THEORY OF METAL CUTTING

INTRODUCTION
In an industry, metal components are made into different shapes and dimensions by using various metal working processes.

*Metal working processes are classified into two major groups. They are:*
Non-cutting shaping or chips less or metal forming process - forging, rolling, pressing, etc. Cutting shaping or metal cutting or chip forming process - turning, drilling, milling, etc.

MATERIAL REMOVAL PROCESSES

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

**Principle of machining**
*Fig. 1.1 typically illustrates the basic principle of machining.* A metal rod of irregular shape, size and surface is converted into a finished product of desired dimension and surface finish by machining by proper relative motions of the tool-work pair.

![Fig. 1.1 Principle of machining (Turning)](image)

![Fig. 1.2 Requirements for machining](image)
Purpose of machining
Most of the engineering components such as gears, bearings, clutches, tools, screws and nuts etc. need dimensional and form accuracy and good surface finish for serving their purposes. Preforming like casting, forging etc. generally cannot provide the desired accuracy and finish. For that such preformed parts, called blanks, need semi-finishing and finishing and it is done by machining and grinding. Grinding is also basically a machining process.

*Machining to high accuracy and finish essentially enables a product:*

- Fulfill its functional requirements.
- Improve its performance.
- Prolong its service.

Requirements of machining
*The essential basic requirements for machining a work are schematically illustrated in Fig. 1.2.* The blank and the cutting tool are properly mounted (in fixtures) and moved in a powerful device called machine tool enabling gradual removal of layer of material from the work surface resulting in its desired dimensions and surface finish. Additionally some environment called cutting fluid is generally used to ease machining by cooling and lubrication.

**TYPES OF MACHINE TOOLS**

**Definition of machine tool**
A machine tool is a non-portable power operated and reasonably valued device or system of devices in which energy is expended to produce jobs of desired size, shape and surface finish by removing excess material from the preformed blanks in the form of chips with the help of cutting tools moved past the work surface(s).

**Basic functions of machine tools**
Machine tools basically produce geometrical surfaces like flat, cylindrical or any contour on the preformed blanks by machining work with the help of cutting tools.

*The physical functions of a machine tool in machining are:*

- Firmly holding the blank and the tool.
- Transmit motions to the tool and the blank.
- Provide power to the tool-work pair for the machining action.
- Control of the machining parameters, i.e., speed, feed and depth of cut.
Specification of machine tools
A machine tool may have a large number of various features and characteristics. But only some specific salient features are used for specifying a machine tool. All the manufacturers, traders and users must know how machine tools are specified.

The methods of specification of some basic machine tools are as follows:

Centre lathe:
- Maximum diameter and length of the jobs that can be accommodated.
- Power of the main drive (motor).
- Range of spindle speeds and range of feeds.
- Space occupied by the machine.

Shaper:
- Length, breadth and depth of the bed.
- Maximum axial travel of the bed and vertical travel of the bed / tool. Maximum length of the stroke (of the ram / tool).
- Range of number of strokes per minute.
- Range of table feed.
- Power of the main drive.
- Space occupied by the machine.

Drilling machine (column type):
- Maximum drill size (diameter) that can be used.
- Size and taper of the hole in the spindle.
- Range of spindle speeds. Range of feeds.
- Power of the main drive.
- Range of the axial travel of the spindle / bed.
- Floor space occupied by the machine.

Milling machine (knee type and with arbor):
- Type; ordinary or swivel bed type. Size of the work table.
- Arbor size (diameter).
- Power of the main drive. Range of spindle speed.
- Floor space occupied.
THEORY OF METAL CUTTING

Types of cutting tools
Cutting tools may be classified according to the number of major cutting edges (points) involved as follows:

Single point:
e.g., turning tools, shaping, planning and slotting tools and boring tools.

Double (two) point:
e.g., drills.

Multipoint (more than two):
e.g., milling cutters, broaching tools, hobs, gear shaping cutters etc.

Geometry of single point cutting (turning) tools
Both material and geometry of the cutting tools play very important roles on their performances in achieving effectiveness, efficiency and overall economy of machining.

Concept of rake and clearance angles of cutting tools
The word tool geometry is basically referred to some specific angles or slope of the salient faces and edges of the tools at their cutting point. Rake angle and clearance angle are the most significant for all the cutting tools. The concept of rake angle and clearance angle will be clear from some simple operations shown in Fig. 1.3.

Definition
Rake angle (γ): Angle of inclination of rake surface from reference plane.
Clearance angle (α): Angle of inclination of clearance or flank surface from the finished surface. Rake angle is provided for ease of chip flow and overall machining. Rake angle may be positive, or negative or even zero as shown in Fig. 1.4 (a, b and c).

Fig. 1.3 Rake and clearance angles of cutting tools

Fig. 1.4 Three possible types of rake angles (a) Positive rake (b) Zero rake (c) Negative rake
Relative advantages of such rake angles are:

**Positive rake** - helps reduce cutting force and thus cutting power requirement.
**Zero rake** - to simplify design and manufacture of the form tools.
**Negative rake** - to increase edge-strength and life of the tool.

Clearance angle is essentially provided to avoid rubbing of the tool (flank) with the machined surface which causes loss of energy and damages of both the tool and the job surface. Hence, clearance angle is a must and must be positive ($\pm 3^0$ to $15^0$) depending upon tool-work materials and type of the machining operations like turning, drilling, boring etc.

**Description of tool geometry in Machine Reference System**

This system is also called as ASA system; ASA stands for American Standards Association.

Geometry of a cutting tool refers mainly to its several angles or slopes of its salient working surfaces and cutting edges. Those angles are expressed with respect to some planes of reference.

In Machine Reference System (ASA), the three planes of reference and the coordinates are chosen based on the configuration and axes of the machine tool concerned. The planes and axes used for expressing tool geometry in ASA system for turning operation are shown in Fig. 1.5 (b).

![Fig 1.5 (a) Basic features of single point reference cutting (turning) tool](image)

![Fig. 1.5 (b) Planes and axes of in ASA system](image)

The planes of reference and the coordinates used in ASA system for tool geometry are:

- $\Pi_R$ - $\Pi_X$ - $\Pi_Y$ and $X_m - Y_m - Z_m$; where,
  - $\Pi_R$ = Reference plane; plane perpendicular to the velocity vector. Shown in Fig. 1.5 (b).
  - $\Pi_X$ = Machine longitudinal plane; plane perpendicular to $\Pi_R$ and taken in the direction of assumed longitudinal feed.
  - $\Pi_Y$ = Machine transverse plane; plane perpendicular to both $\Pi_R$ and $\Pi_X$. [This plane is taken in the direction of assumed cross feed]
The axes $X_m$, $Y_m$ and $Z_m$ are in the direction of longitudinal feed, cross feed and cutting velocity (vector) respectively. The main geometrical features and angles of single point tools in ASA systems and their definitions will be clear from Fig. 1.6.

![Fig. 1.6 Tool angles in ASA system](image)

**Definition of:**

**Shank:** The portion of the tool bit which is not ground to form cutting edges and is rectangular in cross section. [Fig. 1.5 (a)]

**Face:** The surface against which the chip slides upward. [Fig. 1.5 (a)]

**Flank:** The surface which face the work piece. There are two flank surfaces in a single point cutting tool. One is principal flank and the other is auxiliary flank. [Fig. 1.5 (a)]

**Heel:** The lowest portion of the side cutting edges. [Fig. 1.5 (a)]

**Nose radius:** The conjunction of the side cutting edge and end cutting edge. It provides strengthening of the tool nose and better surface finish. [Fig. 1.5 (a)]

**Base:** The underside of the shank. [Fig. 1.5 (a)]

**Rake angles:** [Fig. 1.6]

$\gamma_x = $ Side rake angle (axial rake): angle of inclination of the rake surface from the reference plane ($\pi_R$) and measured on machine reference plane, $\pi_X$.

$\gamma_y = $ Back rake angle: angle of inclination of the rake surface from the reference plane and measured on machine transverse plane, $\pi_Y$.

**Clearance angles:** [Fig. 1.6]

$\alpha_x = $ Side clearance angle (Side relief angle): angle of inclination of the principal flank from the machined surface (or CV) and measured on $\pi_X$ plane.

$\alpha_y = $ Back clearance angle (End relief angle): same as $\alpha_x$ but measured on $\pi_Y$ plane.
**Cutting angles:** [Fig. 1.6]

\( \varphi_s = \) Side cutting edge angle (Approach angle): angle between the principal cutting edge (its projection on \( \Pi_R \)) and \( \Pi_Y \) and measured on \( \Pi_R \).

\( \varphi_e = \) End cutting edge angle: angle between the end cutting edge (its projection on \( \Pi_R \)) from \( \Pi_X \) and measured on \( \Pi_R \).

**Designation of tool geometry**

The geometry of a single point tool is designated or specified by a series of values of the salient angles and nose radius arranged in a definite sequence as follows:

*Designation (Signature) of tool geometry in ASA System* - \( \gamma_y, \gamma_x, \alpha_y, \alpha_x, \varphi_e, \varphi_s, r \) (in inch) Example: A tool having 7, 8, 6, 7, 5, 6, 0.1 as designation (Signature) in ASA system will have the following angles and nose radius.

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<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Back rack angle</td>
<td>7°</td>
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<tr>
<td>Side rake angle</td>
<td>8°</td>
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<td>Back clearance angle</td>
<td>6°</td>
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<td>Side clearance angle</td>
<td>7°</td>
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<tr>
<td>End cutting edge angle</td>
<td>5°</td>
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<tr>
<td>Side cutting edge angle</td>
<td>6°</td>
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<tr>
<td>Nose radius</td>
<td>0.1 inch</td>
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**TYPES OF METAL CUTTING PROCESSES**

*The metal cutting process is mainly classified into two types. They are:*

**Orthogonal cutting process** (Two - dimensional cutting) - The cutting edge or face of the tool is 90° to the line of action or path of the tool or to the cutting velocity vector. This cutting involves only two forces and this makes the analysis simpler.

**Oblique cutting process** (Three - dimensional cutting) - The cutting edge or face of the tool is inclined at an angle less than 90° to the line of action or path of the tool or to the cutting velocity vector. Its analysis is more difficult of its three dimensions.

**Orthogonal and oblique cutting**

It is appears from the diagram *shown in Fig. 1.7 (a and b)* that while turning ductile material by a sharp tool, the continuous chip would flow over the tool’s rake surface and in the direction apparently perpendicular to the principal cutting edge, i.e., along orthogonal plane which is normal to the cutting plane containing the principal cutting edge. But practically, the chip may not flow along the orthogonal plane for several factors like presence of inclination angle, \( \lambda \), etc.
The role of inclination angle, $\lambda$ on the direction of chip flow is schematically shown in Fig. 1.8 which visualizes that:

When $\lambda = 0^0$, the chip flows along orthogonal plane, i.e, $\rho_c = 0^0$.

When $\lambda \neq 0^0$, the chip flow is deviated from $\pi_o$ and $\rho_c = \lambda$ where $\rho_c$ is chip flow deviation (from $\pi_o$) angle.

**Orthogonal cutting:** When chip flows along orthogonal plane, $\pi_o$, i.e., $\rho_c = 0^0$.

**Oblique cutting:** When chip flow deviates from orthogonal plane, i.e. $\rho_c \neq 0^0$.

But practically $\rho_c$ may be zero even if $\lambda = 0^0$ and $\rho_c$ may not be exactly equal to $\lambda$ even if $\lambda \neq 0^0$. Because there is some other (than $\lambda$) factors also may cause chip flow deviation.

**CHIP FORMATION**

**Mechanism of chip formation**

Machining is a semi-finishing or finishing process essentially done to impart required or stipulated dimensional and form accuracy and surface finish to enable the product to:

- Fulfill its basic functional requirements.
- Provide better or improved performance.
- Render long service life.
Machining is a process of gradual removal of excess material from the preformed blanks in the form of chips. *The form of the chips is an important index of machining because it directly or indirectly indicates:*

- Nature and behavior of the work material under machining condition.
- Specific energy requirement (amount of energy required to remove unit volume of work material) in machining work.
- Nature and degree of interaction at the chip-tool interfaces.

*The form of machined chips depends mainly upon:*
- Work material.
- Material and geometry of the cutting tool.
- Levels of cutting velocity and feed and also to some extent on depth of cut.
- Machining environment or cutting fluid that affects temperature and friction at the chip-tool and work-tool interfaces.

*Knowledge of basic mechanism(s) of chip formation helps to understand the characteristics of chips and to attain favorable chip forms.*

**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. 1.10.

![Fig. 1.10 Compression of work material (layer) ahead of the tool tip](image)

The force exerted by the tool on the chip arises out of the normal force, N and frictional force, F as indicated in Fig. 1.10. 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* using a card analogy as shown in Fig. 1.11 (a).

![Card analogy](image)

(a) Shifting of the postcards by partial sliding against each other (b) Chip formation by shear in lamella Fig. 1.11 Piispannen 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. 1.11 (b)*. 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.

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. 1.12*, depend upon:
- Work material.
- Tool; material and geometry.
- The machining speed (VC) and feed (so).
- Cutting fluid application.

![Deformation zones](image)

Fig. 1.12 Primary and secondary deformation zones in the chip
The overall deformation process causing chip formation is quite complex and hence needs thorough experimental studies for clear understanding the phenomena and its dependence on the affecting parameters. The feasible and popular experimental methods for this purpose are:

- Study of deformation of rectangular or circular grids marked on side surface as shown in Fig. 1.13 (a and b).
- Microscopic study of chips frozen by drop tool or quick stop apparatus.
- Study of running chips by high speed camera fitted with low magnification microscope.

It has been established by several analytical and experimental methods including circular grid deformation that though the chips are initially compressed ahead of the tool tip, the final deformation is accomplished mostly by shear in machining ductile materials. However, machining of ductile materials generally produces flat, curved or coiled continuous chips.

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. 1.14 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 work piece through the minimum resistance path as indicated in Fig. 1.14.
Fig. 1.14 Development and propagation of crack causing chip separation.

*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. 1.15 (a, b, c, d and e).

(a) Separation (b) Swelling (c) Further swelling (d) Separation (e) Swelling again Fig. 1.15 Schematic view of chip formation in machining brittle materials

**Built-up-Edge (BUE) formation**

*Causes of formation*

In machining ductile metals like steels with long chip-tool contact length, lot of stress and temperature develops in the secondary deformation zone at the chip-tool interface. Under such high stress and temperature in between two clean surfaces of metals, strong bonding may locally take place due to adhesion similar to welding. Such bonding will be encouraged and accelerated if the chip tool materials have mutual affinity or solubility.

*The weldment starts forming as an embryo at the most favorable location and thus gradually grows as schematically shown in Fig. 1.20.*
With the growth of the BUE, the force, $F$ (shown in Fig. 1.20) also gradually increases due to wedging action of the tool tip along with the BUE formed on it. Whenever the force, $F$ exceeds the bonding force of the BUE, the BUE is broken or sheared off and taken away by the flowing chip. Then again BUE starts forming and growing. This goes on repeatedly.

**Characteristics of BUE**

*Built-up-edges are characterized by its shape, size and bond strength, which depend upon:*

- Work tool materials.
- Stress and temperature, i.e., cutting velocity and feed.
- Cutting fluid application governing cooling and lubrication.

*BUE may develop basically in three different shapes as schematically shown in Fig. 1.21 (a, b and c).*

(a) Positive wedge  (b) Negative wedge  (c) Flat type

Fig. 1.21 Different forms of built-up-edge.

Fig. 1.22 Overgrowing and overflowing of BUE causing surface roughness
In machining too soft and ductile metals by tools like high speed steel or uncoated carbide the BUE may grow larger and overflow towards the finished surface through the flank as shown in Fig. 1.22. While the major part of the detached BUE goes away along the flowing chip, a small part of the BUE may remain stuck on the machined surface and spoils the surface finish. BUE formation needs certain level of temperature at the interface depending upon the mutual affinity of the work-tool materials. With the increase in $V_C$ and so the cutting temperature rises and favors BUE formation.

But if $V_C$ is raised too high beyond certain limit, BUE will be squashed out by the flowing chip before the BUE grows. Fig. 1.23 shows schematically the role of increasing $V_C$ and so on BUE formation (size). But sometime the BUE may adhere so strongly that it remains strongly bonded at the tool tip and does not break or shear off even after reasonably long time of machining. Such harmful situation occurs in case of certain tool-work materials and at speed-feed conditions which strongly favor adhesion and welding.

![Fig. 1.23 Role of cutting velocity and feed on BUE formation](image)

**Effects of BUE formation**

- Formation of BUE causes several harmful effects, such as:
- It unfavorably changes the rake angle at the tool tip causing increase in cutting forces and power consumption.
- Repeated formation and dislodgement of the BUE causes fluctuation in cutting forces and thus induces vibration which is harmful for the tool, job and the machine tool.
- Surface finish gets deteriorated.
- May reduce tool life by accelerating tool-wear at its rake surface by adhesion and flaking occasionally, formation of thin flat type stable BUE may reduce tool wear at the rake face.
TYPES OF CHIPS

Different types of chips of various shape, size, colour etc. are produced by machining depending upon:
Type of cut, i.e., continuous (turning, boring etc.) or intermittent cut (milling). Work material (brittle or ductile etc.).
Cutting tool geometry (rake, cutting angles etc.).
Levels of the cutting velocity and feed (low, medium or high). Cutting fluid (type of fluid and method of application).

The basic major types of chips and the conditions generally under which such types of chips form are given below:

Continuous chips without BUE

When the cutting tool moves towards the work piece, there occurs a plastic deformation of the work piece and the metal is separated without any discontinuity and it moves like a ribbon. The chip moves along the face of the tool. This mostly occurs while cutting a ductile material. It is desirable to have smaller chip thickness and higher cutting speed in order to get continuous chips. Lesser power is consumed while continuous chips are produced. Total life is also mortised in this process. The formation of continuous chips is schematically shown in Fig. 1.24.

The following condition favors the formation of continuous chips without BUE chips:
Work material - ductile.
Cutting velocity - high. Feed - low.
Rake angle - positive and large.
Cutting fluid - both cooling and lubricating.
**Discontinuous chips**  
This is also called as segmental chips. This mostly occurs while cutting brittle material such as cast iron or low ductile materials. Instead of shearing the metal as it happens in the previous process, the metal is being fractured like segments of fragments and they pass over the tool faces. Tool life can also be more in this process. Power consumption as in the previous case is also low. *The formation of continuous chips is schematically shown in Fig. 1.25.*

*The following condition favors the formation of discontinuous chips:*
- Of irregular size and shape: - work material - brittle like grey cast iron.
- Of regular size and shape: - work material ductile but hard and work hardenable.
- Feed rate - large.
- Tool rake - negative.
- Cutting fluid - absent or inadequate.

**Continuous chips with BUE**  
When cutting a ductile metal, the compression of the metal is followed by the high heat at tool face. This in turns enables part of the removed metal to be welded into the tool. This is known as built up edge, a very hardened layer of work material attached to the tool face, which tends to act as a cutting edge itself replacing the real cutting tool edge.

The built-up edge tends to grow until it reaches a critical size (~0.3 mm) and then passes off with the chip, leaving small fragments on the machining surface. Chip will break free and cutting forces are smaller, but the effect is a rough machined surface. The built-up edge disappears at high cutting speeds.

The weld metal is work hardened or strain hardened. While the cutting process is continued, some of built up edge may be combined with the chip and pass along the tool face. Some of the built up edge may be permanently fixed on the tool face. This produces a rough surface finish and the tool life may be reduced. *The formation of continuous chips with BUE is schematically shown in Fig. 1.26.*
The following condition favors the formation of continuous chips with BUE chips:
   a) Work material - ductile.
   b) Cutting velocity - low (~0.5 m/s). Small or negative rake angles.
   c) Feed - medium or large.
   d) Cutting fluid - inadequate or absent.

Often in machining ductile metals at high speed, the chips are deliberately broken into small segments of regular size and shape by using chip breakers mainly for convenience and reduction of chip-tool contact length.

**Chip breakers**

**Need and purpose of chip-breaking**

Continuous machining like turning of ductile metals, unlike brittle metals like grey cast iron, produce continuous chips, which leads to their handling and disposal problems. The problems become acute when ductile but strong metals like steels are machined at high cutting velocity for high MRR by flat rake face type carbide or ceramic inserts. The sharp edged hot continuous chip that comes out at very high speed:

   - Becomes dangerous to the operator and the other people working in the vicinity. May impair the finished surface by entangling with the rotating job.
   - Creates difficulties in chip disposal.

Therefore it is essentially needed to break such continuous chips into small regular pieces for:

   a. Safety of the working people.
   b. Prevention of damage of the product.
   c. Easy collection and disposal of chips.

Chip breaking is done in proper way also for the additional purpose of improving machinability by reducing the chip-tool contact area, cutting forces and crater wear of the cutting tool.

**Principles of chip-breaking**

In respect of convenience and safety, closed coil type chips of short length and ‘coma’ shaped broken-to-half turn chips are ideal in machining of ductile metals and alloys at high speed.

The principles and methods of chip breaking are generally classified as follows:

**Self chip breaking** - This is accomplished without using a separate chip-breaker either as an attachment or an additional geometrical modification of the tool.

**Forced chip breaking** - This is accomplished by additional tool geometrical features or devices.
a) **Self breaking of chips**

Ductile chips usually become curled or tend to curl (like clock spring) even in machining by tools with flat rake surface due to unequal speed of flow of the chip at its free and generated (rubbed) surfaces and unequal temperature and cooling rate at those two surfaces. With the increase in cutting velocity and rake angle (positive) the radius of curvature increases, which is more dangerous.

In case of oblique cutting due to presence of inclination angle, restricted cutting effect etc. the curled chips deviate laterally resulting helical coiling of the chips. *The curled chips may self break:*

By natural fracturing of the strain hardened outgoing chip after sufficient cooling and spring back *as indicated in Fig. 1.27 (a).* This kind of chip breaking is generally observed under the condition close to that which favors formation of jointed or segmented chips.

By striking against the cutting surface of the job, *as shown in Fig. 1.27 (b),* mostly under pure orthogonal cutting.

By striking against the tool flank after each half to full turn *as indicated in Fig. 1.27 (c).*

(b) **Forced chip-breaking**

The hot continuous chip becomes hard and brittle at a distance from its origin due to work hardening and cooling. If the running chip does not become enough curled and work hardened, it may not break. In that case the running chip is forced to bend or closely curl so that it breaks into pieces at regular intervals. Such broken chips are of regular size and shape depending upon the configuration of the chip breaker. *Chip breakers are basically of two types:*

- In-built type.
- Clamped or attachment type.

*In-built breakers are in the form of step or groove at the rake surface near the cutting edges of the tools.*

*SUCH CHIP BREAKERS ARE PROVIDED EITHER:*
After their manufacture - in case of HSS tools like drills, milling cutters, broaches etc and brazed type carbide inserts.

During their manufacture by powder metallurgical process - e.g., throw away type inserts of carbides, ceramics and cermets.

*The basic principle of forced chip breaking is schematically shown in Fig. 1.28.*

When the strain hardened and brittle running chip strikes the heel, the cantilever chip gets forcibly bent and then breaks.

![Diagram of forced chip breaking](image)

W = width, H = height, \( \beta \) = shear angle

*Fig. 1.28 Principle of forced chip breaking*

*Fig. 1.29 (a, b, c and d) schematically shows some commonly used step type chip breakers:*

- Parallel step.
- Angular step; positive and negative type.
- Parallel step with nose radius - for heavy cuts.

![Step type chip breakers](image)

*Fig. 1.29 Step type in-built chip breaker (a) Parallel step (b) Parallel and radiused (c) Positive angular (d) Negative angular*

*Fig. 1.30 (a and b) schematically shows some commonly used groove type in-built chip breakers:*

![Groove type chip breakers](image)
The unique characteristics of in-built chip breakers are:
The outer end of the step or groove acts as the heel that forcibly bends and fractures the running chip.
Simple in configuration, easy manufacture and inexpensive.
The geometry of the chip-breaking features is fixed once made. (i.e., cannot be controlled) Effective only for fixed range of speed and feed for any given tool-work combination.

**MERCHANT’S CIRCLE DIAGRAM and its use**
In orthogonal cutting when the chip flows along the orthogonal plane, \( \pi_0 \), the cutting force (resultant) and its components \( P_Z \) and \( P_{XY} \) remain in the orthogonal plane. *Fig. 1.39 is schematically showing the forces acting on a piece of continuous chip coming out from the shear zone at a constant speed.* That chip is apparently in a state of equilibrium.

Fig 1.39 Development of Merchant’s circle diagram  
Fig. 1.40 Merchant’s Circle Diagram with cutting forces
The forces in the chip segment are:
From job-side:

\[ P_s \] - Shear force.

\[ P_n \] - force normal to the shear force.

From the tool side:
\[ R_1 = R \] (in state of equilibrium)

where, \( R_1 = F + N \)

\( N \) - Force normal to rake face.
\( F \) - Friction force at chip tool interface.

The resulting cutting force \( R \) or \( R_1 \) can be resolved further as,

\[ R_1 = P_Z + P_{XY} \]

where,

\( P_Z \) - Force along the velocity vector.
\( P_{XY} \) - force along orthogonal plane.

The circle(s) drawn taking \( R \) or \( R_1 \) as diameter is called Merchant’s circle which contains all the force components concerned as intercepts. The two circles with their forces are combined into one circle having all the forces contained in that as shown by the diagram called Merchant’s Circle Diagram (MCD) in Fig. 1.40.

The significance of the forces displayed in the Merchant’s Circle Diagram is:
\( P_s \) - The shear force essentially required to produce or separate the chip from the parent body by shear. \( P_n \) - Inherently exists along with \( P_s \).
\( F \) - Friction force at the chip tool interface.
\( N \) - Force acting normal to the rake surface.

\( P_Z = P_{XY} - P_X + P_Y \) = main force or power component acting in the direction of cutting velocity.

The magnitude of \( P_s \) provides the yield shear strength of the work material under the cutting action. The values of \( F \) and the ratio of \( F \) and \( N \) indicate the nature and degree of interaction like friction at the chip tool interface. The force components \( P_X, P_Y, P_Z \) are generally obtained by direct measurement. Again \( P_Z \) helps in determining cutting power and specific energy requirement. The force components are also required to design the cutting tool and the machine tool.
Advantageous use of Merchant’s circle diagram

Proper use of MCD enables the followings:
- Easy, quick and reasonably accurate determination of several other forces from a few known forces involved in machining.
- Friction at chip tool interface and dynamic yield shear strength can be easily determined. Equations relating the different forces are easily developed.

Some limitations of use of MCD:
- Merchant’s circle diagram (MCD) is only valid for orthogonal cutting.
- By the ratio, F/N, the MCD gives apparent (not actual) coefficient of friction. It is based on single shear plane theory.

 TOOL WEAR

Failure of cutting tools

Smooth, safe and economic machining necessitates:
Prevention of premature and terrible failure of the cutting tools. Reduction of rate of wear of tool to prolong its life.

To accomplish the aforesaid objectives one should first know why and how the cutting tools fail. Cutting tools generally fail by:

- Mechanical breakage due to excessive forces and shocks. Such kind of tool failure is random and catastrophic in nature and hence is extremely detrimental.
- Quick dulling by plastic deformation due to intensive stresses and temperature. This type of failure also occurs rapidly and is quite detrimental and unwanted.
- Gradual wear of the cutting tool at its flanks and rake surface.

The first two modes of tool failure are very harmful not only for the tool but also for the job and the machine tool. Hence these kinds of tool failure need to be prevented by using suitable tool materials and geometry depending upon the work material and cutting condition.

But failure by gradual wear, which is inevitable, cannot be prevented but can be slowed down only to enhance the service life of the tool. The cutting tool is withdrawn immediately after it fails or, if possible, just before it totally fails. For that one must understand that the tool has failed or is going to fail shortly.
It is understood or considered that the tool has failed or about to fail by one or more of the following conditions:

(a) In R&D laboratories
- Total breakage of the tool or tool tip(s).
- Massive fracture at the cutting edge(s).
- Excessive increase in cutting forces and/or vibration.
- Average wear (flank or crater) reaches its specified limit(s).

(b) In machining industries
- Excessive (beyond limit) current or power consumption. Excessive vibration and/or abnormal sound (chatter).
- Total breakage of the tool.
- Dimensional deviation beyond tolerance.
- Rapid worsening of surface finish.
- Adverse chip formation.

Mechanisms and pattern (geometry) of cutting tool wear
For the purpose of controlling tool wear one must understand the various mechanisms of wear that the cutting tool undergoes under different conditions.

The common mechanisms of cutting tool wear are:
(a) Mechanical wear
Thermally insensitive type; like abrasion, chipping and de-lamination. Thermally sensitive type; like adhesion, fracturing, flaking etc.
Flank wear is a flat portion worn behind the cutting edge which eliminates some clearance or relief. It takes place when machining brittle materials. Wear at the tool-chip interface occurs in the form of a depression or crater. It is caused by the pressure of the chip as it slides up the face of the cutting tool. Both flank and crater wear take place when feed is greater than 0.15 mm/rev at low or moderate speeds.

(b) Thermo chemical wear
Macro-diffusion by mass dissolution. Micro-diffusion by atomic migration.
In diffusion wear the material from the tool at its rubbing surfaces, particularly at the rake surface gradually diffuses into the flowing chips either in bulk or atom by atom when the tool material has chemical affinity or solid solubility towards the work material. The rate of such tool wears increases with the increase in temperature at the cutting zone. This wear becomes predominant when the cutting temperature becomes very high due to high cutting velocity and high strength of the work material.
(c) **Chemical wear**
Chemical wear, leading to damages like grooving wear may occur if the tool material is not enough chemically stable against the work material and/or the atmospheric gases.

(d) **Galvanic wear**
Galvanic wear, based on electrochemical dissolution, seldom occurs when the work and tool materials are electrically conductive, cutting zone temperature is high and the cutting fluid acts as an electrolyte.

**Measurement of tool wear**
*The various methods are:*

(a) By loss of tool material in volume or weight, in one life time - this method is crude and is generally applicable for critical tools like grinding wheels.

(b) By grooving and indentation method - in this approximate method wear depth is measured indirectly by the difference in length of the groove or the indentation outside and inside the worn area.

(c) Using optical microscope fitted with micrometer - very common and effective method.

(d) Using scanning electron microscope (SEM) - used generally, for detailed study; both qualitative and quantitative.

(e) Talysurf, especially for shallow crater wear.

**TOOL LIFE**

*Definition:*
Tool life generally indicates the amount of satisfactory performance or service rendered by a fresh tool or a cutting point till it is declared failed. *Tool life is defined in two ways:*

(a) **In R & D:** Actual machining time (period) by which a fresh cutting tool (or point) satisfactorily works after which it needs replacement or reconditioning. The modern tools hardly fail prematurely or abruptly by mechanical breakage or rapid plastic deformation. Those fail mostly by wearing process which systematically grows slowly with machining time. In that case, tool life means the span of actual machining time by which a fresh tool can work before attaining the specified limit of tool wear. Mostly tool life is decided by the machining time till flank wear, $V_B$ reaches 0.3 mm or crater wear, $K_T$ reaches 0.15 mm.

(b) **In industries or shop floor:** The length of time of satisfactory service or amount of acceptable output provided by a fresh tool prior to it is required to replace or recondition.
Assessment of tool life
For R & D purposes, tool life is always assessed or expressed by span of machining time in minutes, whereas, in industries besides machining time in minutes some other means are also used to assess tool life, depending upon the situation, such as:
- Number of pieces of work machined.
- Total volume of material removed.
- Total length of cut.

TAYLOR’S TOOL LIFE EQUATION
Wear and hence tool life of any tool for any work material is governed mainly by the level of the machining parameters i.e., cutting velocity ($V_C$), feed ($f$) and depth of cut ($t$). Cutting velocity affects maximum and depth of cut minimum.

The usual pattern of growth of cutting tool wear (mainly $V_B$), principle of assessing tool life and its dependence on cutting velocity are schematically shown in Fig. 1.50.

![Fig. 1.50 Growth of flank wear and assessment of tool life](image)

The tool life obviously decreases with the increase in cutting velocity keeping other conditions unaltered as indicated in Fig. 1.51. If the tool lives, $T_1$, $T_2$, $T_3$, $T_4$ etc are plotted against the corresponding cutting velocities, $V_1$, $V_2$, $V_3$, $V_4$ etc as shown in Fig. 1.51, a smooth curve like a rectangular hyperbola is found to appear. When F. W. Taylor plotted the same figure taking both $V$ and $T$ in log-scale, a more distinct linear relationship appeared as schematically shown in Fig. 1.52.
with the slope, \( n \) and intercept, \( c \), Taylor derived the simple equation as,

\[
\frac{1}{T} = \frac{1}{C_T} V_C^n + \frac{1}{C_T} C
\]

where, \( n \) is called, Taylor’s tool life exponent. The values of both ‘\( n \)’ and ‘\( c \)’ depend mainly upon the tool-work materials and the cutting environment (cutting fluid application). The value of \( C \) depends also on the limiting value of \( V_B \) undertaken (i.e., 0.3 mm, 0.4 mm, 0.6 mm etc.).

**Modified Taylor’s tool life equation**

In Taylor’s tool life equation, only the effect of variation of cutting velocity, \( V_C \) on tool life has been considered. But practically, the variation in feed (\( f \)) and depth of cut (\( t \)) also play role on tool life to some extent. Taking into account the effects of all those parameters, the Taylor’s tool life equation has been modified as,

\[
\frac{1}{T} = \frac{1}{C_T} V_C^x + \frac{1}{C_T} V_C^y + \frac{1}{C_T} V_C^z + \frac{1}{C_T} C
\]

where, \( T = \) tool life in minutes, \( C_T \) a constant depending mainly upon the tool-work materials and the limiting value of \( V_B \) undertaken. \( x \), \( y \) and \( z \) exponents so called tool life exponents depending upon the tool - work materials and the machining environment. Generally, \( x > y > z \) as \( V_C \) affects tool life maximum and \( t \) minimum. The values of the constants, \( C_T \), \( x \), \( y \) and \( z \) are available in Machining Data Handbooks or can be evaluated by machining tests.

**Tool life in terms of metal removal**

The volume of metal removal from the work piece between tool sharpening for definite depth of cut, feed and cutting speed can be determined as follows. For example in case of turning:

\[
\text{Cutting speed } V_C = \pi DN / 1000 \text{ m/min}
\]
where \( D \) - Diameter of work piece (mm).
\( N \) - Rotation speed of work piece (rpm).

Let
\( t \) - Depth of cut (mm).
\( f \) - Feed rate (mm/min).
\( t_{tf} \) - Time of tool failure (min).
\( T \) - Tool life in 1 \( \text{mm}^3 \) of metal removal.

Volume of metal removed per revolution = \( \pi D t f \text{ mm}^3 \)
Volume of metal removed per minute = \( \pi D t f N \text{ mm}^3 \)
Volume of metal removed in ‘\( t_{tf} \)’ minute = \( \pi D t f N t_{tf} \text{ mm}^3 \)
Therefore, Volume of metal removed between tool grinds = \( \pi D t f N t_{tf} \text{ mm}^3 \)
\( T = \pi D t f N t_{tf} \text{ mm}^3 = 1000.V_C t f t_{tf} \text{ mm}^3 \)

Factors affecting tool life

The life of the cutting tool is affected by the following factors:
- Cutting speed.
- Feed and depth of cut.
- Tool geometry.
- Tool material.
- Cutting fluid.
- Work piece material.
- Rigidity of work, tool and machine.
CUTTING TOOL MATERIALS

Essential properties of cutting tool materials

The cutting tools need to be capable to meet the growing demands for higher productivity and economy as well as to machine the exotic materials which are coming up with the rapid progress in science and technology.

The cutting tool material of the day and future essentially require the following properties to resist or retard the phenomena leading to random or early tool failure:

- High mechanical strength; compressive, tensile, and TRA. Fracture toughness - high or at least adequate.
- High hardness for abrasion resistance.
- High hot hardness to resist plastic deformation and reduce wear rate at elevated temperature. Chemical stability or inertness against work material, atmospheric gases and cutting fluids. Resistance to adhesion and diffusion.
- Thermal conductivity - low at the surface to resist incoming of heat and high at the core to quickly dissipate the heat entered.
- High heat resistance and stiffness.
- Manufacturability, availability and low cost.

Needs and chronological development of cutting tool materials

- With the progress of the industrial world it has been needed to continuously develop and improve the cutting tool materials and geometry:
- To meet the growing demands for high productivity, quality and economy of machining.
- To enable effective and efficient machining of the exotic materials those are coming up with the rapid and vast progress of science and technology.
- For precision and ultra-precision machining.
- For micro and even nano machining demanded by the day and future.

It is already stated that the capability and overall performance of the cutting tools depend upon:

1. The cutting tool materials.
2. The cutting tool geometry.
3. Proper selection and use of those tools.
4. The machining conditions and the environments.
Out of which the tool material plays the most vital role. The relative contribution of the cutting tool materials on productivity, for instance, can be roughly assessed from Fig. 1.41.

![Fig. 1.41 Productivity raised by cutting tool materials](image)

<table>
<thead>
<tr>
<th>Need</th>
<th>Year</th>
<th>Development</th>
</tr>
</thead>
<tbody>
<tr>
<td>Automobile</td>
<td>1910</td>
<td>Stellite</td>
</tr>
<tr>
<td>World war - I</td>
<td>1920</td>
<td>HSS (V ~ 4 %, Co ~ 12 % in W &amp; Cr)</td>
</tr>
<tr>
<td>Aircraft</td>
<td>1930</td>
<td>Sintered Carbide for C.I</td>
</tr>
<tr>
<td>World war - II</td>
<td>1940</td>
<td>Carbide for steels</td>
</tr>
<tr>
<td>Chemical, Petro-chemical &amp; Polymer industries</td>
<td>1950</td>
<td>HSS with high V, Mo, Co &amp; C, Plan ceramics, Synthetic Diamond</td>
</tr>
<tr>
<td>Jet engines &amp; Space programs</td>
<td>1960</td>
<td>Ceramics &amp; Cermet</td>
</tr>
<tr>
<td>Reduction of cost of manufacturing</td>
<td>1970</td>
<td>Coated Carbides, PM-HSS &amp; PCD</td>
</tr>
<tr>
<td>Defence super alloys</td>
<td>1980</td>
<td>CBN, Coated HSS &amp; SIALON</td>
</tr>
<tr>
<td>Just-in-time</td>
<td>1990</td>
<td>Diamond coated Carbides</td>
</tr>
</tbody>
</table>

![Fig 1.42 Chronological development of cutting tool materials](image)
Characteristics and applications of cutting tool materials

a) High Speed Steel (HSS)

Advent of HSS in around 1905 made a break through at that time in the history of cutting tool materials though got later superseded by many other novel tool materials like cemented carbides and ceramics which could machine much faster than the HSS tools. The basic composition of HSS is 18% W, 4% Cr, 1% V, 0.7% C and rest Fe. Such HSS tool could machine (turn) mild steel jobs at speed only up to 20 ~ 30 m/min (which was quite substantial those days).

However, HSS is still used as cutting tool material where:

The tool geometry and mechanics of chip formation are complex, such as helical twist drills, reamers, gear shaping cutters, hobs, form tools, broaches etc. Brittle tools like carbides, ceramics etc. are not suitable under shock loading. The small scale industries cannot afford costlier tools. The old or low powered small machine tools cannot accept high speed and feed. The tool is to be used number of times by resharpening.

With time the effectiveness and efficiency of HSS (tools) and their application range were gradually enhanced by improving its properties and surface condition through:

a) Refinement of microstructure.

b) Addition of large amount of cobalt and Vanadium to increase hot hardness and wear resistance respectively.

c) Manufacture by powder metallurgical process.

d) Surface coating with heat and wear resistive materials like TiC, TiN, etc. by Chemical Vapour Deposition (CVD) or Physical Vapour Deposition (PVD).

The commonly used grades of HSS are given in Table 1.1.

<table>
<thead>
<tr>
<th>Type</th>
<th>C</th>
<th>W</th>
<th>Mo</th>
<th>Cr</th>
<th>V</th>
<th>Co</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>T - 1</td>
<td>0.70</td>
<td>18</td>
<td>4</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T - 4</td>
<td>0.75</td>
<td>18</td>
<td>4</td>
<td>1</td>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T - 6</td>
<td>0.80</td>
<td>20</td>
<td>4</td>
<td>2</td>
<td>12</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M - 2</td>
<td>0.80</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>2</td>
<td>64.7</td>
<td></td>
</tr>
<tr>
<td>M - 4</td>
<td>1.30</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M - 15</td>
<td>1.55</td>
<td>6</td>
<td>3</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>M - 42</td>
<td>1.08</td>
<td>1.5</td>
<td>9.5</td>
<td>4</td>
<td>1.1</td>
<td>8</td>
<td>62.4</td>
</tr>
</tbody>
</table>
b) Stellite
This is a cast alloy of Co (40 to 50%), Cr (27 to 32%), W (14 to 19%) and C (2%). Stellite is quite tough and more heat and wear resistive than the basic HSS (18 - 4 - 1). But such stellite as cutting tool material became obsolete for its poor grindability and especially after the arrival of cemented carbides.

c) Sintered Tungsten carbides
The advent of sintered carbides made another breakthrough in the history of cutting tool materials.

i) Straight or single carbide
First the straight or single carbide tools or inserts were powder metallurgically produced by mixing, compacting and sintering 90 to 95% WC powder with cobalt. The hot, hard and wear resistant WC grains are held by the binder Co which provides the necessary strength and toughness. Such tools are suitable for machining grey cast iron, brass, bronze etc. which produce short discontinuous chips and at cutting velocities two to three times of that possible for HSS tools.

ii) Composite carbides
The single carbide is not suitable for machining steels because of rapid growth of wear, particularly crater wear, by diffusion of Co and carbon from the tool to the chip under the high stress and temperature bulk (plastic) contact between the continuous chip and the tool surfaces.

For machining steels successfully, another type called composite carbide have been developed by adding (8 to 20%) a gamma phase to WC and Co mix. The gamma phase is a mix of TiC, TiN, TaC, NiC etc. which are more diffusion resistant than WC due to their more stability and less wettability by steel.

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

d) Plain ceramics
Inherently high compressive strength, chemical stability and hot hardness of the ceramics led to powder metallurgical production of indexable ceramic tool inserts since 1950. Table 1.4 shows the advantages and limitations of alumina ceramics in contrast to sintered carbide. Alumina (Al₂O₃) is preferred to silicon nitride (Si₃N₄) for higher
hardness and chemical stability. Si₃N₄ is tougher but again more difficult to process. The plain ceramic tools are brittle in nature and hence had limited applications.

### Table 1.4 Cutting tool properties of alumina ceramics

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Shortcoming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very high hardness</td>
<td>Poor toughness</td>
</tr>
<tr>
<td>Very high hot hardness</td>
<td>Poor tensile strength</td>
</tr>
<tr>
<td>Chemical stability</td>
<td>Poor TRS</td>
</tr>
<tr>
<td>Antiwelding</td>
<td>Low thermal conductivity</td>
</tr>
<tr>
<td>Less diffusivity</td>
<td>Less density</td>
</tr>
<tr>
<td>High abrasion resistance</td>
<td></td>
</tr>
<tr>
<td>High melting point</td>
<td></td>
</tr>
<tr>
<td>Very low thermal conductivity</td>
<td></td>
</tr>
<tr>
<td>Very low thermal conductivity*</td>
<td></td>
</tr>
<tr>
<td>Very low thermal expansion coefficient</td>
<td></td>
</tr>
</tbody>
</table>

**Basically three types of ceramic tool bits are available in the market:**

- Plain alumina with traces of additives - these white or pink sintered inserts are cold pressed and are used mainly for machining cast iron and similar materials at speeds 200 to 250 m/min.
- Alumina; with or without additives - hot pressed, black colour, hard and strong - used for machining steels and cast iron at VC = 150 to 250 m/min.
- Carbide ceramic (Al₂O₃ + 30% TiC) cold or hot pressed, black colour, quite strong and enough tough - used for machining hard cast irons and plain and alloy steels at 150 to 200 m/min.

The plain ceramic outperformed the existing tool materials in some application areas like high speed machining of softer steels mainly for higher hot hardness as indicated in Fig. 1.43.
However, the use of those brittle plain ceramic tools, until their strength and toughness could be substantially improved since 1970, gradually decreased for being restricted to:

Uninterrupted machining of soft cast irons and steels only
Relatively high cutting velocity but only in a narrow range (200 ~ 300 m/min)
Requiring very rigid machine tools

e) Cubic Boron Nitride

Next to diamond, cubic boron nitride is the hardest material presently available. Only in 1970 and onward CBN in the form of compacts has been introduced as cutting tools. It is made by bonding a 0.5 - 1 mm layer of polycrystalline cubic boron nitride to cobalt based carbide substrate at very high temperature and pressure. It remains inert and retains high hardness and fracture toughness at elevated machining speeds. It shows excellent performance in grinding any material of high hardness and strength. The extreme hardness, toughness, chemical and thermal stability and wear resistance led to the development of CBN cutting tool inserts for high material removal rate (MRR) as well as precision machining imparting excellent surface integrity of the products. Such unique tools effectively and beneficially used in machining wide range of work materials covering high carbon and alloy steels, non-ferrous metals and alloys, exotic metals like Ni-hard, Inconel, Nimonic etc and many non-metallic materials which are as such difficult to machine by conventional tools. It is firmly stable at temperatures up to 1400°C. The operative speed range for CBN when machining grey cast iron is 300 ~ 400 m/min.

Speed ranges for other materials are as follows:
Hard cast iron (> 400 BHN): 80 - 300 m/min. Superalloys (> 35 RC): 80 - 140 m/min.
Hardened steels (> 45 RC): 100 - 300 m/min.

In addition to speed, the most important factor that affects performance of CBN inserts is the preparation of cutting edge. It is best to use CBN tools with a honed or chamfered edge preparation, especially for interrupted cuts. Like ceramics, CBN tools are also available only in the form of indexable inserts. The only limitation of it is its high cost.

(f) Diamond Tools

Single stone, natural or synthetic, diamond crystals are used as tips/edge of cutting tools. Owing to the extreme hardness and sharp edges, natural single crystal is used for many applications, particularly where high accuracy and precision are required. Their important uses are:

Single point cutting tool tips and small drills for high speed machining of non-ferrous metals, ceramics, plastics, composites, etc. and effective machining of difficult-to-
machine materials.
  o Drill bits for mining, oil exploration, etc.
  o Tool for cutting and drilling in glasses, stones, ceramics, FRPs etc. Wire drawing
    and extrusion dies.
  o Super abrasive wheels for critical grinding.

Limited supply, increasing demand, high cost and easy cleavage of natural diamond
demanded a more reliable source of diamond. It led to the invention and manufacture of
artificial diamond grits by ultra-high temperature and pressure synthesis process, which
enables large scale manufacture of diamond with some control over size, shape and
friability of the diamond grits as desired for various applications.

CUTTING FLUIDS

*The basic purposes of cutting fluid application are:*
  o Cooling of the job and the tool to reduce the detrimental effects of cutting
temperature on the job and the tool.
  o Lubrication at the chip - tool interface and the tool flanks to reduce cutting
forces and friction and thus the amount of heat generation.
  o Cleaning the machining zone by washing away the chip - particles and
debris which, if present, spoils the finished surface and accelerates damage
of the cutting edges.
  o Protection of the nascent finished surface - a thin layer of the cutting fluid
sticks to the machined surface and thus prevents its harmful contamination
by the gases like SO\textsubscript{2}, O\textsubscript{2}, H\textsubscript{2}S, and N\textsubscript{X}O\textsubscript{Y} present in the atmosphere.

*However, the main aim of application of cutting fluid is to improve machinability through
reduction of cutting forces and temperature, improvement by surface integrity and
enhancement of tool life.*

*Essential properties of cutting fluids*

To enable the cutting fluid fulfill its functional requirements without harming the
Machine - Fixture - Tool - Work (M-F-T-W) system and the operators, the cutting fluid
should possess the following properties:

*For cooling:*
  High specific heat, thermal conductivity and film coefficient
  for heat transfer. Spreading and wetting ability.

*For lubrication:*
  High lubricity without gumming and foaming. Wetting and spreading.
  High film boiling point.
  Friction reduction at extreme pressure (EP) and temperature.
Chemical stability, non-corrosive to the materials of the M-F-T-W system. Less volatile and high flash point.
High resistance to bacterial growth.
Odourless and also preferably colourless. Non toxic in both liquid and gaseous stage.
Easily available and low cost.

**Principles of cutting fluid action**
The chip-tool contact zone is usually comprised of two parts; *plastic or bulk contact zone and elastic contact zone as indicated in Fig. 1.55.*

![Fig. 1.55 Cutting fluid action in machining](image1)

![Fig. 1.56 Apportionment of plastic and elastic contact zone with increase in cutting velocity](image2)

The cutting fluid cannot penetrate or reach the plastic contact zone but enters in the elastic contact zone by capillary effect. With the increase in cutting velocity, the fraction of plastic contact zone gradually increases and covers almost the entire chip-tool contact zone *as indicated in Fig. 1.56.* Therefore, at high speed machining, the cutting fluid becomes unable to lubricate and cools the tool and the job only by bulk external cooling.

The chemicals like chloride, phosphate or sulphide present in the cutting fluid chemically reacts with the work material at the chip under surface under high pressure and temperature and forms a thin layer of the reaction product. The low shear strength of that reaction layer helps in reducing friction.

To form such solid lubricating layer under high pressure and temperature some extreme pressure additive (EPA) is deliberately added in reasonable amount in the mineral oil or soluble oil.

For extreme pressure, chloride, phosphate or sulphide type EPA is used depending upon the working temperature, i.e. moderate (200°C ~ 350°C), high (350°C ~ 500°C) and very high (500°C ~ 800°C) respectively.
Types of cutting fluids and their application
Generally, cutting fluids are employed in liquid form but occasionally also employed in gaseous form. Only for lubricating purpose, often solid lubricants are also employed in machining and grinding.

The cutting fluids, which are commonly used, are:

Air blast or compressed air only
Machining of some materials like grey cast iron become inconvenient or difficult if any cutting fluid is employed in liquid form. In such case only air blast is recommended for cooling and cleaning.

Solid or semi-solid lubricant
Paste, waxes, soaps, graphite, Moly-disulphide (MoS$_2$) may also often be used, either applied directly to the workpiece or as an impregnant in the tool to reduce friction and thus cutting forces, temperature and tool wear.

Water
For its good wetting and spreading properties and very high specific heat, water is considered as the best coolant and hence employed where cooling is most urgent.

Soluble oil
Water acts as the best coolant but does not lubricate. Besides, use of only water may impair the machine-fixture-tool-work system by rusting. So oil containing some emulsifying agent and additive like EPA, together called cutting compound, is mixed with water in a suitable ratio (1 ~ 2 in 20 ~ 50).

This milk like white emulsion, called soluble oil, is very common and widely used in machining and grinding.

Cutting oils
Cutting oils are generally compounds of mineral oil to which are added desired type and amount of vegetable, animal or marine oils for improving spreading, wetting and lubricating properties. As and when required some EP additive is also mixed to reduce friction, adhesion and BUE formation in heavy cuts.

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

Chemically inactive type - high cooling, anti-rusting and wetting but less lubricating. Active (surface) type - moderate cooling and lubricating.
Cryogenic cutting fluid
Extremely cold (cryogenic) fluids (often in the form of gases) like liquid CO$_2$ or N$_2$ are used in some special cases for effective cooling without creating much environmental pollution and health hazards.

Selection of cutting fluid
The benefits of application of cutting fluid largely depend upon proper selection of the type of the cutting fluid depending upon the work material, tool material and the machining condition. As for example, for high speed machining of not-difficult-to-machine materials greater cooling type fluids are preferred and for low speed machining of both conventional and difficult-to-machine materials greater lubricating type fluid is preferred.
LATHE

CENTRE LATHE
Lathe is the oldest machine tool invented, starting with the Egyptian tree lathes. It is the father of all machine tools. Its main function is to remove material from a work piece to produce the required shape and size. This is accomplished by holding the work piece securely and rigidly on the machine and then turning it against the cutting tool which will remove material from the work piece in the form of chips. It is used to machine cylindrical parts. Generally single point cutting tool is used. In the year 1797 Henry Maudslay, an Englishman, designed the first screw cutting lathe which is the forerunner of the present day high speed, heavy duty production lathe.

CONSTRUCTIONAL FEATURES
Major parts of a centre lathe
Amongst the various types of lathes, centre lathes are the most versatile and commonly used.
Fig. 2.1 shows the basic configuration of a center lathe. The major parts are:

![Fig. 2.1 Schematic view of a center lathe](image)

- **Headstock** It holds the spindle and through that power and rotation are transmitted to the job at different speeds. Various work holding attachments such as three jaw chucks, collets, and centres can be held in the spindle. The spindle is driven by an electric motor
through a system of belt drives and gear trains. Spindle rotational speed is controlled by varying the geometry of the drive train.

**Tailstock** The tailstock can be used to support the end of the work piece with a center, to support longer blanks or to hold tools for drilling, reaming, threading, or cutting tapers. It can be adjusted in position along the ways to accommodate different length work pieces. The tailstock barrel can be fed along the axis of rotation with the tailstock hand wheel.

**Bed** Headstock is fixed and tailstock is clamped on it. Tailstock has a provision to slide and facilitate operations at different locations. The bed is fixed on columns and the carriage travels on it.

**Carriage** It is supported on the lathe bed-ways and can move in a direction parallel to the lathe axis. The carriage is used for giving various movements to the tool by hand and by power. It carries saddle, cross-slide, compound rest, tool post and apron.

**Saddle** It carries the cross slide, compound rest and tool post. It is an H-shaped casting fitted over the bed. It moves alone to guide ways.

**Cross-slide** It carries the compound rest and tool post. It is mounted on the top of the saddle. It can be moved by hand or may be given power feed through apron mechanism.

**Compound rest** It is mounted on the cross slide. It carries a circular base called swivel plate which is graduated in degrees. It is used during taper turning to set the tool for angular cuts. The upper part known as compound slide can be moved by means of a hand wheel.

**Tool post** It is fitted over the compound rest. The tool is clamped in it.

**Apron** Lower part of the carriage is termed as the apron. It is attached to the saddle and hangs in front of the bed. It contains gears, clutches and levers for moving the carriage by a hand wheel or power feed.

**Feed mechanism** The movement of the tool relative to the work piece is termed as “feed”. The lathe tool can be given three types of feed, namely, longitudinal, cross and angular.

When the tool moves parallel to the axis of the lathe, the movement is called longitudinal feed. This is achieved by moving the carriage.

When the tool moves perpendicular to the axis of the lathe, the movement is called cross feed. This is achieved by moving the cross slide.

When the tool moves at an angle to the axis of the lathe, the movement is called angular feed. This is achieved by moving the compound slide, after swiveling it at an angle to the lathe axis.
Feed rod The feed rod is a long shaft, used to move the carriage or cross-slide for turning, facing, boring and all other operations except thread cutting. Power is transmitted from the lathe spindle to the apron gears through the feed rod via a large number of gears.

Lead screw The lead screw is long threaded shaft used as a master screw and brought into operation only when threads have to cut. In all other times the lead screw is disengaged from the gear box and remains stationary. The rotation of the lead screw is used to traverse the tool along the work to produce screw. The half nut makes the carriage to engage or disengage the lead screw.

Kinematic system and working principle of a centre lathe

*Fig. 2.2 schematically shows the kinematic system of a 12 speed centre lathe.*

![Kinematic system of a centre lathe](image)

For machining in machine tools the job and the cutting tool need to be moved relative to each other. **The tool-work motions are:**

- Formative motions: - cutting motion, feed motion.
- Auxiliary motions: - indexing motion, relieving motion.

In lathes: Cutting motion is attained by rotating the job and feed motion is attained by linear travel of the tool either axially for longitudinal feed or radially for cross feed.
It is noted, in general, from Fig. 2.2. The job gets rotation (and power) from the motor through the belt-pulley, clutch and then the speed gear box which splits the input speed into a number (here 12) of speeds by operating the cluster gears.

The cutting tool derives its automatic feed motion(s) from the rotation of the spindle via the gear quadrant, feed gear box and then the apron mechanism where the rotation of the feed rod is transmitted:

- Either to the pinion which being rolled along the rack provides the longitudinal feed. Or to the screw of the cross slide for cross or transverse feed.

While cutting screw threads the half nuts are engaged with the rotating lead screw to positively cause travel of the carriage and hence the tool parallel to the lathe bed i.e., job axis.

The feed-rate for both turning and threading is varied as needed by operating the Norton gear and the Meander drive systems existing in the feed gear box (FGB). The range of feeds can be augmented by changing the gear ratio in the gear quadrant connecting the FGB with the spindle.

As and when required, the tailstock is shifted along the lathe bed by operating the clamping bolt and the tailstock quill is moved forward or backward or is kept locked in the desired location.

*The versatility or working range of the centre lathes is augmented by using several special attachments.*

**HEADSTOCK DRIVING MECHANISMS**
*There are two types of headstock driving mechanisms as follows:*

1. Back geared headstock.
2. All geared headstock.

1. **Back geared headstock**

Back gear arrangement is used for reducing the spindle speed, which is necessary for thread cutting and knurling. *The back gear arrangement is shown in Fig.2.3.*
There is one stepped cone pulley in the lathe spindle. This pulley can freely rotate on the spindle. A pinion gear $P_1$ is connected to small end of the cone pulley. $P_1$ will rotate when cone pulley rotates. Bull gear $G_1$ is keyed to lathe spindle such that the spindle will rotate when Gear $G_1$ rotates. Speed changes can be obtained by changing the flat belt on the steps. A bull gear $G_1$ may be locked or unlocked with this cone pulley by a lock pin.

There are two back gears $B_1$ and $B_2$ on a back shaft. It is operated by means of hand lever $L$; back gears $B_1$ and $B_2$ can be engaged or disengaged with $G_1$ and $P_1$. For getting direct speed, back gear is not engaged. The step cone pulley is locked with the main spindle by using the lock pin. The flat belt is changed for different steps. Thus three or four ranges of speed can be obtained directly.

2. All geared headstock

All geared headstock is commonly used in modern lathes because of the following advantages:

- It gives wider range of spindle speeds.
- It is more efficient and compact than cone pulley mechanism.
- Power available at the tool is almost constant for all spindle speeds. Belt shifting is eliminated.
- The vibration of the spindle is reduced. More power can be transmitted.

The all geared headstock is shown in Fig 2.4.

![Fig. 2.4 All geared headstock](image_url)

The power from the constant speed motor is delivered to the spindle through a belt drive. Speed changing is made by levers. The different spindle speeds are obtained by shifting the levers into different positions to obtain different gear combinations. This mechanism has a splined spindle, intermediate shaft and a splined shaft. The splined shaft receives power from motor through a belt drive.
This shaft has 3 gears namely G₁, G₂ and G₃. These gears can be shifted with the help of lever along the shaft. Gears G₄, G₅ and G₆ are mounted on intermediate shaft and cannot be moved axially. Gears G₇, G₈ and G₉ are mounted on splined headstock spindle and can be moved axially by levers. Gears G₁, G₂ and G₃ can be meshed with the gears G₄, G₅ and G₆ individually. Similarly, gears G₇, G₈, G₉ can be meshed with gear G₄, G₅ and G₆ individually. Thus, it provides nine different speeds.

**FEED MECHANISMS**

The feed mechanism is used to transmit power from the spindle to the carriage. Therefore, it converts rotary motion of the spindle into linear motion of the carriage. The feed can be given either by hand or automatically. For automatic feeding, the following feed mechanisms are used:

a. Tumbler gear reversing mechanism.
b. Quick-change gearbox.
c. Tumbler gear quick-change gearbox.
d. Apron mechanism.
e. Bevel gear feed reversing mechanism.

1. **Tumbler gear reversing mechanism**

Tumbler gear mechanism is used to change the direction of lead screw and feed rod. By engaging tumbler gear, the carriage can be moved along the lathe axis in either direction during thread cutting or automatic machining. *Fig. 2.5 shows the schematic arrangement of tumbler gear reversing mechanism.*

![Fig. 2.5 Tumbler gear reversing mechanism](image)

The tumbler gear unit has two pinions (A and B) of same size and is mounted on a bracket. The bracket is pivoted at a point and can be moved up and down by a lever L. The bracket may be placed in three positions i.e., upward, downward and neutral. Gear ‘C’ is a spindle gear attached to the lathe spindle. Gear ‘D’ is the stud gear. The stud gear is connected to the lead screw gear through a set of intermediate gears.
When the lever is shifted upward position, the gear ‘A’ is engaged with spindle gear ‘C’ and the power is transmitted through C-A-D-E-F. During this position, lead screw will rotate in the same direction as spindle rotates (i.e. both anticlockwise). Now, the carriage moves towards the headstock. When the lever is shifted downward, the gear ‘B’ is engaged with spindle gear ‘C’ and the power is transmitted through C-B-A-D-E-F. Hence, the lead screw will rotate in the opposite direction of the spindle. Now, the carriage moves towards tailstock.

When the bracket is in neutral position, the engagement of tumbler gears is disconnected with the spindle gear. Hence, there is no power transmission to lead screw.

2. Quick-change gear box

Quick-change gearbox is used to get various power feeds in the lathe. Fig. 2.6 shows the schematic arrangement of quick-change gear box.

![Fig. 2.6 quick-change gear box](image)

Power from the lathe spindle is transmitted to feed shaft through tumbler gear, change gear train and quick-change gearbox. Shaft A (Cone gear shaft) contains 9 different sizes of gears keyed with it. Shaft B (Sliding gear shaft) has a gear and it receives 9 different speeds from shaft A by the use of sliding gear. Shaft B is connected to shaft C (Driven shaft) through 4 cone years. Therefore, Shaft C can get 9 X 4 = 36 different speeds. The shaft C is connected to lead screw by a clutch and feed rod by a gear train. Lead screw is used for thread cutting and feed rod is used for automatic feeds.
3. Tumbler gear quick-change gear box

The different speed of the driving shaft is obtained by a tumbler gear and cone gear arrangement.

*Fig. 2.7 shows the schematic arrangement of tumbler gear quick-change gear box.*

![Fig. 2.7 Tumbler gear quick-change gearbox](image)

It is simpler than quick-change gearbox. A tumbler gear and a sliding gear are attached to the bracket as shown in Fig. 2.7. Driving shaft has a cone gear made up of different sizes of gears. The sliding gear is keyed to the driven shaft which is connected by the lead screw or feed rod. The sliding gear can be made to slide and engaged at any desired position. By sliding the sliding gear to various positions and engaging the tumbler gear, various speeds can be obtained.

4. Apron mechanism

*Fig. 2.8 shows the schematic arrangement of apron mechanism.*

![Fig. 2.8 Apron mechanism](image)
Lead screw and feed rod is getting power from spindle gear through tumbler gears. Power is transmitted from feed rod to the worm wheel through gears A, B, C, D and worm.

A splined shaft is attached with worm wheel. The splined shaft is always engaged with the gears F and G which are keyed to the feed check shaft. A knob ‘E’ is fitted with feed check shaft. Feed check knob ‘E’ can be placed in three positions such as neutral, push-in and pull-out.

When the feed check knob ‘E’ is in neutral position, power is not transmitted either to cross feed screw or to the carriage since gears F and G have no connection with H and K. Therefore, hand feed is given as follows. When the longitudinal feed hand wheel rotates, pinion I will also be rotated through I and H. pinion I will move on rack for taking longitudinal feed. For getting cross feed, cross slide screw will be rotated by using cross slide hand wheel.

When the feed check knob ‘E’ is push-in, rotating gear G will be engaged to H. then the power will be transmitted to pinion I. pinion I will rotate on rack. So, automatic longitudinal feed takes place. When the feed check knob ‘E’ is pulled-out, the rotating gear F will be engaged to K. Hence, the power will be transmitted to cross feed screws through L. This leads to automatic cross feed.

For thread cutting, half nut is engaged by half nut lever after putting knob ‘E’ neutral position. Half nut is firmly attached with the carriage. As the lead screw rotates, the carriage will automatically move along the axis of the lathe. Both longitudinal and cross feed can be reversed by operating the tumbler gear mechanism.

5. Bevel gear feed reversing mechanism
The tumbler gear mechanism being a non-rigid construction cannot be used in a modern heavy duty lathe. The clutch operated bevel gear feed reversing mechanism incorporated below the head stock or in apron provides sufficient rigidity in construction. Fig. 2.9 shows the schematic arrangement of bevel gear feed reversing mechanism.

![Fig. 2.9 Bevel gear feed reversing mechanism](image)
The motion is communicated from the spindle gear 2 to the gear on the stud shaft through the intermediate gear. The bevel gear 8 is attached to the gear on the stud shaft and both of them can freely rotate on shaft 7. The bevel gear 8 meshes with bevel gear 12 and 12 mesh with 10. 12, 10 and 8 are having equal number of teeth. The bevel gear 10 can also rotate freely on shaft 7.

A clutch 11 is keyed to the shaft 7 by a feather key and may be shifted to left or right, by the lever 9 to be engaged with the gear 8 or 10 or it remains in the neutral position. When the clutch engages with bevel gear 8, gear 3 which is keyed to the shaft 7 and the lead screw, rotates in the same direction as the gear 2. The direction of rotation is reversed when the clutch 11 engages with gear 10.

WORK HOLDING DEVICES
Chucks - 3 jaw self centering chuck or universal chuck and 4 jaw independent chuck

Fig. 2.10 (a and b) visualizes 3-jaw and 4-jaw chucks which are mounted at the spindle nose and firmly hold the job in centre lathes. Premachined round bars are quickly and coaxially mounted by simultaneously moving the three jaws radially by rotating the scroll (disc with radial threads) by a key as can be seen in the diagram 2.10 (a).

The four jaw chucks, available in varying sizes, are generally used for essentially more strongly holding non-circular bars like square, rectangular, hexagonal and even odder sectional jobs in addition to cylindrical bars, both with and without premachining at the gripping portion. The jaws are moved radially independently by rotating the corresponding screws which push the rack provided on the back side of each jaw as can be seen in the diagram 2.10 (b).

Fig. 2.10 (a) 3-jaw self centering chuck or universal chuck
Magnetic chuck

This is used for holding thin jobs. When the pressure of jaws is to be prevented, this chuck is used. The chuck gets magnetic power from an electro-magnet. Only magnetic materials can be held on this chuck. *Fig. 2.11 shows the magnetic chuck.*

Face plate

A face plate *as shown in Fig. 2.12* consists of a circular disc bored out and threaded to fit the nose of lathe spindle. This has radial, plain and T slots for holding work by bolts and clamps. Face plates are used for holding work pieces which cannot be conveniently held between centres or by chucks.

Angle plate

Angle plate is a cast iron plate that has two faces at right angles to each other. Holes and slots are provided on both faces *as shown in Fig. 2.13 (a).* An angle plate is used along with the face plate when holding eccentric or unsymmetrical jobs that are difficult to grip directly on the face plate *as shown in Fig. 2.13 (b).*
Catch plate or driving plate

It is circular plate of steel or cast iron having a projected boss at its rear. The boss has a threaded hole and it can be screwed to the nose of the headstock spindle. The driving is fitted to the plate. It is used to drive the work piece through a carrier or dog when the work piece is held between the centres.

*Fig. 2.14 shows the catch plate.*

Carriers or Dogs

It is used to transfer motion from the driving plate to the work piece held between centres. The work piece is inserted into the hole of the dog and firmly secured in position by means of set screw.

*The different types of carriers are shown in Fig 2.15.*

Mandrels

A mandrel is a device used for holding and rotating a hollow work piece that has been previously drilled or bored. The work revolves with the mandrel which is mounted between two centres. The mandrel should be true with accurate centre holes for machining outer surface of the work piece concentric with its bore. To avoid distortion and wear it is made of high carbon steel.

The ends of a mandrel are slightly smaller in diameter and flattened to provide effective gripping surface of the lathe dog set screw. The mandrel is rotated by the lathe dog and the catch plate and it drives the work by friction. Different types of mandrels are
employed according to specific requirements. *Fig. 2.16 shows the different types of mandrels in common use.*

**In-between centres (by catch plate and carriers)**

*Fig. 2.17 schematically shows* how long slender rods are held in between the live centre fitted into the headstock spindle and the dead centre fitted in the quill of the tailstock. The torque and rotation are transmitted from the spindle to the job with the help of a lathe dog or catcher which is again driven by a driving plate fitted at the spindle nose.

Depending upon the situation or requirement, different types of centres are used at the tailstock end *as indicated in Fig. 2.18*. A revolving centre is preferably used when desired to avoid sliding friction between the job and the centre which also rotates along with the job.

![Fig. 2.16 Types of mandrels](image)

*Fig. 2.16 Types of mandrels*
**Fig. 2.17 Work held between centres**

**Fig. 2.18 Types of centres**

*Ordinary centre:* It is used for general works.

*Insert type centre:* In this the steel “insert” can be replaced instead of replacing the whole centre. *Half centre:* It is similar to ordinary centre and used for facing bar ends without removal of the centre. *Pipe centre:* It is used for supporting pipes and hollow end jobs. *Ball centre:* It has ball shaped end to minimize the wear and strain. It is suitable for taper turning. *Tipped centre:* Hard alloy tip is brazed into steel shank. The hard tip has high wear resistant. *Revolving centre:* The ball and roller bearings are fitted into the housing to reduce friction and to take up end thrust. This is used in tail stock for supporting heavy work revolving at a high speed.

**In-between headstock and tailstock with additional support of rest**

To prevent deflection of the long slender jobs like feed rod, lead screw etc. due to sagging and cutting forces during machining, some additional supports are provided *as shown in Fig. 2.20.* Such additional support may be a steady rest which remains fixed at a suitable location or a follower rest which moves along with the cutting tool during long straight turning without any steps in the job’s diameter. *Fig. 2.21 (a and b) shows the*
steady rest and follower rest.

Fig. 2.20 Slender job held with extra support by steady rest

Fig. 2.21 (a) Steady rest and (b) Follower rest
TOOL HOLDING DEVICES
Mounting of tools in centre lathe

Different types of tools, used in centre lathes, are usually mounted in the following ways:
- HSS tools (shank type) in tool post.
- HSS form tools and threading tools in tool post. Carbide and ceramic inserts in tool holders.
- Drills and reamers, if required, in tailstock.
- Boring tools in tool post.

*Fig. 2.22 (a and b) is typically showing* mounting of shank type HSS single point tools in rotatable (only one tool) and indexable (up to four tools) tool posts. *Fig. 2.22 (c) typically shows* how a circular form or thread chasing HSS tool is fitted in the tool holder which is mounted in the tool post.

VARIOUS OPERATIONS ON LATHE

The machining operations generally carried out in centre lathe are:
- Rough and finish turning - The operation of producing cylindrical surface.
- Facing - Machining the end of the work piece to produce flat surface.
- Centering - The operation of producing conical holes on both ends of the work piece.
- Chamfering - The operation of beveling or turning a slope at the end of the work piece.
- Shouldering - The operation of turning the shoulders of the stepped diameter work piece.
- Grooving - The operation of reducing the diameter of the work piece over a narrow surface. It is also called as recessing, undercutting or necking.
- Axial drilling and reaming by holding the cutting tool in the tailstock barrel.
- Taper turning by - Offsetting the tailstock.
  - Swiveling the compound slide.
  - Using form tool with taper over short length.
  - Using taper turning attachment if available.
  - Combining longitudinal feed and cross feed, if feasible.
Boring (internal turning); straight and taper – The operation of enlarging the diameter of a hole.
Forming; external and internal.
Cutting helical threads; external and internal.
Parting off - The operation of cutting the work piece into two halves.
Knurling - The operation of producing a diamond shaped pattern or impression on the surface.

In addition to the aforesaid regular machining operations, some more operations are also occasionally done, if desired, in centre lathes by mounting suitable attachments available in the market. Some of those common operations carried out in centre lathe are shown in Fig. 2.30.

Fig. 2.30 Some common machining operations carried out in a centre lathe
TAPER TURNING METHODS
A taper may be defined as a uniform change in the diameter of a work piece measured along its length. *Taper may be expressed in two ways:*
Ratio of difference in diameter to the length. In degrees of half the included angle.  
*Fig. 2.31 shows the details of a taper.*

\[ D - \text{Large diameter of the taper.} \]
\[ d - \text{Small diameter of the taper.} \]
\[ l - \text{Length of tapered part.} \]
\[ \alpha - \text{Half angle of taper.} \]

*Fig. 2.31 Details of a taper*  
Generally, taper is specified by the term conicity. *Conicity is defined as the ratio of the difference in diameters of the taper to its length.*  

Conicity, \( K = \)

Taper turning is the operation of producing conical surface on the cylindrical work piece on lathe.

1. **Taper turning by a form tool**  
*Fig. 2.32 illustrates the method of turning taper by a form tool.* A broad nose tool having straight cutting edge is set on to the work at half taper angle, and is fed straight into the work to generate a tapered surface. In this method the tool angle should be properly checked before use. This method is limited to turn short length of taper only. This is due to the reason that the metal is removed by the entire cutting edge will require excessive cutting pressure, which may distort the work due to vibration and spoil the work surface.

*Fig. 2.32 Taper turning by a form tool*  
*Fig. 2.33 Taper turning by swiveling the compound rest*
2. **Taper turning by swiveling the compound rest**

*Fig. 2.33 illustrates the method of turning taper by swiveling the compound rest.*

This method is used to produce short and steep taper. In this method, work is held in a chuck and is rotated about the lathe axis. The compound rest is swiveled to the required angle and clamped in position.

The angle is determined by using the formula, \( \tan \alpha = \)

Then the tool is fed by the compound rest hand wheel. This method is used for producing both internal and external taper. This method is limited to turn a short taper owing to the limited movement of the compound rest. The compound rest may be swiveled at 45\(^0\) on either side of the lathe axis enabling it to turn a steep taper. The movement of the tool in this method being purely controlled by hand, this gives a low production capacity and poorer surface finish.

3. **Taper turning by offsetting the tailstock**

*Fig. 2.34 illustrates the method of turning taper by offsetting the tailstock.* The principle of turning taper by this method is to shift the axis of rotation of the work piece, at an angle to the lathe axis, which is equal to half angle of the taper, and feeding the tool parallel to the lathe axis.

This is done when the body of the tailstock is made to slide on its base towards or away from the operator by a set over screw. The amount of set over being limited, this method is suitable for turning small taper on long jobs. The main disadvantage of this method is that live and dead centres are not equally stressed and the wear is not uniform. Moreover, the lathe carrier being set at an angle, the angular velocity of the work is not constant.

Fig. 2.34 Taper turning by offsetting the tailstock

*The amount of set over required to machine a particular taper may be calculated as:*
From the right angle triangle ABC in Fig.2.34; \( BC = AB \sin \alpha \), where \( BC = \text{set over} \)

\[
\text{Set over} = L \sin \alpha
\]

If the half angle of taper (\( \alpha \)), is very small, for all practical purposes, \( \sin \alpha = \tan \alpha \)

\[
\text{Set over} = L \tan \alpha = L \times \text{in mm.}
\]

If the taper is turned on the entire length of the work piece, then \( l = L \), and the equation (2.4) becomes:

\[
\text{Set over} = L \times
\]

being termed as the conicity or amount of taper, the formula (2.4) may be written in the following

\[ \text{Set over} = \]

4. Taper turning by using taper turning attachment

*Fig. 2.35 schematically shows a taper turning attachment.* It consists of a bracket or frame which is attached to the rear end of the lathe bed and supports a guide bar pivoted at the centre. The guide bar having graduations in degrees may be swiveled on either side of the zero graduation and is set at the desired angle with the lathe axis. When this attachment is used the cross slide is delinked from the saddle by removing the binder screw. The rear end of the cross slide is then tightened with the guide block by means of a bolt. When the longitudinal feed is engaged, the tool mounted on the cross slide will follow the angular path, as the guide block will slide on the guide bar set at an angle to the lathe axis.

The required depth of cut is given by the compound slide which is placed at right angles to the lathe axis. The guide bar must be set at half taper angle and the taper on the work must be converted in degrees. The maximum angle through which the guide bar may be swiveled is \( 10^0 \) to \( 12^0 \) on either side of the centre line. *The angle of swiveling the guide bar can be determined from the equation 2.2.*

*The advantages of using a taper turning attachment are:*

The alignment of live and dead centres being not disturbed; both straight and taper turning may be performed on a work piece in one setting without much loss of time. Once the taper is set, any length of work piece may be turned taper within its limit. Very steep taper on a long work piece may be turned, which cannot be done by any other method. Accurate taper on a large number of work pieces may be turned. Internal tapers can be turned with ease.
5. Taper turning by combining longitudinal feed and cross feed

Fig. 2.36 illustrates the method of turning taper by combining longitudinal feed and cross feed.

This is a more specialized method of turning taper. In certain lathes both longitudinal and cross feeds may be engaged simultaneously causing the tool to follow a diagonal path which is the resultant of the magnitude of the two feeds. The direction of the resultant may be changed by varying the rate of feeds by changing gears provided inside the apron.

THREAD CUTTING METHODS

Thread cutting is one of the most important operations performed in a centre lathe. It is possible to cut both external and internal threads with the help of threading tools. There are a large number of thread forms that can be machined in a centre lathe such as Whitworth, ACME, ISO metric, etc. The principle of thread cutting is to produce a helical groove on a cylindrical or conical surface by feeding the tool longitudinally when the job is revolved between centres or by a chuck (for external threads) and by a chuck (for internal threads). The longitudinal feed should be equal to the pitch of the thread to be cut per revolution of the workpiece.

The lead screw of the lathe has a definite pitch. The saddle receives its traversing motion through the lead screw. Therefore a definite ratio between the longitudinal feed and rotation of the headstock spindle should be found out so that the relative speeds of rotation of the work and the lead screw will result in the cutting of a thread of the desired pitch. This is effect by change gears arranged between the spindle and the lead screw or by the change gear mechanism or feed gear box used in a modern lathe. Thread cutting on a centre lathe is a slow process, but it is the only process of producing square threads, as other methods develop interference on the helix. Fig.2.37 illustrates the principle of thread cutting.
Thread cutting procedure

1. The work piece should be rotated in anticlockwise direction when viewed from the tail stock end.
2. The excess material is removed from the workpiece to make its diameter equal to the major diameter of the screw thread to be generated.
3. Change gears of correct size are fitted to the end of the bed between the spindle and the lead screw.
4. The thread cutting tool is selected such that the shape or form of the cutting edge is of the same form as the thread to be generated. In a metric thread, the included angle of the cutting edge should be ground exactly 60°.
5. A thread tool gauge or a centre gauge is used against the turned surface of the workpiece to check the form of the cutting edge so that each face may be equally inclined to the centre line of the workpiece. This is illustrated in Fig. 2.38.

Fig. 2.37 Principles of thread cutting

Fig. 2.38 Checking of the cutting edge

Fig. 2.39 Mounting of the cutting tool
6. Then the tool is mounted in the tool post such that the top of the tool nose is horizontal and is in line with the axis of rotation of the workpiece. *This is illustrated in Fig. 2.39.*

7. The speed of the spindle is reduced by $\frac{1}{2}$ to $\frac{1}{4}$ of the speed required for turning according to the type of material being machined.

8. The tool is fed inward until it first scratches the surface of the workpiece. The graduated dial on the cross slide is noted or set to zero. Then the split nut or half nut is engaged and the tool moves along helical path over the desired length.

9. At the end of tool travel, it is quickly withdrawn by means of cross slide. The split nut is disengaged and the carriage is returned to the starting position, for the next cut. These successive cuts are continued until the thread reaches its desired depth (checked on the dial of cross slide).

10. For cutting left hand threads the carriage is moved from left to right (i.e. towards tail stock) and for cutting right hand threads it is moved from right to left (i.e. towards headstock).

**CAPSTAN AND TURRET LATHES**

Capstan and turret lathes are production lathes used to manufacture any number of identical pieces in the minimum time. These lathes are development of centre lathes. The capstan lathe was first developed in the year 1860 by Pratt and Whitney of USA.

*In contrast to centre lathes, capstan and turret lathes:*

- Are relatively costlier.
- Are requires less skilled operator.
- Possess an axially movable indexable turret (mostly hexagonal) in place of tailstock.
- Holds large number of cutting tools; up to four in indexable tool post on the front slide, one in the rear slide and up to six in the turret (if hexagonal) as indicated in the schematic diagrams.
- Are more productive for quick engagement and overlapped functioning of the tools in addition to faster mounting and feeding of the job and rapid speed change.
- Enable repetitive production of same job requiring less involvement, effort and attention of the operator for pre-setting of work-speed and feed rate and length of travel of the cutting tools.
- Are suitable and economically viable for batch production or small lot production. Capable of taking multiple cuts and combined cuts at the same time.
Major parts of capstan and turret lathes
Capstan and turret lathes are very similar in construction, working, application and specification.

Fig. 2.60 schematically shows the basic configuration of a capstan lathe and Fig. 2.61 shows that of a turret lathe. The major parts are:

**Bed**
The bed is a long box like casting provided with accurate guide ways upon which the carriage and turret saddle are mounted. The bed is designed to ensure strength, rigidity and permanency of alignment under heavy duty services.

**Headstock**
The head stock is a large casting located at the left hand end of the bed.

*The headstock of capstan and turret lathes may be of the following types:*
- Step cone pulley driven headstock.
- Direct electric motor driven headstock. All geared headstock.
- Pre-optive or pre-selective headstock.
**Step cone pulley driven headstock:** This is the simplest type of headstock and is fitted with small capstan lathes where the lathe is engaged in machining small and almost constant diameter of workpieces. Only three or four steps of pulley can cater to the needs of the machine. The machine requires special countershaft unlike that of an engine lathe, where starting, stopping and reversing of the machine spindle can be effected by simply pressing a foot pedal.

**Electric motor driven headstock:** In this type of headstock the spindle of the machine and the armature shaft of the motor are one and the same. Any speed variation or reversal is effected by simply controlling the motor. Three of four speeds are available and the machine is suitable for smaller diameter of workpieces rotated at high speeds.

**All geared headstock:** On the larger lathes, the headstocks are geared and different mechanisms are employed for speed changing by actuating levers. The speed changing may be performed without stopping the machine.

**Pre-optive or pre-selective headstock:** It is an all geared headstock with provisions for rapid stopping, starting and speed changing for different operations by simply pushing a button or pulling a lever. The required speed for next operation is selected beforehand and the speed changing lever is placed at the selected position. After the first operation is complete, a button or a lever is simply actuated and the spindle starts rotating at the selected speed required for the second operation without stopping the machine. This novel mechanism is effected by the friction clutches.

**Cross slide and saddle** In small capstan lathes, hand operated cross slide and saddle are used. They are clamped on the lathe bed at the required position. The larger capstan lathes and heavy duty turret lathes are equipped with usually two designs of carriage.

- Conventional type carriage.
- Side hung type carriage.

**Conventional type carriage** This type of carriage bridges the gap between the front and rear bed ways and is equipped with four station type tool post at the front, and one rear tool post at the back of the cross slide. This is simple in construction.

**Side hung type carriage** The side-hung type carriage is generally fitted with heavy duty turret lathes where the saddle rides on the top and bottom guide ways on the front of the lathe bed. The design facilitates swinging of larger diameter of workpieces without being interfered by the cross-slide. The saddle and the cross-slide may be fed longitudinally or crosswise by hand or power. The longitudinal movement of each tool may be regulated by using stop bars or shafts set against the stop fitted on the bed and carriage. The tools
are mounted on the tool post and correct heights are adjusted by using rocking or packing pieces.

**Ram saddle** In a capstan lathe, the ram saddle bridges the gap between two bed ways, and the top face is accurately machined to provide bearing surface for the ram or auxiliary slide. The saddle may be adjusted on lathe bed ways and clamped at the desired position. The hexagonal turret is mounted on the ram or auxiliary slide.

**Turret saddle** In a turret lathe, the hexagonal turret is directly mounted on the top of the turret saddle and any movement of the turret is effected by the movement of the saddle. The movement of the turret may be effected by hand or power.

**Turret** is a hexagonal-shaped tool holder intended for holding six or more tools. Each face of the turret is accurately machined. Through the centre of each face accurately bored holes are provided for accommodating shanks of different tool holders. The centre line of each hole coincides with the axis of the lathe when aligned with the headstock spindle. In addition to these holes, there are four tapped holes on each face of the turret for securing different tool holding attachments. *The photographic view of a hexagonal turret is shown in Fig. 2.62.*

![Photographic view of a hexagonal turret](image)

**Fig. 2.62** Photographic view of a hexagonal turret

**Working principle of capstan and turret lathes**
The work pieces are held in collets or chucks. In turret lathes, large work pieces are held by means of jaw chucks. These chucks may be hydraulically or pneumatically operated. In a capstan lathe, bar stock is held in collet chucks. A bar feeding mechanism is used for automatic feeding of bar stock. At least eleven tools can be set at a time in turret and capstan lathes. Six tools are held on the turret faces, four tools in front square tool post and one parting off tool at the rear tool post. While machining, the turret head moves forward towards the job. After each operation, the turret head goes back. The turret head is indexed automatically and the next tool comes into machining position. The indexing is
done by an indexing mechanism. The longitudinal movement of the turret corresponding to each of the turret position can be controlled independently.

By holding different tools in the turret faces, the operations like drilling, boring, reaming, counter boring, turning and threading can be done on the component. Four tools held on the front tool post are used for different operations like necking, chamfering, form turning and knurling. The parting off tool in the rear tool post is used for cutting off the workpiece. The cross wise movements of the rear and front tool posts are controlled by pre-stops.
SHAPER

INTRODUCTION
The main function of the shaper is to produce flat surfaces in different planes. In general the shaper can produce any surface composed of straight line elements. Modern shapers can generate contoured surface. The shaper was first developed in the year 1836 by James Nasmyth, an Englishman. Because of the poor productivity and process capability the shapers are not widely used nowadays for production. The shaper is a low cost machine tool and is used for initial rough machining of the blanks.

1. According to the type of mechanism used
   **Crank shaper**
   This is the most common type of shaper in which a single point cutting tool is given a reciprocating motion equal to the length of the stroke desired while the work is clamped in position on an adjustable table. In construction, the crank shaper employs a crank mechanism to change circular motion of “bull gear” to reciprocating motion of the ram.

   **Geared type shaper**
   The reciprocating motion of the ram is some type of shaper is effect by means of a rack and pinion. The rack teeth which are cut directly below the ram mesh with a spur gear. The pinion meshing with the rack is driven by a gear train. The speed and the direction in which the ram will traverse depend on the number of gears in the gear train. This type of shaper is not very widely used.

   **Hydraulic shaper**
   In a hydraulic shaper, reciprocating movement of the ram is obtained by hydraulic power. Oil under high pressure is pumped into the operating cylinder fitted with a piston. The end of the piston rod is connected to the ram. The high pressure oil first acts on one side of the piston and then on the other causing the piston to reciprocate and the motion is transmitted to the ram. The speed of the ram is changed by varying the amount of liquid delivered to the piston by the pump.

2. According to the position and travel of ram
   **Horizontal shaper**
   In a horizontal shaper, the ram holding the tool reciprocates in a horizontal axis. Horizontal shapers are mainly used to produce flat surfaces.

   **Vertical shaper**
   In a vertical shaper, the ram holding the tool reciprocates in a vertical axis. The work table of a vertical shaper can be given cross, longitudinal, and rotary movement.
Vertical shapers are very convenient for machining internal surfaces, keyways, slots or grooves. Large internal and external gears may also be machined by indexing arrangement of the rotary table. The vertical shaper which is specially designed for machining internal keyway is called as Keyseater.

**Travelling head shaper**

The ram carrying the tool while it reciprocates moves crosswise to give the required feed. Heavy jobs which are very difficult to hold on the table of a standard shaper and fed past the tool are held static on the basement of the machine while the ram reciprocates and supplies the feeding movements.

3. **According to the type of design of the table**

**Standard or plain shaper**

A shaper is termed as standard or plain when the table has only two movements, vertical and horizontal, to give the feed. The table may or may not be supported at the outer end.

**Universal shaper**

In this type, in addition to the two movements provided on the table of a standard shaper, the table can be swiveled about an axis parallel to the ram ways, and the upper portion of the table can be tilted about a second horizontal axis perpendicular to the first axis. As the work mounted on the table can be adjusted in different planes, the machine is most suitable for different types of work and is given the name “Universal”. A universal shaper is mostly used in tool room work.

4. **According to the type of cutting stroke**

**Push type shaper**

This is the most general type of shaper used in common practice. The metal is removed when the ram moves away from the column, i.e. pushes the work.

**Draw type shaper**

In this type, the metal is removed when the ram moves towards the column of the machine, i.e. draws the work towards the machine. The tool is set in a reversed direction to that of a standard shaper. In this shaper the cutting pressure acts towards the column which relieves the cross rail and other bearings from excessive loading and allows to take deep cuts. Vibration in these machines is practically eliminated. The ram is generally supported by an overhead arm which ensures rigidity and eliminates deflection of the tool.
Major parts of a standard shaper

Fig. 3.1 shows the basic configuration of a standard shaper. The major parts are:

1. Table support
2. Table
3. Clapper box
4. Apron clamping bolt
5. Down feed hand wheel
6. Swivel base degree graduations
7. Hand wheel for position of stroke adjustment
8. Ram block locking handle
9. Ram
10. Column
11. Driving pulley
12. Base
13. Feed disc
14. Pawl mechanism
15. Table elevating screw

Fig. 3.1 Schematic view of a standard shaper

**Base** It provides the necessary support to the machine tool. It is rigidly bolted to the shop floor.
All parts are mounted on the base. It is made up of cast iron to resist vibration and take up high compressive load. It takes the entire load of the machine and the forces set up by the cutting tool during machining.

**Column** It is a box-like casting mounted upon the base. It encloses the drive mechanisms for the ram and the table. Two accurately machined guide ways are provided on the top of the column on which the ram reciprocates. The front vertical face of the column which serves as the guide ways for the cross rail is also accurately machined.

**Cross rail** It is mounted on the front vertical guide ways of the column. It has two parallel guide ways on its top in the vertical plane that is perpendicular to the ram axis. The table may be raised or lowered to accommodate different sizes of jobs by rotating an elevating screw which causes the cross rail to slide up and down on the vertical face of the column. A horizontal cross feed screw which is fitted within the cross rail and parallel to the top guide ways of the cross rail actuates the table to move in a crosswise direction.

**Saddle** It is mounted on the cross rail which holds the table firmly on its top. Crosswise movement of the saddle by rotating the cross feed screw by hand or power causes the table to move sideways.
**Table** It is bolted to the saddle receives crosswise and vertical movements from the saddle and cross rail. It is a box like casting having T-slots both on the top and sides for clamping the work. In a universal shaper the table may be swiveled on a horizontal axis and the upper part of the table may be tilted up or down. In a heavier type shaper, the front face of the table is clamped with a table support to make it more rigid.

**Ram** It holds and imparts cutting motion to the tool through reciprocation. It is connected to the reciprocating mechanism contained within the column. It is semi-cylindrical in form and heavily ribbed inside to make it more rigid. It uses a screwed shaft for altering the position of the ram with respect to the work and holds the tool head at the extreme forward end.

**Tool head** It holds the tool rigidly, provides the feed movement of the tool and allows the tool to have an automatic relief during its return stroke. The vertical slide of the tool head has a swivel base which is held on a circular seat on the ram. So the vertical slide may be set at any desired angle. By rotating the down feed screw handle, the vertical slide carrying the tool executes the feed or depth of cut. The amount of feed or depth of cut may be adjusted by a micrometer dial on the top of the down feed screw. Apron consisting of clapper box, clapper block and tool post is clamped upon the vertical slide by a screw. By releasing the clamping screw, the apron may be swiveled upon the apron swivel pin with respect to the vertical slide. This arrangement is necessary to provide relief to the tool while making vertical or angular cuts. The two vertical walls on the apron called clapper box houses the clapper block which is connected to it by means of a hinge pin. The tool post is mounted upon the clapper block. On the forward cutting stroke the clapper block fits securely to the clapper box to make a rigid tool support. On the return stroke a slight frictional drag of the tool on the work lifts the block out of the clapper box a sufficient amount preventing the tool cutting edge from dragging and consequent wear. The work surface is also prevented from any damage due to dragging. *Fig. 3.2 illustrates the tool head of a shaper.*

![Fig. 3.2 Tool head of a shaper](image-url)
Working principle of a standard shaper

Fig. 3.3 (a) schematically shows the kinematic system of a standard shaper.
Fig. 3.3 (b) shows the basic principle of producing flat surface in a standard shaper.

The bull gear receives its rotation from the motor through the pinion. The rotation of the crank causes oscillation of the link and thereby reciprocation of the ram and hence the tool in straight path. The cutting motion provided by the reciprocating tool and the intermittent feed motion provided by the slow transverse motion of the work at different rate by using the ratchet - pawl system along with the saddle result in producing a flat surface by gradual removal of excess material layer by layer in the form of chips.

The vertical in feed is given either by descending the tool holder or raising the cross rail or both. Straight grooves of various curved sections are also made in shaper by using specific form tools. The single point straight or form tool is clamped in the vertical slide of the tool head, which is mounted at the front face of the reciprocating ram. The work piece is clamped directly on the table or clamped in a vice which is mounted on the table. The changes in length of stroke and position of the stroke required for different machining are accomplished respectively by:
Adjusting the crank length by rotating the bevel gear mounted coaxially with the bull gear. Shifting the ram block nut by rotating the lead screw.
Ram drive mechanism of a shaper

In a shaper, rotary movement of the drive is converted into reciprocating movement of the ram by the mechanism contained within the column of the machine. In a standard shaper metal is removed in the forward cutting stroke and during the return stroke no metal is removed. To reduce the total machining time it is necessary to reduce the time taken by the return stroke. Thus the shaper mechanism should be so designed that it can allow the ram to move at a comparatively slower speed during the forward cutting stroke and during the return stroke it can allow the ram to move at a faster rate to reduce the idle return time. This mechanism is known as quick return mechanism. The reciprocating movement and the quick return of the ram are usually obtained by using any one of the following mechanisms.

1. Crank and slotted link quick return mechanism

![Crank and slotted link quick return mechanism](image)

*Fig. 3.4 Crank and slotted link quick return mechanism*

*The crank and slotted link quick return mechanism is shown in Fig. 3.4.*

This mechanism has a bull gear mounted within the column. The motion or power is transmitted to the bull gear through a pinion which receives its motion from an individual motor. A radial slide is bolted to the centre of the bull gear. This radial slide carries a bull gear sliding block into which the crank pin is fitted. Rotation of the bull gear will cause the crank pin to revolve at a constant speed about the centre of the bull gear. Rocker arm sliding block is mounted upon the crank pin and is free to rotate about the pin. The rocker arm sliding block is fitted within the slotted link and can slide along the slot in the slotted link (rocker arm). The bottom end of the rocker arm is pivoted to the frame of the column. The upper end is forked and connected to the ram block by a pin which can slide in the forked end.
As the bull gear rotates causing the crank pin to rotate, the rocker arm sliding block fastened to the crank pin will rotate on the crank pin circle, and at the same time will move up and down in the slot provided in the slotted link. This up and down movement will give rocking motion (oscillatory motion) to the slotted link (rocker arm), which communicated to the ram. Thus the rotary motion of the bull gear is converted into reciprocating movement of the ram.

2. Whitworth quick return mechanism

![Diagram of Whitworth quick return mechanism](image)

*Fig. 3.7 Whitworth quick return mechanism*

*The Whitworth quick return mechanism is shown in Fig. 3.7.* The bull gear is mounted on a large fixed pin A upon which it is free to rotate. The motion or power is transmitted to the bull gear through a pinion which receives its motion from an individual motor. The crank plate is pivoted eccentrically upon the fixed pin at 5. The crank pin is fitted on the face of the bull gear. The crank plate sliding block is mounted upon the crank pin and it fits into the slot provided on the crank plate. The crank plate sliding block can slide inside the slot. At the other end of the crank plate, a connecting rod connects the crank plate and the ram by two pin 9 and 7. When bull gear will rotate at a constant speed the crank pin with the sliding block will rotate on a crank circle of radius A2 and the sliding block will cause the crank plate to rotate about the point 5 with a variable angular velocity. Pin 9 fitted on the other end of the crank plate will rotate in a circle and the rotary motion of the pin 9 will be converted into reciprocating movement of the ram similar to the crank and connecting rod mechanism. The axis of reciprocating of the ram passes through the pin 5 and is normal to the line A5.

When the crank pin 2 is at the point C the ram will be at the extreme backward position of its stroke. When the crank pin 2 is at the point B the ram will be at the extreme forward position of its stroke. Therefore the forward cutting stroke takes place when the crank pin rotates through the angle CEB (α) and the return stroke takes place when the crank pin rotates through the angle BDC (β). It is clear that the angle α made by the forward or cutting stroke is greater than the angle β described by the return stroke.
The angular velocity of the crank pin being constant, therefore the return stroke is completed within a shorter time for which it is known as quick return motion. The length of stroke of the ram may be changed by shifting the position of pin 9 closer or away from the pivot 5. The position of stroke may be altered by shifting the position of pin 7 on the ram.

3. Hydraulic drive quick return mechanism

A typical hydraulic drive for horizontal shaper is shown in Fig. 3.8. A constant speed motor drives a hydraulic pump which delivers oil at a constant pressure to the line. A regulating valve admits oil under pressure to each end on the piston alternately, at the same time allowing oil from the opposite end of the piston to return to the reservoir.

The piston is pushed by the oil and, being connected to the ram by the piston rod, pushes the ram carrying the tool. The admission of oil to each end of the piston, alternately, is accomplished with the help of trip dogs and pilot valve. As the ram moves and completes its stroke (forward or return) a trip dog will trip the pilot valve which operates the regulating valve. The regulating valve will admit the oil to the other side of the piston and the motion of the ram will get reversed. It is clear that the length of the ram stroke will depend upon the position of the trip dogs. The length of the ram stroke can be changed by unclamping and moving the trip dogs to the desired positions.

The above system is a constant pressure system. The velocity of the ram travel will be directly proportional to the oil pressure and the piston area to which it is applied. The return stroke is quicker, since the piston area on which the oil pressure acts is greater as compared to the other end for which it gets reduced because of the piston rod. Another oil line is connected to a smaller feed cylinder to change the hydraulic power to mechanical power for feeding the work past the tool.
Feed mechanism of a shaper
The mechanism used for providing feed is known as feed mechanism. In a shaper both down feed and cross feed movements may be obtained. Unlike a lathe, these feed movements are provided intermittently and during the end of return stroke only. Vertical or bevel surfaces are produced by rotating the down feed screw of the tool head by hand. This movement of the tool is called down feed.

The horizontal movement of table is called cross feed. Cross feed movement is used to machine a flat horizontal surface. The cross feed of the table is effect by rotating the cross feed screw. This screw is engaged with a nut fitted in the table. Rotation of the cross feed screw causes the table mounted upon the saddle to move sideway s on the cross rail. Cross feed is given either by hand or power. If this screw is rotated manually by handle, then it is called hand feed. If this screw is rotated by power, then it is called automatic feed. The power is given through an automatic feed mechanism. The down feed and cross feed mechanism of a shaper is schematically shown in Fig. 3.10.

Automatic feed mechanism of a shaper
Fig. 3.11 illustrates the automatic feed mechanism of a shaper. In this mechanism, a ratchet wheel is keyed to the end of the cross feed screw. A rocker arm is pivoted at the centre of the ratchet wheel. The rocker arm houses a spring loaded pawl at its top. The spring pushes against the pawl to keep it in contact with the ratchet wheel. The pawl is straight on one side and bevel on the other side. So the pawl moves the ratchet wheel in one direction only. The rocker arm is connected to the driving disc or feed disc by a connecting rod. The driving disc has a T-slot on its face along its diameter. The driving pin or crank pin fits into this slot. One end of the connecting rod is attached to this crank pin.
We know that the table feed is intermittent and is accomplished on the return stroke when the tool has cleared the work piece. The driving disc is driven from the bull gear through a spur gear drive and rotates at the same speed as the bull gear. As the driving disc rotates, the connecting rod oscillates the rocker arm about the cross feed screw. During the forward stroke of the ram, the rocker arm moves in the clockwise direction. As bevel side of the pawl fits on the right side, the pawl slips over the teeth of the ratchet wheel. It gives no movement to the table. During the return stroke of the ram, the rocker arm moves in the counter clockwise direction. The left side of the pawl being straight; so that it moves the ratchet wheel by engaging with it and hence rotates the cross feed screw which moves the table.

A knob at the top of the pawl enables the operator to rotate it $180^0$ to reverse the direction of feed or $90^0$ to stop it altogether. The rate of feed is controlled by adjusting the eccentricity or offset of the crank pin in the driving disc.

**SHAPER TOOLS**

The cutting tool used in a shaper is a single point cutting tool having rake, clearance and other tool angles similar to a lathe tool. It differs from a lathe tool in tool angles. Shaper tools are much more rigid and heavier to withstand shock experienced by the cutting tool at the commencement of each cutting stroke. In a shaper tool the amount of side clearance angle is only $2^0$ to $3^0$ and the front clearance angle is $4^0$ for cast iron and steel. Small clearance angle adds strength to the cutting edge.

As the tool removes metal mostly from its side cutting edge, side rake of $10^0$ is usually provided with little or no rake. A shaper can also use a right hand or left hand tool. High speed steel is the most common material for a shaper tool but shock resistant cemented carbide tipped tool is also used where harder material is to be machined. As in a lathe, tool holders are also used to hold the tool bits.

**Classification of shaper tools**

*Commonly used shaper tools are shown in Fig. 3.22*

**Round nose tool:** This is used for roughing operations. The tool has no top rake. It has side rake angle, in between 10 to $20^0$. Round tool is of two types - plain and bent types. The plain straight type is used for rough machining of horizontal surface. Round nose tool can be left handed or right handed. Another type of round nose tool which is cranked or bent is used for machining vertical surfaces. It is known as round nose cutting down tool.

**Square nose tool:** This tool is used for finishing operations. The cutting edge may have different widths. It is also used to machine the bottom surfaces of key ways and grooves.
**Fig. 3.22 Commonly used shaper tools**

*Side recessing tool:* This is a special tool used for machining T-slots and narrow vertical surfaces. This tool can be both left handed and right handed.

*Parting off tool:* This is used for parting off operation. It is also used for cutting narrow slots. It has no side rake angle. It has front and side clearance angle of $3^0$.

*Goose necked tool:* This is also known as spring tool. The special shape of tool reduces chatter and prevents digging of tool into the work piece. This tool is generally used for finishing cast iron.
SHAPER OPERATIONS

A shaper is a versatile machine tool primarily designed to generate a flat surface by a single point cutting tool. But it may also be used to perform many other operations. The different operations which a shaper can perform are as follows:

Machining flat surfaces in different planes

Fig. 3.23 shows how flat surfaces are produced in a shaper by single point cutting tools in (a) Horizontal (b) Vertical and (c) Inclined planes.

Making features like slots, steps etc. which are also bounded by flat surfaces

Fig. 3.24 visualizes the methods of machining (a) Slot (b) Pocket (c) T-slot and (d) V-block in a shaper by single point cutting tools.
**Forming grooves bounded by short width curved surfaces**

*Fig. 3.25 typically shows* how oil groove and contour form are made in a shaper by using single point form tools.

![Fig. 3.25 Making grooves in a shaper by form tools](image1)

**Cutting external and internal keyways**

*Fig. 3.26 visualizes* the methods of machining (a) External keyway and (b) Internal keyway in a shaper by using single point tools.

![Fig. 3.26 Machining of (a) External keyway and (b) Internal keyway in a shaper](image2)
PLANER

INTRODUCTION
Like shapers, planers are also basically used for producing flat surfaces. But planers are very large and massive compared to the shapers. Planers are generally used for machining large work pieces which cannot be held in a shaper. The planers are capable of taking heavier cuts. The planer was first developed in the year 1817 by Richard Roberts, an Englishman.

Types of planer
The different types of planer which are most commonly used are:

- Standard or double housing planer.
- Open side planer.
- Pit planer.
- Edge or plate planer.
- Divided or latching table planer.

1. Standard or double housing planer
It is most widely used in work shops. It has a long heavy base on which a table reciprocates on accurate guide ways. It has one draw back. Because of the two housings, one on each side of the bed, it limits the width of the work that can be machined. Fig. 3.30 shows a double housing planer.

2. Open side planer
It has a housing only on one side of the base and the cross rail is suspended from the housing as a cantilever. This feature of the machine allows large and wide jobs to be clamped on the table. As the single housing has to take up the entire load, it is made extra-massive to resist the forces. Only three tool heads are mounted on this machine. The constructional and driving features of the machine are same as that of a double housing planer. Fig. 3.31 shows an open side planer.

3. Pit planer
It is massive in construction. It differs from an ordinary planer in that the table is stationary and the column carrying the cross rail reciprocates on massive horizontal rails mounted on both sides of the table. This type of planer is suitable for machining a very large work which cannot be accommodated on a standard planer and the design saves much of floor space. The length of the bed required in a pit type planer is little over the length of the table. Fig. 3.32 shows a pit planer.

4. Edge or plate planer
The design of a plate or edge planer is totally unlike that of an ordinary planer. It is specially intended for squaring and beveling the edges of steel plates used for different pressure vessels and ship-building works. Fig. 3.33 shows an edge planer.
5. **Divided table planer**

This type of planer has two tables on the bed which may be reciprocated separately or together.

This type of design saves much of idle time while setting the work. To have a continuous production one of the tables is used for setting up the work and the other is used for machining. This planer is mainly used for machining identical work pieces. The two sections of the table may be coupled together for machining long work. *Fig. 3.34 shows a divided table planer.*

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*Fig. 3.30 Schematic view of a double housing planer*  
*Fig. 3.31 Schematic view of an open side planer*  
*Fig. 3.34 Schematic view of a divided table planer*
Major parts of a double housing planer

Fig. 3.30 shows the basic configuration of a double housing planer. The major parts are:

**Bed** It is box like casting having cross ribs. It is a very large in size and heavy in weight and it supports the column and all other moving parts of the machine. The bed is made slightly longer than twice the length of the table so that the full length of the table may be moved on it. It is provided with precision ways over the entire length on its top surface and the table slides on it. The hollow space within the box like structure of the bed houses the driving mechanism for the table.

**Table** It supports the work and reciprocates along the ways of the bed. The top face of the planer table is accurately finished in order to locate the work correctly. T-slots are provided on the entire length of the table so that the work and work holding devices may be bolted upon it. Accurate holes are drilled on the top surface of the planer table at regular intervals for supporting the poppet and stop pins. At each end of the table a hollow space is left which acts as a trough for collecting chips. Long works can also rest upon the troughs. A groove is cut on the side of the table for clamping planer reversing dogs at different positions.

**Housing** It is also called columns or uprights are rigid box like vertical structures placed on each side of the bed and are fastened to the sides of the bed. They are heavily ribbed to trace up severe forces due to cutting. The front face of each housing is accurately machined to provide precision ways on which the cross rail may be made to slide up and down for accommodating different heights of work. Two side-tool heads also slide up on it. The housing encloses the cross rail elevating screw, vertical and cross feed screws for tool heads, counterbalancing weight for the cross rail, etc. these screws may be operated either by hand or power.

**Cross rail** It is a rigid box like casting connecting the two housings. This construction ensures rigidity of the machine. The cross rail may be raised or lowered on the face of the housing and can be clamped at any desired position by manual, hydraulic or electrical clamping devices. The two elevating screws in two housing are rotated by an equal amount to keep the cross rail horizontal in any position.

The front face of the cross rail is accurately machined to provide a guide surface for the tool head saddle. Usually two tool heads are mounted upon the cross rail which are called railheads. The cross rail has screws for vertical and cross feed of the tool heads and a screw for elevating the rail. These screws may be rotated either by hand or by power.

**Tool head** It is similar to that of a shaper both in construction and operation.
Working principle of a double housing planer

Fig. 3.35 Principle of producing flat surface

Fig. 3.36 Meshing of bull gear with table rack

Fig. 3.35 shows the basic principle of producing flat surface in a planer. The work piece is mounted on the reciprocating table and the tools are mounted on the tool heads. The tool heads holding the cutting tools are moved horizontally along the cross rail by screw-nut system and the cross rail is again moved up and down along the vertical rails by another screw-nut pair. The simple kinematical system of the planer enables transmission and transformation of rotation of the main motor into reciprocating motion of the large work table and the slow transverse feed motions (horizontal and vertical) of the tool heads. The reciprocation of the table, which imparts cutting motion to the work piece, is attained by rack and pinion (bull gear) mechanism. Fig. 3.36 illustrates meshing of the bull gear with the table rack. The rack is fitted with the table at its bottom surface and the pinion is fitted on the output shaft of the speed gear box. The feed to the tool is given at the end of the return stroke.

TABLE DRIVE MECHANISM OF A PLANER
Open and cross belt drive quick return mechanism

In this mechanism the movement of the table is effect by an open belt and a cross belt drive. It is an old method of quick return drive used in planers of smaller size where the table width is less than 900 mm. Fig. 3.37 schematically shows the open and cross belt drive quick return mechanism of a planer.
Fig. 3.37 Open and cross belt drive quick return mechanism

It has a counter shaft mounted upon the housings receives its motion from an overhead line shaft. Two wide faced pulleys of different diameters are keyed to the counter shaft. The main shaft is placed under the bed. One end of the shaft carries a set of two larger diameter pulleys and two smaller diameter pulleys. The outer pulleys are rotate freely on the main shaft and they are called loose pulleys. The inner pulleys are keyed tightly to the main shaft and they are called fast pulleys. The open belt connects the larger diameter pulley on the countershaft with the smaller diameter pulley on the main shaft. The cross belt connects the smaller diameter pulley on the counter shaft with the larger diameter pulley on the main shaft. The speed of the main shaft is reduced through a speed reduction gear box. From this gear box, the motion is transmitted to the bull gear shaft. The bull gear meshes with a rack cut at the underside of the table and the table will receive a linear movement.

Referring to the Fig. 3.37, the open belt connects the smaller loose pulley, so no motion is transmitted by the open belt to the main shaft. But the cross belt connects the larger fast pulley, so the motion is transmitted by the cross belt to the main shaft. The forward stroke of the table takes place. During the cutting stroke, greater power and less speed is required. The cross belt giving a greater arc of contact on the pulleys is used to drive the table during the cutting stroke. The greater arc of contact of the belt gives greater power and the speed is reduced as the belt connects smaller diameter pulley on the counter shaft and larger diameter pulley on the main shaft. At the end of the forward stroke a trip dog pushes the belt shifter through a lever arrangement. The belt shifter shifts both the belts to the right side.
The open belt is shifted to the smaller fast pulley and the cross belt is shifted to the larger loose pulley. Now the motion is transmitted to the main shaft through the open belt and no motion is transmitted to the main shaft by the cross belt. The direction of rotation of the main shaft is reversed. The return stroke of the table takes place. The speed during return stroke is increased as the open belt connects the larger diameter pulley on the counter shaft with the smaller diameter pulley on the main shaft. Thus a quick return motion is obtained by the mechanism. At the end of the return stroke, the belts are shifted to the left side by another trip dog. So the cycle is repeated. The length and position of the stroke may be adjusted by shifting the position of trip dogs.

**Reversible motor drive quick return mechanism**

All modern planers are equipped with variable speed electric motor which drives the bull gear through a gear train. The most efficient method of an electrical drive is based on Ward Leonard system. *Fig. 3.38 schematically shows the reversible motor drive quick return mechanism of a planer.*

![Reversible motor drive quick return mechanism](image)

This system was introduced by Harry Ward Leonard in 1891. This system consists of an AC motor which is coupled with a DC generator, a DC motor and a reversing switch. When the AC motor runs, the DC motor will receive power from the DC generator. At that time, the table moves in forward direction. At the end of this stroke, a trip dog actuates an electrical reversing switch. Due to this action, it reverses the direction of current in DC generator with increased current strength. Now, the motor rotates in reverse direction with higher speed. So, the table moves in the reverse direction to take the return stroke with comparatively high speed. Thus the quick return motion is obtained by the mechanism.

*The distinct advantages of electrical drive over a belt drive are:*

Cutting speed, stroke length and stroke position can be adjusted without stopping the machine. Large number of cutting speeds and return speeds are available. Quick and accurate control. Push button controls the start, stop and fine movement of the table. Return speed can be greatly increased reducing idle time.
Hydraulic drive quick return mechanism
The hydraulic drive is quite similar to that used for a horizontal shaper. More than one hydraulic cylinder may be used to give a wide range of speeds. The main drawback of the hydraulic drive on long planers is irregular movement of the table due to the compressibility of the hydraulic fluid. The hydraulic drive has been described in Article 3.2.4.3, Page 107 and illustrated in Fig. 3.8.

FEED MECHANISM OF A PLANER
In a planer the feed is provided intermittently and at the end of the return stroke similar to a shaper. The feed of a planer, both down feed and cross feed, is given by the tool head. The down feed is applied while machining a vertical or angular surface by rotating the down feed screw of the tool head.

The cross feed is given while machining horizontal surface by rotating the cross feed screw passes through a nut in the tool head. Both the down feed and cross feed may be provided either by hand or power by rotating two feed screws, contained within the cross rail.

If the two feed screws are rotated manually by a handle, then it called hand feed. If the two feed screws are rotated by power, then it is called automatic feed.

3.3.5.1 Automatic feed mechanism of a planer
Fig. 3.39 illustrates the front and top view of the automatic feed mechanism of a planer. A trip dog is fitted to the planer table. At the end of the return stroke, the trip dog strikes a lever. A pawl attached to this lever rotates a ratchet. So a splined shaft attached to the ratchet rotates. A bevel gear cast integral with a spur gear is fitted freely on the down feed screw. This bevel gear meshes with other bevel gear slides on the splined shaft.

Fig. 3.39 Front and top view of the automatic feed mechanism of a planer
The spur gear meshes with another spur gear which is keyed to the cross feed screw. So the power from the splined shaft is transmitted to the cross feed screw. Then the rotation is transmitted to the tool head through a nut. The tool head moves horizontally. It is known a cross feed. At the end of the forward stroke, another trip dog strikes the lever. The lever comes to its original position. During this time, the pawl slips over the ratchet. The ratchet wheel does not rotate.

For giving automatic down feed, the spur gear keyed to the cross feed screw is disengaged. The bevel gear freely fitted to the down feed rod is keyed to the down feed rod. At the end of return stroke, the power is transmitted to the down feed rod through the lever, ratchet and bevel gears. Then the rotation is transmitted to the tool head though the bevel gears. The tool moves downward.

**Work holding devices used in a planer**
A planer table is used to hold very large, heavy and intricate work pieces, and in many cases, large number of identical work pieces together. Setting up of the work pieces on a planer table requires sufficient amount of skill. *The work piece may be held on a planer table by the following methods:*
  By standard clamping.
  By special fixtures.

**Standard clamping devices**
The standard clamping devices are used for holding most of the work pieces on a planer table.
*The standard clamping devices are as follows:*
  Heavy duty vises.
  T-bolts, step blocks and clamps.
  Stop pins and toe dogs.
  Angle plates.
  Planer jacks.
  Planer centres (similar to shaper centre).
  V-blocks.

*Most of them have been described in Article 3.2.6 and Page 110.*

A planer vise is much more robust in construction than a shaper vise as it is used for holding comparatively larger size of work. The vise may be plain or swiveled base type.

Large work pieces are clamped directly on the table by T-bolts and clamps. Different types of clamps are used for different types of work. *Fig. 3.40 illustrates the method of clamping a large work piece on a planer table.* Step blocks are used to lend support to the other end of the clamp.

Planer jacks are used for supporting the overhanging part of a work to prevent it from bending.
Fig. 3.40 Clamping a large work piece on a planer table

Special fixtures
These are used for holding a large number of identical pieces of work on a planer table. Fixtures are specially designed for holding a particular type of work. By using a fixture the setting time may be reduced considerably compared to the individual setting of work by conventional clamping devices.

*Fig. 3.42 illustrates the use of a fixture.*

Fig. 3.42 Use of a fixture

**PLANER TOOLS**
The cutting tools used on planers are all single point cutting tools. They are in general similar in shapes and tool angles to those used on a lathe and shaper. As a planer tool has to take up heavy cut and coarse feed during a long cutting stroke, the tools are made heavier and larger in cross-section. Planer tools may be solid, forged type or bit type. Bits are made of HSS, stellite or cemented carbide and they may be brazed, welded or
clamped on a mild steel shank. Cemented carbide tipped tool is used for production work.  
Fig. 3.43 shows the typical tools used in a planer.

![Fig. 3.43 Typical tools used in a planer]

**PLANER OPERATIONS**

All the operations done in a shaper can be done in a planer. But large size, stroke length and higher rigidity enable the planers to do more heavy duty work on large jobs and their long surfaces. Simultaneous use of number of tools further enhances the production capacity of planers. The common types of work machined in a planer are: Beds and tables of various machine tools, large structures, long parallel T-slots, V and inverted V type guide ways, frames of different engines and identical pieces of work which may be small in size but large in number.

Machining the major surfaces and guide ways of beds and tables of various machines like lathes, drilling machines, milling machines, grinding machines, broaching machines and planers itself are the common applications of a planer as illustrated in Fig. 3.44. Where the several parallel surfaces of typical machine bed and guide way are machined by a number of single point HSS or carbide tools.

![Fig. 3.44 Machining of a machine bed in a planer]
Besides the general machining work, some other critical work like helical grooving on large rods, long and wide 2-D curved surfaces, repetitive oil grooves etc. can also be made, if needed, by using suitable special attachments.

**Specifications of a planer**

*The planer is specified by the following parameters:*

- Radial distance between the top of the table and the bottom most position of the cross rail. Maximum length of the table and maximum stroke length of table.
- Power of the motor.
- Range of speeds and feeds available.
- Type of feed and type of drives required.
- Horizontal distance between two vertical housings. Net weight of machine and Floor area required.

### DIFFERENCE BETWEEN SHAPER AND PLANER

<table>
<thead>
<tr>
<th>SL. No.</th>
<th>SHAPER</th>
<th>PLANER</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The tool reciprocates and the work is stationary.</td>
<td>The work reciprocates and the tool is stationary.</td>
</tr>
<tr>
<td>2</td>
<td>Feed is given to the work during the idle stroke of the ram.</td>
<td>Feed is given to the tool during the idle stroke of the work table.</td>
</tr>
<tr>
<td>3</td>
<td>It gives more accuracy as the tool is rigidly supported during cutting.</td>
<td>Less accuracy due to the over hanging of the ram.</td>
</tr>
<tr>
<td>4</td>
<td>Suitable for machining small work pieces.</td>
<td>Suitable for machining large work pieces.</td>
</tr>
<tr>
<td>5</td>
<td>Only light cuts can be applied.</td>
<td>Heavy cuts can be applied.</td>
</tr>
<tr>
<td>6</td>
<td>Only one tool can be used at a time. So machining takes longer time.</td>
<td>Vertical and side tool heads can be used at a time. So machining is quicker.</td>
</tr>
<tr>
<td>7</td>
<td>Setting the work piece is easy.</td>
<td>Setting the work piece is difficult.</td>
</tr>
<tr>
<td>8</td>
<td>Only one work piece can be machined at a time.</td>
<td>Several work pieces can be machined at a time.</td>
</tr>
<tr>
<td>9</td>
<td>Tools are smaller in size.</td>
<td>They are larger in size.</td>
</tr>
<tr>
<td>10</td>
<td>Shapers are lighter and smaller.</td>
<td>Planers are heavier and larger.</td>
</tr>
</tbody>
</table>
MILLING MACHINE

INTRODUCTION
This is a machine tool that removes material as the work is fed against a rotating cutter. The cutter rotates at a high speed and because of the multiple cutting edges it removes material at a very fast rate. The machine can also hold two or more number of cutters at a time. That is why a milling machine finds wide application in machine shop. The first milling machine came into existence in about 1770 and was of French origin. The milling cutter was developed by Jacques de Vaucanson in the year 1782. The first successful plain milling machine was designed by Eli Whitney in the year 1818. The universal milling machine was invented in the year 1861 by Joseph R Brown.

3.6 TYPES OF MILLING MACHINE
Milling machines are broadly classified as follows:

Column and knee type
- Hand milling machine.
- Plain or horizontal milling machine.
- Universal milling machine.
- Vertical milling machine.

Manufacturing or bed type
- Simplex milling machine.
- Duplex milling machine.
- Triplex milling machine.

Planer type

Special type
- Drum milling machine.
- Rotary table milling machine.
- Profile milling machine.
- Pantograph milling machine.
- Planetary milling machine.

Column and knee type milling machines
This is the most commonly used machine in view of its flexibility and easier setup. In such small and medium duty machines the table with work travels above the saddle in horizontal direction (X axis) (left and right). The saddle with table moves on the slideways provided on the knee in transverse direction (Y axis) (front and back). The knee with saddle and table moves on a dovetail guide ways provided on the column in vertical direction (Z axis) (up and down).
**Hand milling machine**

This is the simplest form of milling machine where even the table feed is also given manually. The cutter is mounted on a horizontal arbor. This is suitable for light and simple milling operations such as machining slots, grooves and keyways. *Fig. 3.52 (a) shows the photographic view of a horizontal hand milling machine and Fig. 3.52 (b) shows that of a vertical hand milling machine.*

![Horizontal Hand Milling Machine](image1.png)  
![Vertical Hand Milling Machine](image2.png)

**Plain or horizontal milling machine**

This non automatic general purpose milling machine of small to medium size possesses a single horizontal axis milling arbor. The work table can be linearly fed along three axes (X, Y, and Z) only. The table may be fed by hand or power. These machines are most widely used for piece or batch production of jobs of relatively simple design and geometry. *Fig. 3.53 schematically shows the basic configuration of a horizontal milling machine.*

![Plain or Horizontal Milling Machine](image3.png)

**Fig. 3.52 (a) Horizontal hand milling machine**  
**Fig. 3.52 (b) Vertical hand milling machine**  
**Fig. 3.53 Plain or horizontal milling machine**
Universal milling machine
It is so named because it may be adapted to a very wide range of milling operations. It can be distinguished from a plain milling machine in that the table of a universal milling machine is mounted on a circular swiveling base which has degree graduations, and the table can be swiveled to any angle up to 45° on either side of the normal position.

Thus in a universal milling machine, in addition to the three movements as incorporated in a plain milling machine, the table have a fourth movement when it is fed at an angle to the milling cutter. This additional feature enables it to perform helical milling operation which cannot be done on a plain milling machine unless a spiral milling attachment is used. The capacity of a universal milling machine is considerably increased by the use of special attachments such as dividing head or index head, vertical milling attachment, rotary attachment, slotting attachment, etc. The machine can produce spur, spiral, bevel gears, twist drills, reamers, milling cutters, etc. besides doing all conventional milling operations.

*Fig. 3.54 schematically shows the basic configuration of a universal milling machine.*

Omniversal milling machine

*Fig. 3.55 schematically shows the basic configuration of an omniversal milling machine.*

In this machine, the table besides having all the movements of a universal milling machine can be tilted in a vertical plane by providing a swivel arrangement at the knee. Also the entire knee assembly is mounted in such a way that it may be fed in a longitudinal direction horizontally. The additional swiveling arrangement of the table enables it to machine taper spiral grooves in reamers, bevel gears, etc. It is essentially a tool room and experimental shop machine.

Vertical milling machine

This machine is very similar to a horizontal milling machine. The only difference is the spindle is vertical. The work table may or may not have swiveling features. The spindle head may be swiveled at an angle, permitting the milling cutter to work on angular surfaces. In some machines, the spindle can also be adjusted up or down relative to the work piece. This machine works using end milling and face milling cutters. This machine
is adapted for machining grooves, slots and flat surfaces.

*Fig. 3.56 schematically shows the basic configuration of a vertical milling machine.*

![Vertical milling machine](image)

**Manufacturing or bed type milling machines**

The fixed bed type milling machines are comparatively large, heavy, and rigid and differ radically from column and knee type milling machines by the construction of its table mounting. The table is mounted directly on the guide ways of the fixed bed. The table movement is restricted to reciprocation at right angles to the spindle axis with no provision for cross or vertical adjustment. The cutter mounted on the spindle head may be moved vertically on the column, and the spindle may be adjusted horizontally to provide cross adjustment. The name simplex, duplex and triplex indicates that the machine is provided with single, double and triple spindle heads respectively. In a duplex machine, the spindle heads are arranged on each side of the table. In triplex type the third spindle (vertical) is mounted on a cross rail. The usual feature of these machines is the automatic cycle of operation for feeding the table, which is repeated in a regular sequence. The feed cycle of the table includes the following: Start, rapid approach, slow feed for cutting, rapid traverse to the next work piece, quick return and stop. This automatic control of the machine enables it to be used with advantage in repetitive types of work.

*Fig. 3.57 (a) and (b) shows the simplex milling machine and duplex milling machine.*
MAJOR PARTS OF A COLUMN AND KNEE TYPE MILLING MACHINE

The general configuration of a column and knee type conventional milling machine with horizontal arbor is shown in Fig. 3.53. The major parts are:

**Base** It is accurately machined on its top and bottom surface and serves as a foundation member for all other parts. It carries the column at its one end. In some machines, the base is hollow and serves as a reservoir for cutting fluid.

**Column** It is the main supporting frame mounted vertically on the base. The column is box shaped, heavily ribbed inside and houses all the driving mechanisms for the spindle and table feed. The front vertical face of the column is accurately machined and is provided with dovetail guide ways for supporting the knee. The top of the column is finished to hold an over arm that extends outward at the front of the machine.

**Knee** It slides up and down on the vertical guide ways of the column face. The adjustment of height is effected by an elevating screw mounted on the base that also supports the knee. The knee houses the feed mechanism of the table, and different controls to operate it. The top face of the knee forms a slideway for the saddle to provide cross travel of the table.

**Table** The table rests on ways on the saddle and travels longitudinally. The top of the table is accurately finished and T-slots are provided for clamping the work and other fixtures on it. A lead screw under the table engages a nut on the saddle to move the table horizontally by hand or power. The longitudinal travel of the table may be limited by fixing trip dogs on the side of the table. In universal machines, the table may also be swiveled horizontally.
**Overhanging arm**  The overhanging arm that is mounted on the top of the column extends beyond the column face and serves as a bearing support for the other end of the arbor. The arm is adjustable so that the bearing support may be provided nearest to the cutter.

**Front brace**  The front brace is an extra support that is fitted between the knee and the over arm to ensure further rigidity to the arbor and the knee. The front brace is slotted to allow for the adjustment of the height of the knee relative to the over arm.

**Spindle**  The spindle of the machine is located in the upper part of the column and receives power from the motor through belts, gears, clutches and transmits it to the arbor. The front end of the spindle just projects from the column face and is provided with a tapered hole into which various cutting tools and arbors may be inserted. The accuracy in metal machining by the cutter depends primarily on the accuracy, strength, and rigidity of the spindle.

**Arbor**  It may be considered as an extension of the machine spindle on which milling cutters are securely mounted and rotated. The arbors are made with taper shanks for proper alignment with the machine spindles having taper holes at their nose. The arbor may be supported at the farthest end from the overhanging arm or may be of cantilever type which is called stub arbor. The arbor shanks are properly gripped against the spindle taper by a draw bolt which extends throughout the length of the hollow spindle. The threaded end of the draw bolt is fastened to the tapped hole of the arbor shank and then the lock nut is tightened against the spindle. The spindle has also two keys for imparting positive drive to the arbor in addition to the friction developed in the taper surfaces. The cutter is set at the required position on the arbor by spacing collars or spacers of various lengths but of equal diameter. The entire assembly of the milling cutter and the spacers are fastened to the arbor by a long key. The end spacer on the arbor is slightly larger in diameter and acts as a bearing bush for bearing support which extends from the over arm.

**Working principle of a column and knee type milling machine**  
*Fig. 3.63 shows the basic principle of producing flat surface in a milling machine by a plain milling cutter.*

The kinematic system comprising of several mechanisms enables transmission of motion and power from the motor to the cutting tool for its rotation at varying speeds and to the work table for its slow feed motions along X, Y and Z directions. The milling cutter mounted on the horizontal milling arbor, receives its rotary motion at different speeds from the main motor through the speed gear box. The feeds of the work piece can be given by manually or automatically by rotating the respective wheels by hand or by power. The work piece is clamped on the work table by a work holding device. Then the work piece is fed against the rotating multipoint cutter to remove the excess material at a very fast rate.
Work holding devices used in a milling machine

It is necessary that the work piece should be properly and securely held on the milling machine table for effective machining operations. The work piece may be supported on the milling machine table by using any one of the following work holding devices depending upon the geometry of the work piece and nature of the operation to be performed.

- T-bolts and clamps.
- Angle plate.
- V-blocks.
- Vises.
- Special fixtures.
- Dividing heads.

**T-bolts and clamps** Bulky work pieces of irregular shapes are clamped directly on the milling machine table by using T-bolts and clamps. Fig. 3.15 illustrates the use of T-bolts and clamps. Different designs of clamps are used for different patterns of work. Fig. 3.65 shows the different types of clamps.

![Fig. 3.65 Different types of clamps](image)

**Angle plate** The angle plate has been described in Article 3.2.6.3, Page 112 and illustrated in Fig. 3.19. Sometimes a titling type angle plate in which one face can be adjusted relative to another face for milling at a required angle is also used. Fig. 3.66 shows a tilting type angle plate.
Fig. 3.66 Tilting type angle plate

**V-blocks** The V-block has been described in Article 3.2.6.4, Page 112 and illustrated in Fig. 3.20. This is used for holding shafts on the table in which keyways, slots and flats are to be milled.

**Vises** The different types of vise has been described in Article 3.2.6.1, Page 110 and illustrated in Fig. 3.12 (a), (b) and (c). Vises are the most common appliances for holding work on milling machine table due to its quick loading and unloading arrangement.

**Special fixtures** The fixtures are special devices designed to hold work for specific operations more efficiently than standard work holding devices. Fixtures are especially useful when large numbers of identical parts are being produced. By using fixtures loading, locating, clamping and unloading time is greatly minimized.

**CUTTER HOLDING DEVICES USED IN A MILLING MACHINE**
There are several methods of holding and rotating milling cutters by the machine spindle depending on the different designs of the cutters. They are:

**Arbors**
The cutters have a bore at the centre are mounted and keyed on a short shaft called arbor. The arbor has been described in Article 3.6.5, Page 133 and illustrated in Fig. 3.62.

**Collets**
A milling machine collet is a form of sleeve bushing for reducing the size of the taper hole at the nose of the spindle so that an arbor or a milling cutter having a smaller shank than the spindle taper can be fitted into it. *Fig. 3.70 (a) illustrates a milling machine collet.*

**Adapter**
An adapter is a form of collet used on milling machine having standardized spindle end. Cutters having straight shanks are usually mounted on adapters. An adapter can be connected with the spindle by a draw bolt or it may be directly bolted to it. *Fig. 3.70 (b) illustrates a milling machine adapter.*
Spring collets
Straight shank cutters are usually held on a special adapter called “spring collet” or “spring chuck”. The cutter shank is introduced in the cylindrical hole provided at the end of the adapter and then the nut is lightened. This causes the split jaws of the adapter to spring inside, and grip the shank firmly. Fig. 3.70 (c) illustrates a spring collet.

Bolted cutters
The face milling cutters of larger diameter having no shank are bolted directly on the nose of the spindle. For this purpose four bolt holes are provided on the body of the spindle. This arrangement of holding cutter ensures utmost rigidity. Fig. 3.70 (d) illustrates a face milling cutter bolted on the spindle.

Screwed on cutters
The small cutters having threaded holes at the centre are screwed on the threaded nose of an arbor which is mounted on the spindle in the usual manner. Fig. 3.70 (e) shows a screwed on cutter.

Fig. 3.70 Different types of cutter holding devices used in milling machines