 Definition of feed, depth of cut and cutting speed

### L 2.1 Cutting Speed

Cutting speed of a cutting tool can be defined as the rate at which its cutting edge passes over the surface of the work piece in unit time. it is normally expressed in terms of surface speed in metre per minute.

It is very important aspect in machining since it considerably affects the tool life and efficiency of machining. selection of a proper cutting speed is very important.

- if it is too high, the tool gets overheated and its cutting edge may fail.
- if it too low, too much time is consumed in machining and full cutting capacity of the tool and machine are not utilise, which result in lowering of productivity and increasing the production cost.

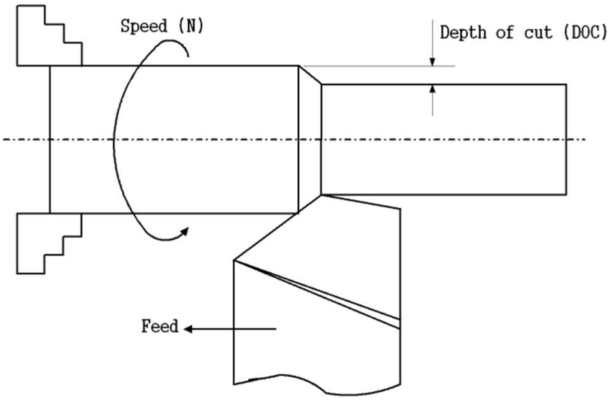

Fig. 2.1 Showing Speed, feed and DOC

Cutting speed (V) = π DN/1000 m/min

Where, D = diameter of the workpiece (mm)

N = rpm of the work

**Cutting speed depends upon the following factors:**

- Tool material.
- Work material.
- Depth of cut.
- Tool geometry.
- Type of machine tool.
- Surface quality required.

**L 2.1 Quiz**

Q. If it is too high, the tool gets overheated and its cutting edge may fail.

- True
- False

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### L 2.2 Feed

Feed off the cutting tool can be defined as the distance it travels along or into the work piece for each pass of its point through a particular position in unit time (x m/rec or mm/rev). The cutting speed and feed of the cutting tool is largely influenced by the following factors:

- material being machined
- material of the cutting tool
- geometry of the cutting tool
- Required degree of surface finish
- rigidity of the machine tool being used
- type of coolant being used

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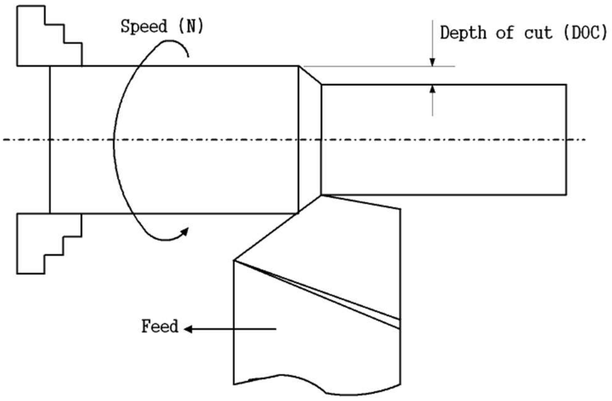

Fig. 2.1 Showing Speed, feed and DOC

### L 2.2 Quiz

what is feed?

- It is relative motion of the tool in one revolution of the work piece.
- it is the speed of work piece
- It is the speed of cutting tool
- it is the depth of cut

### L 2.3 Depth of Cut (DOC)

It is indicative of the penetration of the cutting edge of the tool into the work piece material in each pass, measured perpendicular to the machine surface, i.e., it determines the thickness of metal layer removed by the cutting tool in one pass.

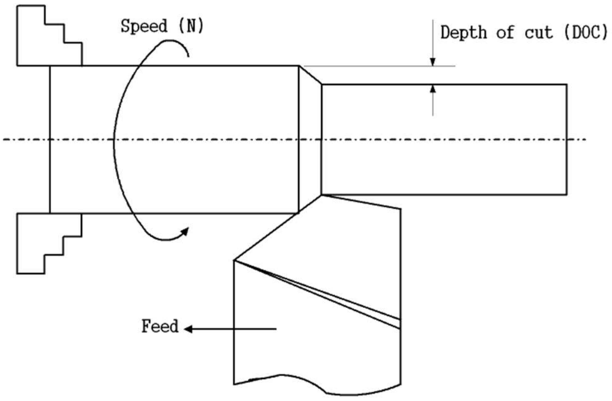

Fig. 2.1 Showing Speed, feed and DOC

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e.g. Turning operation on lathe

depth of cut = D-d / 2

D = original diameter of the stock in mm

d = diameter obtained after turning in mm

### L 2.3 Quiz

An aluminium stock has length = 200mm, diameter = 20mm. Turning on lathe to reduce diameter of stock to 19.5 mm. Calculate DOC.

- 0.2 mm
- 0.25 mm
- 0.15 mm

- 0.3 mm

## L 3.1 specific cutting energy

**Specific energy** is the amount of **energy** required to remove a unit volume of the work material.

The rate of energy consumption during machining ($P_m$) is the product of the cutting speed ($V_C$) and the cutting force ($F_C$). Thus,

$$P_m = F_C . V_C$$

Both the rate of energy consumption and the metal removal rate are proportional to the cutting speed. A parameter giving an indication of the efficiency of the process, independent of the cutting speed, is there for the energy consumed per unit volume of metal removed, referred to as be specific cutting energy ($P_S$). This parameter is given by

$$P_5 = \frac{P_m}{MRR} = \frac{F_c}{A_0}$$

$A_O$ = cross-section area of the uncut chip

The specific cutting energy can vary considerably for a given material and is affected by changes in cutting speed, feed, tool rake, and so on. However, for a given tool rake at high cutting speeds and large feeds the specific cutting energy tends to become constant, as can be seen in figure 3.1. This constant value can be a useful guide, in practice, to the forces required to cut a given material at large speeds and feeds.

## L 3.1 Quiz

What is specific cutting energy?

- it is the amount of energy required to remove the unit volume of the work material.
- it is the metal removing rate.
- it is the rate of energy consumption during machining

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**L 4.1 Machining Time**

In this section we study how to calculate Machining Time in different machining operation like Turning, Drilling, Shaping and milling operation.

Let us start with Turning operation on lathe machine.

Turning, on a lathe, is the removal of excess material form the workpiece by means of a pointed tool, to produce a cylindrical or cone shaped surface. From cutting speed, r.p.m. of job are calculated by using the formula.

$$N = \frac{1000\,V}{\pi D}$$

where

N = r.p.m. of job

V = cutting speed in meters/minute

D = Diameter of the stock to be turned (in mm)

if f = Feed per revolution (in mm)

L = Length of stock to be turned (in mm)

T = Time required for turning (in minutes)

$$\text{Then } T = \frac{L}{f \times N}$$

Length of cut: It is the distance travelled by the tool to machine the workpiece and is calculated as follows:

Length of cut (L) = Approach length + Length of work piece to be machined +Over travel

Approach is the distance a tool travels, from the time it touches the work piece until it is cutting to full depth. Over travel is the distance the tool is fed while it is not cutting. It is the distance over which the tool idles before it enters and after it leaves the cut. These terms are explained in the Fig. for a cutting operation on lathe.

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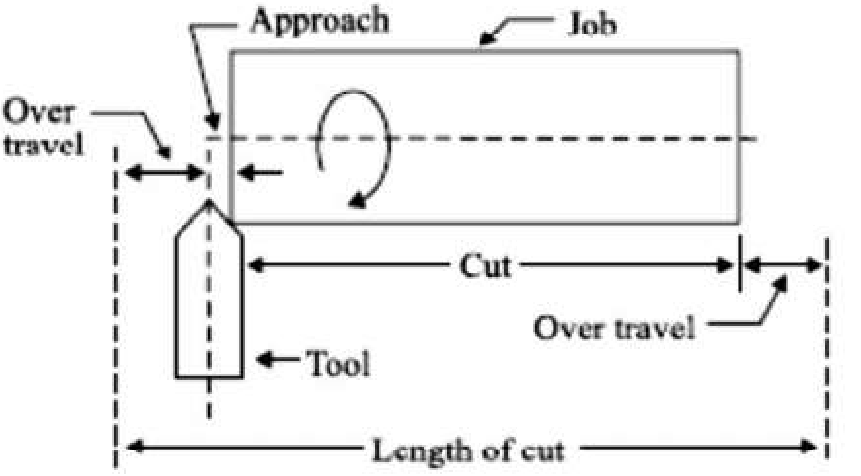
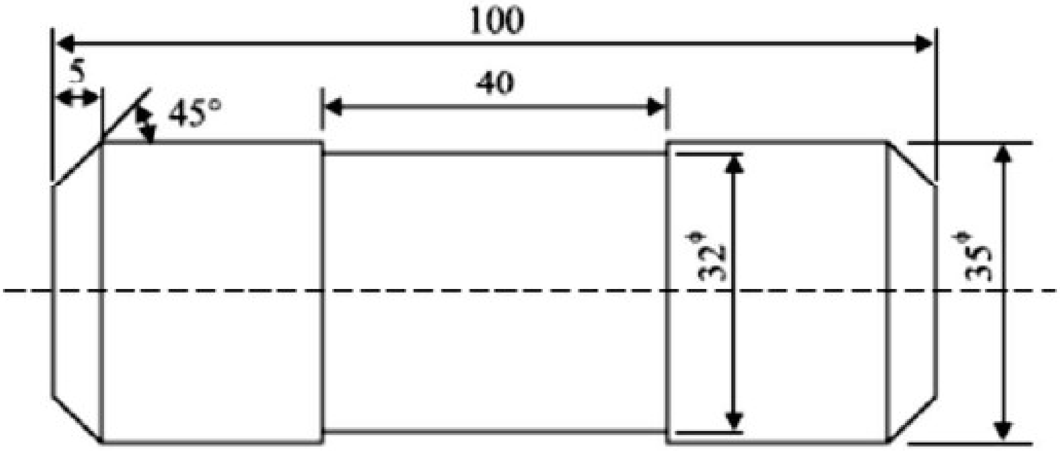


Total tool travel = length of job + approach + over travel

**Q. 1.** A mild steel bar 100 mm long and 38 mm in diameter is turned to 35 mm dia. And was again turned to a diameter of 32 mm over a length of 40 mm as shown in the Fig. The bar was machined at both the ends to give a chamfer of 45° × 5 mm after facing. Calculate the machining time. Assume cutting speed of 60 m/min and feed 0.4 mm/rev. The depth of cut is not to exceed 3 mm in any operation.



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**Solution** : *Ist operation* : Turning from f 38 mm to f 35 mm

$$v = 60 \text{ meters/min.}$$

$$D = 38 \text{ mm}$$

$$N = \frac{1,000\,v}{\pi D} = \frac{1,000 \times 60}{\pi \times 38}$$

$$= 503 \text{ r.p.m.}$$

$$\text{Time taken} = \frac{\text{Length of cut}}{\text{r.p.m.} \times \text{Feed/rev.}}$$

$$= \frac{100}{503 \times 0.4} = 0.5 \text{ mm}$$

*2nd operation* : External relief

$$L = 40 \text{ mm.}$$

$$D = 35 \text{ mm.}$$

$$V = 60 \text{ m/min.}$$

$$N = \frac{60 \times 1,000}{\pi \times 35} = 545 \text{ r.p.m.}$$

$$\text{Time taken for second operation} = \frac{\text{Length}}{\text{r.p.m.} \times \text{Feed/rev}}$$

$$= \frac{40}{545 \times 0.4} = 0.18 \text{ min.}$$

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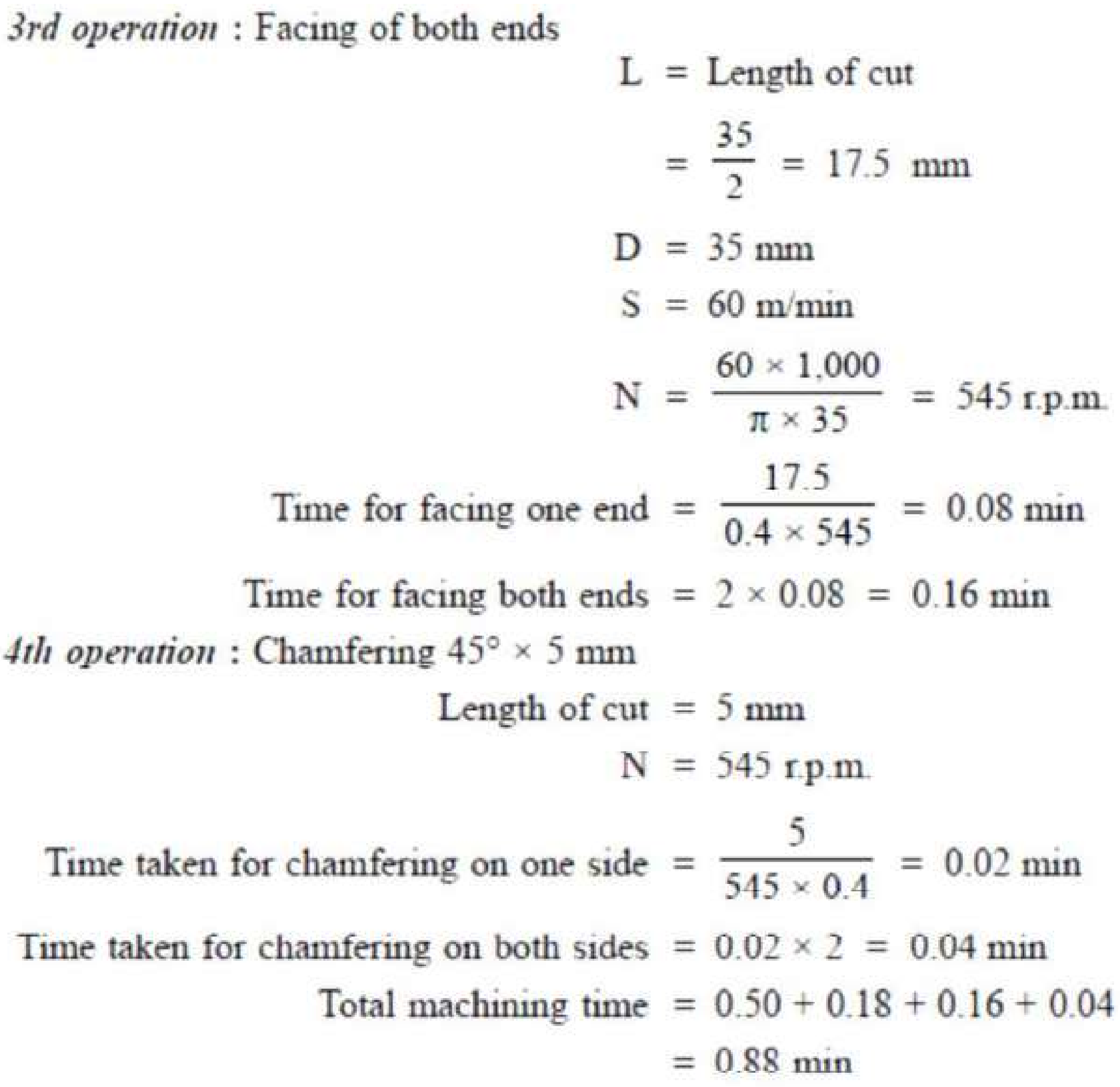

*3rd operation* : Facing of both ends

$$L = \text{Length of cut}$$

$$= \frac{35}{2} = 17.5 \text{ mm}$$

$$D = 35 \text{ mm}$$

$$S = 60 \text{ m/min}$$

$$N = \frac{60 \times 1{,}000}{\pi \times 35} = 545 \text{ r.p.m.}$$

$$\text{Time for facing one end} = \frac{17.5}{0.4 \times 545} = 0.08 \text{ min}$$

$$\text{Time for facing both ends} = 2 \times 0.08 = 0.16 \text{ min}$$

*4th operation* : Chamfering 45° × 5 mm

$$\text{Length of cut} = 5 \text{ mm}$$

$$N = 545 \text{ r.p.m.}$$

$$\text{Time taken for chamfering on one side} = \frac{5}{545 \times 0.4} = 0.02 \text{ min}$$

$$\text{Time taken for chamfering on both sides} = 0.02 \times 2 = 0.04 \text{ min}$$

$$\text{Total machining time} = 0.50 + 0.18 + 0.16 + 0.04$$

$$= 0.88 \text{ min}$$

**L 4.1 Quiz**

Q. A hollow workpiece of 60 mm outside die. and 150 mm length is held on a mandrel between centers and turned all over 4 passes. If the approach length 20mm, overtravel 12mm, average feed 0.8mm/rev, cutting speed 30m/min. Calculate the machining time.

- 5.72 min.
- 4.72 min.
- 6.72 min.
- 5.00 min.

**L 4.1 Remedial Class**

Sol.

Given data,

D = 60mm

V = 30m/min

L = 150mm

N = 4

Approach length = 20mm

Overtravel = 12mm

Feed = 0.8mm/rev

T = ?

So,

$$N = \frac{1000\,V}{\pi D}$$

**N = 159 rpm,**

Then,

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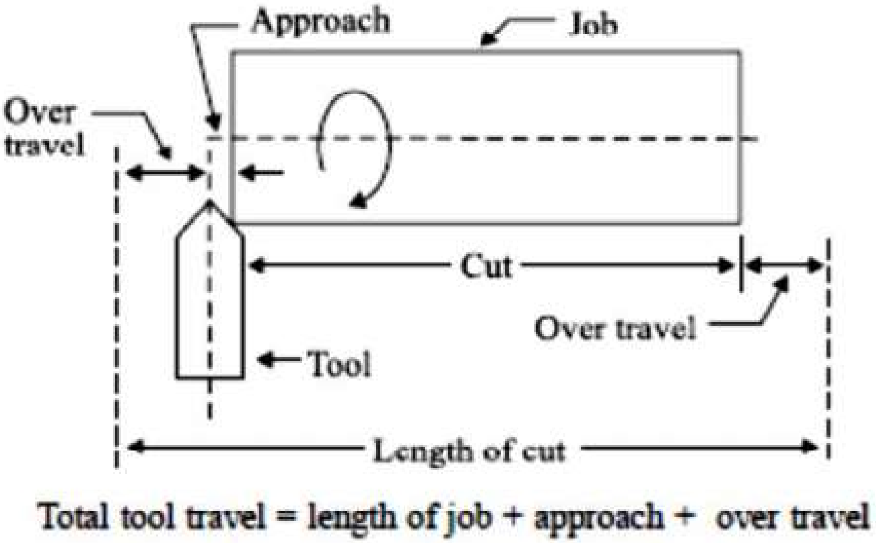

L = 150 + 20 + 12

**L = 182 mm**

Then,

$$\text{Then } T = \frac{L}{f \times N}$$

T = 1.43 min

No. Of passes = 4

**Total Machining Time = 1.43 x 4 = 5.72 min**

### L 4.2 Machining Time in Drilling

In Drilling operation, the Machining time is given by,

$$T = \frac{L}{N \times f} \text{ min}$$

Where, N = rpm of drill

L = Length of axial travel of drill in mm

F = feed mm/rev

T= Machining Time

Now, L = *l* + a ( see fig. 4.2)

*Where, L* = Depth or thickness of workpiece

A = approach of drill

A = 0.3d

D = Dia. Of drill

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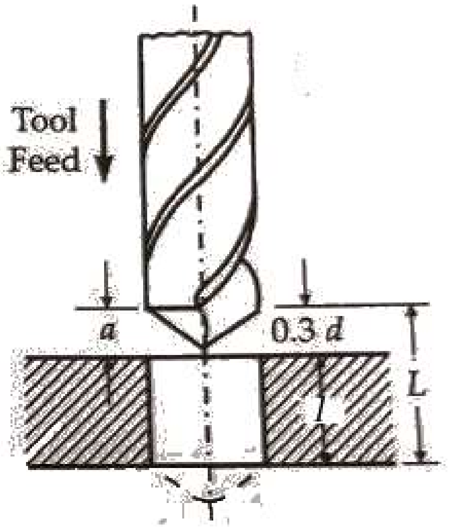

Fig. 4.2

Q. Calculate the machining time for drilling 4 holes of 16 mm dia. Each on a flange from the following data:

Flange thickness = 30 mm

Cutting speed = 22 m/min

Feed = 0.2 mm/rev

Sol. Given Data,

L = 30 mm

V = 22 m/min

F = 0.2 mm/rev

D = 16 mm

No. Of holes = 4

T = ?

So,

$$N = \frac{1000V}{\pi D}$$

**N = 438 rpm**

Then,

L = l + a

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$= 30 + (0.3 \times 16)$

**L = 34.8 mm**

So,

$$T = \frac{L}{N \times f} \text{ min}$$

**T = 0.39 min**

## L 4.2 Quiz

Find the time required to drill 4 holes in a cast iron flange each of 2 cm depth, if the hole diameter is 2 cm. Assume cutting speed as 21.9 m/min. and feed as 0.02mm/rev.

- 1.846 min
- 2.568 min
- 0.846 min
- 1.2 min

L 4.2 Remedial Class

Solution.

Depth of hole = 2 cm = 20 mm

Diameter of hole = 2 cm = 20 mm

Cutting speed = 21.9 m/min

Feed = 0.02 cm/rev,

Depth hole = l + 0.3 d = 2 + 0.3 (2) = 2.6

Number of holes = 4

(i) N = $(1000\ V) / \pi\ D$

= (1000 x 21.9) / 3.14 x 20

= **350 rpm**

(ii) T = Depth of hole / (Feed x rpm)

= 2.6 / (0.02 x 350)

= **0.3714 min**

(ii) Time for drilling four holes = 0.3714 × 4 = **1.486 min.**

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### L 4.3 Machining Time in Shaping (Shaper)

Refer to Fig. 4.3 for understanding the tool positions and other related terms.

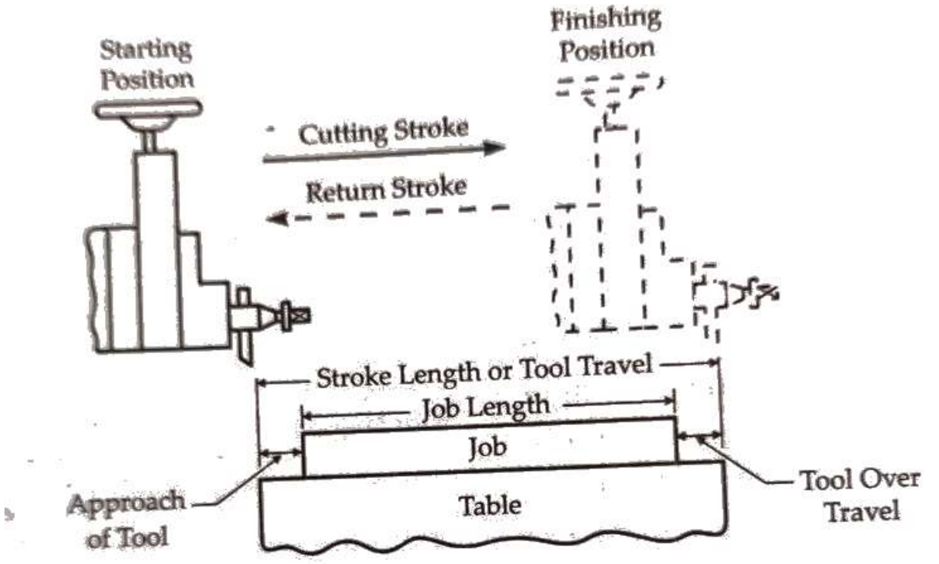

Fig. 4.3

Let

L = Length of stroke or Tool travel, in meters.

l= Length or breadth of job, over which the tool passes, in meters

$l_1$= Tool approach i.e., the distance it has to travel before starting actual cutting in meters.

$l_2$= Overtravel I.e., the distance through which the tool travels beyond the work-surface in meters

f = Feed per cycle, in mm.

m = Ratio of return time to cutting time.

$V_1$= Average cutting speed, in meters per min.

$V_2$= Average return speed, in meters per min.

n = No. of cycles required.

Now,

$$\textbf{Cutting speed } (v_1) = \frac{\text{Length of cutting stroke}}{\text{Time taken in cutting stroke}}$$

$$\textbf{Cutting time} = \frac{\text{Length of cutting stroke}}{\text{Cutting speed in m / min.}} = \frac{L}{v_1} \text{ min}$$

$$= \frac{l + l_1 + l_2}{v_1} \text{ min}$$

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and N**on-cutting time** or **Idle time**

$$= \frac{\text{Length of stroke in metres}}{\text{Return speed in metres / min.}} = \frac{L}{v_2}$$

$$= \frac{l + l_1 + l_2}{v_2}$$

Now, Total time per cycle

$$= \frac{L}{v_1} + \frac{L}{v_2} = \frac{L}{v_1} + K \times \frac{L}{v_1}$$

[where **K** = ratio of *Idle stroke time* to *Cutting stroke time*]

$$\textbf{Total time} = \frac{L}{v_1} + K\frac{L}{v_1} = \frac{L(1+K)}{v_1} \text{ minutes}$$

For shaping a workpiece an allowance of about 5 mm is left on either side of it. Thus, the

Shaping width of the workpiece is obtained as:

**Shaping width B =Width of workpiece + 2 x allowance**

$$\textbf{No. of Cycles required } (n) = \frac{\text{Shaping width}}{\text{Feed per cycle}} = \frac{B}{f}$$

**Machining time** = No. of cycles × time required for each cycle

$$= \frac{B}{f} \times \frac{L(1+K)}{v_1} \text{ min} = \frac{LB(1+K)}{f \times v_1} \text{ min}$$

**Q.** A CI. plate measuring 300 mm x 100 mm x 40 mm is to be rough shaped along its wider face. Calculate the Machining Time taking Approach = 25 mm, Overtravel = 5 mm, Cutting speed = 12 m/min, Return speed = 20 m/min, Allowance on either side of the plate width = 5 mm and feed per cycle = 1 mm.

**Solution.** Now

Length of Stroke (L) = 300 + 25+ 25 = 350 mm

$$\textbf{Cutting stroke time} \quad = \frac{L}{v_1} = \frac{350}{1000 \times 12} = \mathbf{0.029 \text{ min.}}$$

$$\text{Idle stroke time} \quad = \frac{L}{v_2} = \frac{350}{1000 \times 20} = \mathbf{0.0175 \text{ min.}}$$

Time per cycle = 0.029 + 0.0175 = **0.0465 min.**

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Shaping width B = I 00 + 5+ 5 =**110 mm.**

No. of cycles required $(n)$

$$= \frac{B}{f} = \frac{110}{1} = \mathbf{110\ cycles.}$$

Machining time = n x time per cycle

= 110 x 0.0465 = **5.12min.**

**L 4.3 Quiz**

A mild steel plate 400 mm x 800 mm x 30 mm is to be shaped along its wider face. The Ratio of Return time to Cutti11g time is 2: 3 and the Feed per cycle is 2 mm. Tool approach and Over-travel respectively are 50 mm each. Select a suitable Cutting speed and calculate the Machining Time required for machining the given plate with H.S.S. tools. (Use $V_1 = 24$)

- 12.8125 min = 13 min (say)
- 12.2586 min = 12 min (say)
- 13.35 min = 13 min (say)
- 11 min

**L 4.3 Remedial Class**

**Solution.** Length of stroke L = 8OO+ 50 + 50 = 900 mm= **0.9 m**

Cutting stroke time = L / $V_1$ = 0.9 / 24

= 0.0375 min.

Return time / Cutting time = 2 / 3 [Given]

$$\therefore \quad \text{Return time} = \frac{2}{3} \times \text{cutting time}$$

$$= \frac{2}{3} \times 0.0375 = \mathbf{0.025\ min.}$$

And Total time per cycle = 0.0375 + 0.025 = 0.0625 min.

Shaping width B = 400 + 2 x 5 = 410 mm

No. of cycles required = 410/2 = 205 Cycles

.-. Tota l m machining time = 205 x 0.0625 min

= 12.8125 min = 13 min (say)

**L 4.4 Machining Time in Milling**

The following factors are to be considered in Estimate the Machining time in any type of milling operation:

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1. Total length of job to be machined.
2. Approach i.e., the distance through which the cutter has to move before the full depth of cut is acquired.
3. Over run i.e., the distance through which the cutter has to move further, after the job length is over, to be clear of the job.
4. Number of cuts.
5. Cutting speed.
6. The amount of feed per minute.

Figures 4.4.a and 4.4.b show Milling Operations being performed by using the Plain and Face milling cutters respectively.

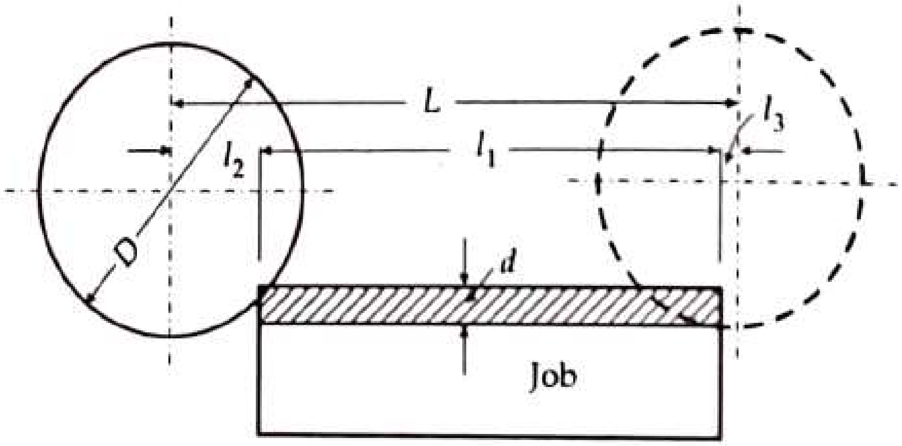

Fig. 4.4.a Plain Milling

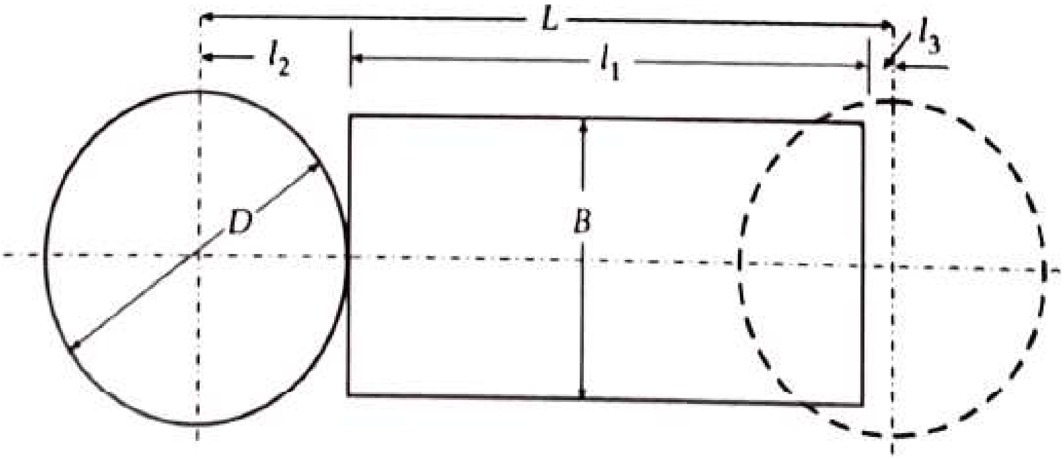

Fig. 4.4.b Face Milling

Let,

$l_1$ = Length of the job to be machined in mm.

$l_2$ = Approach in mm

$l_3$ = Overrun of the cutter in mm.

If L be the total distance of table or cutter travel, then:

$$L = l_1 + l_2 + l_3$$

Now, in Plain Milling, if D mm be the diameter of the cutter and d mm be the total depth of the cut, then the approach $l_2$ is given by:

$$l_2 = \sqrt{d(D-d)} \text{ mm}$$

In Face Milling, let b mm be the width of the Job D mm the diameter of the cutter, then the Approach in this case is given by:

$$l_2 = 0.5\,(D - \sqrt{D^2 - b^2}\,) \text{ mm}$$

The Overrun of the cutter, depending upon the size of the machined surface, can take from 1 to 6 mm

Now, if n be the number of cuts and f the feed in mm per minute, then the Machining Time T in minutes can be calculated from:

$$T = \frac{L \times n}{f} \text{ minutes}$$

For finding out the Total Floor Time, Handling time should be added to the actual Machining time calculated above.

### L 5.1 ORTHOGONAL AND OBLIQUE CUTTING

The process of Metal Cutting is divided into the following two main classes:

1. Orthogonal cutting, and
2. Oblique cutting.

A caparison between these two methods is clearly illustrated in Figs. 5.1 and 5.2. In Fig. 5.1 is shown as to how these two Cutting Methods differ while turning a job on a lathe.

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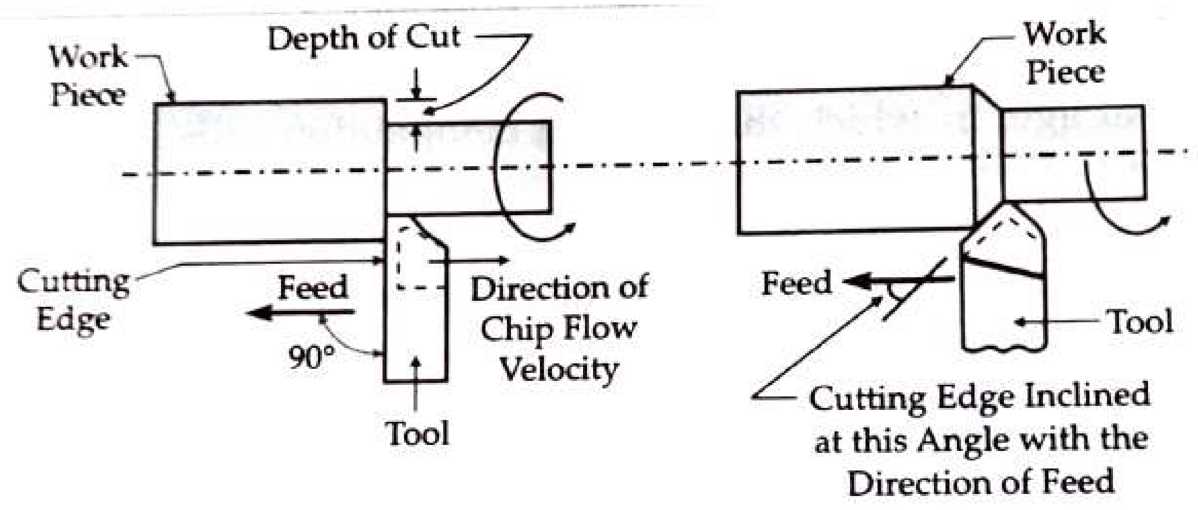
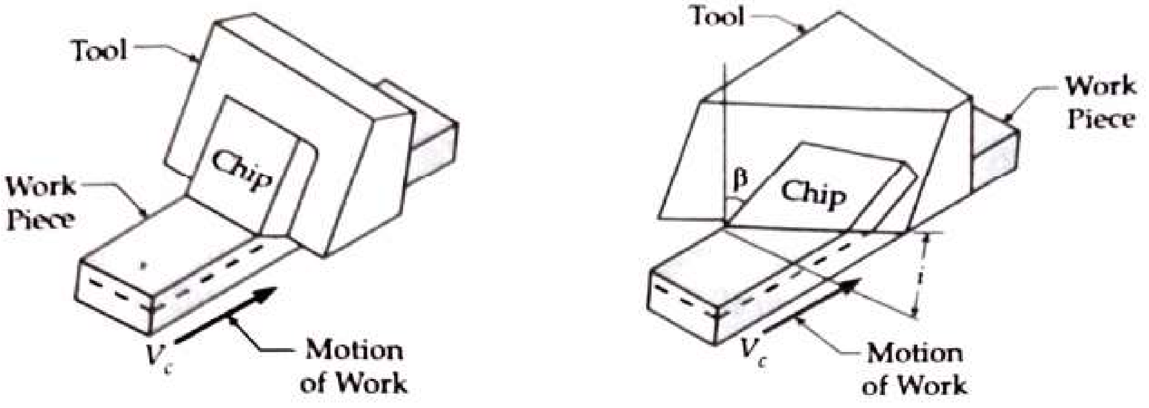


(a) Orthogonal

(b) Oblique

Fig. 5.1 Orthogonal and Oblique cutting processes in Turning.

Similarly, Fig. 5.2 shows the difference between these two methods as applied to the Planing work, in which the tool remans stationary and the work piece reciprocates past it.



(a) Orthogonal cutting

(b) Oblique cutting

Fig. 5.2 Orthogonal and Oblique cutting processes in Planing.

Basically, in Orthogonal cutting, the cutting edge of the tool remains at right angles to the direction of cutting velocity [Fig. 5.1 (a)] or work feed [Fig. 5.2 (a)]. This type of cutting is also known as Two-dimensional Cutting. In Oblique cutting, the cutting edge of the tool is inclined at an acute angle with the direction of tool feed or work feed, the chip being disposed of at a certain angle. This type of cutting is also called Three-dimensional Cutting. The main features of the two types of cutting are summarised below :

**Orthogonal Cutting**

1. The cutting edge of the tool remains normal to the direction of tool feed or work feed.

2. The direction of the chip flow velocity is normal to the cutting edge of the tool.
3. The angle of inclination 'i' of the cutting edge of the tool with the normal to the velocity Vc is 'Zero'.
4. The chip flow angle ' β', i.e., the angle between the direction of chip flow and the normal to the cutting edge of the tool, measured in the plane of the tool face, is 'Zero'.
5. The cutting edge is longer than the width of the cut.

The last condition may not be fulfilled in some cases. It is then called Semi-Orthogonal or Restricted Orthogonal cutting.

**Oblique Cutting**

1. The cutting edge of the tool always remains inclined at an acute angle to the direction of tool feed or work feed.
2. The direction of the chip flow velocity is at an angle ' β' with the normal to the cutting edge of the tool. The angle is known as Chip flow Angle.
3. The cutting edge of the tool is inclined at an angle 'i' with the normal to the direction of work feed tool feed i.e. velocity 'Vc'.
4. Three mutually perpendicular component of cutting forces act at the cutting edge of the tool
5. The cutting edge may or may not be longer than the width of the cut.

An interesting feature to note here will be that most of the metal cutting carried out in workshops is through Oblique Cutting method, but all our further discussions on metal catting will be in the context of Orthogonal Cutting because of its simplicity. However, it won't matter much since most of the general principles of Orthogonal Cutting are equally applicable to Oblique Cutting.

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**L 5.1 Quiz**

True / False

In orthogonal cutting, the cutting edge of the tool remains normal to the direction of tool feed or work feed.

- True
- False

L 6.1 **Classification of cutting Tools**

All the cutting tools used in metal cutting can be broadly classified as:

1. Single point Tools, i.e., those having only One cutting edge; such as Lathe toots, Shaper tools, Planer tools, Boring tools, etc.
2. Multi-point Tools, i.e., those having more than one cutting edges; such as, milling cutters, Drills, Broaches, Grinding wheels, etc. These tools may, for the sake of analysis, be considered as consisting of a number of Single point tools, each forming a cutting edge.

The Cutting tools can also be classified according to the motion as:

- Linear motion tools; Lathe, Boring, Broaching, Planing, Shaping tools, etc.
- Rotary motion tools; Milling cutters, Grinding wheels, etc.
- Linear and Rotary tools; Drills, Honing tools, Boring Heads, etc.

**L 6.2 Tool Geometry (Single Point Cutting Tool)**

Before proceeding further, it would be advisable to be acquainted with a few important terms related to the Geometry of Single point tools (See Fig. 6.1 and 6.2).

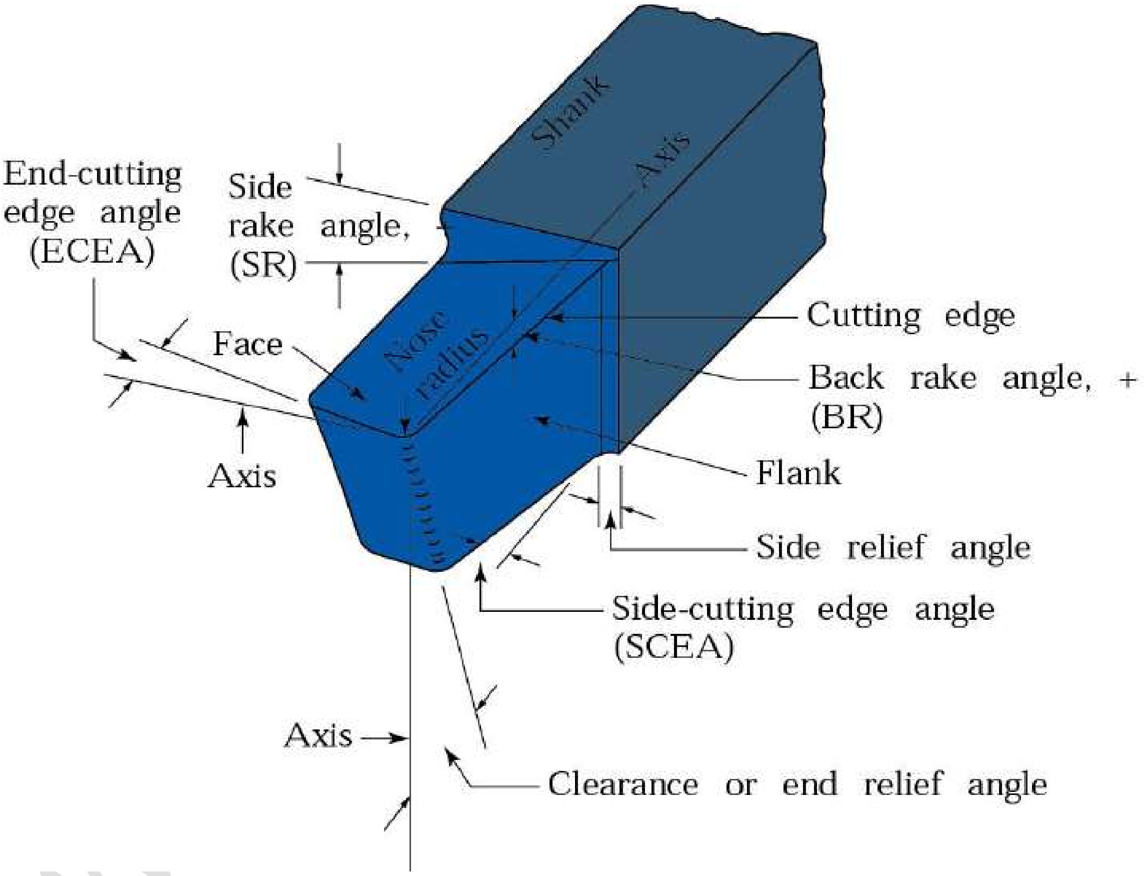

Fig. 6.1 Single Point cutting tool geometry body parts and angles

1. **Shank** It forms the main body of a solid tool and it is this part of the tool which is gripped in the Tool Holder.
2. **Face** It is the top surface of the tool between the shank and the point of the tool. In the cutting action, the chips flow along this surface only.
3. **Point I**t is the wedge-shaped portion where the face and flank of the tool meet. It is the cutting part of the tool. It is also called nose, particularly in case of Round nose tools.

4. **Flank** Portion of the tool which faces the work is termed as flank. It is the surface adjacent to and below the cutting edge when the tool lies in a horizontal position.
5. **Base.** It is actually the bearing surface of the tool on whi ch it is held in a Tool holder or clamped directly in a Tool post.
6. **Heel.** It is the curved portion at the bottom of the tool where the base and flank of the tool meet, as sh0wn in Fig. 6.2.
7. **Nose radius,** If the Cutting tip (nose) of a single point tool carries a sharp cutting point, the cutting tip is weak. It is, therefore, highly stressed during the operation, may fail or lose its cutting ability soon and produce marks on the machined surface. In order to prevent these harmful effects the nose is provided with a radius, called Nose radius. It enables greater strength of the Cutting tip, a prolonged Tool life and a superior Surface finish on, the workpiece. Also, as the value of this radius increases, a higher cutting speed can be used. But if it is too large it may lead to Chatter. So, a balance has to be maintained. Its value normally varies from 0.4 mm to 1.6 mm, depending upon several factors like depth of cut, amount of feed, type of cutting, type of tool (solid or with insert), etc.

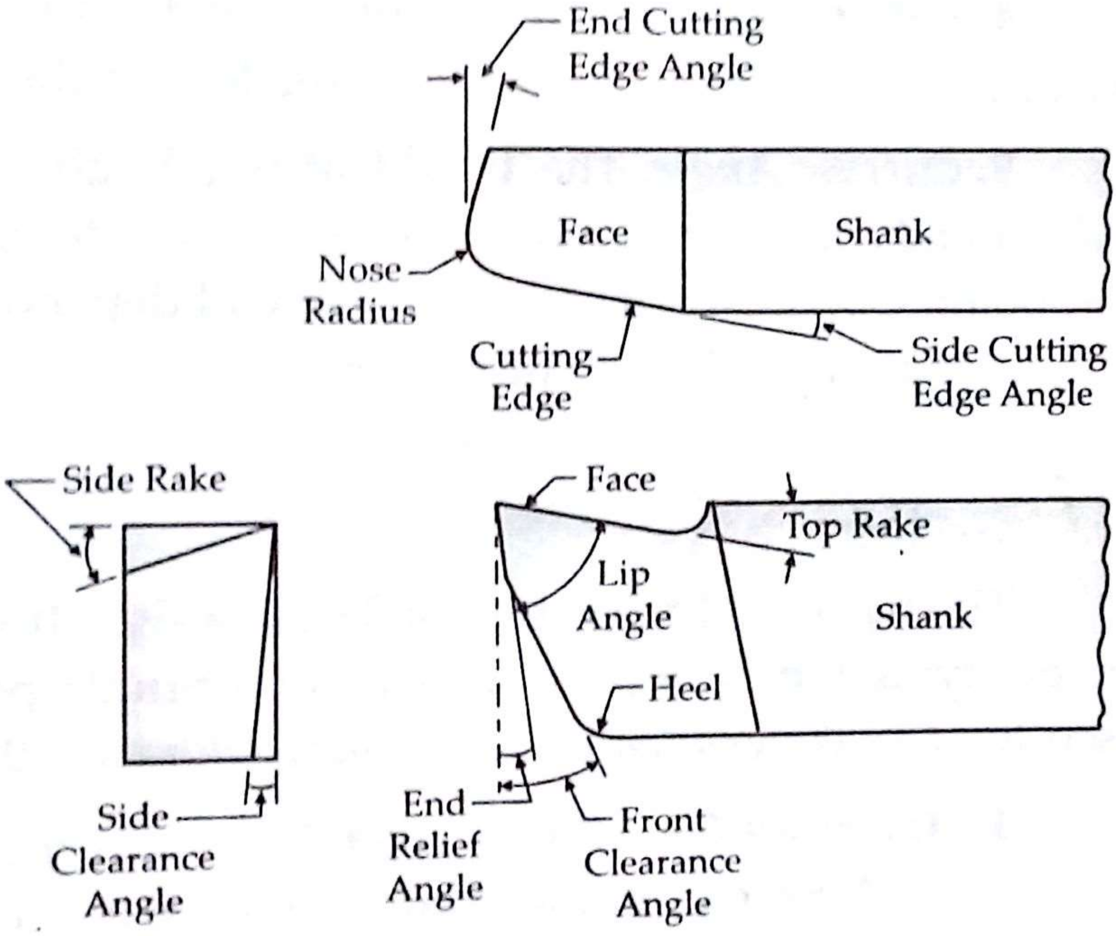

Fig. 6.2 Principal Angles of a Single point Cutting Tool

## PRINCIPAL ANGLES OF SINGLE POINT TOOLS

The different Angles provided on Single point Tools play a significant role in successful and efficient machining of different metals. A thorough study of these tool angles is, therefore, a must. The main angles provided on these tools are shown in Fig. 6.2 and the average values of these angles for cutting different metals are given later in Lathe Work.

1. **Rake angle.** It is the angle formed between the face of the tool and a plane parallel to its base. If this inclination is towards the shank, it is known as Back Rake or Top Rake. When it is measured towards the side of the tool, it is called the **Side rake**. These rake angles guide the chips away from the cutting edge, thereby reducing the chip pressure on the face and increasing the keenness of the tool so that less power is required for cutting. It is important to note that an increased rake angle will reduce the strength of the cutting edge. With the result, the tool use for cutting hard metals are given smaller rake angles whereas those used for softer metals contain larger rakes. **Negative Rake.** The rake angles described above are called positive rake angles. When no rake is provided on the tool, it is said to have a zero rake. When the face of the tool is so ground that it slopes upwards from the point it is said to contain a **negative rake.** it obviously reduces the keenness of the tool and increases strength of the cutting edge. Such a rake is usually employed on carbide tipped tool when they are used for machining extra hard surfaces, Harden steel parts and for taking intermittent cuts. it tool with negative rake will have a larger lip angle result in a stronger tool another advantage of negative rake particularly in case of tip tool is that the tendency of the cheap pressure is to press the tape against the body of the tool this is obviously a favorable factor for tip tools the value of negative rake on these tools normally varies from 5 to 10 degree
2. **Lip Angle.** The angle between the face and the flank of the tool is known as lip angle. it is also sometimes called the angle of keenness of the tool. strength of the cutting edge or point of the tool is directly affected by this angle. larger the lip angle stronger will be the cutting edge and vice versa. it would be absurd that, since the clearance angle remains practically constant in all the cases, this angle varies inversely as the rake angle. it is only for this reason that when harder metal is to be machined that is is stronger tool is required the rake angle is reduced and consequently the lip angle is increased. this simultaneously call for reduced cutting speed, which is a disadvantage. this lip angle is, therefore, kept as low as possible without making the cutting edge so weak that it becomes unsuitable for cutting.
3. **Clearance angle.** it is the angle formed by the front or side surface of the tool which are adjacent and below the cutting edge when the tool is held in a horizontal position it is the angle between one of the surfaces and a plain normal to the base of the tool. when the surface considered for this purpose in in front of the tool that is just below the point, the angle formed is called for Front clearance and when the surface below the side cutting edge is considered the angle formed is known as site clearance angle the purpose of providing front clearance is to allow the tool to cut freely without rubbing against the surface of the job and that of the side clearance to direct the cutting thrust to the metal area adjacent to the cutting edge.
4. **relief angle.** it is the angle formed between the flank of the tool and a perpendicular line drawn from the cutting point to the base of the tool.
5. **Cutting angle.** the total cutting angle of the tool is the angle formed between the tool phase and a line through the point which is a tangent to be machined surface of the work at that point.

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obviously, its correct value will depend upon the position of the tool in which it is held in relation to the axis of the job.

**L 6.1 Quiz**

Q. A cutting tool can never have its

(a) rake angle – positive

(b) rake angle – negative

(c) clearance angle – positive

(d) clearance angle – negative

## L 6.3 REFERENCE PLANES

The following two Systems of Reference planes are used to describe the geometry and locate the different parameters of a Single Point Cutting Tool :

1. The Coordinate System

In this system, it is assumed that the tool, although held in position in space with reference to the Workpiece, is not operating on the workpiece. This situation can be conceived as this tool being held in position by hand against a stationary workplace. It is for the reason that this system is also known as tool in hand system. This system consists of three principal reference planes as shown in figure 6.3. the horizontal plane which contains the base of the Shank of the cutting tool is known as base plane. This second reference plane is a vertical plane normal to the base plane and parallel to the direction of feed of the cutting tool. It is called the longitudinal plane. The third reference plane called the transverse plane is perpendicular to both the above reference planes and is parallel to the transverse motion of the tool that is the depth of cut. this combination of reference planes is known as coordinate system of reference planes.

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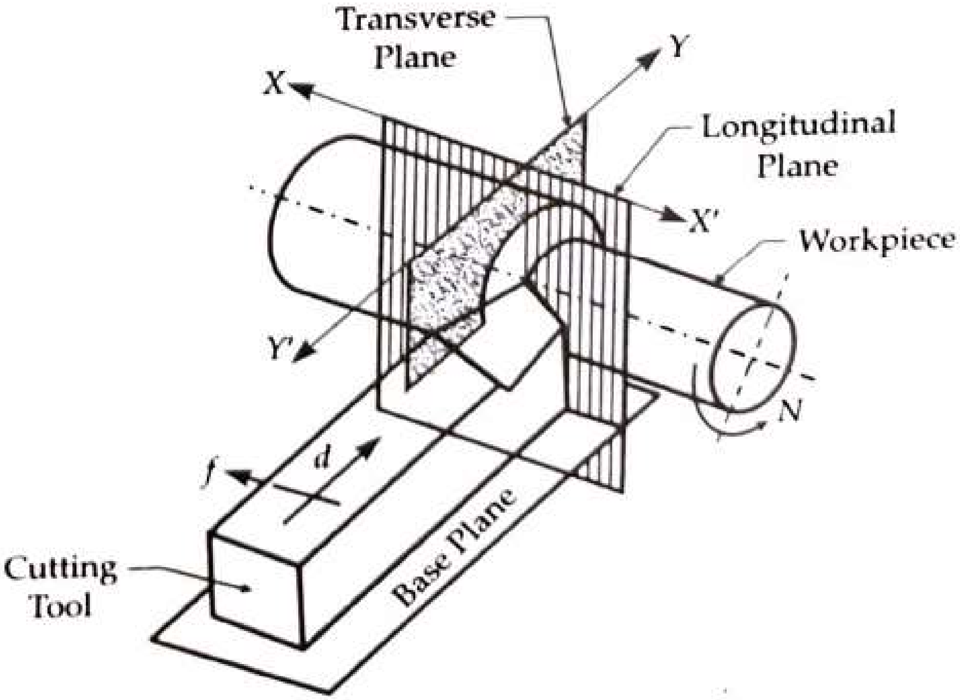

Fig. 6.3 tool and workpiece in coordinate system of reference planes

**2. The orthogonal system**

in this system of reference planes, it is assumed that the cutting tool is operating against the workpiece. As usual, there are three main reference planes. One of these, the horizontal plane, contain the base of the cutting tool and is known as the base plane. The second plane, which is perpendicular to the base plane, contain the principal cutting edge and is called the cutting plane. The third plane, which is perpendicular to both the above planes, is known as orthogonal plane. This set of reference planes is known as orthogonal system of reference planes and is shown in figure 6.4

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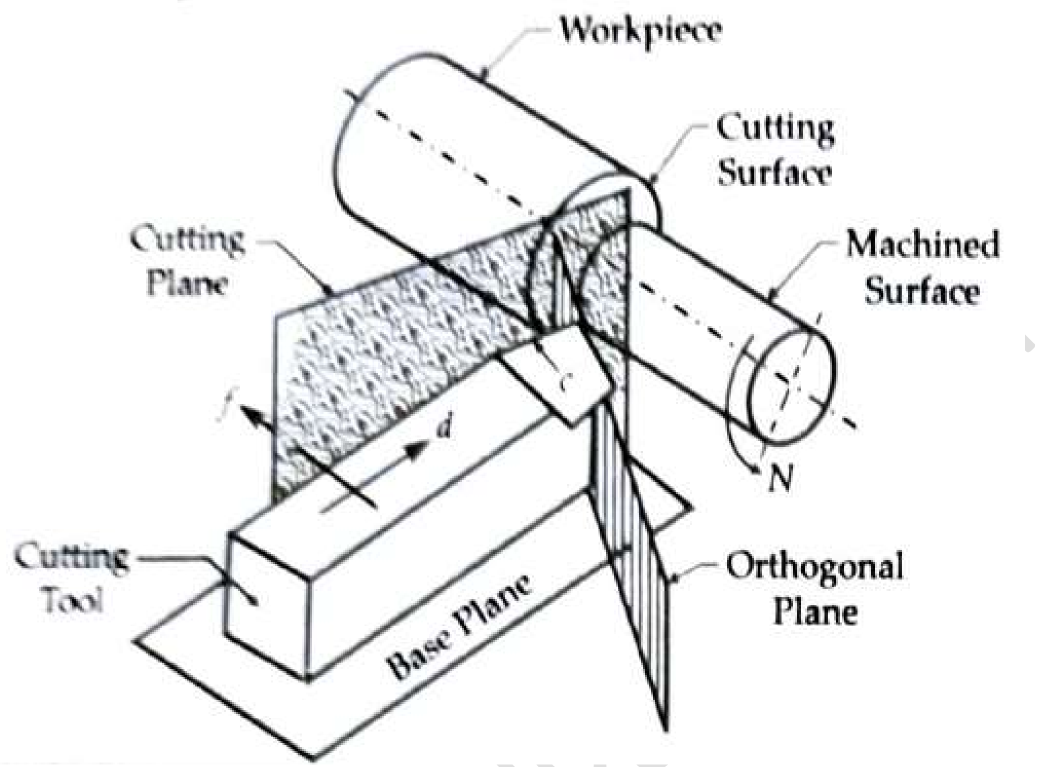

Fig. 6.4 Tool and workpiece in orthogonal system of reference planes

## L 6.4 TOOL GEOMETRY IN COORDINATE SYSTEM

This System, having been adopted by American Standards Association (A.S.A), is also known as A.S.A system of Tool Signature. Also, because of the nomenclature of reference planes as X, Y and Z, some authors describe it as X-Y-Z Plane System. This system is quite convenient in describing the Tool angles of a Single-point Cutting Tool. This system of Reference Planes, together with the principal angles of a Single Point Cutting Tool, is shown in Fig. 6.5. The various tool angles shown. in the figure are:

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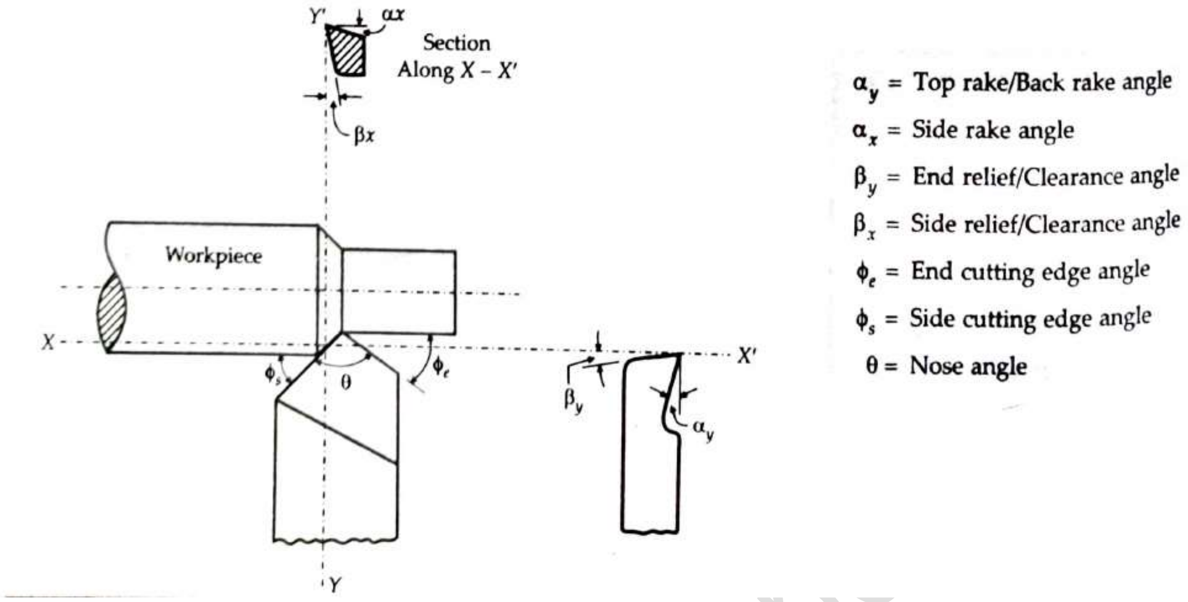

Fig. 6.5 Tool angles in Coordinate System (A.S.A system).

While describing the tool geometry in this system the different parameters are mentioned in the order - Back rake, Side rake, Eed Relief Angle, Side relief angle, End cutting edge angle, Side cutting edge angle and Nose radius. The value of nose angle will depend upon the values of and cutting-edge angle and side cutting edge angle.

Q. Describe a Tool with 8, 10, 6, 6, 6, 10, 2 signatures in A.S.A system.

Ans.

| | |
|---|---|
| Back rake | $\alpha_y = 8°$ |
| Side rake | $\alpha_x = 10°$ |
| End relief angle | $\beta_y = 6°$ |
| Side relief angle | $\beta_x = 6°$ |
| End cutting edge angle | $\phi_e = 6°$ |
| Side cutting edge angle | $\phi_s = 10°$ |
| Nose radius | = 2 mm |

**TOOL GEOMETRY IN ORTHOGONAL SYSTEM**

This system is also known as Orthogonal Rake System (O.R.S.) or International System. Further, because of the nomenclature (L, Mand N) of the Principal planes (See Fig. 6.6), it is also described by some authors as L-M-N Planes System. As already stated earlier, the tool in this system is supported to be operating on the workpiece. Therefore, many tool parameters are variable in this system and their actual values are affected by the tool position with regard to the tool position with regard to the operation. The different Tool angles in this System, are shown in Fig. 6.6.

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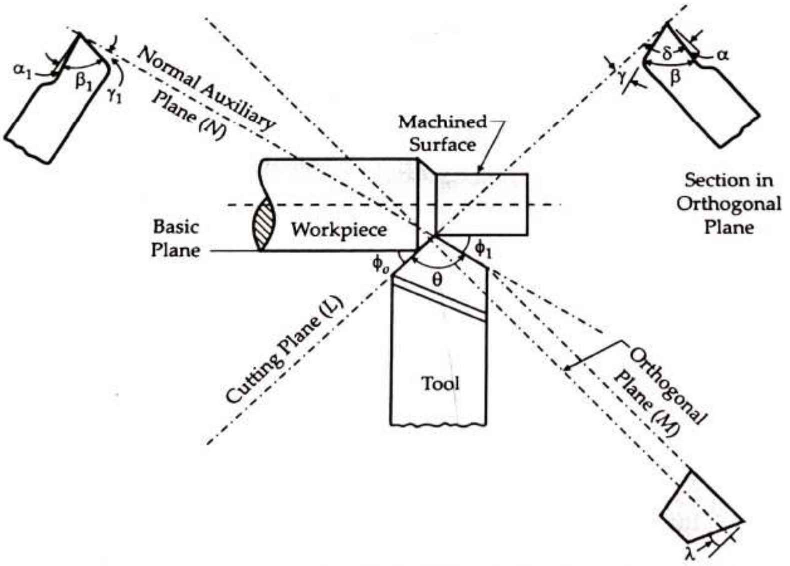


$\phi_0$ = Plan approach angle or Principal Cutting edge angle or Primary cutting edge angle or Major cutting edge angle or simply Approach angle.

$\phi_1$ = Auxiliary cutting edge angle or Auxiliary cutting angle or Minor cutting edge angle or Secondary cutting edge angle

$\lambda$ = Angle of Inclination or Inclination angle

$\alpha$ = Orthogonal rake angle

$\gamma$ = Side relief angle

$\beta$ = Wedge angle

$\delta$ = Cutting angle ($= \gamma + \beta$)

$\alpha_1$ = Side rake angle

$\gamma_1$ = End relief angle

$\beta_1$ = Side wedge angle

Fig. 6.6 Tool angles in Orthogonal (O.R.S.) or International System.

In ORS System, only the main parameters of a Single Point Cutting Tool are designated as shown in the given example.

For example, a Cutting Tool designated as 0-10-5-5-8-90-1 will have the following values of its different parameters:

| | |
|---|---|
| $\lambda = 0°$ | *(Inclination angle)* |
| $\alpha = 10°$ | *(Orthogonal rake angle)* |
| $\gamma = 5°$ | *(Side relief angle)* |
| $\gamma_1 = 5°$ | *(End relief angle)* |
| $\phi_1 = 8°$ | *(Auxiliary cutting angle)* |
| $\phi_0 = 90°$ | *(Approach angle)* |
| $R = 1$ mm | *(Nose radius)* |

## INTER-RELATIONSHIP BETWEEN ASA AND ORS SYSTEMS

Several times we are required to convert some Tool Parameters in ASA system to ORS system and vice versa. The following relationships will help in such conversions:

$$\tan\alpha = \tan\alpha_y \cdot \cos\phi_0 + \tan\alpha_x \cdot \sin\phi_0 \quad \text{\_\_\_\_\_\_\_\_\_\_ } 6.1$$

$$\tan\lambda = \tan\alpha_y \cdot \sin\phi_0 - \tan\alpha_x \cdot \tan\phi_0 \quad \text{\_\_\_\_\_\_\_\_\_\_ } 6.2$$

$$\tan\alpha_x = \sin\phi_0 \cdot \tan\alpha - \cos\phi_0 \cdot \tan\lambda \quad \text{\_\_\_\_\_\_\_\_\_\_ } 6.3$$

$$\tan\alpha_y = \cos\phi_0 \cdot \tan\alpha + \sin\phi_0 \cdot \tan\lambda \quad \text{\_\_\_\_\_\_\_\_\_\_ } 6.4$$

Q. A single point Cutting tool has a Back rake of 10° and Side rake of 14°. Calculate its (1) Orthogonal rake and (ii) inclination angle when the approach angle is 70°.

Ans.

| | |
|---|---|
| Back rake | $(\alpha_y) = 10°$ |
| Side rake | $(\alpha_x) = 14°$ |
| Approach angle | $(\phi_0) = 70°$ |

By using equation we get

$$\tan\alpha = \tan\alpha_y \cdot \cos\phi_0 + \tan\alpha_x \cdot \sin\phi_0$$

$$= \tan 10° \cdot \cos 70° + \tan 14° \cdot \sin 70°$$

$$= 0.1763 \times 0.3420 + 0.2493 \times 0.9397 = 0.2932$$

$$\therefore \quad \alpha = \tan^{-1} 0.2932 = \mathbf{16°21'}$$

Also, by using equation (4.2), we get

$$\tan\lambda = \tan\alpha_y \cdot \sin\phi_0 - \tan\alpha_x \cdot \cos\phi_0$$

$$= \tan 10° \times \sin 70° - \tan 14° \times \cos 70°$$

$$= 0.1763 \times 0.9397 - 0.2493 \times 0.3420 = 0.1657 - 0.0853 = 0.0804$$

$$\therefore \quad \lambda = \tan^{-1} 0.0804 = \mathbf{4°36'}$$

**Ans.** *Orthogonal rake* $(\alpha) = \mathbf{16°21'}$

*Inclination angle* $(\lambda) = \mathbf{4°36'}$

L 6.4 Quiz

Q. In an Orthogonal Cutting (turning) operation on a lathe the cutting tool used had the Tool designation of 0-10-6-6-8-80-1 mm in ORS system. Calculate the values of (i) Back rake and (ii) Side rake.

a. Back rake = 1°44'

Side rake = 9°51'

b. Back rake = 1°84'

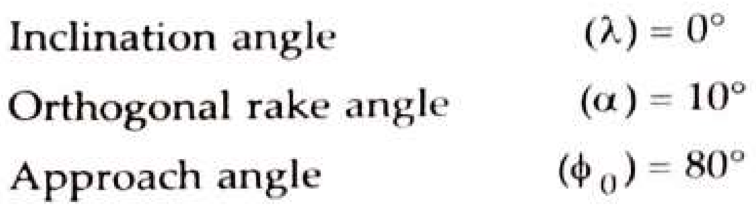
   Side rake = 9°81'

c. Back rake = 2°84'

   Side rake = 8°81'

L 6.4 Remedial Class

The given values in the problem are :



Inclination angle $(\lambda) = 0^\circ$

Orthogonal rake angle $(\alpha) = 10^\circ$

Approach angle $(\phi_0) = 80^\circ$

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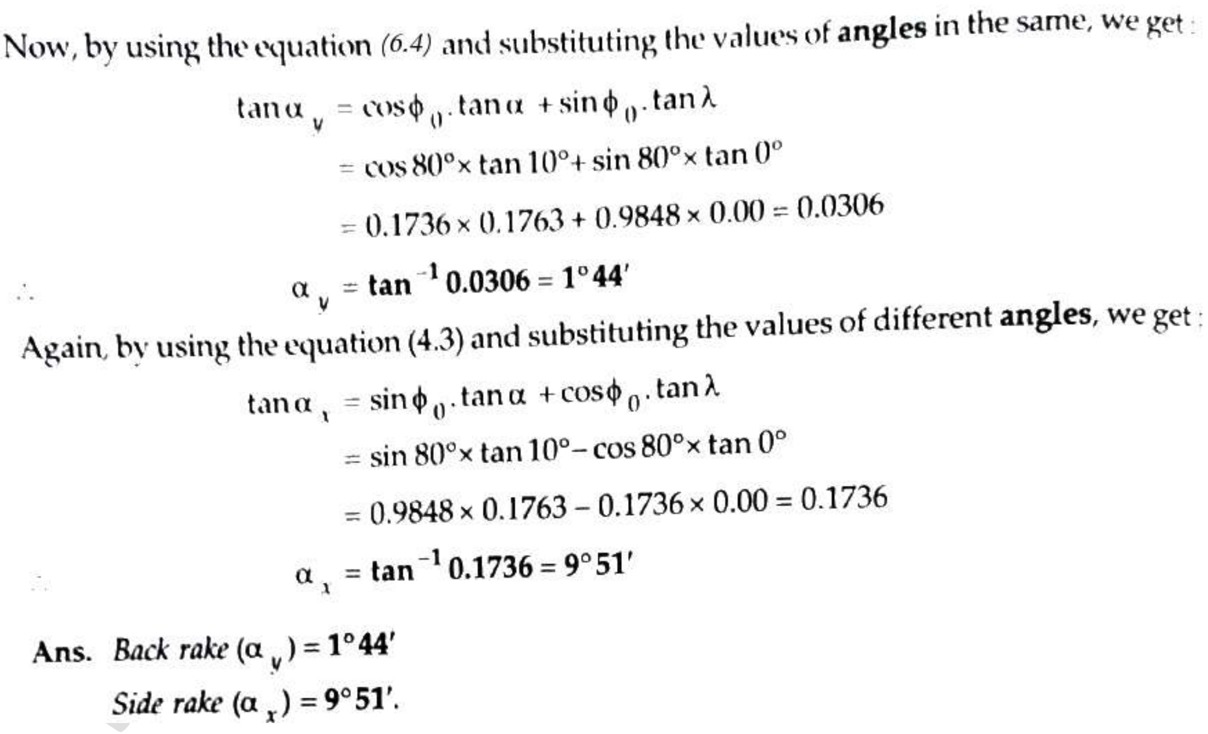

Now, by using the equation *(6.4)* and substituting the values of **angles** in the same, we get :

$$\tan\alpha_y = \cos\phi_0 . \tan\alpha + \sin\phi_0 . \tan\lambda$$

$$= \cos 80^\circ \times \tan 10^\circ + \sin 80^\circ \times \tan 0^\circ$$

$$= 0.1736 \times 0.1763 + 0.9848 \times 0.00 = 0.0306$$

$$\therefore \quad \alpha_y = \tan^{-1} 0.0306 = 1^\circ 44'$$

Again, by using the equation (4.3) and substituting the values of different **angles**, we get :

$$\tan\alpha_x = \sin\phi_0 . \tan\alpha + \cos\phi_0 . \tan\lambda$$

$$= \sin 80^\circ \times \tan 10^\circ - \cos 80^\circ \times \tan 0^\circ$$

$$= 0.9848 \times 0.1763 - 0.1736 \times 0.00 = 0.1736$$

$$\therefore \quad \alpha_x = \tan^{-1} 0.1736 = 9^\circ 51'$$

**Ans.** *Back rake* $(\alpha_y) = 1^\circ 44'$

*Side rake* $(\alpha_x) = 9^\circ 51'$.

**L 7.1 CHIP FORMATION**

Consider Fig. 7.1, which represents an Orthogonal Cutting. It is a schematic representation of a Shaping operation, in which the workpiece remains stationary and the tool advances into the workpiece towards the left. Thus, the metal in front of the tool get; compressed very severely, causing Shear stress. This stress is maximum along a plane, called Shear plane. If the material of the workpiece is ductile, the material flows plastically along the shear plane, forming the chip, which flows upwards along the face of the tool.

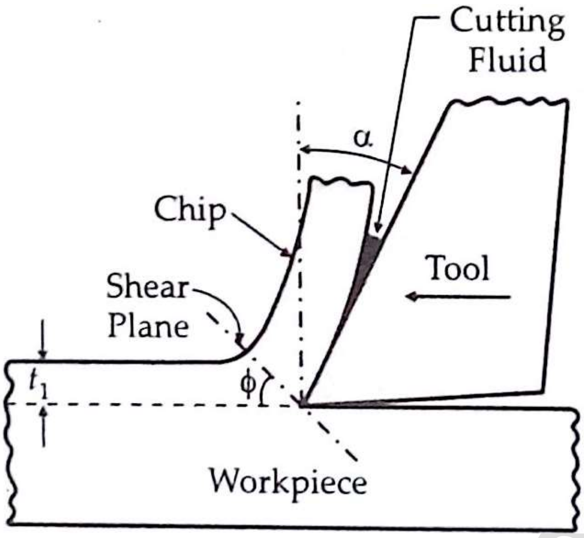

Fig. 7.1

Strictly speaking, the complete plastic deformation of the metal does not take place entirely along the shear plane only, but it actually occurs over a definite area, represented by **PQRS** in Fig. 7.2. The metal structure starts getting elongated along the line **PQ** below the share plane and continues up to the line **RS** above the shear plane, where its deformation is complete. The complete area represented by **PQRS**, within which the metal deformation occurs, is known as **Shear Zone**. For the sake of clarity in explanation, the lines PQ and RS are shown as exactly parallel in the diagram, but actually they may not be so. They will actually be inclined to each other such that the **shear zone** contained between them will be of wedge shape, with its thicker portion near the tool and the thinner one opposite to it. This shape of the shear zone is one of the reasons due to which the Chip curls. The produced chip is very hot and its safe disposal is very necessary. The various devices used for its disposal.

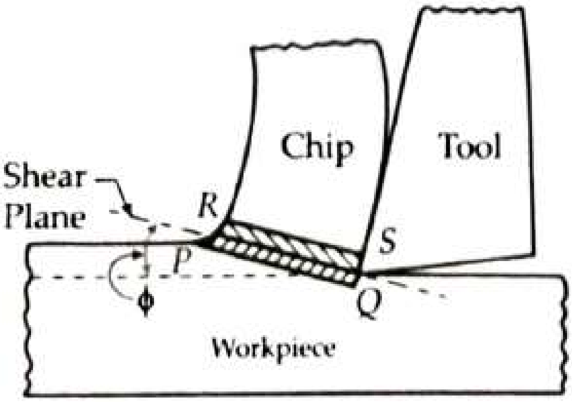

Fig.7.2 The Shear Zone.

**• Mechanism of chip formation in machining ductile materials**

During continuous 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 Fig. 7.3.

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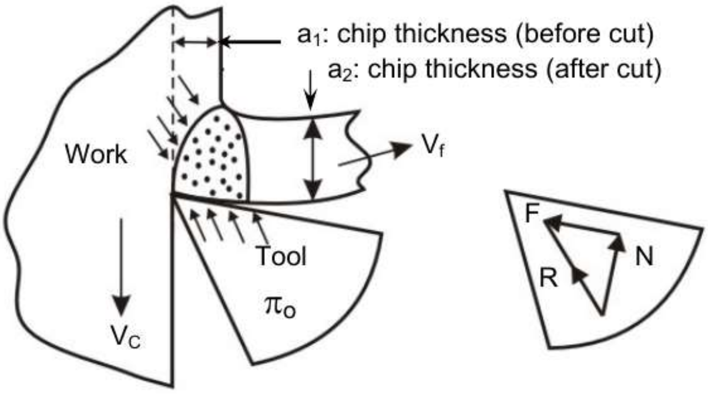
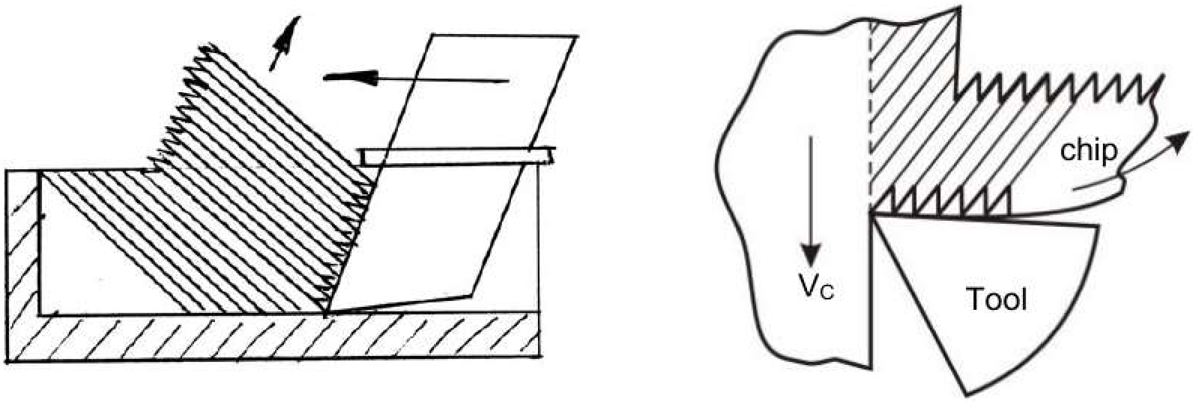


**Fig. 7.3** *Compression of work material (layer) ahead of the tool tip*

The force exerted by the tool on the chip arises out of the normal force, N and frictional force, F as indicated in Fig. 7.3. Due to such compression, shear stress develops, within that compressed region, in different magnitude, in different directions and rapidly increases in magnitude. 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 takes place resulting shear deformation in that region and the plane of maximum shear stress. But the forces causing the shear stresses in the region of the chip quickly diminishes and finally disappears while that region moves along the tool rake surface towards and then goes beyond the point of chip-tool engagement. As a result the slip or shear stops propagating long before total separation takes place. In the mean time the succeeding portion of the chip starts undergoing compression followed by yielding and shear. This phenomenon repeats rapidly resulting in formation and removal of chips in thin layer by layer. This phenomenon has been explained in a simple way by Piispannen [1] using a card analogy as shown in Fig. 7.4.



(a) Shifting of the postcards by partial sliding against each other

(b) Chip formation by shear in lamella.

**Fig. 7.4** *Piispanen model of card analogy to explain chip formation in machining ductile materials*

In actual machining chips also, such serrations are visible at their upper surface as indicated in Fig. 7.4. The lower surface becomes smooth due to further plastic deformation due to intensive rubbing with the tool at high pressure and temperature. The pattern of shear deformation by lamellar sliding, indicated in the model, can also be seen in actual chips by proper mounting, etching and polishing the side surface of the machining chip and observing under microscope.

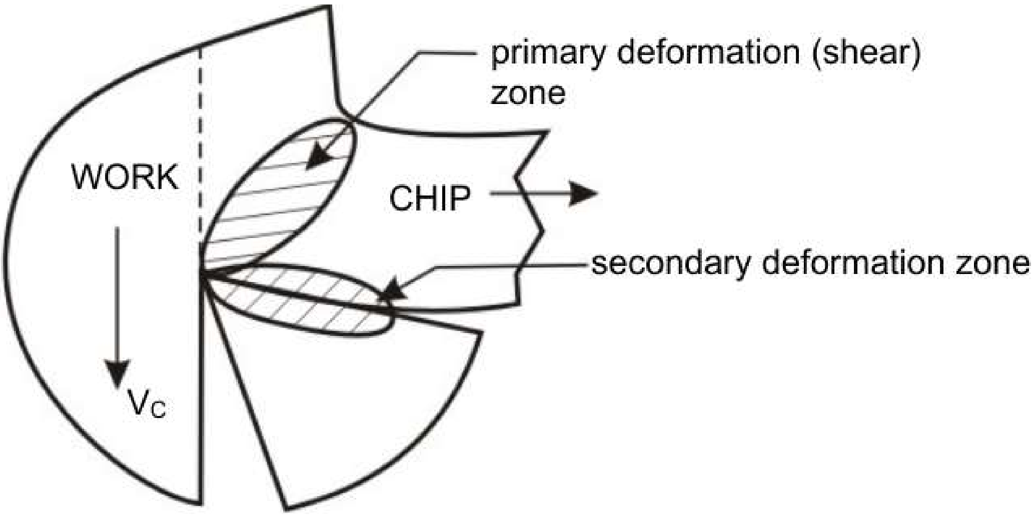


*Fig. 7.5 Primary and secondary deformation zones in the chip.*

The pattern and extent of total deformation of the chips due to the primary and the secondary shear deformations of the chips ahead and along the tool face, as indicated in Fig. 7.5, depend upon

- work material
- tool material and geometry
- the machining speed (VC) and feed (so)
- cutting fluid application

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- **Mechanism of chip formation in machining brittle materials**

The basic two mechanisms involved in chip formation are

- Yielding – generally for ductile materials
- Brittle fracture – generally for brittle materials

During machining, first a small crack develops at the tool tip as shown in Fig. 7.6 due to wedging action of the cutting edge. At the sharp crack-tip stress concentration takes place. In case of ductile materials immediately yielding takes place at the crack-tip and reduces the effect of stress concentration and prevents its propagation as crack. But in case of brittle materials the initiated crack quickly propagates, under stressing action, and total separation takes place from the parent workpiece through the minimum resistance path as indicated in Fig. 7.6. 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. 7.7.

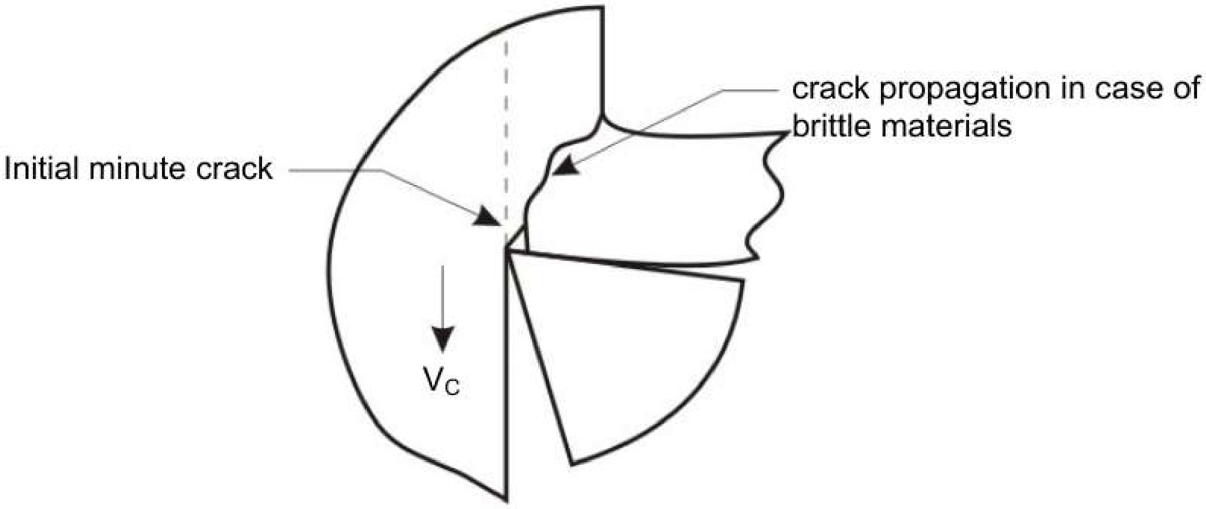
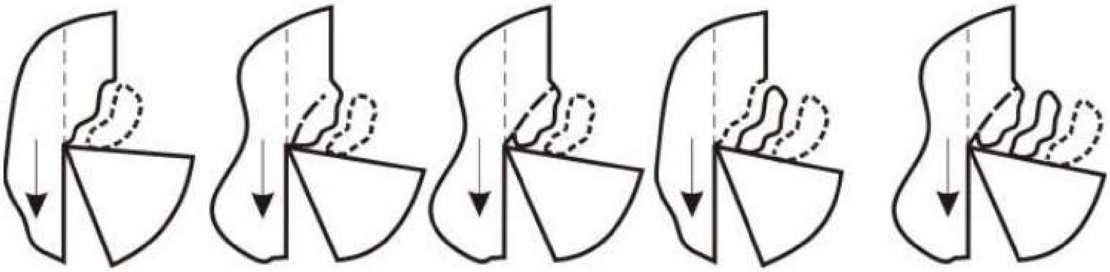


*Fig. 7.6 Development and propagation of crack causing chip separation.*



(a) separation (b) swelling (c) further swelling (d) separation (e) swelling again

*Fig. 7.7 Schematic view of chip formation in machining brittle materials.*

**L 7.2 TYPES OF CHIPS**

The Chips produced during machining of various metals can be broadly classified into the following three types. The production of any particular type will largely depend upon the type of material being machined and the cutting conditions.

1. **Discontinuous or Segmental Chips**

This type of Chips is produced during machining of **brittle materials like cast iron and bronze**. These chips are produced in the form of **small segments**, as illustrated in Fig. 7.8. In machining of such materials, as the tool advances forward, the shear-plane angle gradually reduces until the value of compressive stress acting on the shear plane becomes too low to prevent rapture. At this stage, any further advancement of the tool results in the fracture of the metal ahead of it, thus producing a **segment of the Chip.** With further advancement of the tool, the processes of metal fracture and production of chip segments go on being repeated, and this is how the **Discontinuous Chips** are produced. Such chips are also sometimes produced in the machining of ductile materials when l**ow cutting speeds** are used and adequate **lubrication is not provided**. This causes **excessive friction** between the C**hip and Tool face**, leading to the fracture of the chip into small segments. This will also result in excessive **Wear on the tool** and a **poor surface finish** on the workpiece. Other factors responsible for promoting the production of Discontinuous Chips are **smaller rake angle** on the tool and **too much depth of cut.**

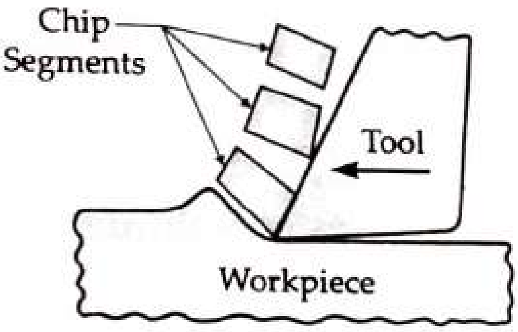


Fig. 7.8 Discontinuous Chip.

2. **Continuous Chip**

As is evident from the name, the presence of separated segmental elements is totally eliminated in this case. this type of chip is produced while machining a ductile material, like mild steel, under favorable cutting condition, such as high cutting speed and minimum friction between the chip and the tool face. if otherwise, it will break and form the segmental chip. the friction at the chip tool interface can be minimized by polishing the tool face and at adequate use of coolant. Also, with diamond tools the friction is less. the basis of the production of a continuous chip is the continuous plastic deformation of the metal ahead of the tool, the chip moving smoothly up the tool face. Other factors responsible for promoting its production are bigger rake angle, finer feed and keen cutting edge of the tool.

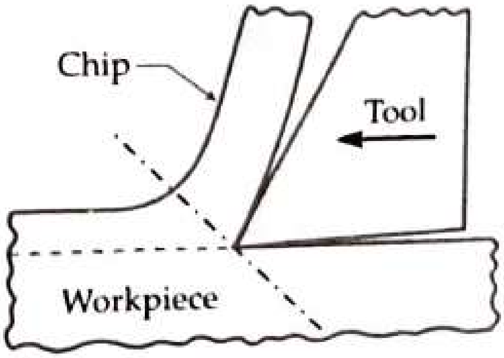


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Fig. 7.9 Continuous Chip

### 3. Continuous Chip with Built-up Edge

Such a chip is usually from while machining ductile material, when high friction exists at the chip tool interface. The upward flowing chip exerts pressure on the tool face. The normal reaction $N_R$ of the chip on the tool face is quite high, and is maximum at the cutting edge or nose of the tool. This gives rise to an excessively high temperature and the compressed metal adjacent to the tool nose gets welded to it. The chip is also sufficiently hot and gets oxidised as it comes off the tool and turn blue in color. The extra metal welded to the nose or point of the tool is called **built up edge.** This metal is highly strain hardened and brittle. With the result, as the chip flows up the tool, the built up edge is broken and carried away with the chip while the rest of it adheres to the surface of the Workpiece, making it rough. Due to the built-up edge the rake angle is also altered and so is the cutting force. The common factors responsible for the formation of built up edge are low cutting speed, excessive feed, small rake angle and lack of lubricant.

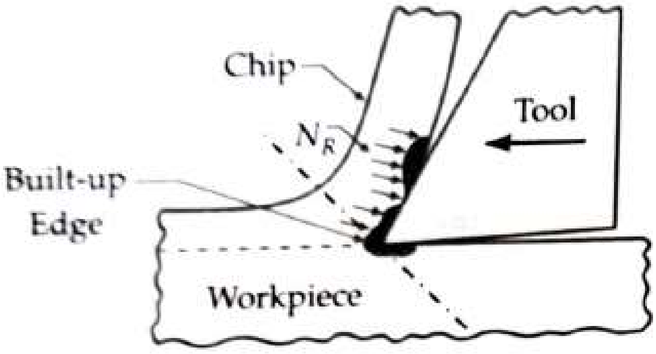

Fig.7.10 Continuous Chip with Built-up Edge.

**Adverse Effects of Built-up Edge Formation**

(a) Rough surface finish on the workpiece.

(b) Fluctuating cutting force, causing vibrations in Cutting Tool.

(c) Chances of carrying away some material from the tool by the built-up surface, producing Crater on the tool face and causing tool wear.

**For avoiding the formation of Built-up Edge the following precautions are required:**

(a) The coefficient of friction at the chip-tool interface should be minimised by means of polishing the tool face and adequate supply of coolant during the operation.

(b) The Rake angle should be kept large.

(c) High cutting speeds and low feeds should be employed, because at high speeds the strength of the weld becomes low. Similarly, at very high temperature also the strength of the weld becomes low.

**L 7.2 Quiz**

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Which type of chips form while machining of brittle materials?

- Continuous chip
- discontinuous chips
- Built-up chips
- all of the given ans. with some proportion

Continuous chips are formed during metal cutting operation due to

- ductile work materials
- large rake angle
- high cutting speed
- all of the above

**L 8.1 CHIP THICKNESS RATIO & SHARE PLANE ANGLE**

During the cutting action of a metal it will be observed that the thickness of the deformed or upward flowing chip is more than the actual depth of cut.

- It is because the chip flows upwards at a slower rate than the velocity of the cut.
- The velocity of the chip flow is directly affected by the shear plane angle. The smaller this angle the slower will be the chip-flow-velocity and, therefore, larger will be the thickness of the chip.

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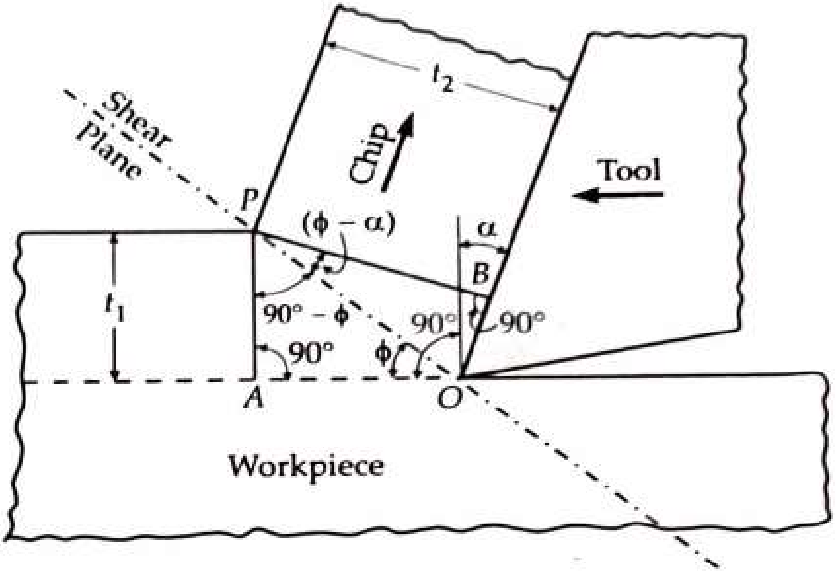

Fig. 8.1 An Orthogonal Cutting Operation.

Refer to Fig. 8.1. Let,

$t_1$ = Chip thickness prior to deformation

$t_2$ = Chip thickness after deformation

The above discussion leads to the result that $\mathbf{t_2 > t_1}$

The Chip thickness ratio ' **r'** is given by:

$$r = \frac{t_1}{t_2} \quad \text{----------------------------------------------- (1)}$$

Since $t_2$ is always greater than $t_1$, the value of chip thickness ratio **'r' is less than unity**. The higher the value of 'r' the better is supposed to be the cutting action.

The reverse of 'r' is known as Chip Reduction Coefficient. If **'k' is the Chip Reduction Coefficient**, then :

$$k = \frac{1}{r} \quad \text{---------------------------------------(2)}$$

Now, in Orthogonal Cutting the width of the chip equals the width of the cut. Considering the specific gravity of the metal as constant, the volume of the chip produced will be equal to the volume of the metal cut. Widths of both being equal, the product of the chip thickness and its length will, therefore, be equal to the product of the thickness and the length of the metal cut. If $L_1$ and $L_2$ are the lengths of the metal cut and the chip respectively, it follows that:

$$t_1 \cdot L_1 = t_2 \cdot L_2$$

$$\frac{t_1}{t_2} = \frac{L_2}{L_1}$$

$$\frac{t_1}{t_2} = r \qquad \text{[See equation } (1) \text{ ]}$$

$$r = \frac{t_1}{t_2} = \frac{L_2}{L_1}$$

$$\boxed{k = \frac{1}{r} = \frac{t_2}{t_1} = \frac{L_1}{L_2}} \quad (3)$$

In the given Fig. 8.1, we have two right angled triangles **OAP** and **OBP**. Considering the right-angled triangle **OAP**, we have:

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$$\frac{AP}{OP} = \sin AOP = \sin\phi$$

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$$\therefore \qquad OP = \frac{AP}{\sin\phi} \qquad [\text{But, } AP = t_1]$$

or,

But,

$$\therefore \qquad \boxed{OP = \frac{t_1}{\sin\phi}} \qquad (4)$$

∴

Now, considering the right angled triangle **$OBP$**, we have

$$\frac{BP}{OP} = \sin BOP = \sin(90 - \phi + \alpha) = \cos(\phi - \alpha)$$

or,

$$\therefore \qquad OP = \frac{BP}{\cos(\phi - \alpha)} \qquad [\text{But, } BP = t_2]$$

$$\therefore \qquad \boxed{OP = \frac{t_2}{\cos(\phi - \alpha)}} \qquad (5)$$

Now, by equating the equations (4) and (5) for $OP$, we get

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

or,

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

$$\therefore \qquad \boxed{r = \frac{\sin\phi}{\cos(\phi - \alpha)}} \qquad (6)$$

The equation (6) above can be expanded as :

$$r = \frac{\sin\phi}{\cos\phi\,\cos\alpha + \sin\phi\,\sin\alpha}$$

$$r(\cos\phi \,.\, \cos\alpha) + r(\sin\phi \,.\, \sin\alpha) = \sin\phi$$

$$\therefore \qquad \frac{r(\cos\phi \,.\, \cos\alpha)}{\sin\phi} + \frac{r(\sin\phi \,.\, \sin\alpha)}{\sin\phi} = 1$$

$$\therefore \qquad \frac{r\cos\alpha}{\tan\phi} + r\sin\alpha = 1$$

$$\therefore \qquad \frac{r\cos\alpha}{\tan\phi} = 1 - r\sin\alpha$$

$$\therefore \qquad \boxed{\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}.} \qquad (7)$$

Also, by substituting the value of '$r$' in terms of $t_1$ and $t_2$, we get

$$\boxed{\tan\phi = \frac{t_1 / t_2 \cos\alpha}{1 - t_1 / t_2 \sin\alpha}} \qquad (8)$$

$\tan\phi$ = *Share Plane Angle*

$\alpha$ = *Tool Rake Angle*

Q. In Orthogonal Turning of a mild steel bar of 60 mm diameter on a lathe a feed of 0.8 mm was used. A Continuous chip of 1.4 mm thickness was removed at a Rotational Speed of 80 r.p.m. of work. Calculate the thickness ratio (r), chip reduction ratio (k) and the total length of the chip removed in 0ne minute.

Soi.: We Know.

$$r = \frac{t_1}{t_2}$$

Now, $t_1$ = feed rate mm/rev. = 0.8 mm

and $t_2$ = given thickness of cut chip = 1.4 mm

$$\therefore \qquad r = \frac{0.8}{1.8} = 0.57 \text{ Ans.}$$

Also, from equation *(3)* , we have

$$K = \frac{1}{r} = \frac{1}{0.57} = 1.75 \text{ Ans.}$$

Again, from equation we have :

$$r = \frac{L_2}{L_1}$$

$$\begin{aligned} \therefore \qquad L_2 &= r \times L_1 \\ &= 0.57 \times \pi \times D \times N \\ &= 0.57 \times \pi \times 60 \times 80 = 3912 \text{ mm} \end{aligned}$$

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**L 8.1 Quiz**

Which of the following is correct about chip thickness ratio ‘r’?

a) r<1
b) r=1
c) r>1
d) None of the mentioned

Explanation: Uncut chip thickness is always less than cut chip thickness and ‘r’ is the ratio of cut chip thickness to uncut chip thickness.

If t1 denotes the uncut chip thickness and t2 denotes cut chip thickness ratio then, which of the following equation is correct about chip thickness ratio ‘r’?
a) r=t1/t2
b) r=t2/t1
c) r=t1*t2
d) None of the mentioned

Explanation: ‘r’ is the ratio of cut chip thickness to uncut chip thickness. Here t1 is the uncut chip thickness and t2 is the cut chip thickness.

Which of the following is the correct relation for chip thickness ratio ‘r’?
Given that: ϕ=shear angle
α=rake angle
a) tan ϕ= cosα/(1-r*sinϕ)
b) tan ϕ= rcosα/(1-r*sinα)
c) tan ϕ= rcosα/(1-sinα)
d) tan ϕ= cosα/(r-r*sin α)

Answer: b
Explanation: Value of chip thickness ratio is given by: tan ϕ= rcosα/(1-r*sinϕ) . ‘r’ is the chip thickness ratio, which is the ratio of cut chip thickness to uncut chip thickness.

### L 9.1 Velocity Relationship

The relationship of different velocities for Orthogonal Cutting is shown in Fig. 9.1. Let the velocities depicted in the diagram, be as follows:

$V_c$= Velocity of tool relative to work, or the Cutting Velocity.

$V_f$ = Velocity of chip flow relative to tool, or the Chip flow velocity.

$V_s$ = Velocity of displacement of the chip along the shear plane relative to work, or the Velocity of Shear.

Of the above three Velocities the Cutting velocity Vc is always known. The other two can be computed with its help of the following relations, which refer to the velocity diagram shown on the right-hand side in Fig. 9.1.

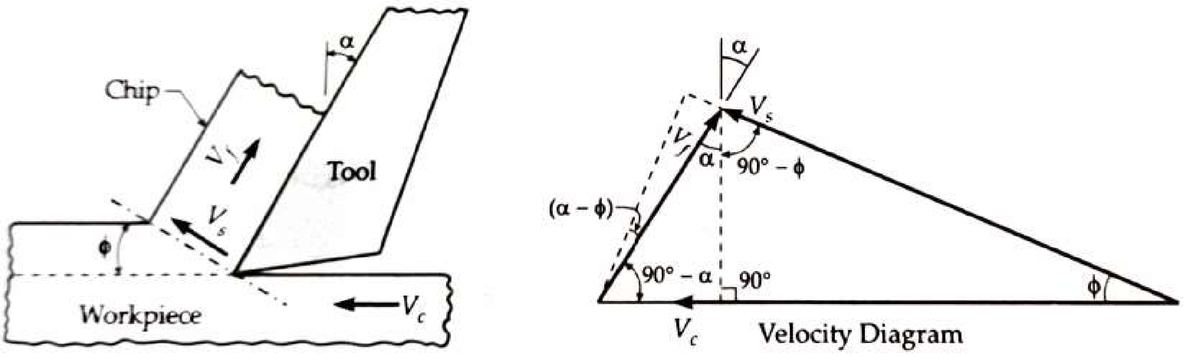

Fig. 9.1 Velocity relationships.

From standard trigonometrical l ratios, we get:

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$$\frac{V_c}{\sin(90-\phi+\alpha)} = \frac{V_f}{\sin\phi} = \frac{V_s}{\sin(90-\alpha)}$$

or,

$$\frac{V_c}{\sin[90-(\phi+\alpha)]} = \frac{V_f}{\sin\phi} = \frac{V_s}{\cos\alpha}$$

or,

$$\frac{V_c}{\cos(\phi-\alpha)} = \frac{V_f}{\sin\phi} = \frac{V_s}{\cos\alpha}$$

From these relations the values of $V_f$ and $V_s$ can be derived in terms of the known velocity Vc as follows:

$$\boxed{V_s = V_c \cdot \frac{\cos\alpha}{\cos(\phi-\alpha)}} \text{———} (1)$$

$$\boxed{V_f = V_c \frac{\sin\phi}{\cos(\phi-\alpha)}} \text{———} (2)$$

But, it has already been shown in equation (L8-6) that:

$$r = \frac{\sin\phi}{\cos(\phi-\alpha)}$$

Therefore, by substituting this value in equation (2), we get:

$$\boxed{V_f = V_c \times r} \text{———} (3)$$

The same relationship can also be derived by equating the two volumes of material, which are equal in Orthogonal Cutting, such as :

**Volume** of material cut per unit of time = **Volume** of the material flowing up as **chip**

i.e., $V_c . t_1 . w = V_f . t_2 . w$ [$w$ = width of cut]

or, $\frac{V_c . t_1}{t_2} = V_f$

or, $V_f = V_c . \frac{t_1}{t_2}$ $\left[\text{But, } \frac{t_1}{t_2} = r\right]$

$\therefore$ $V_f = V_c . r$

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### L 10.1 FORCE RELATIONSHIP IN ORTHOGONAL CUTTING

It is clear from Fig. 10.1 that a number of forces act on the chip during metal cutting. The relationships among these forces were established by Merchant (Merchant's circle suggested by V.E. Merchant in 1945) with the following assumptions:

1. Cutting velocity always remains constant.

2. Cutting edge of the tool remains sharp throughout cutting and there is no contact between the workpiece and tool flank.

3. There is no sideways flow of chip.

4. Only continuous chip is produced.

5. There is no built-up Edge.

6. No consideration is made of the inertia force of the chip.

7.The behaviour of chip is like that of a free body which is in the state of a stable equilibrium due to the action of two resultant forces which are equal opposite and collinear.

However, there were a number of flaws and practical difficulties in these assumptions and that is why they were modified later.

Figure 10.1 illustrates the forces acting on a chip in Orthogonal Cutting. The forces represented are the following:

$F_s$ = Metal resistance to shear in chips formation, acting along the shear plane, or Shear **Force.**

$F_n$= Backing up force exerted by the workpiece on the chip, acting normal to the shear plane.

N = Force exerted by the tool on the chip, acting normal to the tool face.

F = µN = Frictional resistance of the tool against the chip flow, acting along the tool face, 'µ' being the coefficient of friction between the tool face and the- chip.

µ = F/N

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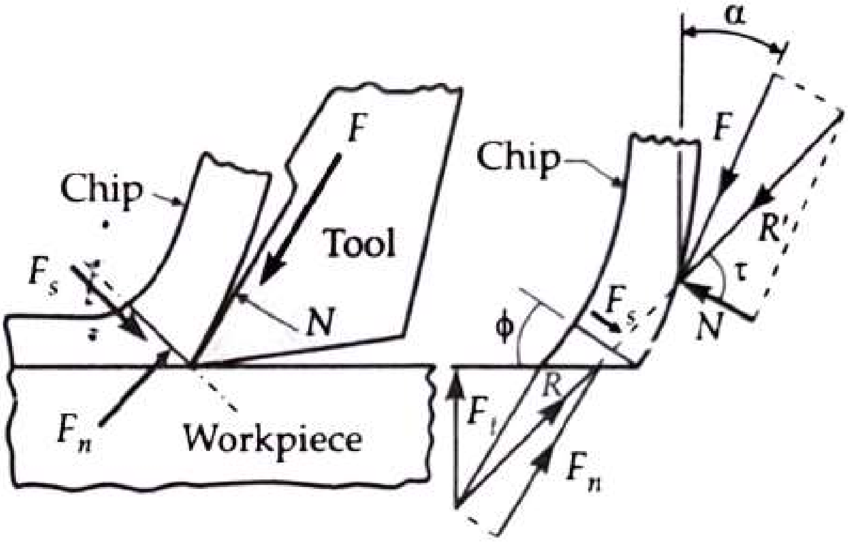

Fig. 10.1 Forces acting on a Chip in Orthogonal Cutting.

These forces are vectorially represented in the free-body diagram shown on the right-hand side in Fig. 10.1. It will be observed that forces $F_s$ and $F_n$ can be easily replaced by their resultant R and force's F and N by their resultant R'. Thus, all these forces are resolved to only two forces R and R'. For equilibrium, these forces R and R' should be equal, act opposite to each other and should be collinear, i.e.,

$$\vec{R'} = \vec{F} + \vec{N}$$

and,

$$\vec{R} = \vec{F_s} + \vec{F_n}$$

$$= \vec{F_c} + \vec{F_t}$$

or,

$$\vec{R} = \vec{R'}$$

For the convenience in studying further relationship, the two Triangles of Forces of the above free body diagram have been combined together in Fig. 10.2, called the Merchant's Circle Diagram for Cutting Forces, in which the following new components figure:

$F_c$ = Horizontal cutting force exerted by the tool on the workpiece.

$F_t$ = Vertical or tangential force which helps in holding the tool in position and acts on the tool nose.

These two forces can easily be found out with the help of Strain Gauges or Force Dynamometer. The angle α is a known quantity, being the rake angle of the tool. With the help of the equations given in Lecture 8.1, Eq. 7 & 8, the value of ' ϕ ' can also be determined. When all these four values, i.e., of $F_c$, $F_t$, α, and ϕ are known, all the other forces can be easily calculated with the help of geometry with reference to Fig. 10.2, as follows:

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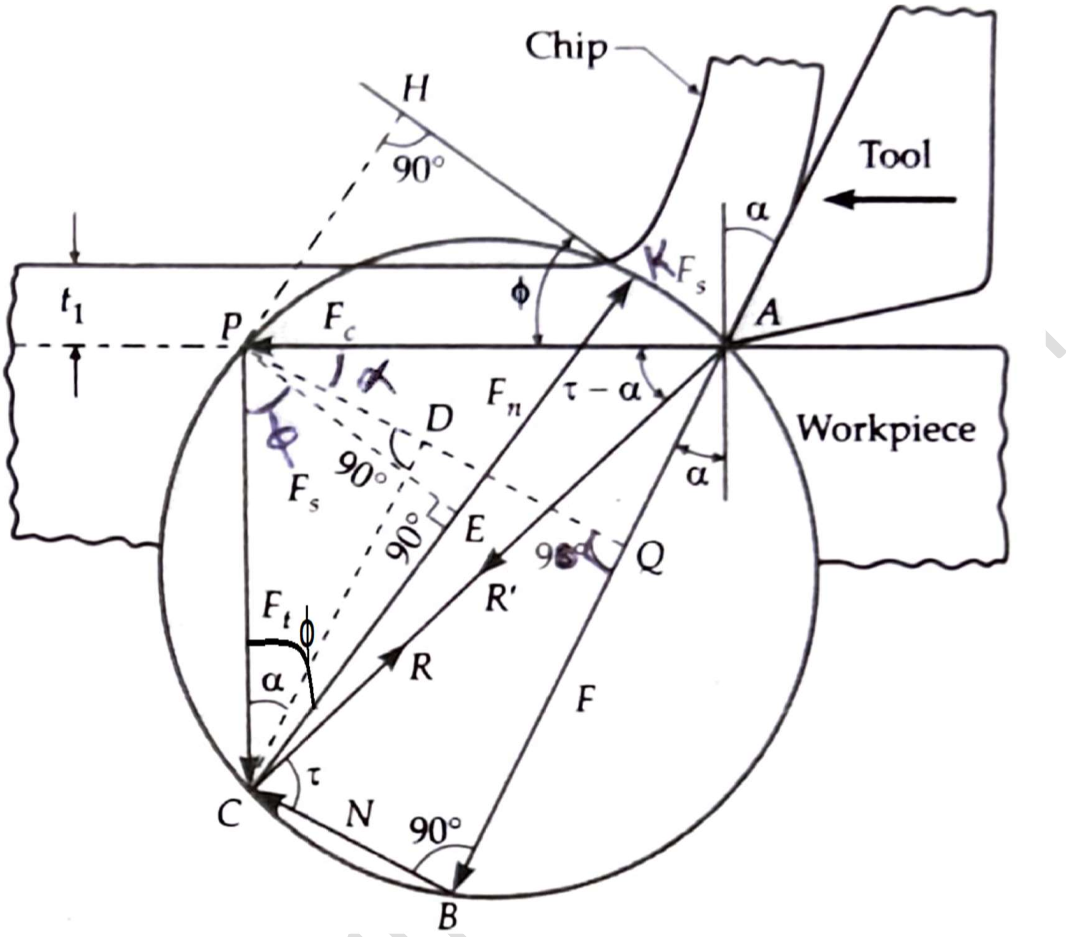

Fig. 10.2 Forces acting in Orthogonal Cutting (Merchant's Circle Diagram).

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$F = AQ + QB$

$= AQ + DC$ [∵ QB = DC]

I.e. **$F = F_c \sin\alpha + F_t \cos\alpha$** ...................................................... **(1)**

and $N = QD = PQ - PD$

or, **$N = F_c \cos\alpha - F_t \sin\alpha$** ........................................................**(2)**

Again, $F = AH - HK$

$= AH - PE$

**$F = F_c \cos\phi - F_t \sin\phi$** ........................................................**(3)**

$F_n = CK = CE + EK$

$= CE + PH$ [EK = PH]

$$F_n = F_t \cos\phi + F_c \sin\phi \quad \text{.......................................................................(4)}$$

and, $$F_c = AC\cos(\tau - \alpha)$$

or, $$F_c = R\cos(\tau - \alpha) \quad \text{..............................................................(5)}$$

also, $$F_s = R\cos(\phi + \tau - \alpha) \quad \text{..............................................................(6)}$$

Now, $$\frac{F_c}{F_s} = \frac{R\cos(\tau - \alpha)}{R\cos(\phi + \tau - \alpha)} = \frac{\cos(\tau - \alpha)}{\cos(\phi + \tau - \alpha)}$$

$$\therefore \quad F_c = F_s \cdot \frac{\cos(\tau - \alpha)}{\cos(\phi + \tau - \alpha)} \quad \text{..................................................(7)}$$

From equations (1) and (2) , we have :

$$\frac{F}{N} = \frac{F_c\sin\alpha + F_t\cos\alpha}{F_c\cos\alpha - F_t\sin\alpha} = \mu \quad \text{......................................(8)}$$

Also, by dividing the numerator and denominator both by cosα, we get:

$$\frac{F}{N} = \frac{F_t + F_c\tan\alpha}{F_c - F_t\tan\alpha} = \mu \quad \text{..................................................(9)}$$

Fron, right angled triangle ABC, we also have:

$$\frac{F}{N} = \tan\tau = \mu \quad \text{.....................................................................(10)}$$

Where, μ = Kinetic coefficient of friction between the upward sliding chip and tool face

and,

$\tau$ = Angle of friction

$$\tau = \tan^{-1}\mu = \tan^{-1}\frac{F}{N}$$

Further, $$\frac{CP}{AP} = \tan PAC$$

By substituting the values of CP, AP and angle PAC, we get:

$$\frac{F_t}{F_c} = \tan(\tau - \alpha) \quad \text{...................................................(11)}$$

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### L 10.2 Numerical

**Q**. A Carbide Lipped Tool of designation 0-10-5-5-8-90-1 mm (ORS) is used to turn a steel workpiece of 50 mm dia. with a Cutting Speed of 240 m/min and Feed of 0.25 mm/rev. The data obtained shows the cutting force = 180 kg, Feed force = 100 kg and Chip thickness = 0.32 mm. Calculate Shear angle, Shear force, Normal force acting on Shear plane, Friction force, Coefficient of friction, friction angle and Velocity of chip flow.

**Sol.**

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We know that $r = \frac{t_1}{t_2}$

In the present case $t_1$ = feed/rev. = 0.25 mm and, $t_2 = \mathbf{0.32\ mm}$

$\therefore$ $r = \frac{0.25}{0.32} = 0.78$

and $\alpha = 10°$ [From given tool signature]

Also, $\tan\phi = \frac{r\cos\alpha}{1 - r\sin\alpha}$

By substituting the values of $r$ and $\alpha$, we get,

$$\tan\phi = \frac{0.78\cos 10°}{1 - 0.78\sin 10°}$$

$$= \frac{0.78 \times 0.9848}{1 - 0.78 \times 0.1736} = \mathbf{0.8884}$$

$\therefore$ $\phi = \tan^{-1} 0.8884$

or, $\boldsymbol{\phi = 41°37' = 42°\ (say)}$ **Ans.**

Now, **Shear force** $F_s = F_c\cos\phi - F_t\sin\phi$

From the given data $F_c = 180$ kg

$F_t = 100$ kg

and, $\phi = \mathbf{42°}$

$\therefore$ $F_s = 180 \times \cos 42° - 100 \times \sin 42°$

or, $F_s = \mathbf{67\ kg}$ **Ans.**

The **Normal force** acting on the *Shear plane* ($F_n$) is given by :

$$F_n = F_t\cos\phi + F_c\sin\phi$$

$$= 100 \times \cos 42° + 180 \times \sin 42°$$

$$= 100 \times 0.7431 + 180 \times 0.6691$$

*i.e.,* $F_n = \mathbf{194.75\ kg}$ **Ans.**

Now, the **Friction force** ($F$) is given by :

$$F = F_c\sin\alpha + F_t\cos\alpha$$

$$= 180 \times \sin 10° + 100 \times \cos 10°$$

$$= 180 \times 0.1736 + 100 \times 0.9848$$

*i.e.,* $F = \mathbf{129.73\ kg}$ **Ans.**

Also, the **Coefficient of friction** (μ) is given by :

$$\mu = \frac{F_c \sin\alpha + F_t \cos\alpha}{F_c \cos\alpha - F_t \sin\alpha}$$

$$= \frac{180 \times \sin 10° + 100 \cos 10°}{180 \times \cos 10° - 100 \sin 10°} = \frac{180 \times 0.1736 + 100 \times 0.9848}{180 \times 0.9848 - 100 \times 0.1736}$$

$$\mu = \mathbf{0.67} \quad \textbf{Ans.}$$

The **Angle of Friction** (τ) is given by :

$$\tau = \tan^{-1}\mu = \tan^{-1} 0.67$$

$$\tau = \mathbf{34° \ (Approx.)} \quad \textbf{Ans.}$$

The **Chip flow Velocity** ($V_f$) is given by :

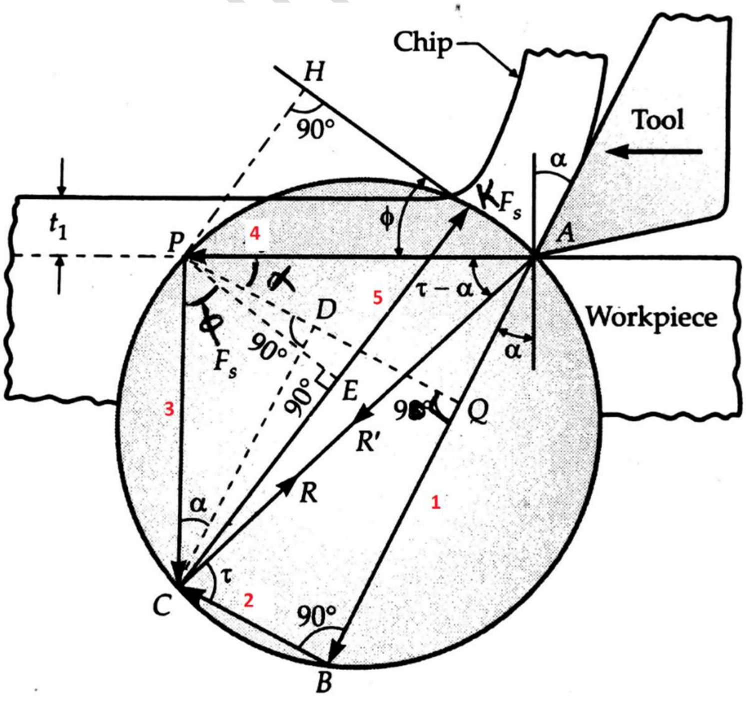
$$V_f = V_c \times r$$

$$= 240 \times 0.78 \ \text{m/min}$$

$$V_f = \mathbf{187 \ m/min.} \quad \textbf{Ans.}$$

**L 10.1 Quiz**

Match the 1, 2, 3, 4, & 5 with correct force.



### L 11.1 Stress and Strain in the Chip

A Chip is supposed to experience both the stress and strain during metal machining because it is produced as a result of plastic deformation of the metal. For calculating their values, the conditions at the cutting plane are considered. In Fig. 11.1, you will notice that two mutually perpendicular forces $F_s$ and $F_n$ act on the shear plane. The average stresses on the shear plane area are:

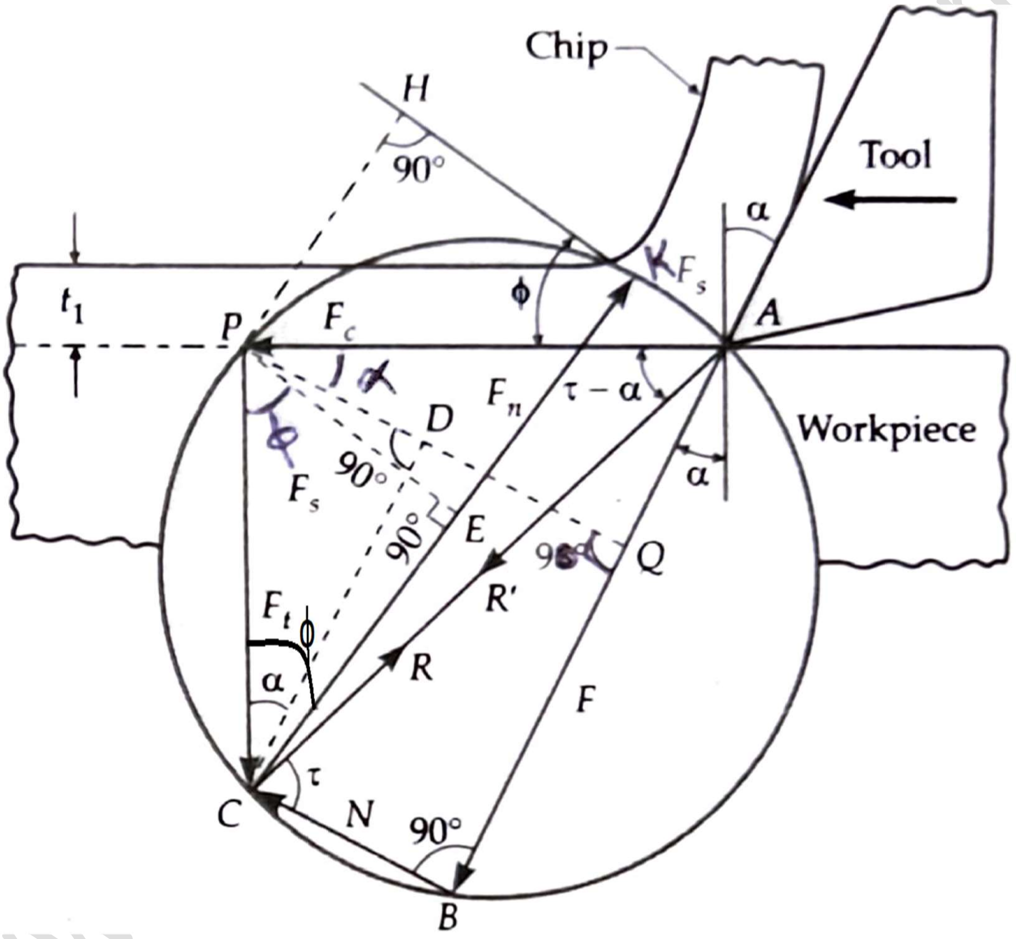


Fig. 11.1 Forces acting in Orthogonal Cutting (Merchant's Circle Diagram).

**Mean Shear stress** $(\tau_s) = \dfrac{F_s}{A_s}$ (kgf/mm$^2$) ..................................(1)

and, **Mean normal stress** $(\sigma_s) = \dfrac{F_n}{A_s}$ (kgf/mm$^2$) ...............................(2)

where, $F_s$ = Shea r force in kgs ;

and $F_n$ = Normal force in kgs

and $A_s$ = Area of shear plane

$$= \frac{A_0}{\sin\phi} \qquad [\text{where, } A_0 = \text{Area of chip before removal} = t_1 . w]$$

We Know,

$$F_s = F_c \cos\phi - F_t \sin\phi$$

By substituting the values of $F_s$ and $A_s$ in equation (1), we get

$$\tau_s = \frac{F_s}{A_s} = \frac{F_c \cos\phi - F_t \sin\phi}{A_0 / \sin\phi}$$

$$= \frac{F_c \cos\phi + F_t \sin\phi}{A_0} . \sin\phi \text{ kg/mm}^2 \qquad \text{..................(3)}$$

$$\tau_s = \frac{F_c \cos\phi + F_t \sin\phi}{t_1 \times w} . \sin\phi \text{ kg/mm}^2 \qquad \text{..................(4)}$$

We also know,

$$F_n = F_t \cos\phi + F_c \sin\phi$$

By substituting this value of $F_n$ and that of $A_s$ in equation (2), we get,

$$\sigma_s = \frac{F_n}{A_s} = \frac{F_n \cos\phi - F_c \sin\phi}{A_0 / \sin\phi}$$

$$= \frac{F_t \cos\phi + F_c \sin\phi}{A_0} . \sin\phi \text{ kg/mm}^2 \qquad \text{..............................(5)}$$

$$\sigma_s = \frac{F_t \cos\phi + F_c \sin\phi}{t_1 \times w} . \sin\phi \text{ kg/mm}^2 \qquad \text{............................(6)}$$

**Now, let the shear strain = γ**

Considering no loss of work during shearing:

Work done in shearing a unit volume of the metal = Shear stress x Shear strain

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i.e.,
$$\frac{F_s \times V_s}{t_1 \times w \times V_c} = \tau_s \times \gamma$$

$$\therefore \qquad \gamma = \frac{F_s \cdot V_s}{\tau_s \times t_1 \times w \times V_c}$$

But we know that

$$\tau_s = \frac{F_s}{A_s} = \frac{F_s}{A_0} .\sin\phi$$

By substituting the value of $\tau_s$ the above equation, we get

$$\gamma = \frac{F_s . V_s}{\frac{F_s}{A_0} \sin\phi \times (t_1 \times w) . V_c} = \frac{F_s \times A_0}{F_s \sin\phi} \times \frac{1}{t_1 \times w} \times \frac{V_s}{V_c}$$

$$= \frac{\cancel{F_s}\cancel{(t_1 \times w)}}{\cancel{F_s} \sin\phi} \cdot \frac{1}{\cancel{t_1 \times w}} \cdot \frac{V_s}{V_c} = \frac{V_s}{V_c} \cdot \frac{1}{\sin\phi} \qquad \text{..................................(7)}$$

We Know,

$$\frac{V_s}{V_c} = \frac{\cos\alpha}{\cos(\phi - \alpha)}$$

So,

$$\gamma = \frac{\cos\alpha}{\cos(\phi - \alpha)\sin\phi} \qquad \text{............................ (8)}$$

## L 12.1 WORK DONE IN CUTTING

The total work done is cutting is equal to the sum of the work done in shearing the metal and the work done in overcoming the friction.

Now, if

W = Total work done

$W_s$ = Work done in shear

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$W_f$ = Work done against friction

Then, $W = W_s + W_f$ ……………………………………………(1)

If no work is lost, the total work done must-be equal to the work supplied by the motor.

i.e., work supplied by the motor should be = $W_s + W_f$

Now, the work supplied by the motor is partly used in cutting and partly in feeding the tool. If Wm be the work supplied by the motor, then:

$W_m$ = Work consumed in cutting+ Work spent in feeding

= $F_e$ x $V_e$ + $F_t$ x feed velocity

In comparison to the cutting velocity the feed velocity is very nominal.

Similarly, $F_t$ is very small as compared to $F_e$. So, the work spent in feeding can be considered as negligible.

Therefore, $W_m = F_c \times V_c$ ………………………………………………(2)

A so , under ideal conditions, i.e. when there is no loss of work ,

$$W_m = W$$

Therefore, $F_c \times V_c = W_s + W_f$ ……………………………………(3)

Now, $W_s = F_s \times V_s$ (Shear Force x shear velocity)

And, $W_f = F \times V_f$ (Friction force x velocity of chip flow)

Or, $(F_c \times V_c) = (F_s \times V_s) + (F \times V_f)$ …………………………………(4)

In the forces are taken in KG and velocities in meters per minute, the work done will be in kgf-m/min.

Total work done per unit volume of the metal removed unit time.

$$= \frac{\text{Total work done in cutting per unit time}}{\text{Volume of the metal removed in unit time}}$$

$$= \frac{F_c \times V_c}{A_0 \times V_c} \quad \text{[where } A_0 = \text{cross-sectional area of chip before removal]}$$

$$= \frac{F_c}{A_0} \quad \text{……………………………………………………………………………(5)}$$

## L 12.2 Horse Power Calculation

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$$\text{H.P. required in cutting} = \frac{\text{Work done in cutting / min}}{4500}$$

$$= \frac{F_c \times V_c}{4500}\ \text{h. p.} \qquad \text{.................................(6)}$$

or

$$= \frac{F_c \times V_c}{4500 \times 1.36}\ \text{kW} \qquad \text{.................................(7)}$$

where, $F_c$ is in kg, and $V_c$ in m/min.

## L 13.1 The Size Effect

The resultant tool force in metal cutting is distributed over the area of the tool that contact the chip and workpiece. No cutting tool is perfectly sharp and in the idealized picture shown in figure 13.1. The cutting edge is represented by a cylindrical surface joining the tool flank and the tool face. As the tool edge "plows” it's way through the work material, the force that acts on the tool cutting edge forms only a small proportion of the cutting force at large value of the undeformed chip thickness $t_1$. At small value of $t_1$, however, the force that act only tool edge is proportionality large and cannot be neglected.

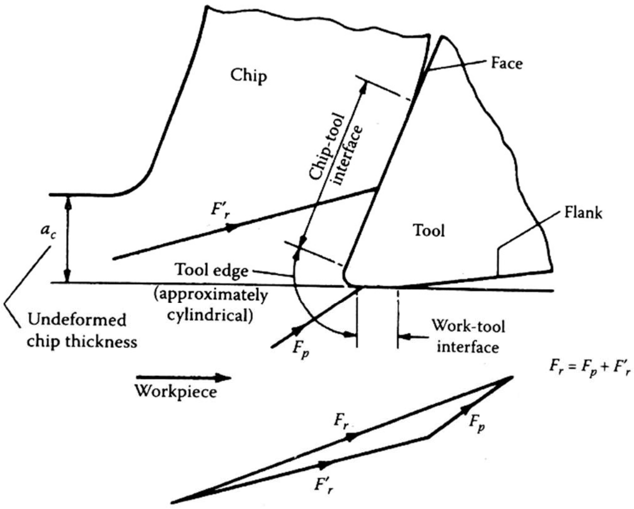

**FIGURE 13.1** Contact regions on a cutting tool, where $F_r$ = resultant tool force, $F'_r$ = force required to remove chip, and $F_p$ = plowing force acting on the tool edge and work-tool interface region.

Because of the high stresses acting near the tool cutting edge, deformation of the tool material may occur in the reason. The deformation would cause contact between the tool and the new workpiece surface over a small area of the tool flank.

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The force acting only tool edge and the force that may act on the tool flank do not contribute to removal of the chip. These forces will be referred to collectively as the plowing force ($F_p$).

The existence of the plowing force result in certain important effects and can explain the so-called "size effect". This term refers to the increase in specific cutting energy ($P_s$) at low value of undeformed chip thickness ($t_1$).

At the relatively small values of chip thickness occurring in process, the specific cutting energy (Ps) increases rapidly with decreasing undeformed chip thickness ($t_1$). It is thought that the plowing force (Fp) is constant and therefore become a greater proportion of the total cutting force as the chip thickness decreases. (Fig.13.2 & 13.3)

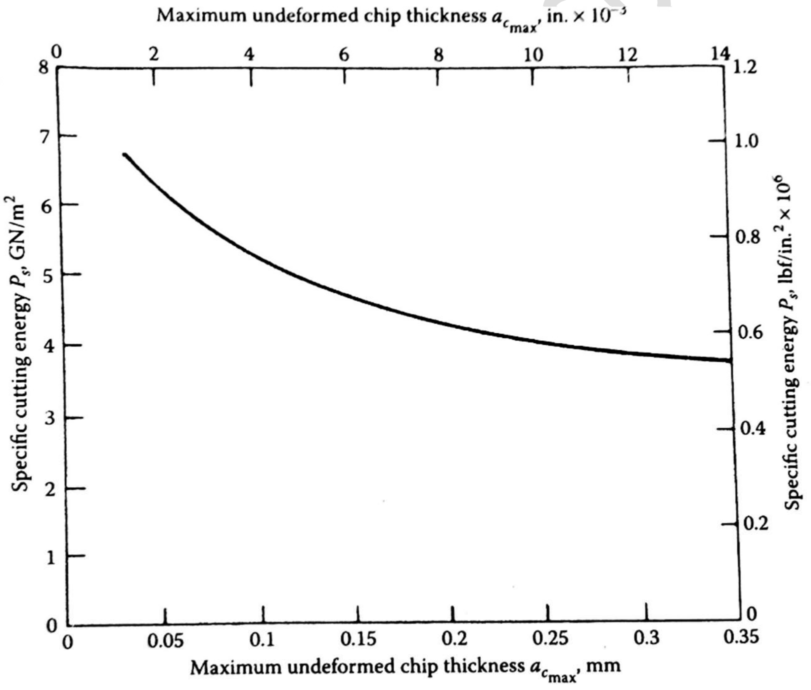

**FIGURE 13.2** Effect of maximum undeformed chip thickness $a_{c_{max}}$ on specific cutting energy $p_s$ during slab milling, where the material is steel, 57 ton/in.$^2$, UTS.

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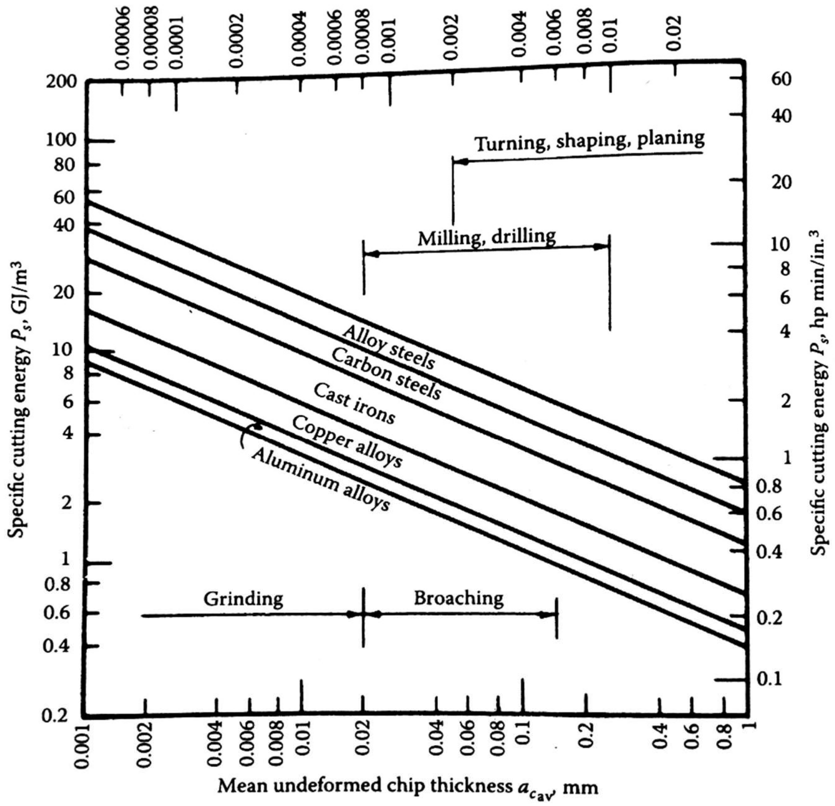

**FIGURE** 13.3 Approximate values of the specific cutting energy $p_s$ for various materials and operations.

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### L 14.1 Apparent mean shear strength of work material

Many analyses of the metal cutting processes have been developed. In general, assumptions have to be made which are often valid only for a restricted range of conditions. A particular difficulty in formulating an analysis off the metal cutting process is the lack of constraint in the process that reduce the range of boundary condition that can be applied. A unique solution does not exist for a particular set of cutting conditions and further that parameters such as the cutting forces, cutting ratio and so on that occurs in a particular case, depends on the conditions that exist when the tool first Contacts the workpiece. A further complication is that different forms of the chip formation mechanism occurs at various cutting conditions.

- Ernst & Merchant suggested that: -

Apparent shear strength

$$\tau_s = \frac{Fs}{As} = \frac{[(Fs\ Cos\emptyset) - (Ft\ Sin\emptyset)]sin\emptyset}{Ao}$$

$A_s$ = Shear plane area

Experiment work of "P.W. Wallance and G. Boothroyd" in 1964 show that the apparent shear strength calculated in the way, remains constant for a given work material over a wide variety of cutting condition. It has been observed, however, that all small feeds, apparent shear strength increases with a decrease in feed. This exception of the constancy of apparent shear strength can be explained by the existence of a constant plowing forces. If plowing force is subtracted from the resultant cutting force ($F_r$), then $F'_r$ (the force required to remove the chip and acting on the Tool face).

$$F'_r = F_r - F_p$$

$$\tau'_s = \left[\left(F'_c \cos\phi\right) - \left(F'_t \sin\phi\right)\right]\frac{\sin\phi}{A_c}$$

where

$F'_c$ = cutting component of $F'_r$
$F'_t$ = thrust component of $F'_r$
$\tau'_s$ = constant property of the work material

Now, above given apparent shear strength remains constant with respect to changing in feed.

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