Module
1
Classification of Metal Removal Processes and Machine tools

Lesson
1

Introduction to Manufacturing and Machining

Instructional objectives

At the end of this lesson, the student would be able to :

(i) Identify the necessity of “manufacturing”
(ii) Define with examples the concept of “manufacturing”
(iii) List the main classifications of the manufacturing processes with examples
(iv) State the main purposes of “machining”
(v) Define with examples the concept of “machining”
(vi) State with example the principles of “machining”
(vii) State with examples the main requirements for “machining”
(viii) State with examples the main functions of “Machine tools”
(ix) Define the concept of “machine tools”

(i) Manufacturing – Need and concept

The progress and the prosperity of human civilization are governed and judged mainly by improvement and maintenance of standard of living through availability or production of ample and quality goods and services for men’s material welfare (MMW) in all respects covering housing, clothing, medicine, education, transport, communication and also entertainment. The successful creation of men’s material welfare (MMW) depends mainly on

- availability of natural resources (NR)
- exertion of human effort (HE); both physical and mental
- development and use of power tools and machines (Tools),

This can be depicted in a simple form,

$$MMW = NR(HE)^{TOOLS}$$

where, NR: refers to air, water, heat and light, plants and animals and solid and liquid minerals

TOOLS: refers to power plants, chemical plants, steel plants, machine tools etc. which magnify human capability.

This clearly indicates the important roles of the components; NR, HE and TOOLS on achieving MMW and progress of civilization.

Production or manufacturing can be simply defined as value addition processes by which raw materials of low utility and value due to its inadequate material properties and poor or irregular size, shape and finish are converted into high utility and valued products with definite dimensions, forms and finish imparting some functional ability. A typical example of manufacturing is schematically shown in Fig. 1.1.

A lump of mild steel of irregular shape, dimensions and surface, which had almost no use and value, has been converted into a useful and valuable product like bolt by a manufacturing process which imparted suitable features, dimensional accuracy and surface finish, required for fulfilling some functional requirements.

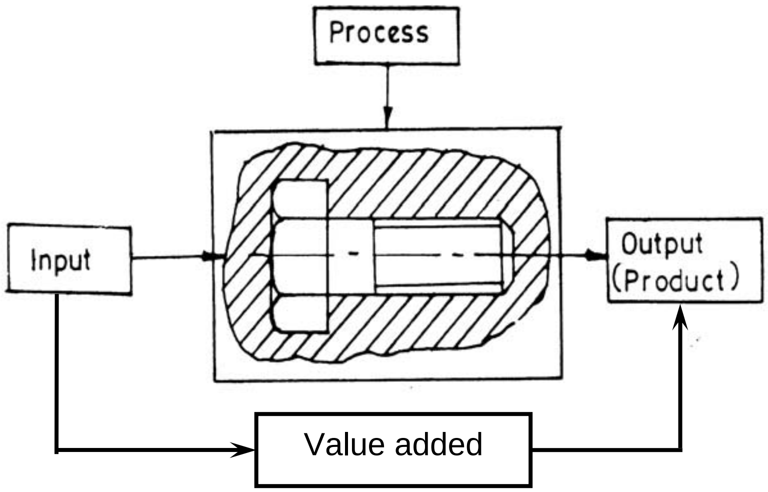


Fig. 1.1 *Value addition by manufacturing.*

Production Engineering covers two domains:

(a) Production or Manufacturing Processes

(b) Production Management

(a) Manufacturing Processes

This refers to science and technology of manufacturing products effectively, efficiently, economically and environment-friendly through

- Application of any existing manufacturing process and system
- Proper selection of input materials, tools, machines and environments.
- Improvement of the existing materials and processes
- Development of new materials, systems, processes and techniques

All such manufacturing processes, systems, techniques have to be

- Technologically acceptable
- Technically feasible
- Economically viable
- Eco-friendly

Manufacturing Science and technology are growing exponentially to meet the growing demands for;

(i) Increase and maintenance of productivity, quality and economy specially in respect of liberalisation and global competitiveness

(ii) Making micro and ultra precision components for the modern electronics, computers and medical applications
(iii) Processing exotic materials, coming up with rapid and vast advent of science and technology like aerospace and nuclear engineering.

(b) Production Management

This is also equally important and essential in the manufacturing world. It mainly refers to planning, coordination and control of the entire manufacturing in most profitable way with maximum satisfaction to the customers by best utilization of the available resources like man, machine, materials and money. It may be possible to manufacture a product of given material and desired configuration by several processes or routes as schematically indicated in Fig. 1.2.

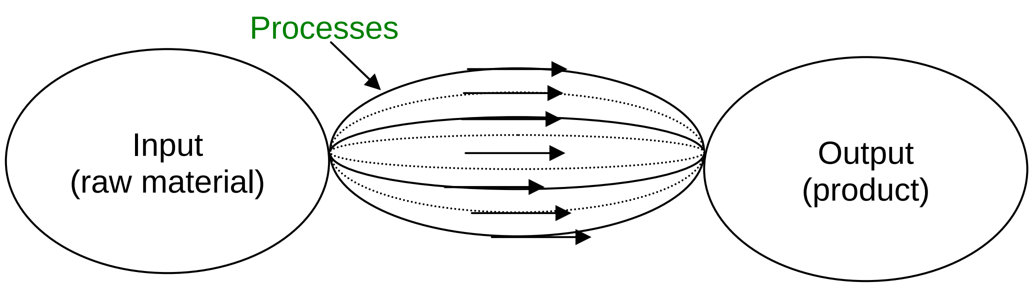


Fig. 1.2 *Possibility of manufacturing in number of routes.*

The various process routes may be different in respect of principle, technique, quality of products and time requirement and cost of manufacture. The best one is to be selected based on some criteria. Achieving the goal in manufacturing requires fulfillment of one or more of the following objectives:

- reduction of manufacturing time
- increase of productivity
- reduction of manufacturing cost
- increase in profit or profit rate

The most significant and ultimate objective, i.e., "Increase in Profit, P_r", can be attained by

(i) reducing the overall manufacturing cost, C_m
(ii) increase in revenue, R by increasing quality and reliability of the products
(iii) enhancement of saleable production

As has been indicated in Fig. 1.3

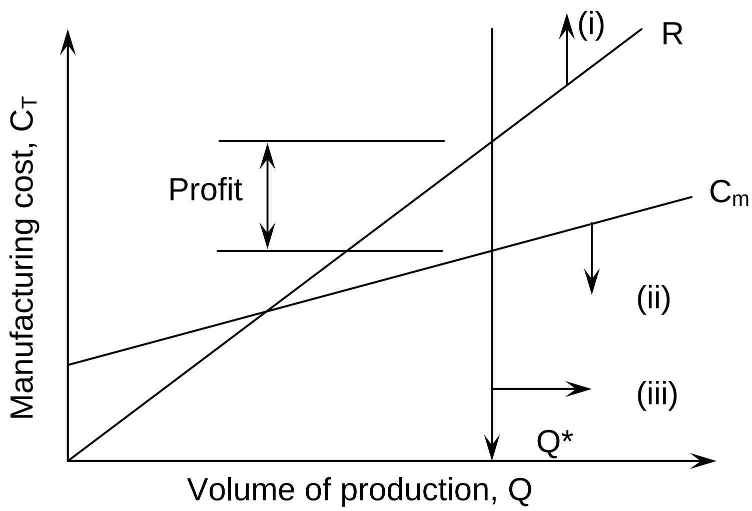


Fig. 1.3 *Strategies of increasing profit.*

Production management integrates and accomplishes all such essential activities leading to maximum benefits by best utilization of the resources and strategies.

(ii) Broad classification of Engineering Manufacturing Processes.

It is extremely difficult to tell the exact number of various manufacturing processes existing and are being practiced presently because a spectacularly large number of processes have been developed till now and the number is still increasing exponentially with the growing demands and rapid progress in science and technology. However, all such manufacturing processes can be broadly classified in four major groups as follows:

(a) Shaping or **forming**

Manufacturing a solid product of definite size and shape from a given material taken in three possible states:

- in solid state – e.g., forging rolling, extrusion, drawing etc.
- in liquid or semi-liquid state – e.g., casting, injection moulding etc.
- in powder form – e.g., powder metallurgical process.

(b) Joining process

Welding, brazing, soldering etc.

(c) Removal process

Machining (Traditional or Non-traditional), Grinding etc.

(d) Regenerative manufacturing

Production of solid products in layer by layer from raw materials in different form:

- liquid – e.g., stereo lithography
- powder – e.g., selective sintering
- sheet – e.g., LOM (laminated object manufacturing)
- wire – e.g., FDM. (Fused Deposition Modelling)

Out of the aforesaid groups, Regenerative Manufacturing is the latest one which is generally accomplished very rapidly and quite accurately using CAD and CAM for Rapid Prototyping and Tooling.

(iii) Machining – Purpose, Principle and Definition

(a) 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

(b) Principle of Machining

The basic principle of machining is typically illustrated in Fig. 1.4.

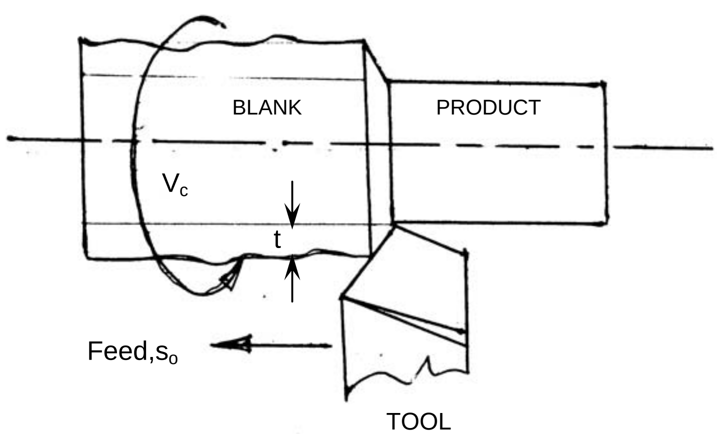


Fig. 1.4 *Principle of machining (turning)*

A metal rod of irregular shape, size and surface is converted into a finished rod of desired dimension and surface by machining by proper relative motions of the tool-work pair.

(c) Definition of Machining: Machining is an essential process of finishing by which jobs 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).

(iv) Machining requirements

The essential basic requirements for machining work are schematically illustrated in Fig. 1.5

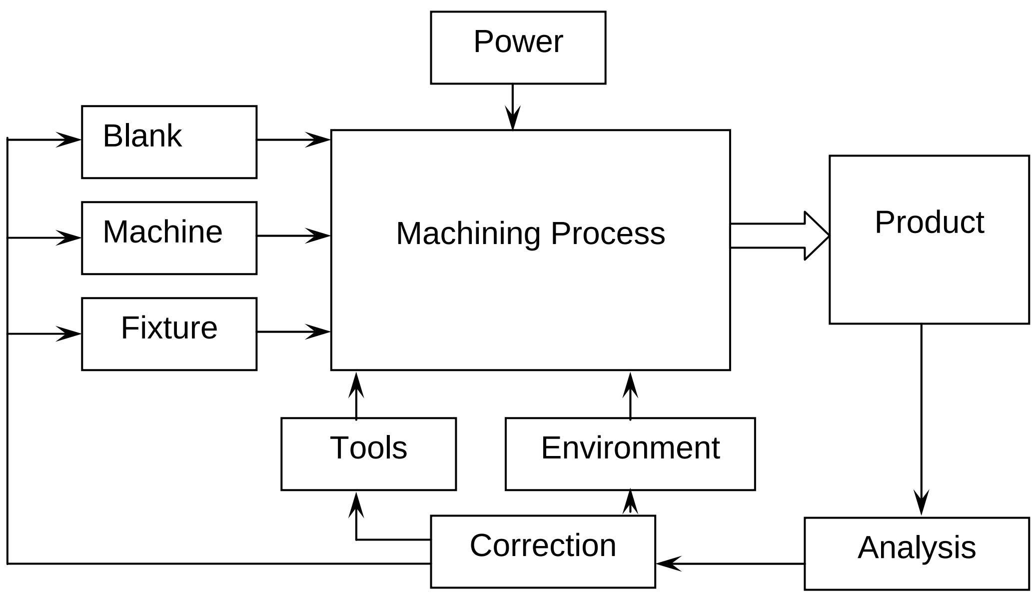


***Fig. 1.5** Requirements for machining*

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.

(v) 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.

(vi) Machine Tool - definition

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).

A. Quiz Test:

Select the correct answer from the given four possible answers: -

1. Machining is a
   (a) shaping process
   (b) removal process
   (c) regenerative process
   (d) joining process.

2. An object is machined to
   (a) fulfill its functional requirement
   (b) provide desirably good performance
   (c) render longer service life
   (d) all of the above.

3. Feed rate is expressed in turning operation by
   (a) mm/revolution
   (b) mm/stroke
   (c) mm per min
   (d) none of the above.

4. Rapid prototyping is a
   (a) joining process
   (b) removal process
   (c) regenerative manufacturing process
   (d) finishing process.

B. Exercises:

1. What should be the aims and objectives in manufacturing of any product?

2. Justify "Machining is a value addition process".

3. Why even a battery operated pencil sharpener cannot be accepted as a machine tool?

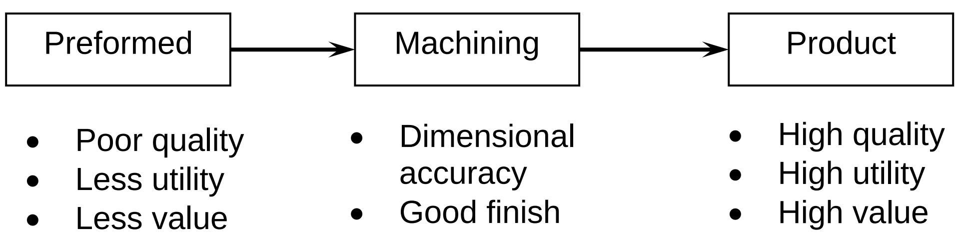
4. Why is making profit must for any industry ?

Answers of the given questions.

A. 1. – (b)
2. – (d)
3. – (a)
4. – (c)

B.
Ans. 1 Aim – enhance profit rate and job opportunity
Objectives –
- reduce manufacturing time
- increase rate of production
- reduce cost of manufacturing
- raise profit and profit rate

Ans.2



Ans. 3 Inspite of having all other major features of machine tools, the sharpener is of low value.

Ans. 4 For
- Maintenance, repair & replacement
- Modernisation
- Increase salary / incentive
- Expansion

Module
1

Classification of Metal Removal Processes and Machine tools

Lesson 2

Basic working principle, configuration, specification and classification of machine tools

Instructional Objectives

At the end of this lesson, the students should be able to :

(a) Describe the basic functional principles of machine tools
   (i) Illustrate the concept of Generatrix and Directrix
   (ii) Demonstrate Tool – work motions
   (iii) Give idea about machine tool drives

(b) Show configuration of basic machine tools and state their uses

(c) Give examples of machine tools - specification

(d) Classify machine tools broadly.

Basic functional principles of machine tool operations

Machine Tools produce desired geometrical surfaces on solid bodies (preformed blanks) and for that they are basically comprised of;

- Devices for firmly holding the tool and work
- Drives for providing power and motions to the tool and work
- Kinematic system to transmit motion and power from the sources to the tool-work
- Automation and control systems
- Structural body to support and accommodate those systems with sufficient strength and rigidity.

For material removal by machining, the work and the tool need relative movements and those motions and required power are derived from the power source(s) and transmitted through the kinematic system(s) comprised of a number and type of mechanisms.

(i) Concept of Generatrix and Directrix

- Generation of flat surface

The principle is shown in Fig. 2.1 where on a flat plain a straight line called Generatrix (G) is traversed in a perpendicular direction called Directrix (D) resulting a flat surface.

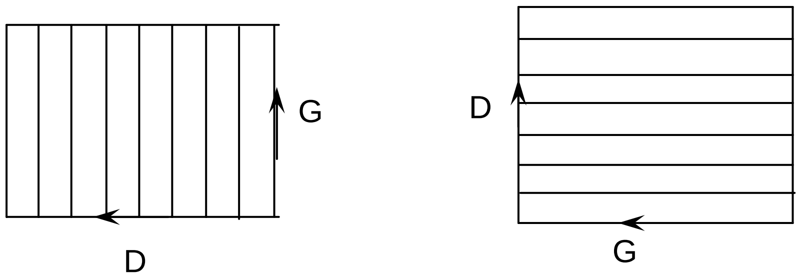
- Generation of cylindrical surfaces

The principles of production of various cylindrical surfaces (of revolution) are shown in Fig. 2.2, where,

— A long straight cylindrical surface is obtained by a circle (G) being traversed in the direction (D) parallel to the axis as shown in Fig. 2.2(a)

— A cylindrical surface of short length is obtained by traversing a straight line (G) along a circular path (D) as indicated in Fig. 2.2(b)

— Form cylindrical surfaces by rotating a curved line (G) in a circular path (D) as indicated in Fig. 2.2 (c and d).



(a) (b)

Fig. 2.1 *Generation of flat surfaces by Generatrix and Directrix.*

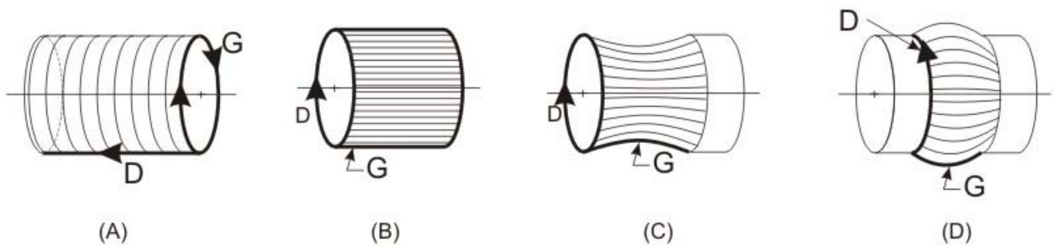


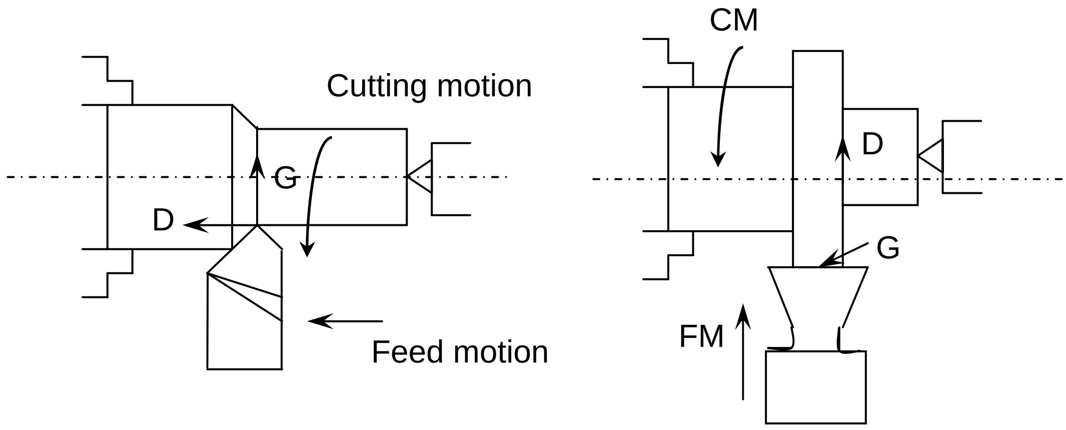
Fig. 2.2 *Generation of cylindrical surfaces (of revolution)*

(ii) Tool – work motions

The lines representing the Generatrix and Directrix are usually produced by the locus of a point moving in two different directions and are actually obtained by the motions of the tool-tip (point) relative to the work surface. Hence, for machining flat or curved surfaces the machine tools need relative tool work motions, which are categorized in following two groups:

- Formative motions namely
  - Cutting motion (CM)
  - Feed motion (FM)
- Auxiliary motions such as
  - Indexing motion
  - Additional feed motion
  - Relieving motion

The Generatrix and Directrix, tool and the work and their motions generally remain interconnected and in different way for different machining work. Such interconnections are typically shown in Fig. 2.3 for straight turning and in Fig. 2.4 for shaping.



(a) longitudinal turning (b) transverse turning

Fig. 2.3 *Principle of turning (cylindrical surface)*

The connections in case of straight longitudinal turning shown in Fig. 2.3 (a) are:

Generatrix (G) – Cutting motion (CM) – Work (W)
Directrix (D) – Feed motion (FM) – Tool (T)

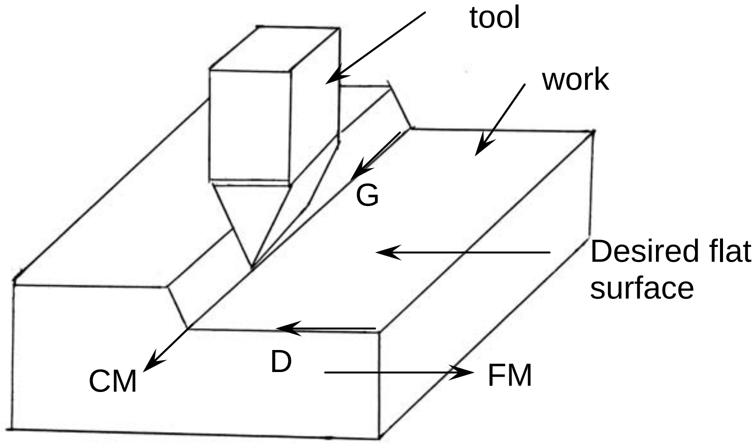


Fig. 2.4 *Principle of producing flat surface in shaping machine*

In case of making flat surface in a shaping machine as shown in Fig. 2.4 the connections are:

G – CM – T
D – FM – W

which indicates that in shaping flat surfaces the Generatrix is provided by the cutting motion imparted to the cutting tool and the Directrix is provided by the feed motion of the work.

Flat surfaces are also produced by planning machines, mainly for large jobs, where the cutting motion is imparted to the work and feed motion to the tool and the connections will be:

G – CM – Work
D – FM – Tool

The Genratrix and Directrix can be obtained in four ways:

- Tracing (Tr) – where the continuous line is attained as a trace of path of a moving point as shown in Fig. 2.3 and Fig. 2.4.
- Forming (F) – where the Generatrix is simply the profile of the cutting edge as indicated in Fig. 2.2 (c and d)
- Tangent Tracing (TTr) – where the Directrix is taken as the tangent to the series of paths traced by the cutting edges as indicated in Fig. 2.5.
- Generation (G): Here the G or D is obtained as an envelope being tangent to the instantaneous positions of a line or surface which is rolling on another surface. Gear teeth generation by hobbing or gear shaping is the example as can be seen in Fig. 2.6.

Fig. 2.5 typically shows the tool-work motions and the corresponding Generatrix (G) and Directrix (D) while producing flat surface by a plain or slab milling cutter in a conventional horizontal arbour type milling machine. The G and D are connected here with the tool work motions as

G – x – T – F
D – FM – W – T.Tr
CM – T

Here G and D are independent of the cutting motion and the G is the line of contact between the milling cutter and the flat work surface. The present cutter being of roller shape, G has been a straight line and the surface produced has also been flat. Form milling cutters will produce similar formed surfaces as shown in Fig. 2.7 where the 'G' is the tool-form.

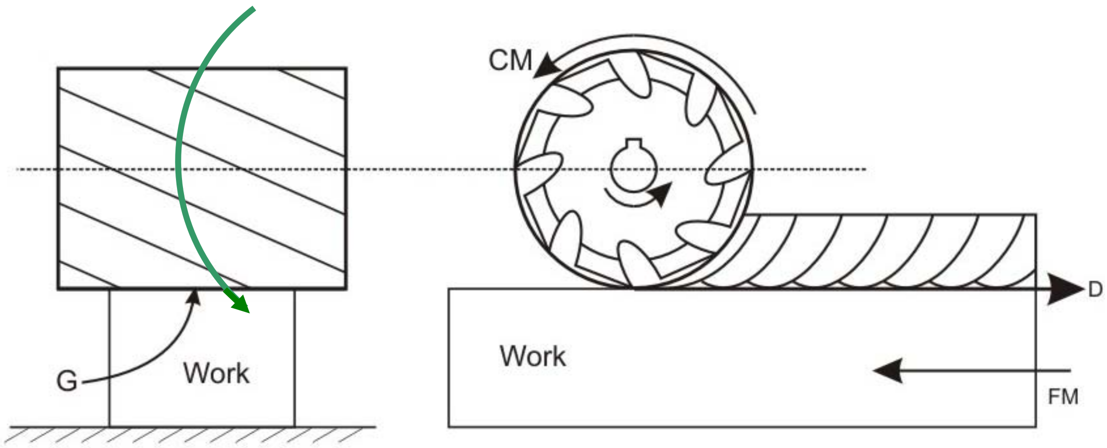


Fig. 2.5 *Directrix formed by tangent tracing in plain milling*

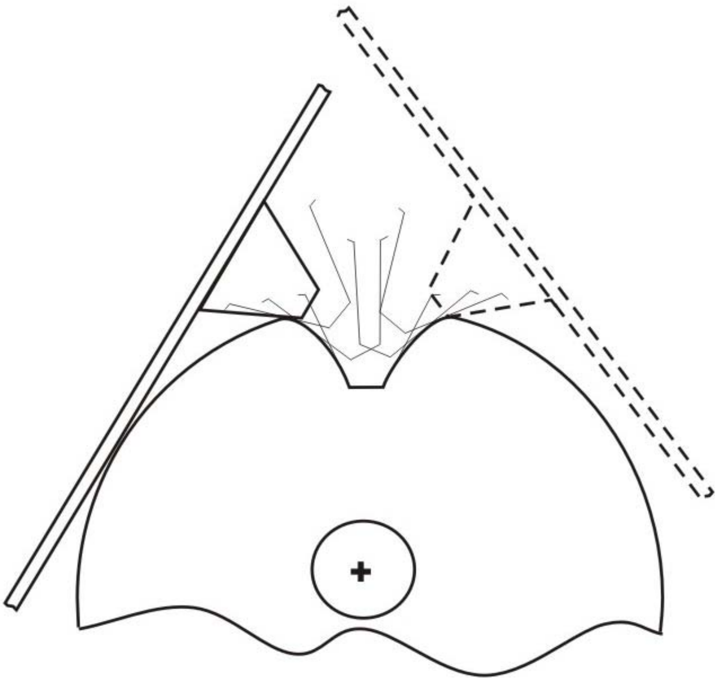


Fig. 2.6 *Generatrix (or Directrix) in gear teeth cutting by generation.*

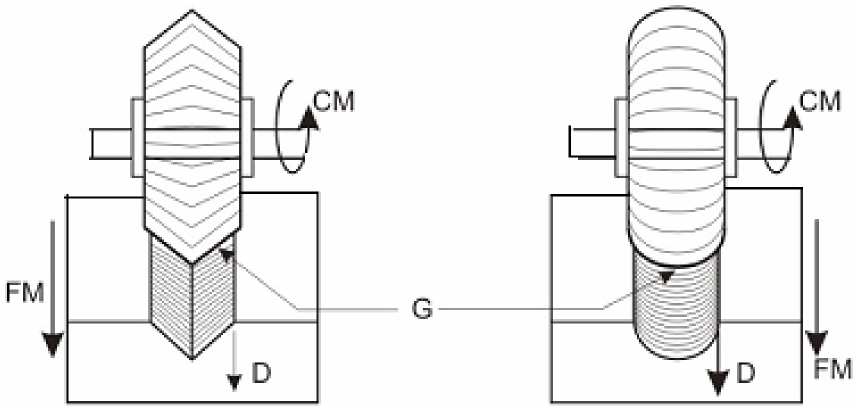


Fig. 2.7 *Tool-work motions and G & D in form milling*

For making holes in drilling machines both the cutting motion and the feed motion are imparted to the cutting tool i.e., the drill bit whereas the workpiece remains stationary. This is shown in Fig. 2.8. The G and D are linked with the tool-work in the way:

G – CM – T – Tr
D – FM – W – Tr

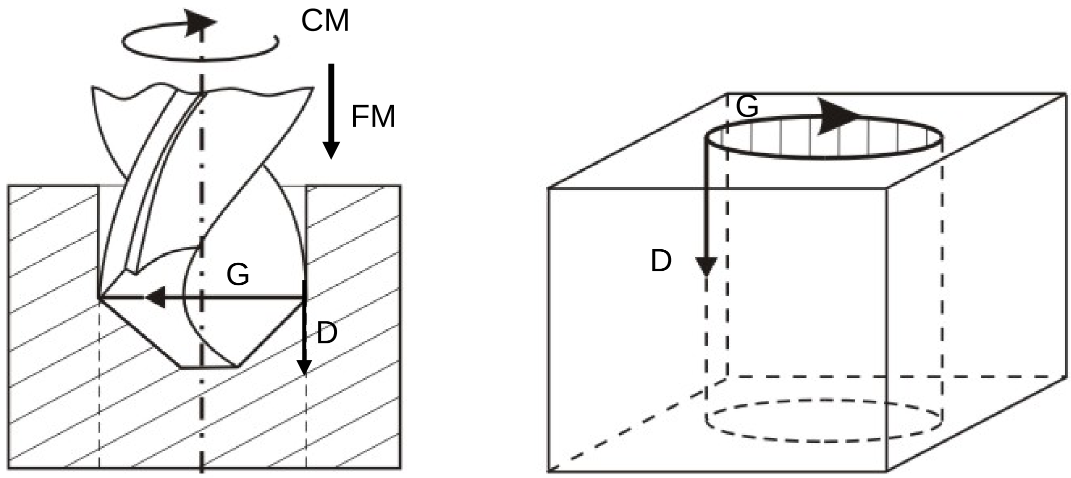


Fig. 2.8 *Tool-work motions and G & D in drilling.*

Boring machines are mostly used for enlargement and finishing of existing cylindrical holes. Boring machines are of two types:

- Vertical boring machine – low or medium duty and high precision, e.g., Jig boring machine
- Horizontal axis boring machine – medium or heavy duty.

In respect of tool-work motions and G and D, vertical boring and drilling are same. In horizontal boring machine the feed motion is imparted to the work to provide the Directrix by Tracing.

(iii) Machine tool drives

For the desired tool-work motions with power, machine tools are driven by electric motors and use of some mechanisms like belt-pulley, gears etc. In some machine tools, the tool-work motions are provided by hydraulic drive also.

Machine tools essentially need wide ranges of cutting speed and feed rate to enable

- Machining different jobs (material and size)
- Using different cutting tools (material, geometry and size)
- Various machining operations like high speed turning to low speed thread cutting in lathes
- Degree of surface finish desired.

Machine tool drives may be

- o Stepped drive
- o Stepless drive

Stepped drives are very common in conventional machine tools where a discrete number of speeds and feeds are available and preferably in G.P. (Geometric Progression) series. Whereas the modern CNC machine tools are provided with stepless drives enabling optimum selection and flexibly automatic control of the speeds and feeds.

Stepped drive is attained by using gear boxes or cone pulley (old method) along with the power source. Stepless drive is accomplished usually by

- Variable speed AC or DC motors
- Stepper or servomotors
- Hydraulic power pack

Configuration of Basic Machine Tools and their use

- **Centre lathes**
  - configuration

  Fig. 2.9 shows the general configuration of center lathe. Its major parts are:

  - o Head stock: it holds the blank and through that power and rotation are transmitted to the job at different speeds
  - o tailstock: supports longer blanks and often accommodates tools like drills, reamers etc for hole making.
  - o carriage: accommodates the tool holder which in turn holds the moving tools
  - o bed: ∆ headstock is fixed and tailstock is clamped on it. Tailstock has a provision to slide and facilitate operations at different locations
    - ∆ carriage travels on the bed
  - o columns: on which the bed is fixed
  - o work-tool holding devices

— uses of center lathes

Centre lathes are quite versatile being used for various operations:

— turning — [external, internal] — [straight, taper, stepped]

— facing, centering, drilling, recessing and parting

— thread cutting; external and internal

— knurling.

Some of those common operations are shown in Fig. 2.10. Several other operations can also be done in center lathes using suitable attachments.

- **Shaping machine**

  Fig. 2.11 shows the general configuration of shaping machine. Its major parts are:

  - o Ram: it holds and imparts cutting motion to the tool through reciprocation
  - o Bed: it holds and imparts feed motions to the job (blank)
  - o Housing with base: the basic structure and also accommodate the drive mechanisms

o Power drive with speed and feed change mechanisms.

Shaping machines are generally used for producing flat surfaces, grooving, splitting etc. Because of poor productivity and process capability these machine tools are not widely used now-a-days for production.

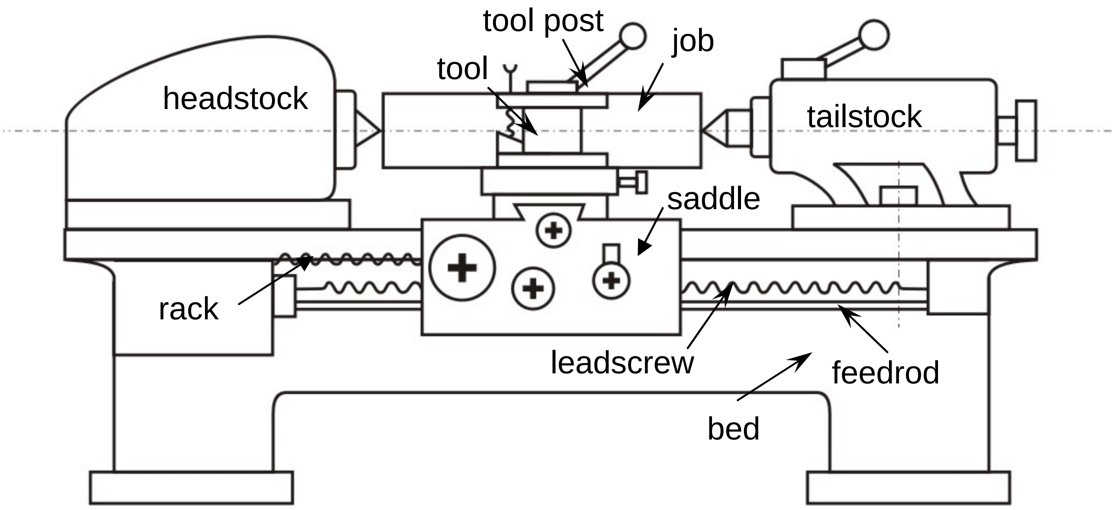


Fig. 2.9 *Schematic view of a center lathe*

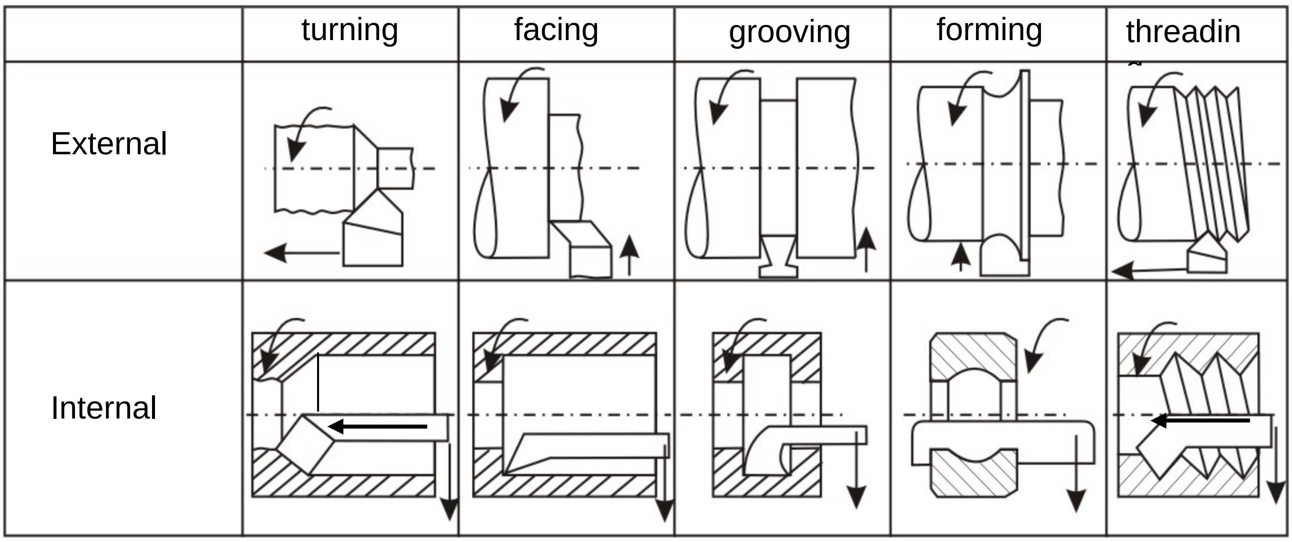


Fig. 2.10 *Some common machining operations done in center lathes.*

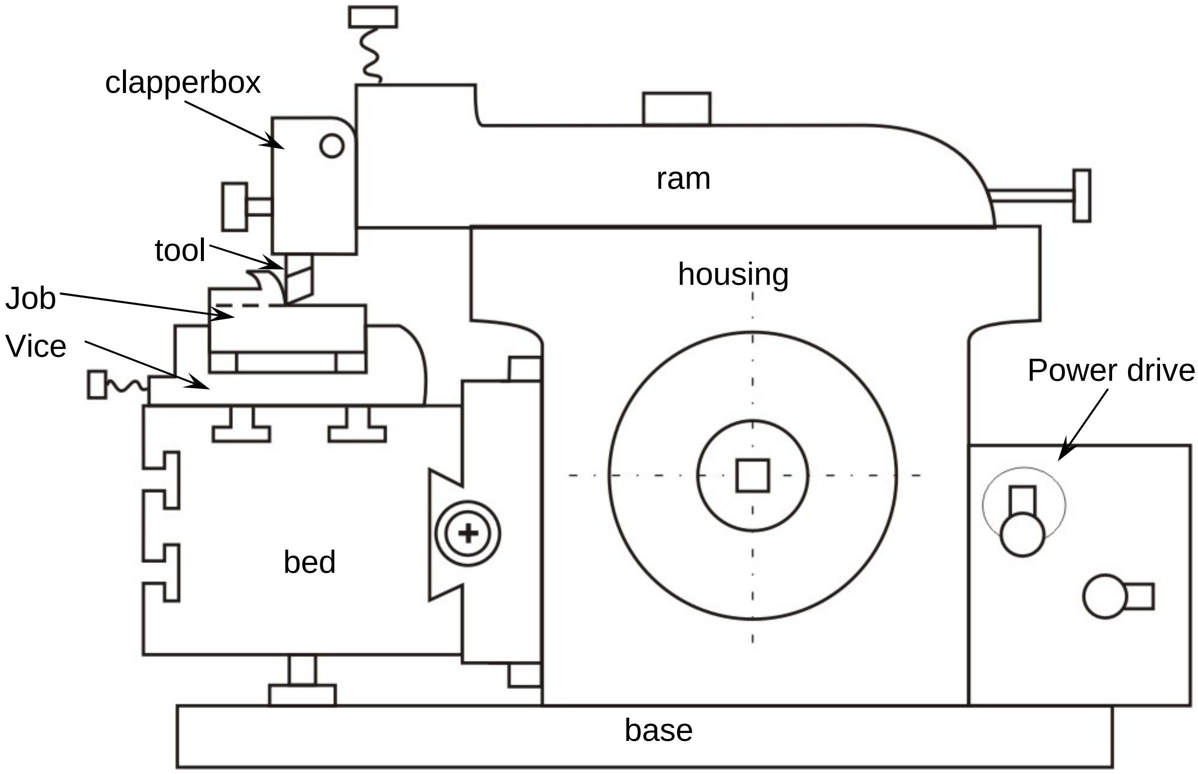


Fig. 2.11 *Schematic view of a shaping machine*

- **Planing machine**
  The general configuration is schematically shown in Fig. 2.12. This machine tool also does the same operations like shaping machine but the major differences are:
  - In planing the job reciprocates for cutting motion and the tool moves slowly for the feed motions unlike in shaping machine.
  - Planing machines are usually very large in size and used for large jobs and heavy duty work.

- **Drilling machine**
  Fig. 2.13 shows general configuration of drilling machine, column drill in particular. The salient parts are
  - Column with base: it is the basic structure to hold the other parts
  - Drilling head: this box type structure accommodates the power drive and the speed and feed gear boxes.
  - Spindle: holds the drill and transmits rotation and axial translation to the tool for providing cutting motion and feed motion – both to the drill.

    Drilling machines are available in varying size and configuration such as pillar drill, column drill, radial drill, micro-drill etc. but in working principle all are more or less the same.

  Drilling machines are used:
  - Mainly for drilling (originating or enlarging cylindrical holes)

- o Occasionally for boring, counter boring, counter sinking etc.
- o Also for cutting internal threads in parts like nuts using suitable attachment.

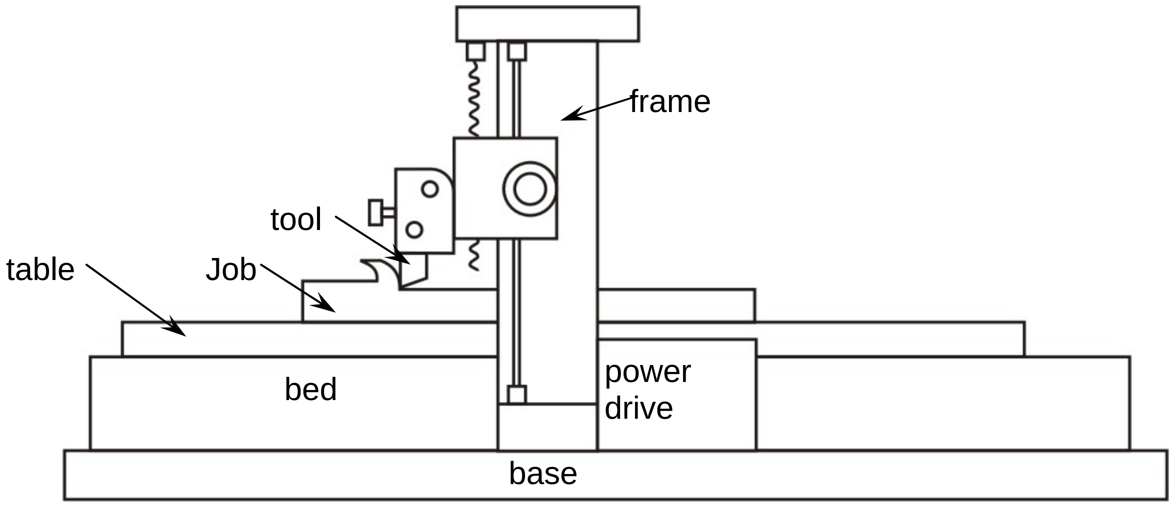


Fig. 2.12 *Schematic view of a planning machine*

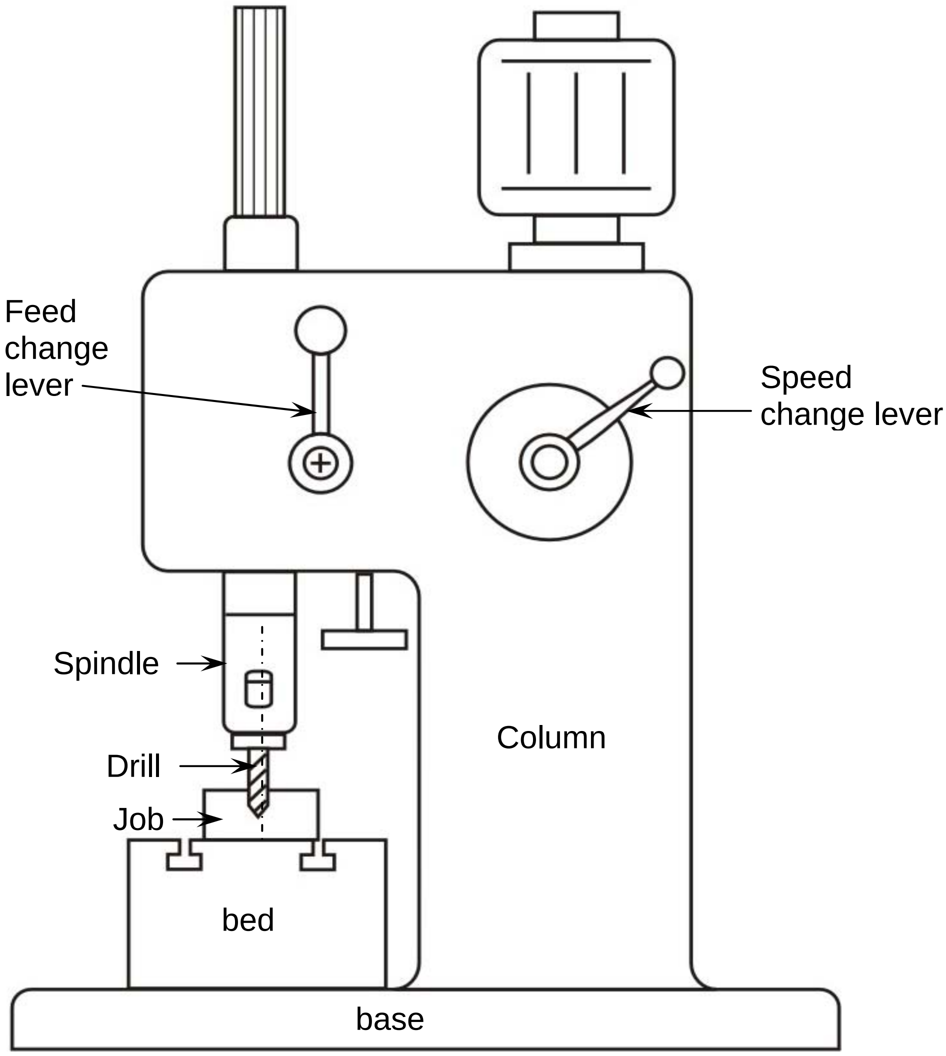


Fig. 2.13 *Schematic view of a drilling machine*

- **Milling machine**

  The general configuration of knee type conventional milling machine with horizontal arbour is shown in Fig. 2.14. Its major parts are
    - Milling arbour: to hold and rotate the cutter
    - Ram: to support the arbour
    - Machine table: on which job and job holding devices are mounted to provide the feed motions to the job.
    - Power drive with Speed and gear boxes: to provide power and motions to the tool-work
    - Bed: which moves vertically upward and downward and accommodates the various drive mechanisms
    - Column with base: main structural body to support other parts.

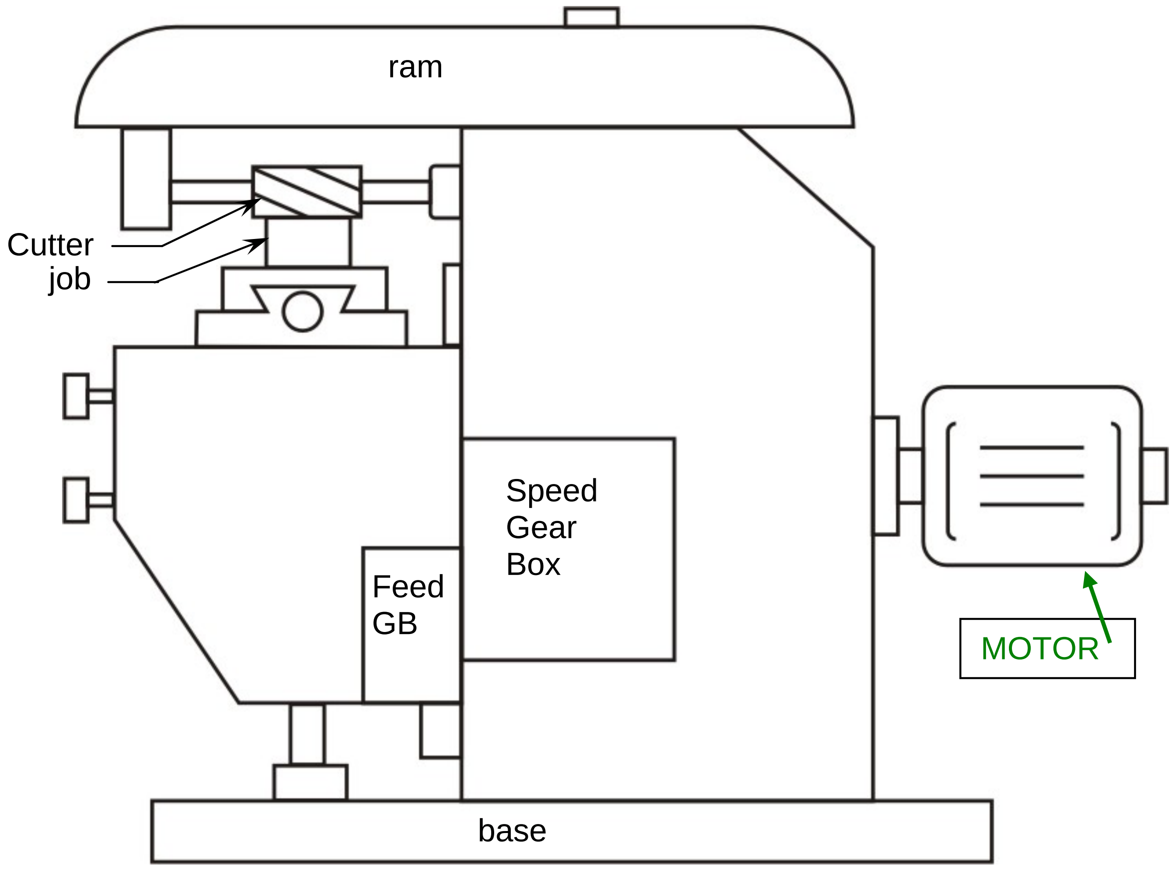
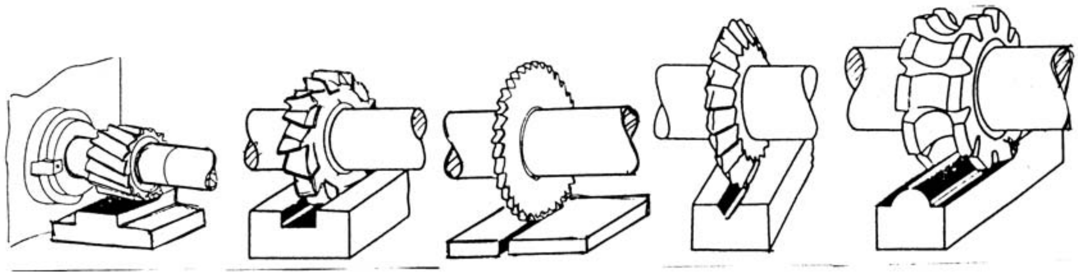


Fig. 2.14 *Schematic view of a milling machine*

Milling machines are also quite versatile and can do several operations like
- making flat surfaces
- grooving, slitting and parting
- helical grooving

- forming 2-D and 3-D contoured surfaces

Fig. 2.15 shows some of the aforesaid milling operations.



surfacing slotting slitting grooving forming

Fig. 2.15 *Some common milling operation*

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 are machine tools 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
  - Range of feeds
  - Space occupied by the machine.

- **Shaping machine**
  - 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

o **Milling machine** (knee type and with arbour)
  - Type; ordinary or swiveling bed type
  - Size of the work table
  - Range of travels of the table in X-Y-Z directions
  - Arbour size (diameter)
  - Power of the main drive
  - Range of spindle speed
  - Range of table feeds in X-Y-Z directions
  - Floor space occupied.

Broad classification of Machine Tools

Number of types of machine tools gradually increased till mid 20th century and after that started decreasing based on Group Technology.
However, machine tools are broadly classified as follows:

- According to direction of major axis :
  - horizontal center lathe, horizontal boring machine etc.
  - vertical – vertical lathe, vertical axis milling machine etc.
  - inclined – special (e.g. for transfer machines).

- According to purpose of use :
  - general purpose – e.g. center lathes, milling machines, drilling machines etc.
  - single purpose – e.g. facing lathe, roll turning lathe etc.
  - special purpose – for mass production.

- According to degree of automation
  - non-automatic – e.g. center lathes, drilling machines etc.
  - semi-automatic – capstan lathe, turret lathe, hobbinh machine etc.
  - automatic – e.g., single spindle automatic lathe, swiss type automatic lathe, CNC milling machine etc.

- According to size :
  - heavy duty – e.g., heavy duty lathes (e.g. ≥ 55 kW), boring mills, planning machine, horizontal boring machine etc.
  - medium duty – e.g., lathes – 3.7 ~ 11 kW, column drilling machines, milling machines etc.
  - small duty – e.g., table top lathes, drilling machines, milling machines.
  - micro duty – e.g., micro-drilling machine etc.

- According to precision :

- ordinary – e.g., automatic lathes
- high precision – e.g., Swiss type automatic lathes

- According to number of spindles :
  - single spindle – center lathes, capstan lathes, milling machines etc.
  - multi-spindle – multispindle (2 to 8) lathes, gang drilling machines etc.

- According to blank type :
  - bar type (lathes)
  - chucking type (lathes)
  - housing type

- According to type of automation :
  - fixed automation – e.g., single spindle and multispindle lathes
  - flexible automation – e.g., CNC milling machine

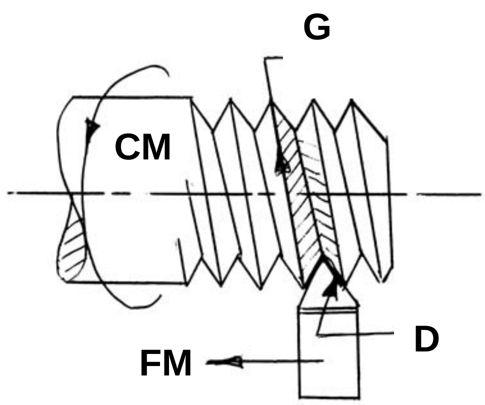
- According to configuration :
  - stand alone type – most of the conventional machine tools.
  - machining system (more versatile) – e.g., transfer machine, machining center, FMS etc.

Exercise – 2

1. Show the tool-work motions and the Generatrix and Directrix in external thread cutting in centre lathe. Also state how those 'G' & 'D' are obtained.
2. In which conventional machine tools flat surface can be produced ?
3. State the major differences between shaping machine and planing machine.
4. In which machine tools both the cutting motion & the feed motion are imparted to the tool ?
5. How is feed expressed in turning, shaping, drilling and milling ?

Answers

Ans. Q 1



G – x – T – F
D – (CM+FM) – (T+W) - T

Ans. Q. 2
Flat surfaces can be produced in

- centre lathes – e.g., facing
- shaping, slotting and planing machines
- milling machines

Ans. Q. 3

Shaping machine	Planing machine
o for small and medium size jobs	o for medium and large size jobs
o tool reciprocates and provide CM	o job on table reciprocates and provide CM
o feed motion is given to the job	o feed motion is given to the tool
o G – CM – T – Tr D – FM – W – Tr	o G – CM – W – Tr D – FM – T – Tr

Ans. Q. 4
Both CM and FM are imparted to the tool in

- drilling machine
- vertical boring machine

Ans. Q. 5

- turning – mm/rev
- shaping – mm/stroke
- drilling machine – mm/rev
- milling machine – mm/min

Module 2

Mechanics of Machining (Metal Cutting)

Lesson
3
Geometry of single point cutting tools

Instructional objectives

At the end of this lesson, the student should be able to :

(a) conceive rake angle and clearance angle of cutting tools
(b) classify systems of description of tool geometry
(c) demonstrate tool geometry and define tool angles in :
- Machine Reference System
- Orthogonal Rake System and
- Normal Rake System

(d) designate cutting tool geometry in ASA, ORS and NRS

Geometry of single point 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.

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.

(i) 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. 3.1

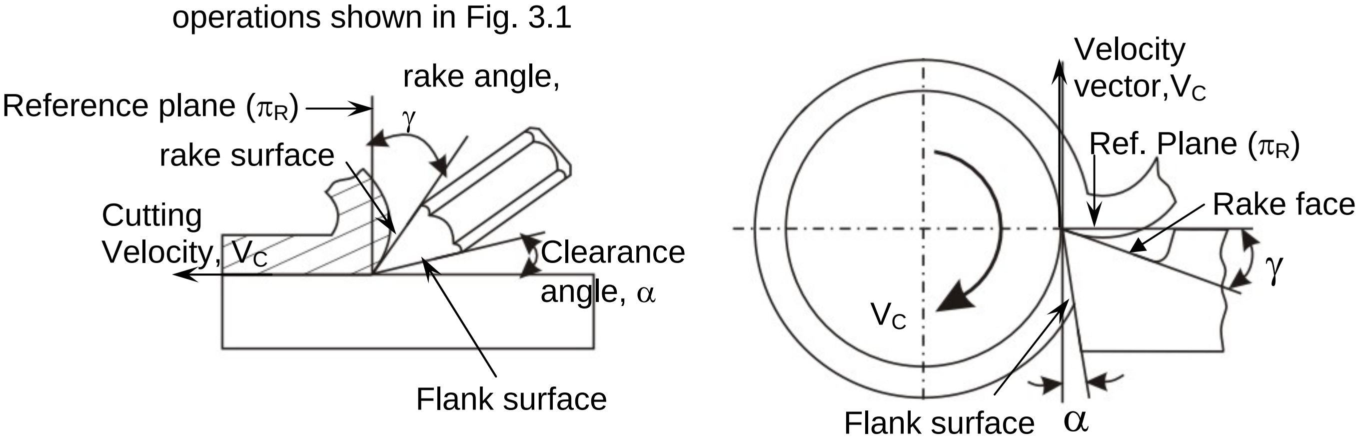
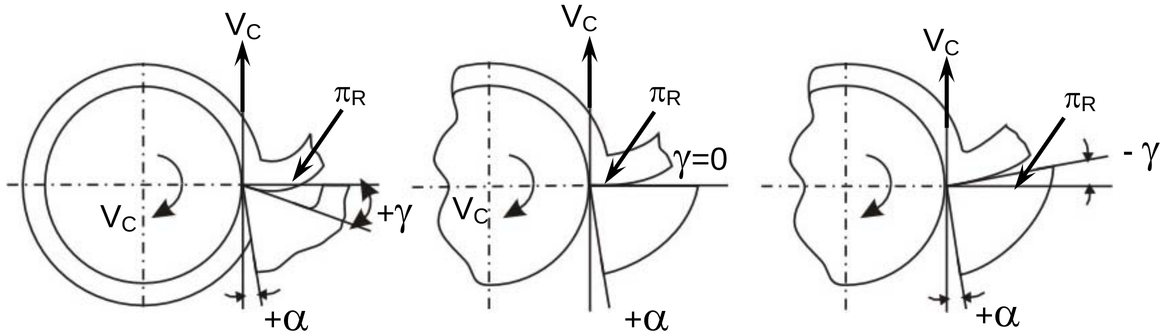


***Fig. 3.1** Rake and clearance angles of cutting tools.*

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. 3.2.



(a) positive rake (b) zero rake (c) negative rake

Fig. 3.2 *Three possible types of rake angles*

Relative advantages of such rake angles are:

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

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 ($3^o \sim 15^o$ depending upon tool-work materials and type of the machining operations like turning, drilling, boring etc.)

(ii) Systems of description of tool geometry

- Tool-in-Hand System – where only the salient features of the cutting tool point are identified or visualized as shown in Fig. 3.3. There is no quantitative information, i.e., value of the angles.
- Machine Reference System – ASA system
- Tool Reference Systems
    - ∗ Orthogonal Rake System – ORS
    - ∗ Normal Rake System – NRS
- Work Reference System – WRS

(iii) Demonstration (expression) of tool geometry in :

- **Machine Reference System**

This system is also called ASA system; ASA stands for American Standards Association. Geometry of a cutting tool refers mainly to its

several angles or slope of its salient working surfaces and cutting edges. Those angles are expressed w.r.t. 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. 3.4.

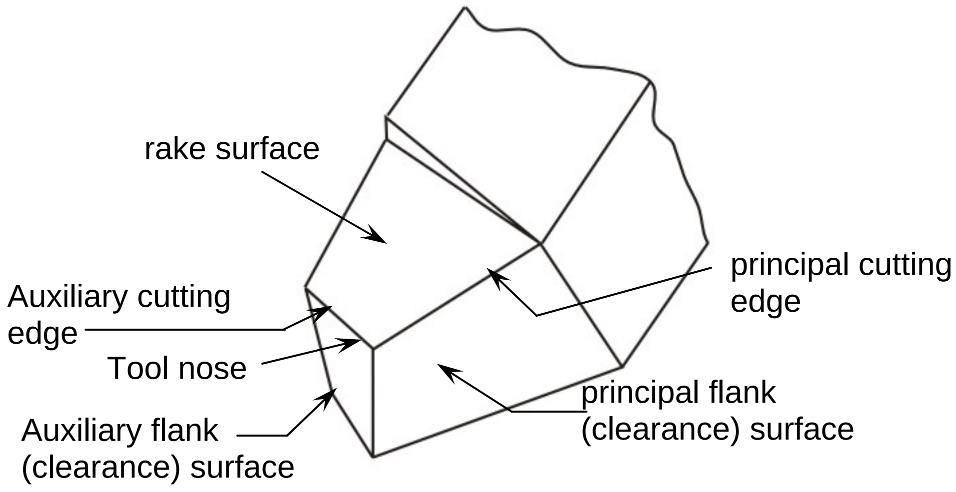


Fig. 3.3 *Basic features of single point tool (turning) in Tool-in-hand system*

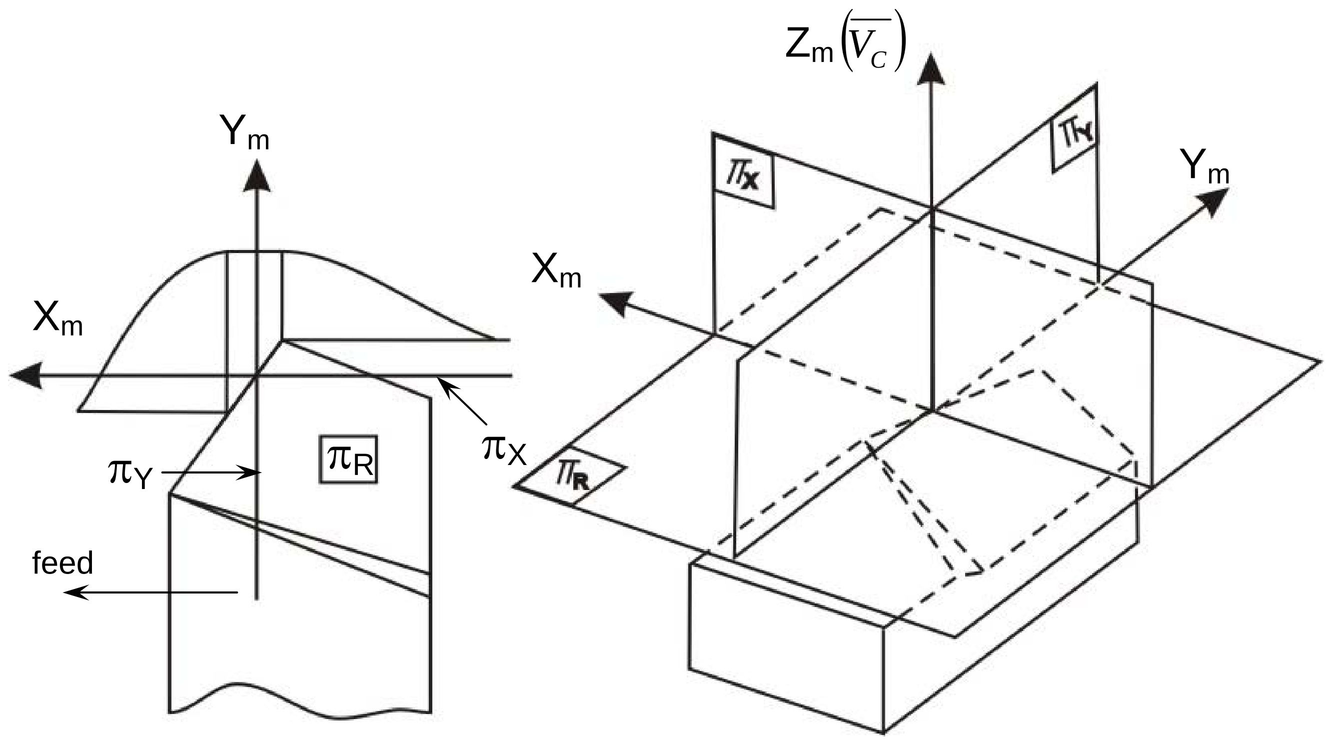


Fig. 3.4 *Planes and axes of reference in ASA system*

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

$$\pi_R - \pi_X - \pi_Y \text{ and } X_m - Y_m - Z_m$$

where,

π_R = Reference plane; plane perpendicular to the velocity vector (shown in Fig. 3.4)

π_X = Machine longitudinal plane; plane perpendicular to π_R and taken in the direction of assumed longitudinal feed

π_Y = Machine Transverse plane; plane perpendicular to both π_R and π_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. 3.5.

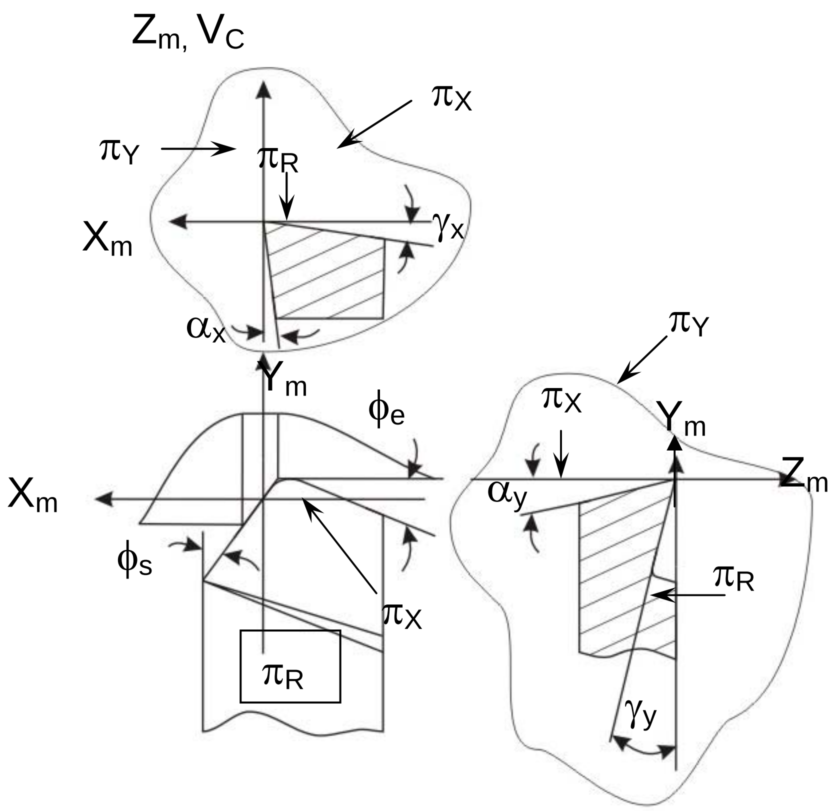


Fig. 3.5 *Tool angles in ASA system*

Definition of:

- Rake angles: [Fig. 3.5] in ASA system

γ_x = side (axial rake: angle of inclination of the rake surface from the reference plane (π_R) and measured on Machine Ref. Plane, π_X.

γ_y = back rake: angle of inclination of the rake surface from the reference plane and measured on Machine Transverse plane, π_Y.

- Clearance angles: [Fig. 3.5]

α_X = side clearance: angle of inclination of the principal flank from the machined surface (or $\overline{V_C}$) and measured on π_X plane.

α_Y = back clearance: same as α_x but measured on π_Y plane.

- Cutting angles: [Fig. 3.5]

ϕ_S = approach angle: angle between the principal cutting edge (its projection on π_R) and π_Y and measured on π_R

ϕ_e = end cutting edge angle: angle between the end cutting edge (its projection on π_R) from π_X and measured on π_R

- Nose radius, r (in **inch**)

r = nose radius : curvature of the tool tip. It provides strengthening of the tool nose and better surface finish.

- **Tool Reference Systems**
  - **Orthogonal Rake System – ORS**

    This system is also known as ISO – old.

The planes of reference and the co-ordinate axes used for expressing the tool angles in ORS are:

π_R - π_C - π_O and X_o - Y_o - Z_o

which are taken in respect of the tool configuration as indicated in Fig. 3.6

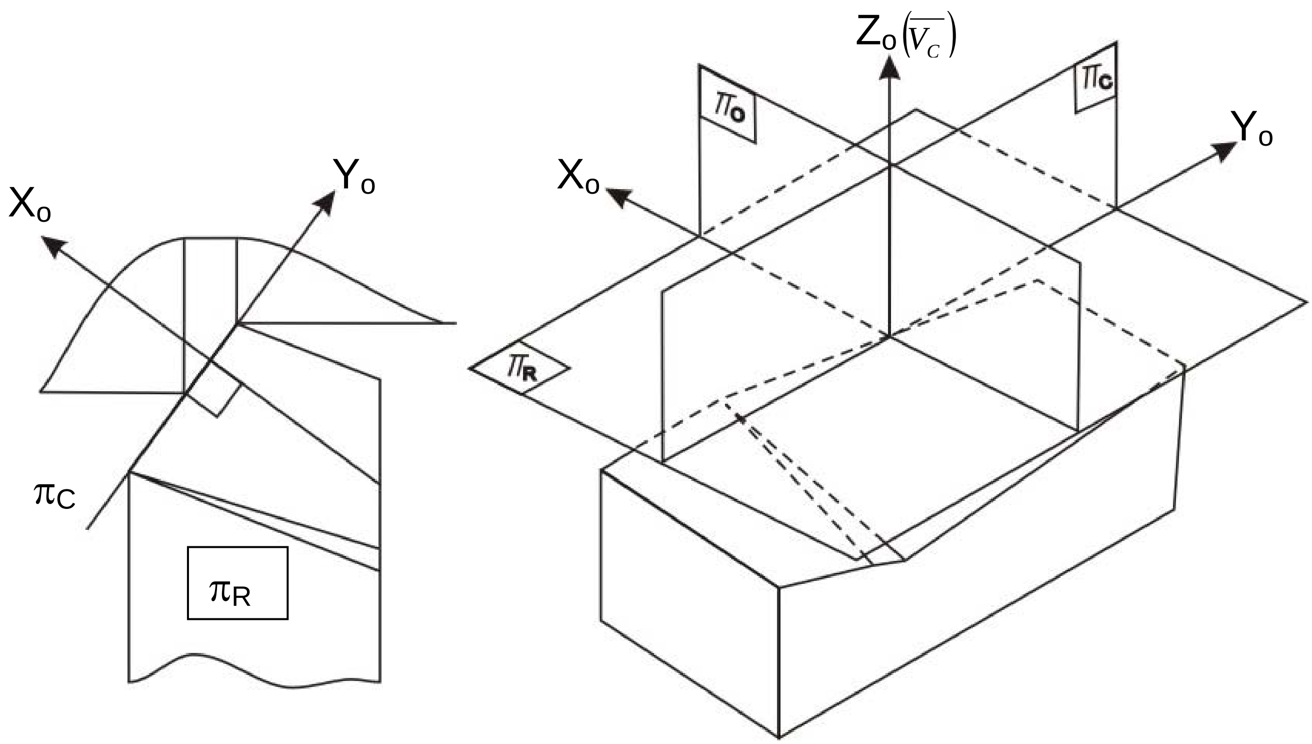


Fig. 3.6 *Planes and axes of reference in ORS*

where,

π_R = Refernce plane perpendicular to the cutting velocity vector, $\overline{V_C}$

π_C = cutting plane; plane perpendicular to π_R and taken along the principal cutting edge

π_O = Orthogonal plane; plane perpendicular to both π_R and π_C

and the axes;

X_o = along the line of intersection of π_R and π_O

Y_o = along the line of intersection of π_R and π_C

Z_o = along the velocity vector, i.e., normal to both X_o and Y_o axes.

The main geometrical angles used to express tool geometry in Orthogonal Rake System (ORS) and their definitions will be clear from Fig. 3.7.

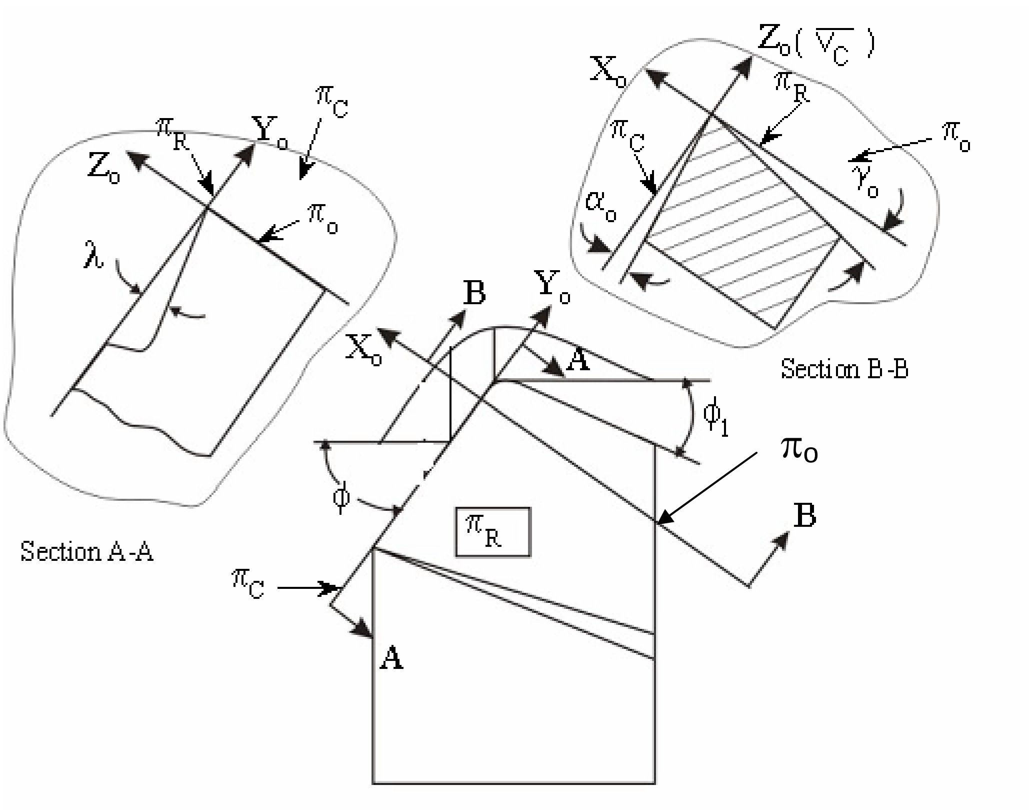


Fig. 3.7 *Tool angles in ORS system*

Definition of –

- Rake angles [Fig. 3.7] in ORS

γ_o = orthogonal rake: angle of inclination of the rake surface from Reference plane, π_R and measured on the orthogonal plane, π_o

λ = inclination angle; angle between π_C from the direction of assumed longitudinal feed [π_X] and measured on π_C

- Clearance angles [Fig. 3.7]

α_o = orthogonal clearance of the principal flank: angle of inclination of the principal flank from π_C and measured on π_o

α_o' = auxiliary orthogonal clearance: angle of inclination of the auxiliary flank from auxiliary cutting plane, π_C' and measured on auxiliary orthogonal plane, π_o' as indicated in Fig. 3.8.

- Cutting angles [Fig. 3.7]

ϕ = principal cutting edge angle: angle between π_C and the direction of assumed longitudinal feed or π_X and measured on π_R

ϕ_1 = auxiliary cutting angle: angle between π_C' and π_X and measured on π_R

- Nose radius, r (mm)

r = radius of curvature of tool tip

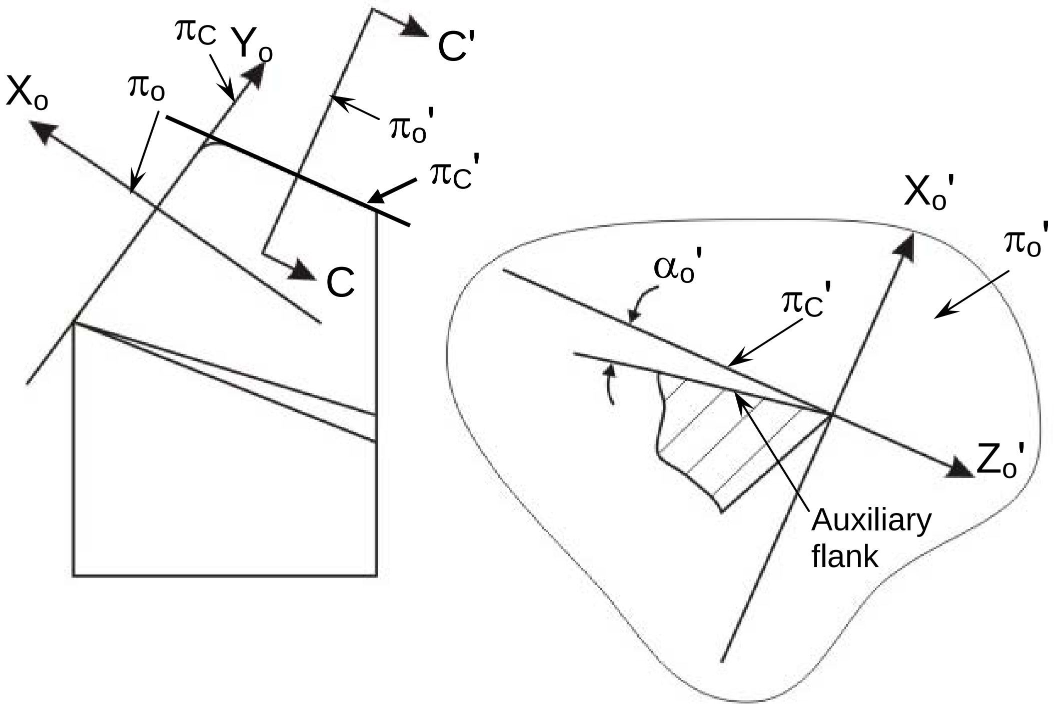


Fig. 3.8 Auxiliary orthogonal clearance angle

- **Normal Rake System – NRS**

  This system is also known as ISO – new.

ASA system has limited advantage and use like convenience of inspection. But ORS is advantageously used for analysis and research in machining and tool performance. But ORS does not reveal the true picture of the tool geometry when the cutting edges are inclined from the reference plane, i.e., $\lambda \neq 0$. Besides, sharpening or resharpening, if necessary, of the tool by grinding in ORS requires some additional calculations for correction of angles.

These two limitations of ORS are overcome by using NRS for description and use of tool geometry.
The basic difference between ORS and NRS is the fact that in ORS, rake and clearance angles are visualized in the orthogonal plane, π_o, whereas in NRS those angles are visualized in another plane called Normal plane, π_N. The orthogonal plane, π_o is simply normal to π_R and π_C irrespective of the inclination of the cutting edges, i.e., λ, but π_N (and π_N' for auxiliary cutting edge) is always normal to the cutting edge. The differences between ORS and NRS have been depicted in Fig. 3.9.
The planes of reference and the coordinates used in NRS are:

π_{RN} - π_C - π_N and X_n – Y_n – Z_n

where,

π_{RN} = normal reference plane

π_N = Normal plane: plane normal to the cutting edge

and

$X_n = X_o$

Y_n = cutting edge

Z_n = normal to X_n and Y_n

It is to be noted that when $\lambda = 0$, NRS and ORS become same, i.e. $\pi_o \cong \pi_N$, $Y_N \cong Y_o$ and $Z_n \cong Z_o$.
Definition (in NRS) of

- Rake angles

γ_n = normal rake: angle of inclination angle of the rake surface from π_R and measured on normal plane, π_N

α_n = normal clearance: angle of inclination of the principal flank from π_C and measured on π_N

α_n'= auxiliary clearance angle: normal clearance of the auxiliary flank (measured on π_N' – plane normal to the auxiliary cutting edge.

The cutting angles, ϕ and ϕ_1 and nose radius, r (mm) are same in ORS and NRS.

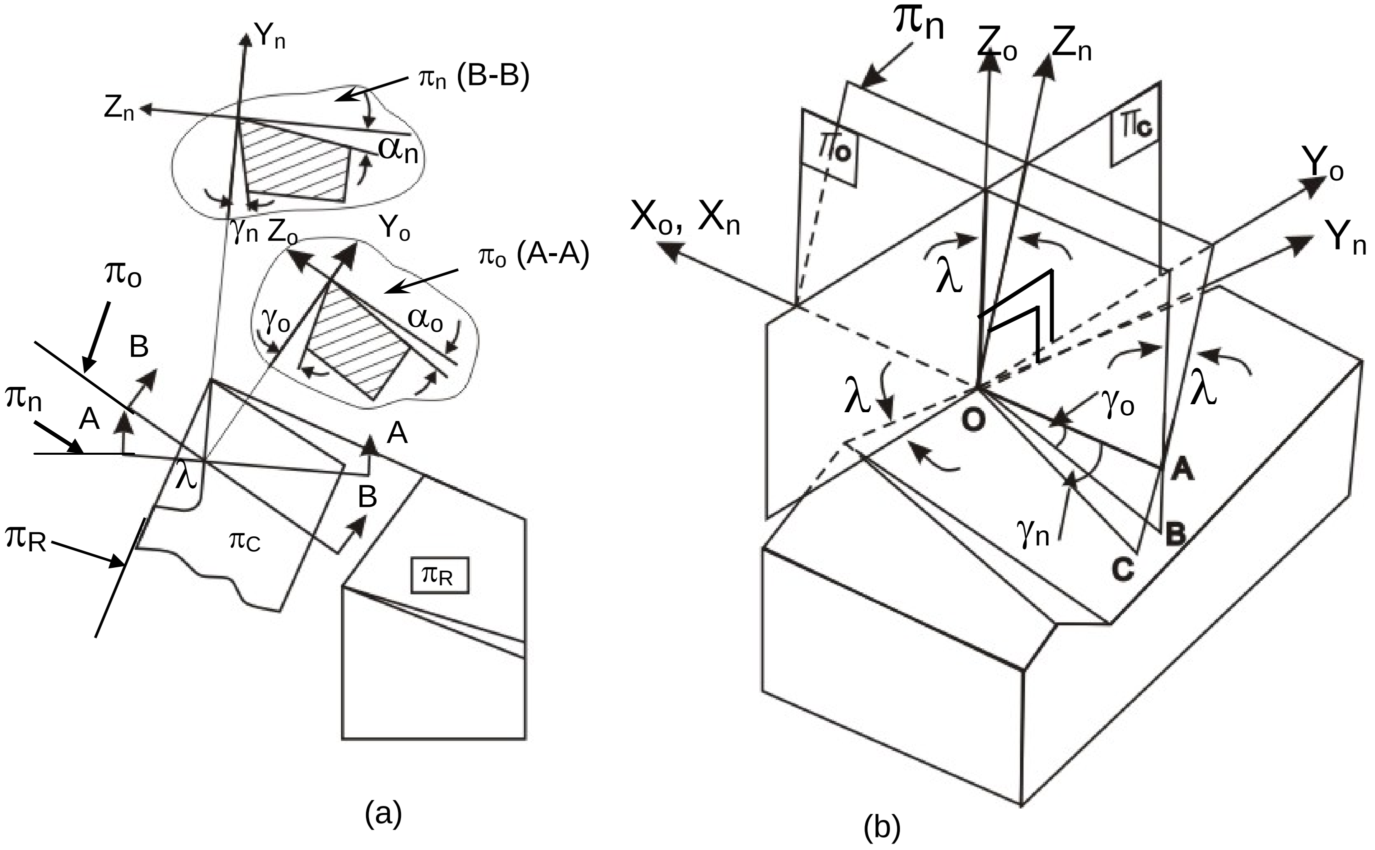


***Fig. 3.9** Differences of NRS from ORS w.r.t. cutting tool geometry.*

(b) 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 –

  γ_y, γ_x, α_y, α_x, ϕ_e, ϕ_s, r (inch)

- ORS System –

  λ, γ_o, α_o, α_o', ϕ_1, ϕ, r (mm)

- NRS System –

  λ, γ_n, α_n, α_n', ϕ_1, ϕ, r (mm)

Exercise – 3

Quiz Test:

Select the correct answer from the given four options :

1. Back rake of a turning tool is measured on its
   (a) machine longitudinal plane
   (b) machine transverse plane
   (c) orthogonal plane
   (d) normal plane

2. Normal rake and orthogonal rake of a turning tool will be same when its
   (a) $\phi = 0$
   (b) $\phi_1 = 0$
   (c) $\lambda = 0$
   (d) $\phi_1 = 90^o$

3. Normal plane of a turning tool is always perpendicular to its
   (a) π_X plane
   (b) π_Y plane
   (c) π_C plane
   (d) none of them

4. Principal cutting edge angle of any turning tool is measured on its
   (a) π_R
   (b) π_Y
   (c) π_X
   (d) π_o

5. A cutting tool can never have its
   (a) rake angle – positive
   (b) rake angle – negative
   (c) clearance angle – positive
   (d) clearance angle – negative

6. Orthogonal clearance and side clearance of a turning tool will be same if its perpendicular cutting edge angle is
   (a) $\phi = 30^o$
   (b) $\phi = 45^o$
   (c) $\phi = 60^o$
   (d) $\phi = 90^o$

7. Inclination angle of a turning tool is measured on its
   (a) reference plane
   (b) cutting plane
   (c) orthogonal plane
   (d) normal plane

8. Normal rake and side rake of a turning tool will be same if its
   (a) $\phi = 0^o$ and $\lambda = 0^o$
   (b) $\phi = 90^o$ and $\lambda = 0^o$
   (c) $\phi = 90^o$ and $\lambda = 90^o$
   (d) $\phi = 0^o$ and $\lambda = 90^o$

Answer of the objective questions

1 – (b)
2 – (c)
3 – (c)
4 – (a)
5 – (d)
6 – (d)
7 – (b)
8 – (b)

Module
2
Mechanics of Machining

Lesson
4
Conversion of tool angles from one system to another

Instructional objectives

At the end of this lesson the students should be able to

(i) State the purposes of conversion of tool angles
(ii) Identify the four different methods of conversion of tool angles
(iii) Employ the graphical method for conversion of
- Rake angles
- clearance angles
- Cutting angles

From ASA to ORS and ORS to ASA systems
(iv) Convert rake angle and clearance angle from ORS to NRS
(v) Demonstrate tool angle's relationship in some critical conditions.

(i) Purposes of conversion of tool angles from one system to another

- To understand the actual tool geometry in any system of choice or convenience from the geometry of a tool expressed in any other systems
- To derive the benefits of the various systems of tool designation as and when required
- Communication of the same tool geometry between people following different tool designation systems.

(ii) Methods of conversion of tool angles from one system to another

- Analytical (geometrical) method: simple but tedious
- Graphical method – Master line principle: simple, quick and popular
- Transformation matrix method: suitable for complex tool geometry
- Vector method: very easy and quick but needs concept of vectors

(iii) Conversion of tool angles by Graphical method – Master Line principle.

This convenient and popular method of conversion of tool angles from ASA to ORS and vice-versa is based on use of Master lines (ML) for the rake surface and the clearance surfaces.

- **Conversion of rake angles**

The concept and construction of ML for the tool rake surface is shown in Fig. 4.1.

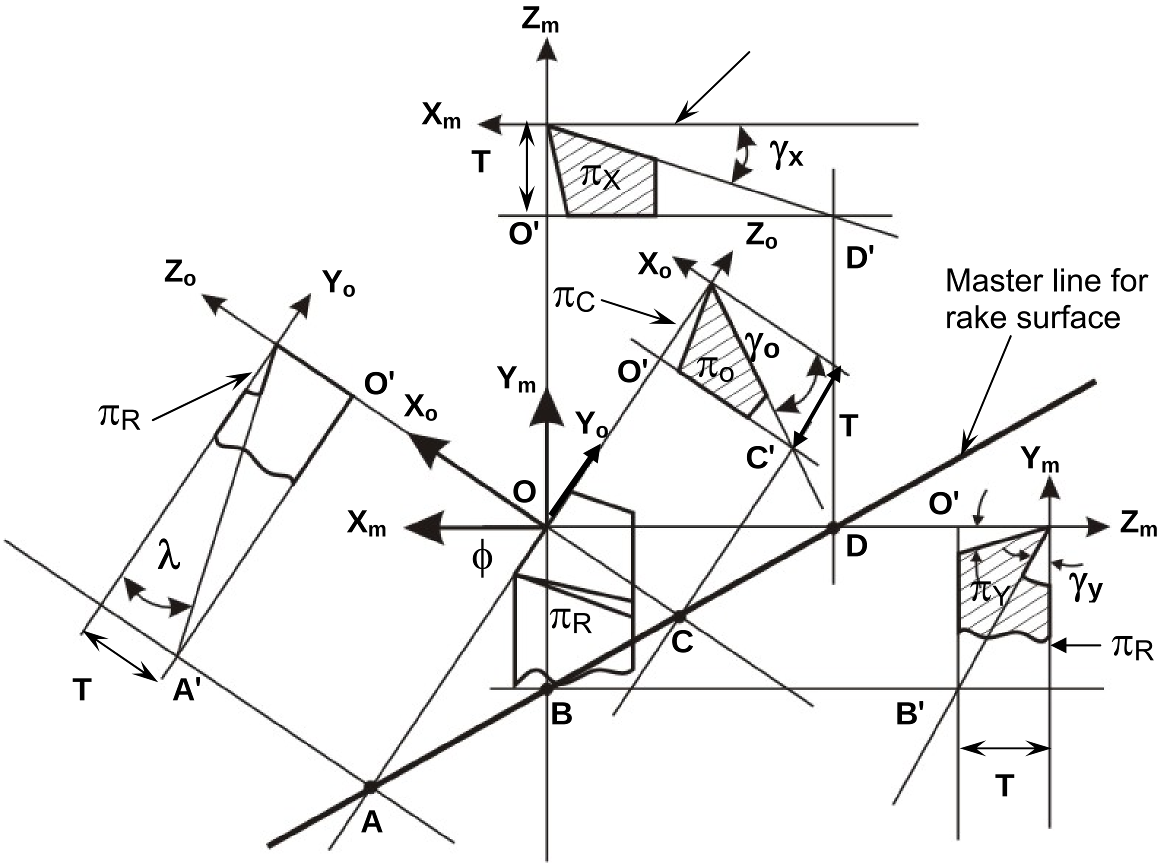


***Fig. 4.1** Master line for rake surface (with all rake angles: positive)*

In Fig. 4.1, the rake surface, when extended along π_X plane, meets the tool's bottom surface (which is parallel to π_R) at point D' i.e. D in the plan view. Similarly when the same tool rake surface is extended along π_Y, it meets the tool's bottom surface at point B' i.e., at B in plan view. Therefore, the straight line obtained by joining B and D is nothing but the line of intersection of the rake surface with the tool's bottom surface which is also parallel to π_R. Hence, if the rake surface is extended in any direction, its meeting point with the tool's bottom plane must be situated on the line of intersection, i.e., BD. Thus the points C and A (in Fig. 4.1) obtained by extending the rake surface along π_o and π_C respectively upto the tool's bottom surface, will be situated on that line of intersection, BD.
This line of intersection, BD between the rake surface and a plane parallel to π_R is called the **"Master line of the rake surface"**.

From the diagram in Fig. 4.1,

$$OD = T\cot\gamma_X$$

$$OB = T\cot\gamma_Y$$

$$OC = T\cot\gamma_o$$

$$OA = T\cot\lambda$$

Where, T = thickness of the tool shank.
The diagram in Fig. 4.1 is redrawn in simpler form in Fig. 4.2 for conversion of tool angles.

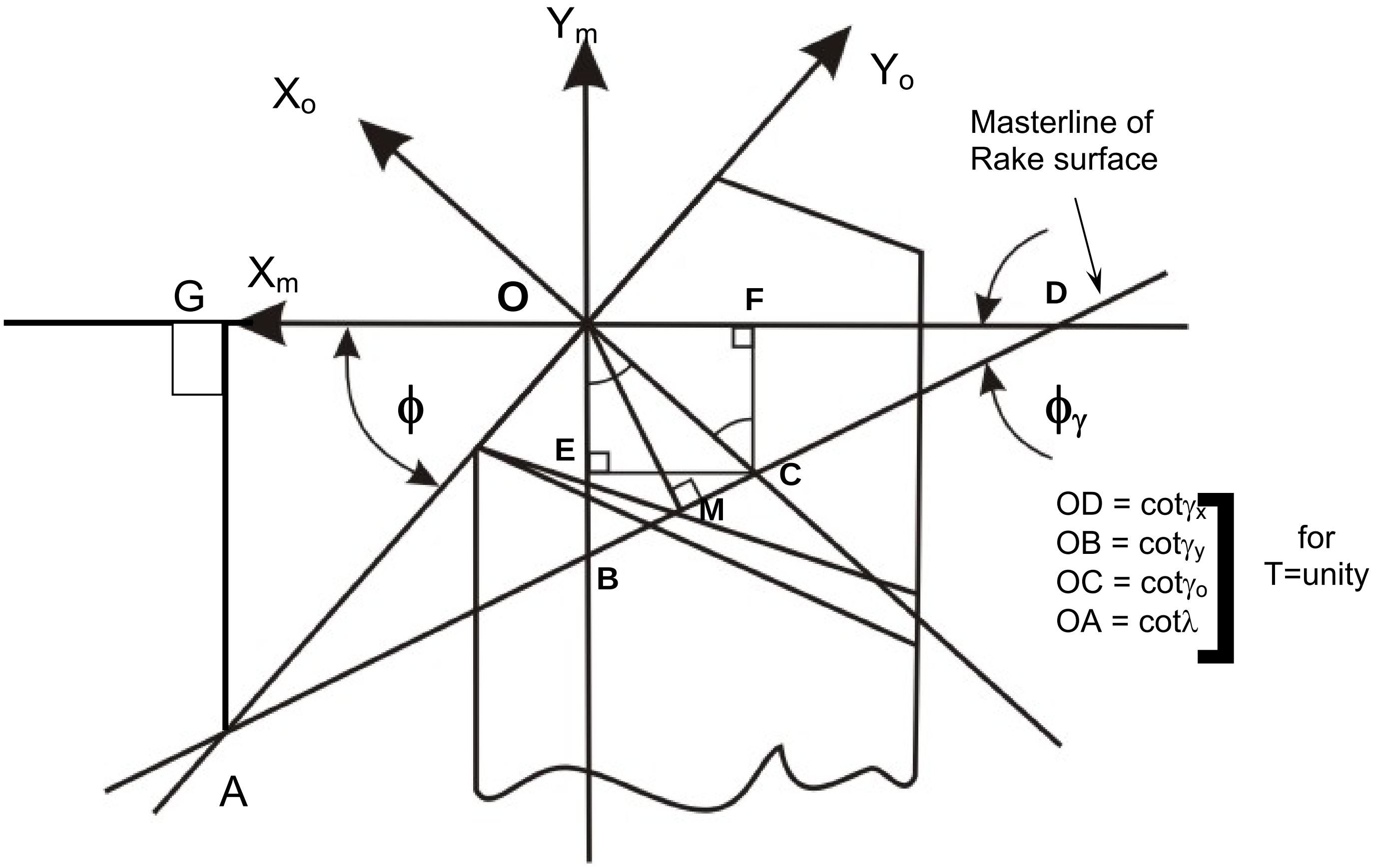


***Fig. 4.2** Use of Master line for conversion of rake angles.*

- **Conversion of tool rake angles from ASA to ORS**

γ_o and λ (in ORS) = f (γ_x and γ_y of ASA system)

$$\tan\gamma_o = \tan\gamma_x \sin\varphi + \tan\gamma_y \cos\varphi \qquad (4.1)$$

and

$$\tan\lambda = -\tan\gamma_x \cos\varphi + \tan\gamma_y \sin\varphi \qquad (4.2)$$

Proof of Equation 4.1:

With respect to Fig. 4.2,
Consider, ΔOBD = Δ OBC + Δ OCD
Or, ½ OB.OD = ½ OB.CE + ½ OD.CF
Or, ½ OB.OD = ½ OB.OCsinϕ + ½ OD.OCcosϕ
Dividing both sides by ½ OB.OD.OC,

$$\frac{1}{OC} = \frac{1}{OD}\sin\varphi + \frac{1}{OB}\cos\varphi$$

i.e. $\tan\gamma_o = \tan\gamma_x \sin\varphi + \tan\gamma_y \cos\varphi$ — Proved.

Similarly Equation 4.2 can be proved considering;

Δ OAD = Δ OAB + Δ OBD

i.e., ½ OD.AG = ½ OB.OG + ½ OB.OD

where, AG = OAsinϕ

and OG = OAcosϕ

Now dividing both sides by ½ OA.OB.OD,

$$\frac{1}{OB}\sin\varphi = \frac{1}{OD}\cos\varphi + \frac{1}{OA}$$

$$\tan\lambda = -\tan\gamma_x\cos\varphi + \tan\gamma_y\sin\varphi \quad \text{— Proved.}$$

The conversion equations 4.1 and 4.2 can be combined in a matrix form,

$$\begin{bmatrix}\tan\gamma_o\\ \tan\lambda\end{bmatrix} = \begin{bmatrix}\sin\phi & \cos\phi\\ -\cos\phi & \sin\phi\end{bmatrix}\begin{bmatrix}\tan\gamma_x\\ \tan\gamma_y\end{bmatrix} \qquad (4.3)$$

(ORS) (ASA)

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

- Conversion of rake angles from ORS to ASA system

γ_x and γ_y (in ASA) = f(γ_o and $\lambda$of ORS)

$$\tan\gamma_x = \tan\gamma_o\sin\varphi - \tan\lambda\cos\varphi \qquad (4.4)$$

and $$\tan\gamma_y = \tan\gamma_o\cos\varphi + \tan\lambda\sin\varphi \qquad (4.5)$$

The relations (4.4) and (4.5) can be arrived at indirectly using Equation 4.3.

By inversion, Equation 4.3 becomes,

$$\begin{bmatrix}\tan\gamma_x\\ \tan\gamma_y\end{bmatrix} = \begin{bmatrix}\sin\phi & -\cos\phi\\ \cos\phi & \sin\phi\end{bmatrix}\begin{bmatrix}\tan\gamma_o\\ \tan\lambda\end{bmatrix} \qquad (4.6)$$

from which equation 4.4 and 4.5 are obtained.

The conversion equations 4.4 and 4.5 can also be proved directly from the diagram in Fig. 4.2

Hints

To prove equation 4.4, proceed by taking (from Fig. 4.2)

Δ OAD = Δ OAC + Δ OCD,

[involving the concerned angles γ_o, λ and γ_x i.e., OC, OA and OD]

And to prove Equation 4.5, proceed by taking

Δ OAC = Δ OAB + Δ OBC

[involving the concerned angles γ_o, λ and γ_y i.e., OC, OA and OB]

- Maximum rake angle (γ_{max} or γ_m)

The magnitude of maximum rake angle (γ_m) and the direction of the maximum slope of the rake surface of any single point tool can be easily derived from its geometry specified in both ASA or ORS by using the diagram of Fig. 4.2. The smallest intercept OM normal to the Master line (Fig. 4.2) represents γ_{max} or γ_m as

$OM = \cot \gamma_m$

Single point cutting tools like HSS tools after their wearing out are often resharpened by grinding their rake surface and the two flank surfaces.

The rake face can be easily and correctly ground by using the values of γ_m and the orientation angle, ϕ_γ (visualized in Fig. 4.2) of the Master line.

- Determination of γ_m and ϕ_γ from tool geometry specified in ASA system.

In Fig. 4.2,

Δ OBD = ½ OB.OD = ½ BD.OM

or, ½ OB.OD = ½ $\sqrt{OB^2 + OD^2}.OM$

Dividing both sides by ½ OB.OD.OM

$$\frac{1}{OM} = \sqrt{\frac{1}{OD^2} + \frac{1}{OB^2}}$$

or
$$\tan\gamma_m = \sqrt{\tan^2\gamma_x + \tan^2\gamma_y} \qquad (4.7)$$

Again from Δ OBD

$$\tan\varphi_\gamma = \frac{OB}{OD}$$

or
$$\phi_\gamma = \tan^{-}\left(\frac{\tan\gamma_x}{\tan\gamma_y}\right) \qquad (4.8)$$

- γ_m and ϕ_γ from tool geometry specified in ORS

Similarly from the diagram in Fig. 4.2, and taking Δ OAC, one can prove

$$\tan\gamma_m = \sqrt{\tan^2\gamma_o + \tan^2\lambda} \qquad (4.9)$$

$$\phi_\gamma = \phi - \tan^{-}\left(\frac{\tan\lambda}{\tan\gamma_o}\right) \qquad (4.10)$$

- **Conversion of clearance angles from ASA system to ORS and vice versa by Graphical method.**

Like rake angles, the conversion of clearance angles also make use of corresponding Master lines. The Master lines of the two flank surfaces are nothing but the dotted lines that appear in the plan view of the tool (Fig. 4.3).

The dotted line are the lines of intersection of the flank surfaces concerned with the tool's bottom surface which is parallel to the Reference plane π_R. Thus according to the definition those two lines represent the Master lines of the flank surfaces.

Fig. 4.4 shows the geometrical features of the Master line of the principal flank of a single point cutting tool.

From Fig. 4.4,

$OD = T\tan\alpha_x$

$OB = T\tan\alpha_y$

$OC = T\tan\alpha_o$

OA = Tcotλ where, T = thickness of the tool shank.

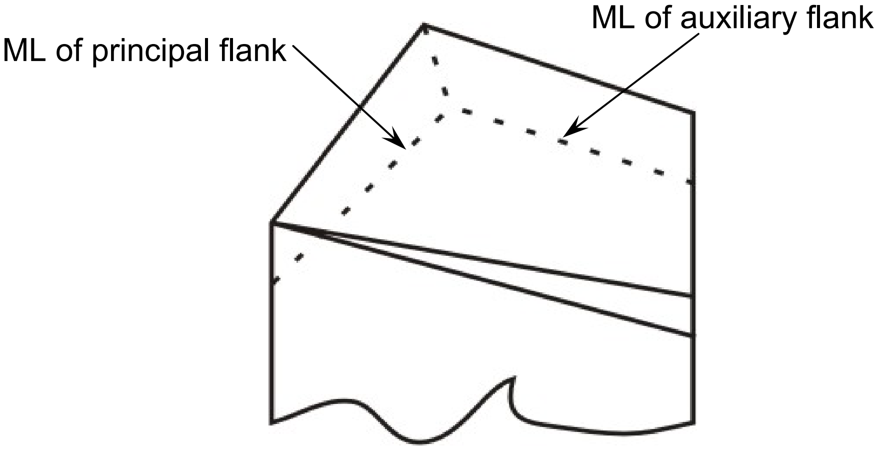


Fig. 4.3 *Master lines (ML) of flank surfaces.*

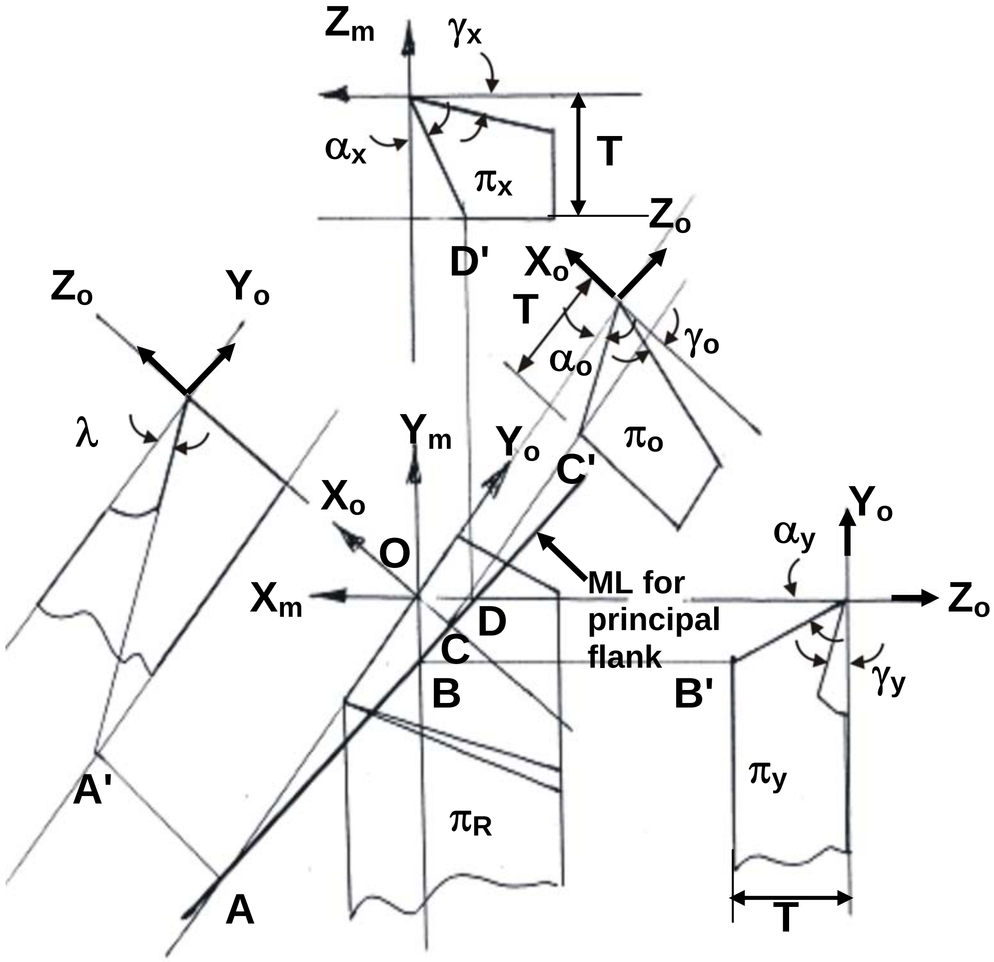


Fig. 4.4 *Master line of principal flank.*

The diagram in Fig. 4.4 is redrawn in simpler form in Fig. 4.5 for conversion of clearance angles.
The inclination angle, λ basically represents slope of the rake surface along the principal cutting edge and hence is considered as a rake angle. But λ appears in the analysis of clearance angles also because the principal cutting edge belong to both the rake surface and the principal flank.

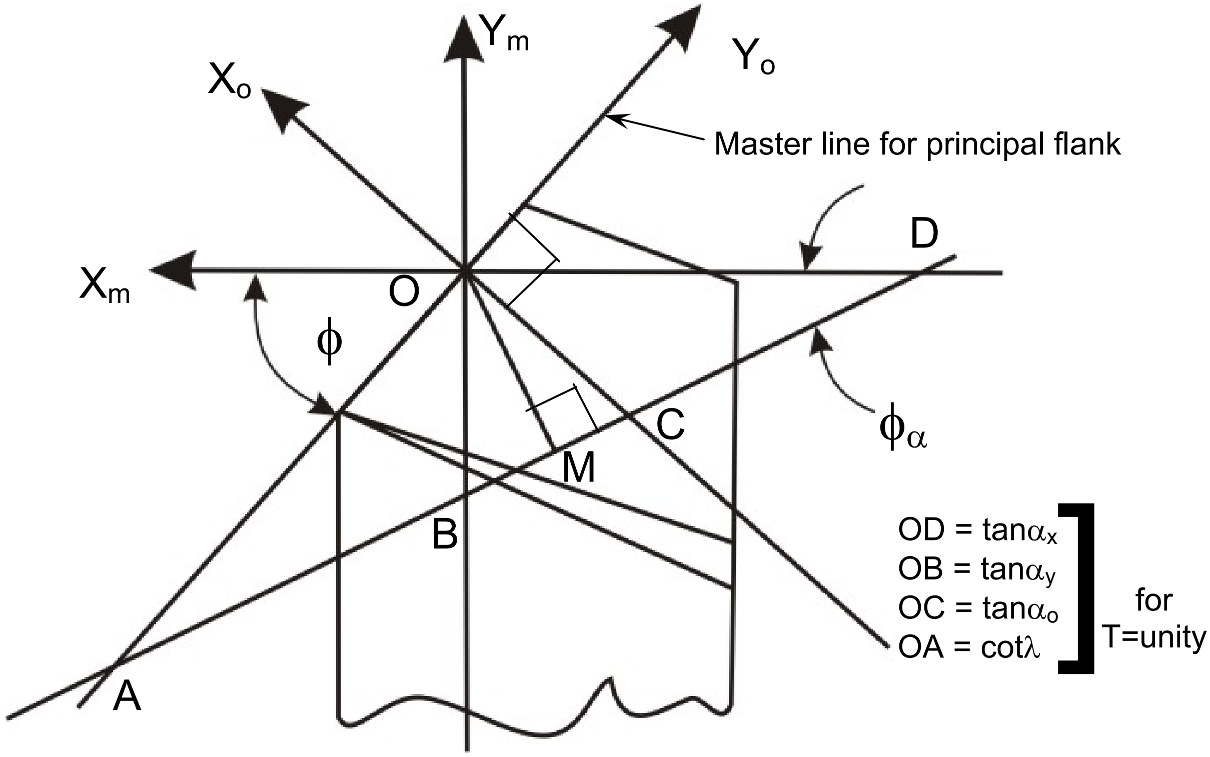


***Fig. 4.5** Use of Master line for conversion of clearance angles.*

- Conversion of clearance angles from ASA to ORS

Angles, α_o and λ in ORS = f(α_x and α_y in ASA system)
Following the same way used for converting the rake angles taking suitable triangles (in Fig. 4.2), the following expressions can be arrived at using Fig. 4.5:

$$\cot\alpha_o = \cot\alpha_x \sin\varphi + \cot\alpha_y \cos\varphi \qquad (4.11)$$

and $$\tan\lambda = -\cot\alpha_x \cos\varphi + \cot\alpha_y \sin\varphi \qquad (4.12)$$

Combining Equation 4.11 and 4.12 in matrix form

$$\begin{bmatrix} \cot\alpha_o \\ \tan\lambda \end{bmatrix} = \begin{bmatrix} \sin\phi & \cos\phi \\ -\cos\phi & \sin\phi \end{bmatrix} \begin{bmatrix} \cot\alpha_x \\ \cot\alpha_y \end{bmatrix} \tag{4.13}$$

- Conversion of clearance angles from ORS to ASA system

α_x and α_y (in ASA) = f(α_o and λ in ORS)

Proceeding in the same way using Fig. 4.5, the following expressions are derived

$$\cot\alpha_x = \cot\alpha_o \sin\varphi - \tan\lambda\cos\varphi \tag{4.14}$$

and $$\cot\alpha_y = \cot\alpha_o \cos\varphi + \tan\lambda\sin\varphi \tag{4.15}$$

The relations (4.14) and (4.15) are also possible to be attained from inversions of Equation 4.13 as indicated in case of rake angles.

- Minimum clearance, α_{min} or α_m

The magnitude and direction of minimum clearance of a single point tool may be evaluated from the line segment OM taken normal to the Master line (Fig. 4.5) as OM = $\tan\alpha_m$

The values of α_m and the orientation angle, ϕ_α (Fig. 4.5) of the principal flank are useful for conveniently grinding the principal flank surface to sharpen the principal cutting edge.

Proceeding in the same way and using Fig. 4.5, the following expressions could be developed to evaluate the values of α_m and ϕ_α

- From tool geometry specified in ASA system

$$\cot\alpha_m = \sqrt{\cot^2\alpha_x + \cot^2\alpha_y} \tag{4.16}$$

and $$\phi_\gamma = \tan^{-1}\left(\frac{\cot\alpha_x}{\cot\alpha_y}\right) \tag{4.17}$$

- From tool geometry specified in ORS

$$\cot\alpha_x = \sqrt{\cot^2\alpha_0 + \tan^2\lambda} \tag{4.18}$$

and $$\phi_\alpha = \phi - \tan^{-1}\left(\frac{\tan\lambda}{\cot\alpha_o}\right) \tag{4.19}$$

Similarly the clearance angles and the grinding angles of the auxiliary flank surface can also be derived and evaluated.

- Interrelationship amongst the cutting angles used in ASA and ORS

The relations are very simple as follows:

ϕ (in ORS) = 90^o - ϕ_s (in ASA) (4.20)

and ϕ_1(in ORS) = ϕ_e (in ASA) (4.21)

(iv) Conversion of tool angles from ORS to NRS

The geometry of any single point tool is designated in ORS and NRS respectively as,

λ, γ_o, α_o, α_o', ϕ_1, ϕ, r (mm) – ORS
λ, γ_n, α_n, α_n', ϕ_1, ϕ, r (mm) – NRS

The two methods are almost same, the only difference lies in the fact that γ_o, α_o and α_o' of ORS are replaced by γ_n, α_n and α_n' in NRS.
The corresponding rake and clearance angles of ORS and NRS are related as ,

$$\tan\gamma_n = \tan\gamma_o\cos\lambda \quad (4.22)$$

$$\cot\alpha_n = \cot\alpha_o\cos\lambda \quad (4.23)$$

and $$\cot\alpha_n' = \cot\alpha_o'\cos\lambda' \quad (4.24)$$

The equation 4.22 can be easily proved with the help of Fig. 4.6.

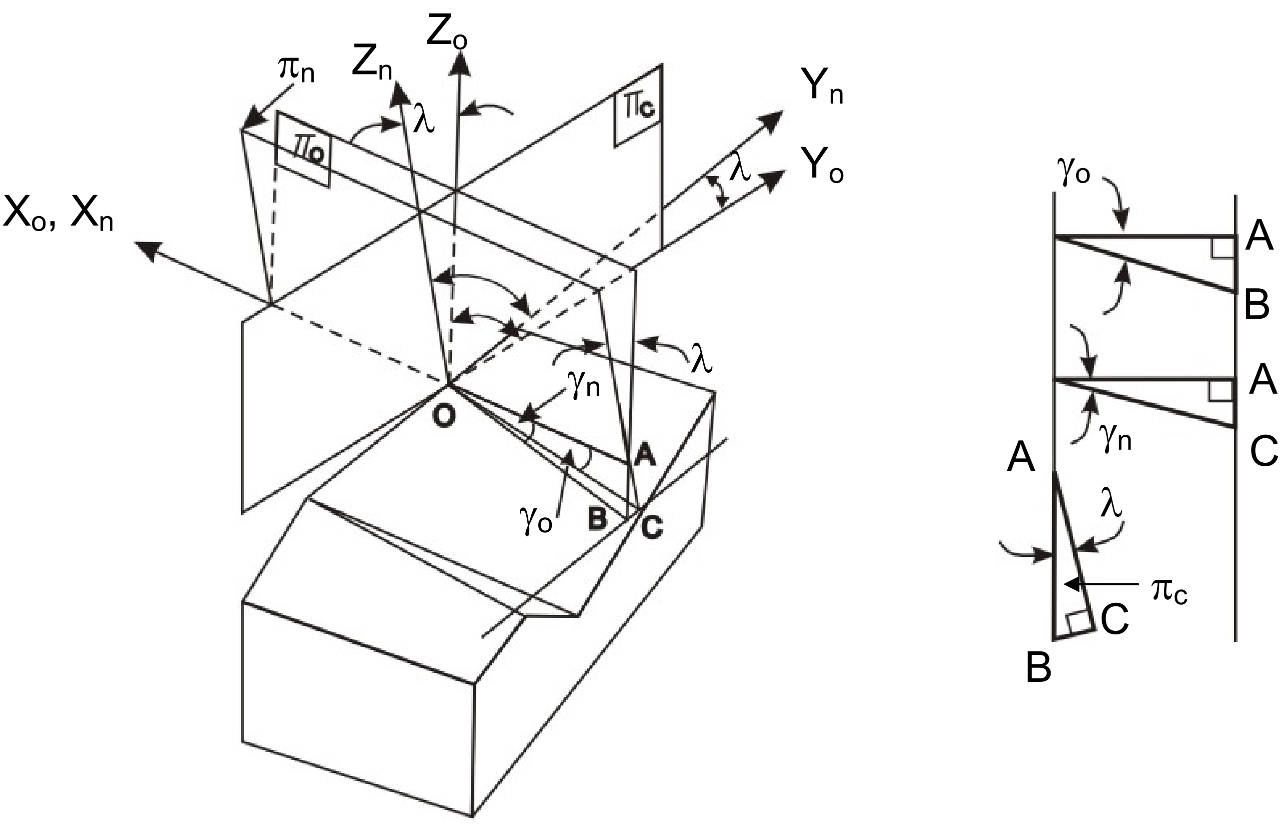


***Fig. 4.6** Relation between normal rake (γ_n) and orthogonal rake (γ_o)*

The planes π_o and π_n are normal to Y_o and Y_n (principal cutting edge) respectively and their included angle is λ when π_o and π_n are extended below OA (i.e. π_R) they intersect the rake surface along OB and OC respectively.
Therefore,

$\angle AOB = \gamma_o$
$\angle AOC = \gamma_n$
where, $\angle BAC = \lambda$

Now $AC = AB\cos\lambda$
Or, $OA\tan\gamma_n = (OA\tan\gamma_o)\cos\lambda$
So, $\mathbf{\tan\gamma_n = \tan\gamma_o\cos\lambda}$ proved

The equation (4.23) relating α_n and α_o can be easily established with the help of Fig. 4.7.

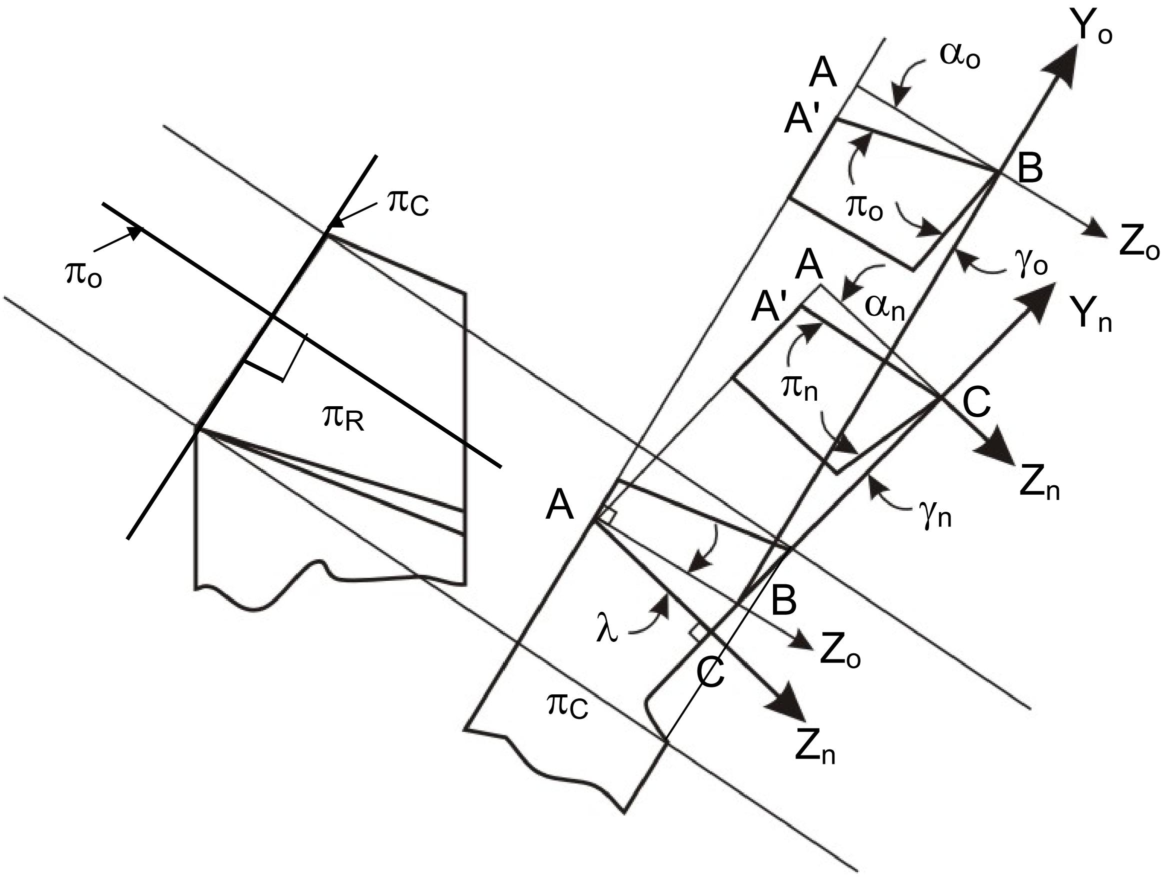


Fig. 4.7 Relation between normal clearance, α_n and orthogonal clearance, α_o

From Fig. 4.7,

$AC = AB\cos\lambda$

Or $AA'\cot\alpha_n = AA'\cot\alpha_o\cos\lambda$

$\therefore$ $\mathbf{\cot\alpha_n = \cot\alpha_o\cos\lambda}$ proved

Similarly it can be proved,

$\cot\alpha_n' = \cot\alpha_o'\cos\lambda'$

where λ' is the inclination angle of the auxiliary cutting edge.

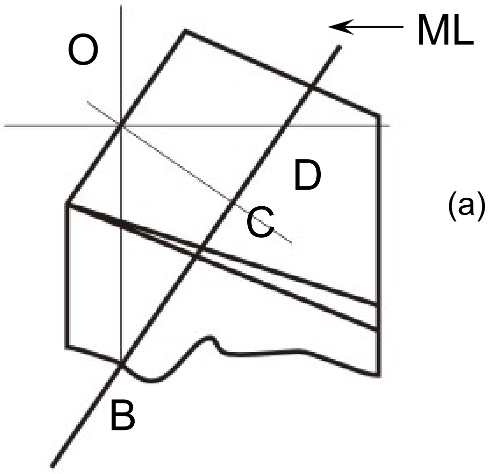
(v) Tool geometry under some critical conditions

- Configuration of Master lines (in graphical method of tool angle conversion) for different tool geometrical conditions.

The locations of the points 'A', 'B', 'C', 'D' and 'M' along the ML will be as shown in Fig. 4.2 when all the corresponding tool angles have some positive values. When any rake angle will be negative, the location of the corresponding point will be on the other side of the tool.

Some typical configurations of the Master line for rake surface and the corresponding geometrical significance are indicated in Fig. 4.8.

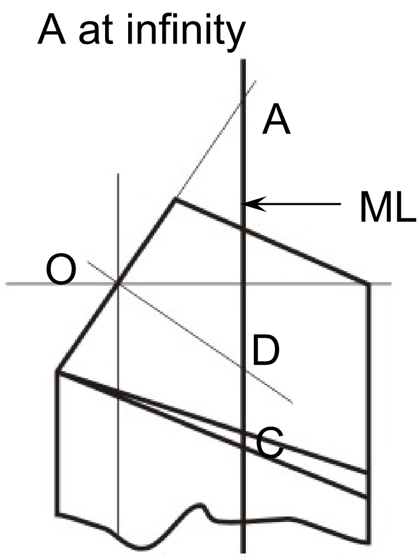
Configuration of ML | **Tool geometry**



(a)

for ML parallel to π_C

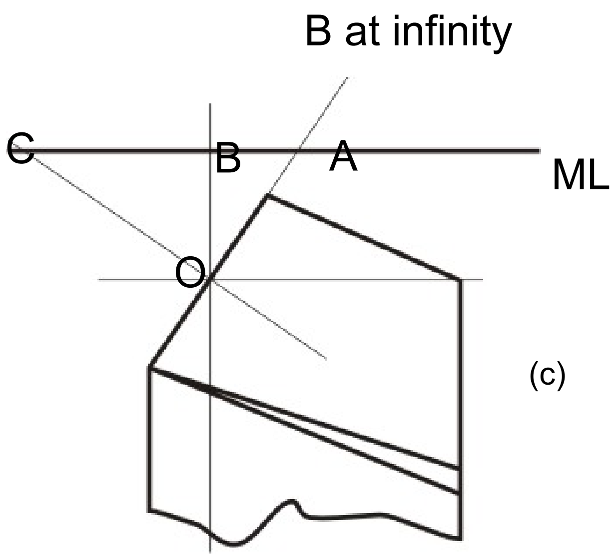
γ_x = positive
γ_y = positive
γ_o = positive
λ = 0
$\gamma_m = \gamma_o$



(b)

for ML parallel to π_Y

γ_x = positive
γ_y = 0
γ_o = positive
λ = negative
$\gamma_m = \gamma_x$



(c)

for ML parallel to π_X

γ_x = 0
γ_y = negative
γ_o = negative
λ = negative
$|\gamma_m| = |\gamma_y|$

Fig. 4.8 *Tool geometry and Master line (rake face) in some typical conditions.*

- Tool angles' relations in some critical conditions

From the equations correlating the cutting tool angles, the following critical observations are made:

- When $\phi = 90^o$; $\gamma_x = \gamma_o$ for $\pi_X = \pi_o$
- When $\lambda = 0$; $\gamma_n = \gamma_o$
  $\alpha_n = \alpha_o$
- When λ=0 and $\phi = 90^o$; $\gamma_n=\gamma_o=\gamma_x$ pure orthogonal cutting
  $(\pi_N=\pi_o=\pi_X)$

Exercise – 4

A. Quiz test

Select the correct answer from the given four options

1. The master line for the rake surface of the turning tool of geometry : -
   10^o, 0^o, 8^o, 6^o, 15^o, 30^o, 0.1 (inch)
   (a) machine longitudinal plane
   (b) machine transverse plane
   (c) cutting plane
   (d) orthogonal plane

2. If the approach angle of a turning tool be 30^o, the value of its principal cutting edge angle will be
   (a) O deg.
   (b) 30^o deg.
   (c) 60^o deg.
   (d) 90^o deg.

3. The value of side rake of the turning tool of geometry : -
   0^o, 10^o, 8^o, 6^o, 20^o, 60^o, 0 (mm) will be
   (a) 0^o deg.
   (b) 10^o deg.
   (c) 8^o deg.
   (d) 6^o deg.

4. The values of orthogonal clearance and normal clearance of a turning tool will be same if,
   (a) ϕ=0
   (b) $\alpha_X = \alpha_Y$

(c) $\lambda = 0$
(d) none of the above

5. The angle between orthogonal plane and normal plane of a turning tool is
   (a) γ_o
   (b) ϕ
   (c) γ_n
   (d) λ

B. Problem

1. Determine the values of normal rake of the turning tool whose geometry is designated as : 10^o, -10^o, 8^o, 6^o, 15^o, 30^o, 0 (inch)?

2. Determine the value of side clearance of the turning tool whose geometry is specified as 0^o, -10^o, 8^o, 6^o, 20^o, 60^o, 0 (mm) ?

Solutions of Exercise – 4

A. Quiz test
1 – (a)
2 – (c)
3 – (b)
4 – (c)
5 – (d)

B. Problems

Ans. 1

Tool geometry given :
10^o, -10^o, 8^o, 6^o, 15^o, 30^o, 0 (inch)
γ_y, γ_x, α_y, α_x, ϕ_e, ϕ_s, r – ASA

$\tan\gamma_n = \tan\gamma_o \cos\lambda$
where,
$\tan\gamma_o = \tan\gamma_x \sin\phi + \tan\gamma_y \cos\phi$
$= \tan(-10^o)\sin(90^o - 30^o) + \tan(10^o)\cos(90^o - 30^o)$
$= -0.065$
So, $\gamma_o = -3.7^o$
And $\tan\lambda = -\tan\gamma_x \cos\phi + \tan\gamma_y \sin\phi$
$= -\tan(-10^o)\cos(90^o - 30^o) + \tan(10^o)\sin(90^o - 30^o)$
$= 0.2408$
So, $\lambda = 13.54^o$

$\tan\gamma_n = \tan\gamma_o \cos\lambda = \tan(-3.7)\cos(13.54) = -0.063$
So, $\gamma_n = -3.6^o$ Ans.

Ans. 2

Tool geometry given : 0^o, $- 10^o$, 8^o, 6^o, 20^o, 60^o, 0 (mm)
λ, γ_o, α_o, α_o', ϕ_1, ϕ, r (mm)

$\cot\alpha_x = \cot\alpha_o \sin\phi - \tan\lambda\cos\phi$
$= \cot 8.\sin 60 - \tan 0.\cos 60$
$= \cot 8.\sin 60$
$= 6.16$

So, $\alpha_x = 9.217^o$ Ans.

Module 2

Mechanics of Machining

Lesson
5
Mechanism of chip formation

Instructional Objectives

At the end of this lesson, the student would be able to

(i) describe with illustration the mechanism of chip formation in machining
   - ductile materials and
   - brittle materials

(ii) illustrate and assess geometrical characteristics of ductile chips :
   - chip reduction coefficient & cutting ratio
   - shear angle and cutting strain

(iii) Identify and state the causes, characteristics and effects of built – up – edge (BUE) formation.

(iv) Classify chips and identify the condition for different chip forms.

(i) Mechanism of chip formation in machining

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 behaviour 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 depend 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 favourable 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. 5.1.

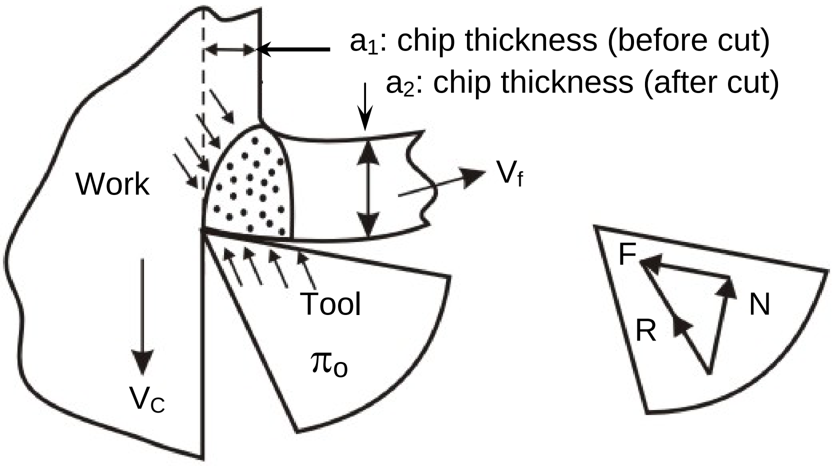


***Fig. 5.1** Compression of work material (layer) ahead of the tool tip*

The force exerted by the tool on the chip arises out of the normal force, N and frictional force, F as indicated in Fig. 5.1.
Due to such compression, shear stress develops, within that compressed region, in different magnitude, in different directions and rapidly increases in magnitude. Whenever and wherever the value of the shear stress reaches or exceeds the shear strength of that work material in the deformation region, yielding or slip takes place resulting shear deformation in that region and the plane of maximum shear stress. But the forces causing the shear stresses in the region of the chip quickly diminishes and finally disappears while that region moves along the tool rake surface towards and then goes beyond the point of chip-tool engagement. As a result the slip or shear stops propagating long before total separation takes place. In the mean time the succeeding portion of the chip starts undergoing compression followed by yielding and shear. This phenomenon repeats rapidly resulting in formation and removal of chips in thin layer by layer. This phenomenon has been explained in a simple way by Piispannen [1] using a card analogy as shown in Fig. 5.2.

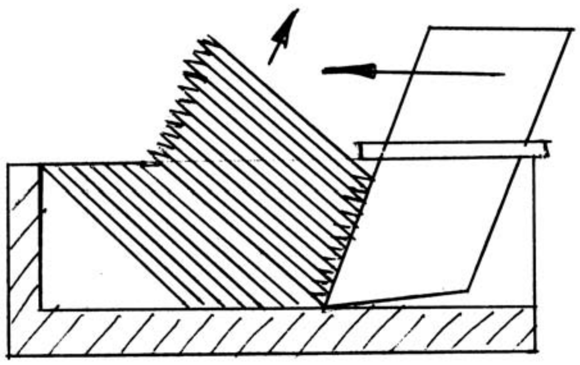
In actual machining chips also, such serrations are visible at their upper surface as indicated in Fig. 5.2. The lower surface becomes smooth due to further plastic deformation due to intensive rubbing with the tool at high pressure and temperature. The pattern of shear deformation by lamellar sliding, 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,

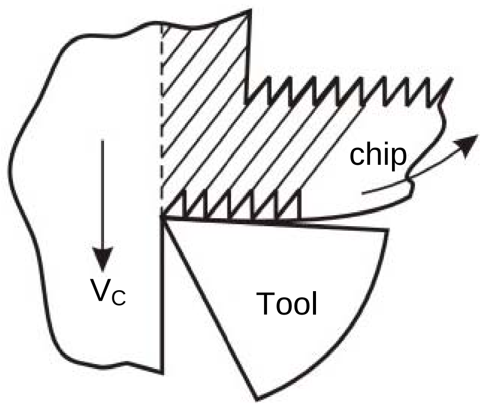
as indicated in Fig. 5.3, depend upon

[1] Piispannen V., "Theory of formation of metal chips", J. Applied Physics, Vol. 19, No. 10, 1948, pp. 876.

- work material
- tool; material and geometry
- the machining speed (V_C) and feed (s_o)
- cutting fluid application



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



(b) Chip formation by shear in lamella.

***Fig. 5.2** Piispanen model of card analogy to explain chip formation in machining ductile materials*

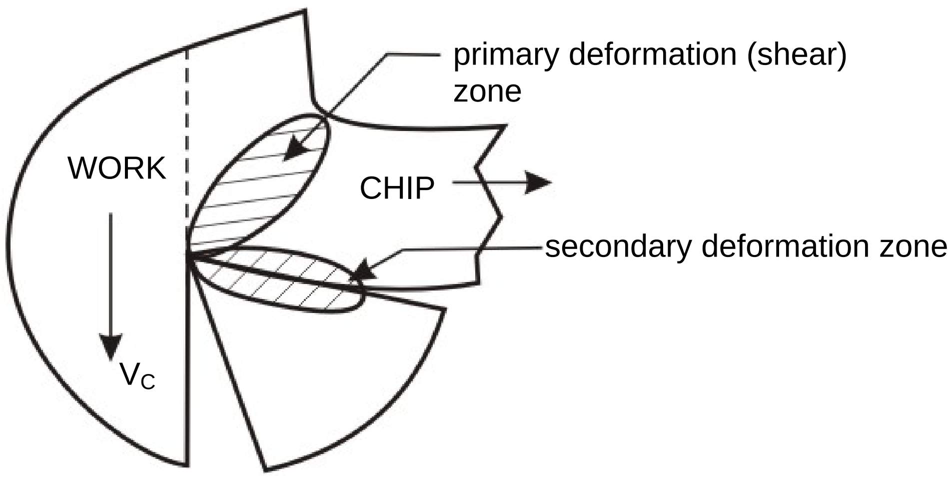


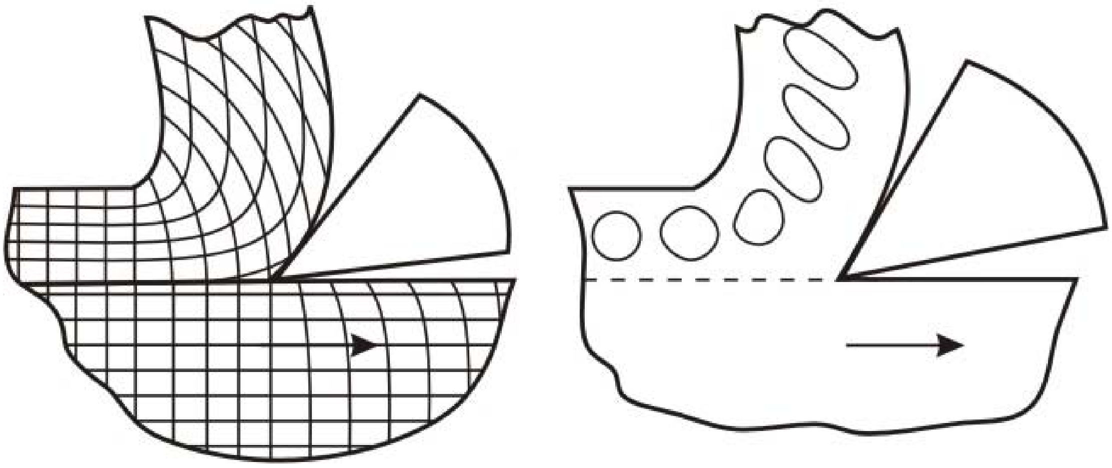
***Fig. 5.3** Primary and secondary deformation zones in the chip.*

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 [2] for this purpose are:

- Study of deformation of rectangular or circular grids marked on the side surface as shown in Fig. 5.4

[2] Bhattacharya, A.., "Metal cutting – Theory and Practice", Book, New Central Book Agency, Kolkata.

- 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.



(a) rectangular grids (b) circular grids

Fig. 5.4 *Pattern of grid deformation during chip formation.*

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. 5.5 due to wedging action of the cutting edge. At the sharp crack-tip stress concentration takes place. In case of ductile materials immediately yielding takes place at the crack-tip and reduces the effect of stress concentration and prevents its propagation as crack. But in case of brittle materials the initiated crack quickly propagates, under stressing action, and total separation takes place from the parent workpiece through the minimum resistance path as indicated in Fig. 5.5.
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. 5.6.

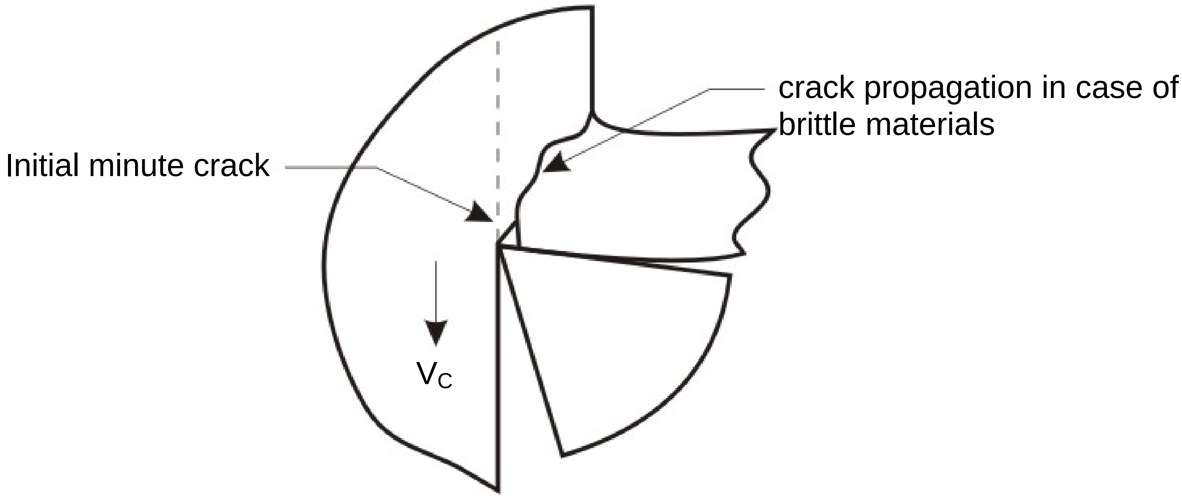


Fig. 5.5 *Development and propagation of crack causing chip separation.*

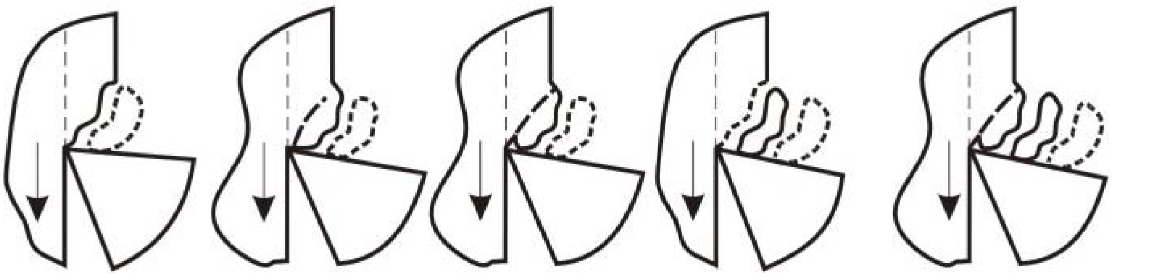


Fig. 5.6 *Schematic view of chip formation in machining brittle materials.*

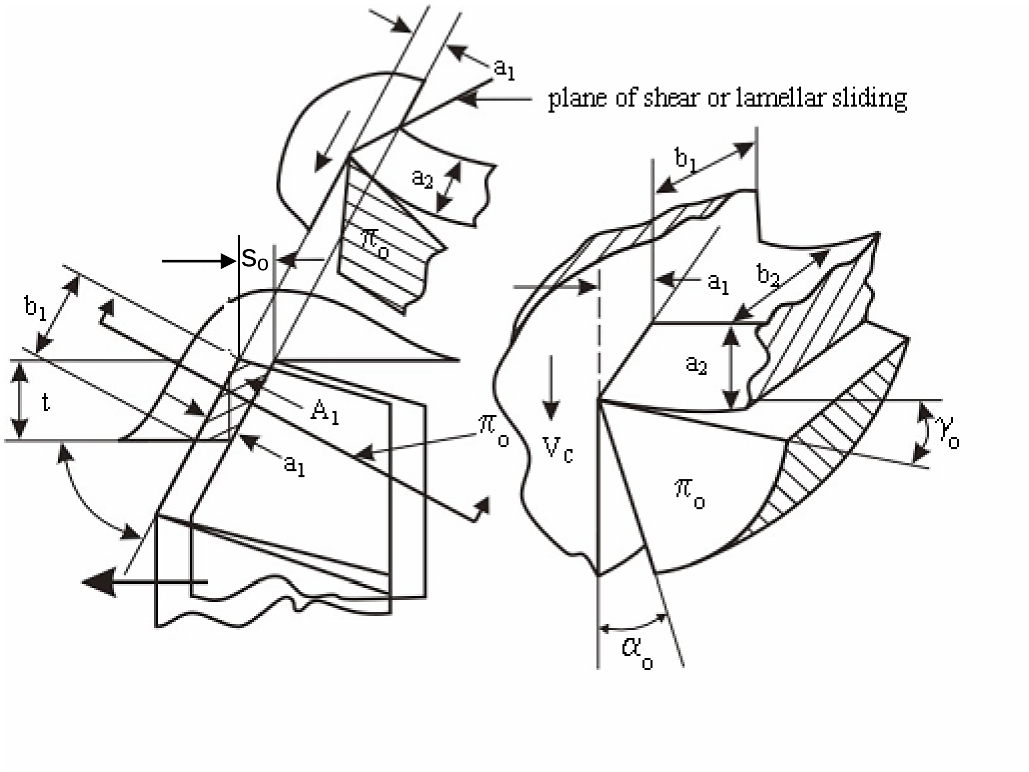
(ii) Geometry and characteristics of chip forms

The geometry of the chips being formed at the cutting zone follow a particular pattern especially in machining ductile materials. The major section of the engineering materials being machined are ductile in nature, even some semi-ductile or semi-brittle materials behave ductile under the compressive forces at the cutting zone during machining.
The pattern and degree of deformation during chip formation are quantitatively assessed and expressed by some factors, the values of which indicate about the forces and energy required for a particular machining work.

- **Chip reduction coefficient or cutting ratio**

The usual geometrical features of formation of continuous chips are schematically shown in Fig. 5.7.
The chip thickness (a_2) usually becomes larger than the uncut chip thickness (a_1). The reason can be attributed to

- compression of the chip ahead of the tool
- frictional resistance to chip flow
- lamellar sliding according to Piispannen



(a) (b)

Fig. 5.7 *Geometrical features of continuous chips' formation.*

The significant geometrical parameters involved in chip formation are shown in Fig. 5.7 and those parameters are defined (in respect of straight turning) as:

t = depth of cut (mm) – perpendicular penetration of the cutting tool tip in work surface
s_o = feed (mm/rev) – axial travel of the tool per revolution of the job
b_1 = width (mm) of chip before cut
b_2 = width (mm) of chip after cut
a_1 = thickness (mm) of uncut layer (or chip before cut)
a_2 = chip thickness (mm) – thickness of chip after cut
A_1 = cross section (area, mm^2) of chip before cut

The degree of thickening of the chip is expressed by

$$\zeta = \frac{a_2}{a_1} > 1.00 \text{ (since } a_2 > a_1) \quad (5.1)$$

where, ζ = chip reduction coefficient

$a_1 = s_o \sin\phi$ (5.2)

where ϕ = principal cutting edge angle

Larger value of ζ means more thickening i.e., more effort in terms of forces or energy required to accomplish the machining work. Therefore it is always desirable to reduce a_2 or ζ without sacrificing productivity, i.e. metal removal rate (MRR).

Chip thickening is also often expressed by the reciprocal of ζ as,

$$\frac{1}{\zeta} = r = \frac{a_1}{a_2} \quad (5.3)$$

where, r = cutting ratio

The value of chip reduction coefficient, ζ (and hence cutting ratio) depends mainly upon

- tool rake angle, γ
- chip-tool interaction, mainly friction, μ

Roughly in the following way [3]

$$\zeta = e^{\mu(\frac{\pi}{2} - \gamma_o)} \quad \text{[for orthogonal cutting]} \quad (5.4)$$

$\pi/2$ and γ_o are in radians

The simple but very significant expression (5.4) clearly depicts that the value of ζ can be desirably reduced by

- Using tool having larger positive rake
- Reducing friction by using lubricant

The role of rake angle and friction at the chip-tool interface on chip reduction coefficient are also schematically shown in Fig. 5.8.

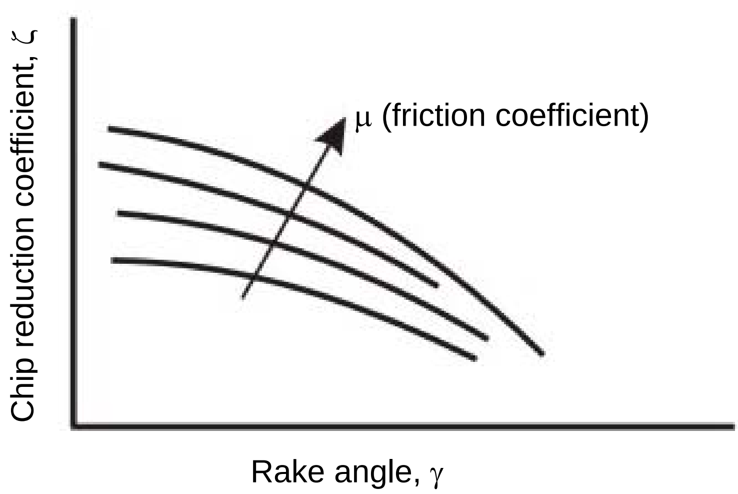


Fig. 5.8 *Role of rake angle and friction on chip reduction coefficient*

Chip reduction coefficient, ζ is generally assessed and expressed by the ratio of the chip thickness, after (a_2) and before cut (a_1) as in equation 5.1.

But ζ can also be expressed or assessed by the ratio of

[3] Kronenberg, M., "A new approach to some relationships in the Theory of Metal Cutting", J. Applied Physics, Vol.6, No. 6, 1945.

- Total length of the chip before (L_1) and after cut (L_2)
- Cutting velocity, V_C and chip velocity, V_f

Considering total volume of chip produced in a given time,

$$a_1b_1L_1 = a_2b_2L_2 \tag{5.5}$$

The width of chip, b generally does not change significantly during machining unless there is side flow for some adverse situation.
Therefore assuming, $b_1=b_2$ in equation (5.5), ζ comes up to be,

$$\zeta\left(=\frac{a_2}{a_1}\right)=\frac{L_1}{L_2} \tag{5.6}$$

Again considering unchanged material flow (volume) ratio, Q

$$Q = (a_1b_1)V_C = (a_2b_2)V_f \tag{5.7}$$

Taking $b_1=b_2$,

$$\zeta\left(=\frac{a_2}{a_1}\right)=\frac{V_C}{V_f} \tag{5.8}$$

Equation (5.8) reveals that the chip velocity, V_f will be lesser than the cutting velocity, V_C and the ratio is equal to the cutting ratio, $r\left(=\frac{1}{\zeta}\right)$

- **Shear angle**

It has been observed that during machining, particularly ductile materials, the chip sharply changes its direction of flow (relative to the tool) from the direction of the cutting velocity, V_C to that along the tool rake surface after thickening by shear deformation or slip or lamellar sliding along a plane. This plane is called shear plane and is schematically shown in Fig. 5.9.

Shear plane: Shear plane is the plane of separation of work material layer in the form of chip from the parent body due to shear along that plane.
Shear angle: Angle of inclination of the shear plane from the direction of cutting velocity [as shown in Fig. 5.9].

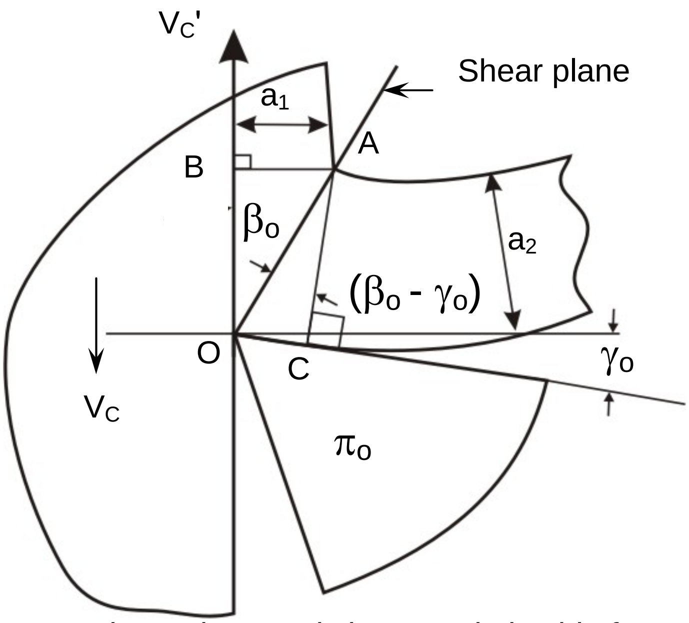


Fig. 5.9 *Shear plane and shear angle in chip formation*

The value of shear angle, denoted by β_o (taken in orthogonal plane) depends upon

- Chip thickness before and after cut i.e. ζ
- Rake angle, γ_o (in orthogonal plane)

From Fig. 5.9,

AC = a_2 = OAcos(β_o-γ_o)

And AB = a_1 = OAsinβ_o

Dividing a_2 by a_1

$$\frac{a_2}{a_1} = \zeta = \frac{\cos(\beta_o - \gamma_o)}{\sin \beta_o} \qquad (5.9)$$

or, $$\tan \beta_o = \frac{\cos \gamma_o}{\zeta - \sin \gamma_o} \qquad (5.10)$$

Replacing chip reduction coefficient, ζ by cutting ratio, r, the equation (5.10) changes to

$$\tan \beta_o = \frac{r \cos \gamma_o}{1 - r \sin \gamma_o} \qquad (5.11)$$

Equation 5.10 depicts that with the increase in ζ, shear angle decreases and vice-versa. It is also evident from equation (5.10) as well as equation (5.4) that shear angle increases both directly and indirectly with the increase in tool rake angle. Increase in shear angle means more favourable machining condition requiring lesser specific energy.

- **Cutting strain**

The magnitude of strain, that develops along the shear plane due to machining action, is called cutting strain (shear). The relationship of this cutting strain, ε with the governing parameters can be derived from Fig. 5.10.

Due to presence of the tool as an obstruction the layer 1 has been shifted to position 2 by sliding along the shear plane.
From Fig. 5.10,

Cutting strain (average), $\varepsilon = \frac{\Delta s}{Y} = \frac{PM}{ON}$

or, $\varepsilon = \frac{PN + NM}{ON} = \frac{PN}{ON} + \frac{NM}{ON}$

or, $$\varepsilon = \cot \beta_o + \tan(\beta_o - \gamma_o) \qquad (5.12)$$

(iii) 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 favourable location and thus gradually grows as schematically shown in Fig. 5.11.

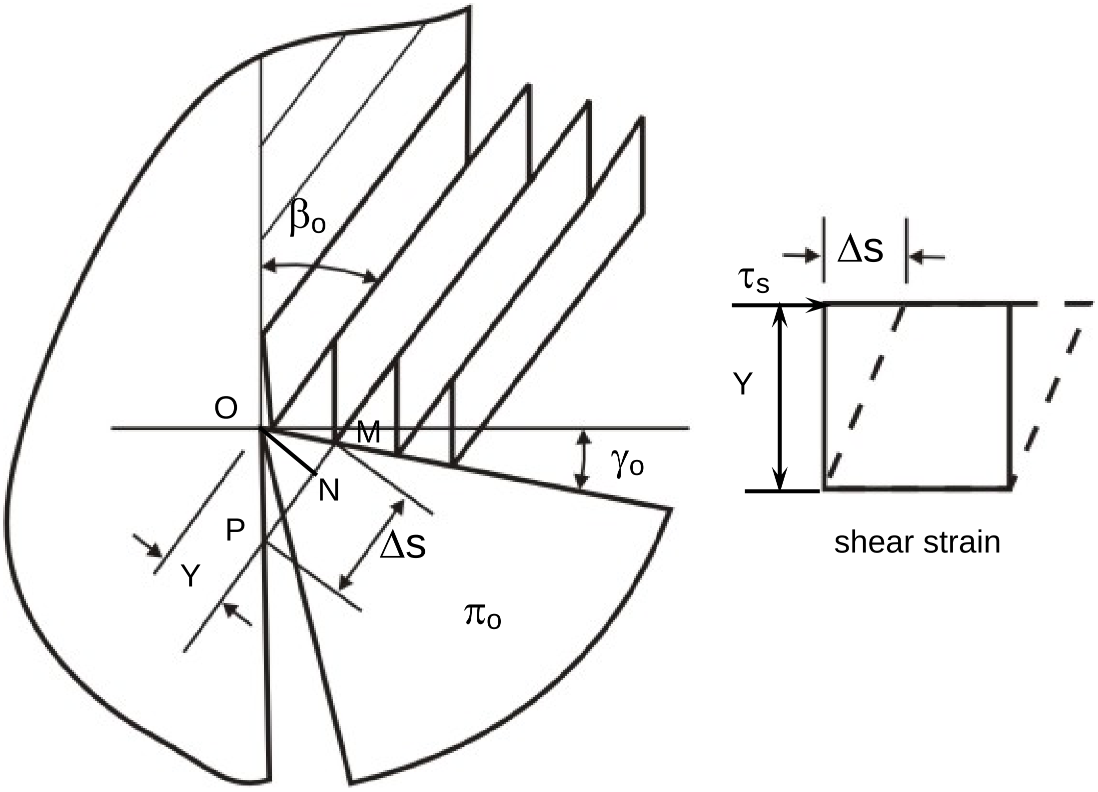


Fig. 5.10 *Cutting strain in machining*

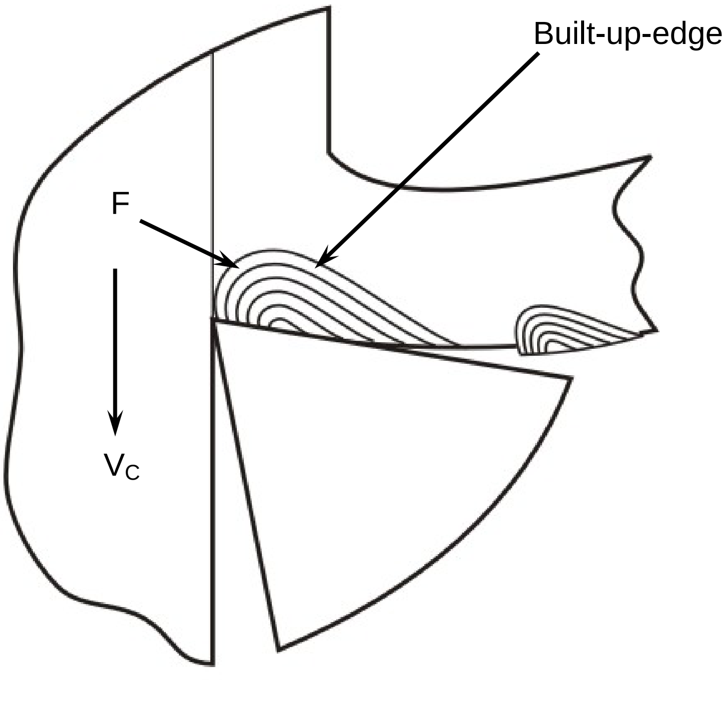


Fig. 5.11 *Scheme of built-up-edge formation*

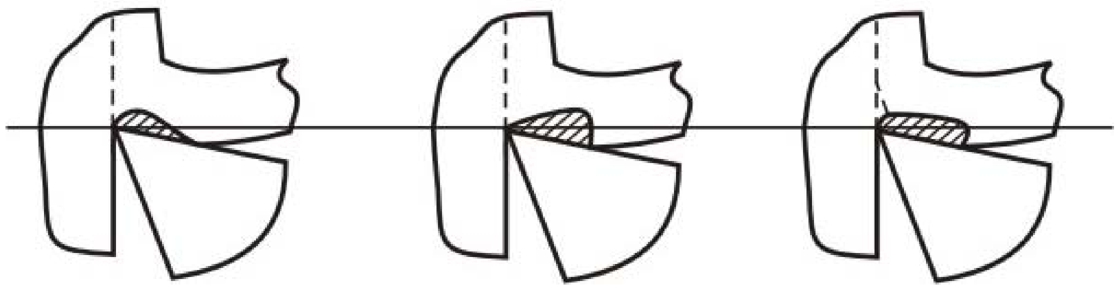
With the growth of the BUE, the force, F (shown in Fig. 5.11) also gradually increases due to wedging action of the tool tip along with the BUE formed on it. Whenever the force, F exceeds the bonding force of the BUE, the BUE is broken or sheared off and taken away by the flowing chip. Then again BUE 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. 5.12.



(a) positive wedge (b) negative wedge (c) flat type

Fig. 5.12 *Different forms of built-up-edge.*

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. 5.13

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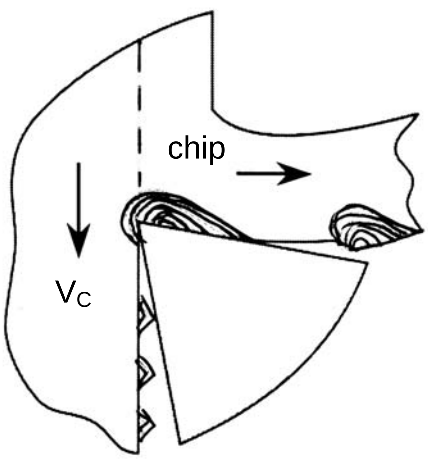


Fig. 5.13 *Overgrowing and overflowing of BUE causing surface roughness*

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 s_o the cutting temperature rises and favours 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. 5.14 shows schematically the role of increasing V_C and s_o 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 detrimental situation occurs in case of certain tool-work materials and at speed-feed conditions which strongly favour adhesion and welding.

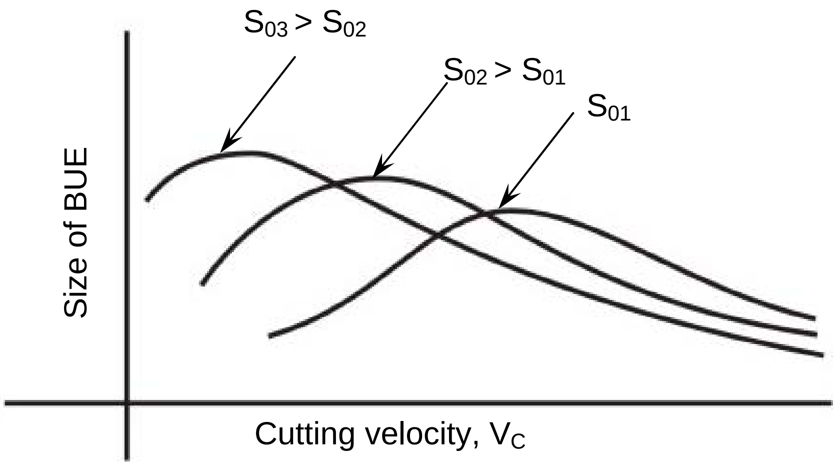


Fig. 5.14 *Role of cutting velocity and feed on BUE formation.*

- Effects of BUE formation

Formation of BUE causes several harmful effects, such as:

- It unfavourably 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.

(iv) Types of chips and conditions for formation of those 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:

- Discontinuous type
  - 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 – large
    - tool rake – negative
    - cutting fluid – absent or inadequate
- Continuous type
  - Without BUE : work material – ductile
    Cutting velocity – high
    Feed – low
    Rake angle – positive and large
    Cutting fluid – both cooling and lubricating
  - With BUE : - work material – ductile
    - cutting velocity – medium
    - feed – medium or large
    - cutting fluid – inadequate or absent.
- Jointed or segmented type
  - work material – semi-ductile
  - cutting velocity – low to medium
  - feed – medium to large
  - tool rake – negative
  - cutting fluid – 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.

Exercise - 5

A. Quiz Test

Identify the correct one out of the four given answers

1.In turning mild steel the value of ζ will be

(a) > 1.0
(b) < 1.0
(c) = 1.0
(d) none of the above

2.The value of shear angle, β_o depends upon

(a) tool rake angle
(b) friction at chip-tool interface
(c) built – up – edge formation
(d) all of the above

3.Shaping grey cast iron block will produce

(a) continuous chip with BUE
(b) continuous chip without BUE
(c) discontinuous chip of irregular size & shape
(d) discontinuous chip of regular size & shape

4.The value of chip reduction coefficient, ζ does not depend upon

(a) cutting velocity
(b) depth of cut
(c) cutting tool material
(d) tool rake angle

B. Numerical Problem

1.During plain turning mild steel by a tool of geometry, 0^o, 0^o, 8^o, 7^o, 15^o, 90^o, 0 (mm) at s_o= 0.2 mm/rev, the chip thickness was found to be 0.5 mm. Determine the values of ζ and β_o in the above case.

Answers

A. Quiz Test

1 – (a)
2 – (d)
3 – (c)
4 – (b)

B. Numerical Problem

$$\zeta = \frac{a_2}{a_1} = \frac{a_2}{s_o \sin\phi} = \frac{0.5}{0.2x \sin 90^o} = 2.5$$

$$\tan\beta_o = \frac{\cos\gamma_o}{\zeta - \sin\gamma_o} = \frac{\cos 0^o}{2.5 - \sin 0^o} \; [\because \gamma_o = 0^o]$$

$$= \frac{1}{\zeta} = \frac{1}{2.5} = 0.4$$

$$\therefore \beta_o = \tan^{-1}(0.4) = 21.8^o$$

Module 2

Mechanics of Machining

Lesson
6
Orthogonal and oblique cutting

Instructional Objectives

At the end of this lesson, the student would be able to

(i) define and distinguish, with illustrations, between orthogonal cutting and oblique cutting
(ii) identify the causes of oblique cutting and chip flow deviation
(iii) determine angle of chip flow deviation.
(iv) illustrate and deduce effective rake angle
(v) state the effects of oblique cutting

(i) Orthogonal and oblique cutting

It is appears from the diagram in Fig. 6.1 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, λ, etc.

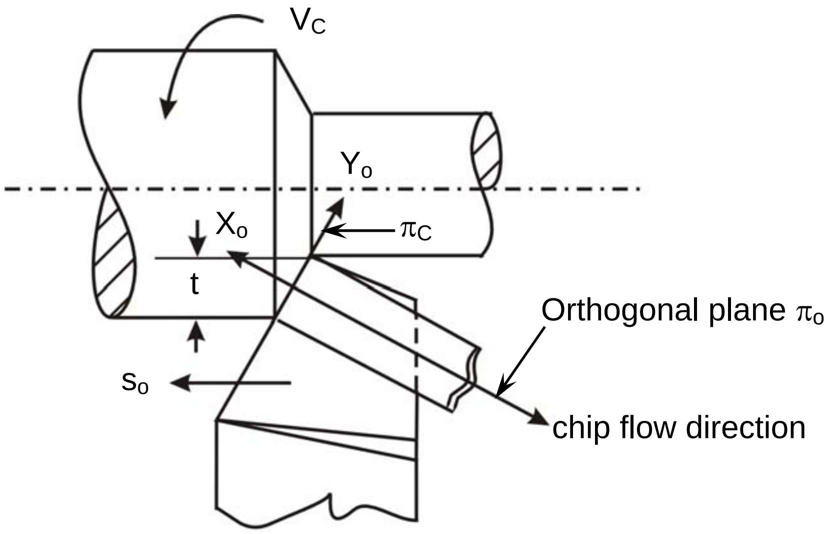
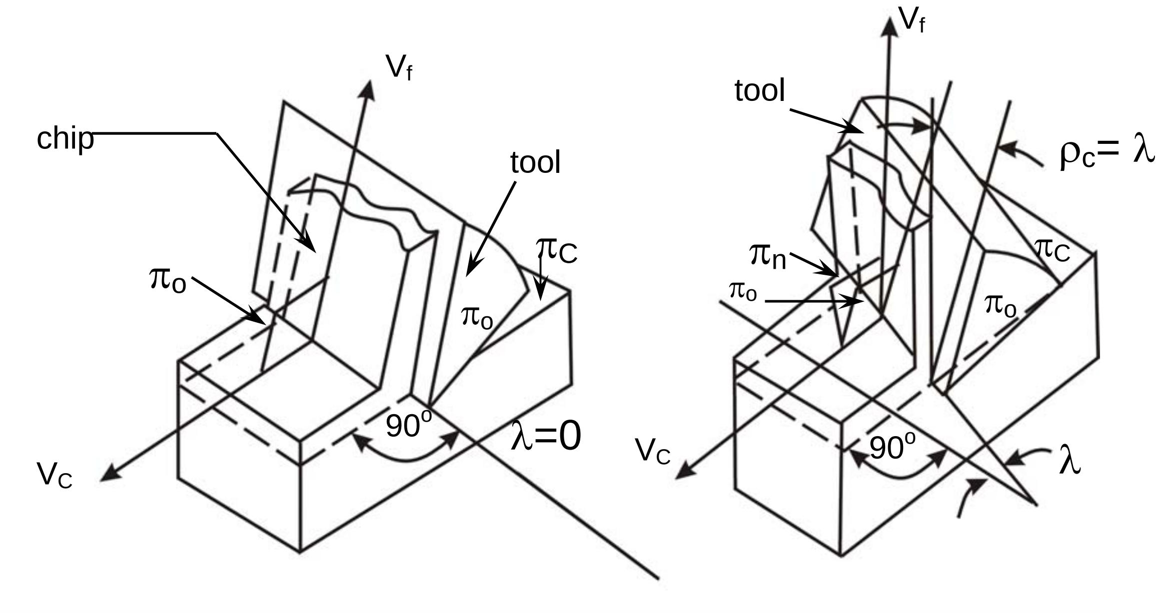


Fig. 6.1 *Ideal direction of chip flow in turning*

The role of inclination angle, λ on the direction of chip flow is schematically shown in Fig. 6.2 which visualises that,

- when λ=0, the chip flows along orthogonal plane, i.e, $\rho_c = 0$
- when $\lambda \neq 0$, the chip flow is deviated from π_o and $\rho_c = \lambda$ where ρ_c is chip flow deviation (from π_o) angle



(a) $\lambda = 0$ (b) $\lambda \neq 0$

Fig. 6.2 *Role of inclination angle, λ on chip flow direction*

Orthogonal cutting: when chip flows along orthogonal plane, π_o, i.e., $\rho_c = 0$
Oblique cutting : when chip flow deviates from orthogonal plane, i.e. $\rho_c \neq 0$
But practically ρ_c may be zero even if $\lambda = 0$ and ρ_c may not be exactly equal to λ even if $\lambda \neq 0$. Because there are some other (than λ) factors also which may cause chip flow deviation.
Pure orthogonal cutting: This refers to chip flow along π_o and $\phi = 90^o$ as typically shown in Fig. 6.3 where a pipe like job of uniform thickness is turned (reduced in length) in a center lathe by a turning tool of geometry; $\lambda = 0$ and $\phi = 90^o$ resulting chip flow along π_o which is also π_x in this case.

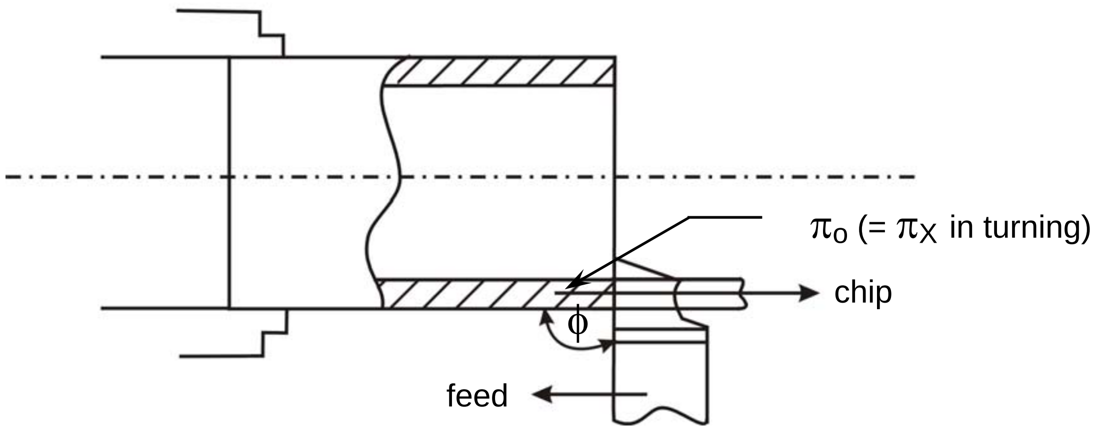


Fig. 6.3 *Pure orthogonal cutting (pipe turning)*

(ii) Causes and amount of chip flow deviation

The deviation of chip flow in machining like turning by single point tool may deviate from the orthogonal plane due to the following three factors:

- Restricted cutting effect (RCE)
- Tool-nose radius (r)
- Presence of inclination angle, $\lambda \neq 0$.

- **Restricted cutting effect**

In machining like turning, shaping etc by single point turning tool, the metal removal is accomplished mainly by the principal cutting edge. But the auxiliary cutting edge also takes part in machining to some extent depending upon the auxiliary cutting edge angle, ϕ_1 and the magnitude of feed, s_o, as indicated in Fig. 6.4. A small volume of the job in the form of a helical rib of small triangular section remains uncut. This causes surface roughness, in the form of fine threads called feed marks or scallop marks as shown in Fig. 6.4. The work material flows out in the form of chip at velocity V_A when the auxiliary cutting edge plays negligible role on chip formation. But when the auxiliary cutting edge keeps sizeable contact with the workpiece, then the material that comes out from that edge at velocity say V_B, interferes with the main stream of the chip causing chip flow deviation from the direction of V_A by an angle say ψ from the direction of V_A as shown in Fig. 6.4. This phenomenon is called **restricted contact cutting effect (RCE).**

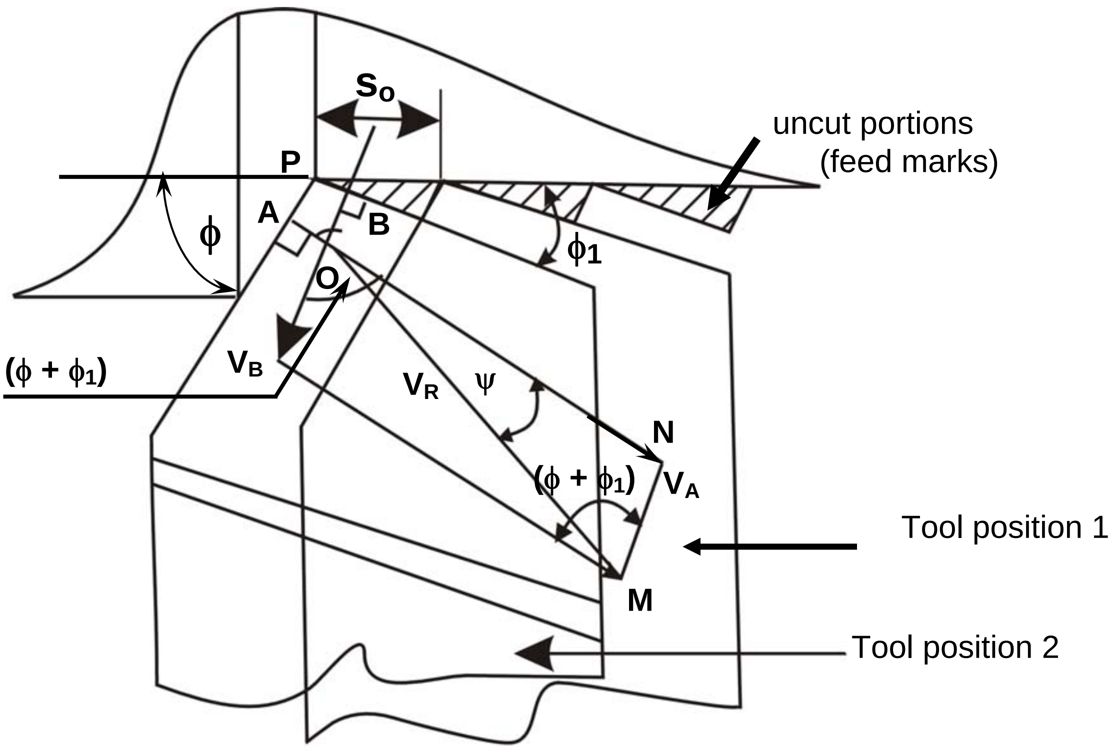


Fig. 6.4 *Chip flow deviation by Restricted Cutting Effect (RCE)*

From Fig. 6.4,

Angle $\angle APB = 180^o - (\phi + \phi_1)$ (6.1)

And $\angle AOB = (\phi + \phi_1)$ (6.2)

From properties of triangle, ΔAMN,

$$\frac{V_B}{\sin\psi} = \frac{V_A}{\sin(\phi + \phi_1 - \psi)}$$

or, $$\frac{\sin(\phi + \phi_1 - \psi)}{\sin\psi} = \frac{V_A}{V_B} \quad (6.3)$$

Assuming [Rozeinberg and Evemein] $$\frac{V_A}{V_B} = \frac{(t/\sin\phi)}{s_o/2} = \frac{2t}{s_o \sin\phi} \quad (6.4)$$

Equation (6.4) can be rewritten as

$$\frac{\sin(\phi + \phi_1)\cos\psi - \cos(\phi + \phi_1)\sin\psi}{\sin\psi} = \frac{2t}{s_o \sin\phi} \quad (6.5)$$

On simplification, equation (6.4), ψ can be expressed as,

$$\tan\psi = \frac{\sin(\phi + \phi_1)}{\frac{2t}{s_o \sin\phi} + \cos(\phi + \phi_1)} \quad (6.5)$$

Equation (6.5) indicates that even in absence of λ the chip flow may deviate, and the angle of deviation, ψ, though small, depends upon the cutting angles and depth of cut to feed ratio (t/s_o).

- **Effect of tool nose radius, r**

Equation (6.5) indicates that chip flow deviation is significantly influenced by the principal cutting edge angle, ϕ. In nose radiused tool, the value of ϕ continuously varies starting from zero over the curved portion of the principal cutting edge. Such variation in ϕ reasonably influences the chip flow deviation. Therefore, to incorporate the effect of tool nose radiusing also, the ϕ in equation (6.5) need to be replaced by the average value of ϕ i.e., ϕ_{avg} which can be determined with the help of the diagram shown in Fig. 6.5.

From Fig. 6.5,

$$\phi_{avg} = \frac{\overline{AB} x \frac{\phi}{2} + \overline{BC} x \phi}{\overline{AB} + \overline{BC}} \quad (6.6)$$

where, $\overline{AB} = r\phi$

and $\overline{BC} = \frac{t_2}{\sin\phi} = \frac{t - t_1}{\sin\phi}$

here $t_1 = r - r\cos\phi$

Thus, $$\phi_{avg} = \frac{\frac{\phi}{2} + [\frac{t}{r} + \cos\phi - 1]\frac{1}{\sin\phi}}{1 + \frac{[\frac{t}{r} + \cos\phi - 1]}{\phi\sin\phi}} \quad (6.7)$$

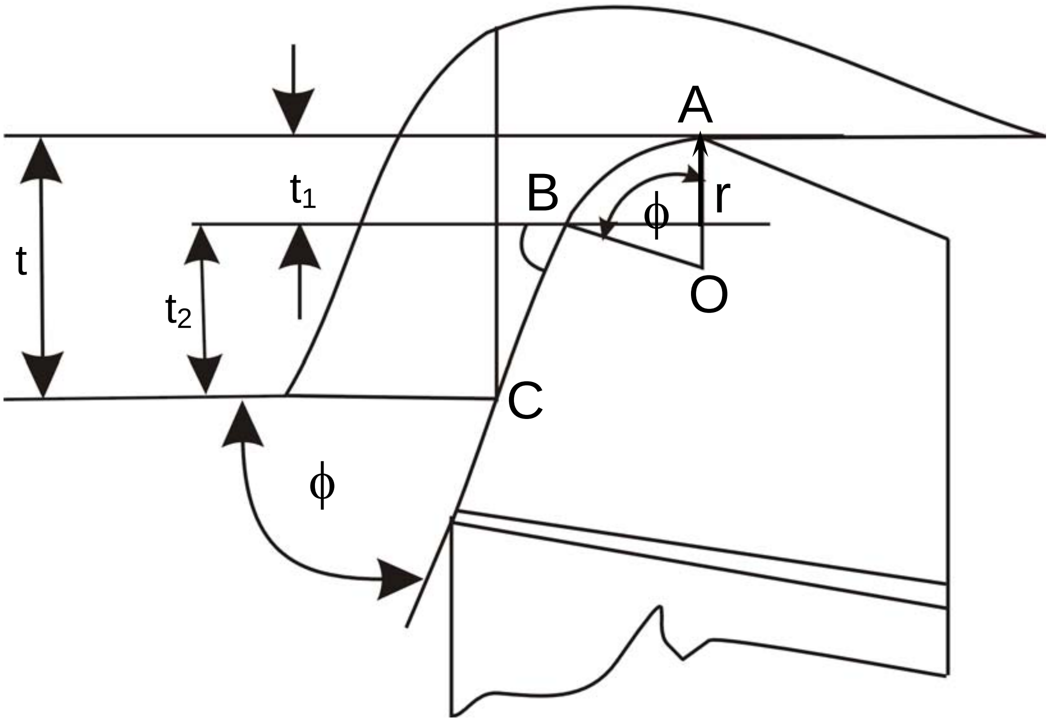


Fig. 6.5 *Variation of principal cutting edge angle in nose radiused tools.*

It is to be noted in equation (6.7) that the difference between ϕ and ϕ_{avg} is governed mainly by the depth of cut to nose radius ratio, i.e., $\frac{t}{r}$.

Therefore to incorporate the effect of nose radiusing along with restricted contact cutting effect, the ϕ in equation (6.5) has to be replaced by ϕ_{avg} to be determined by equation (6.7) resulting,

$$\tan\psi = \frac{\sin(\phi_{avg} + \phi_1)}{\frac{2t}{s_o \sin\phi_{avg}} + \cos(\phi + \phi_{avg})} \quad (6.8)$$

- **Effect of inclination angle, λ**

In absence of RCE and nose radius the chip flow deviation will be governed only by the value of λ as indicated in Fig. 6.6.

Therefore the combined effects of RCE, tool nose radiused and presence of λ will cause chip flow deviation angle, ρ_c as

$$\rho_c = \psi + \lambda \quad (6.9)$$

Generally, compared to λ, ψ is very small.

So approximately [s(S)tabler], $\rho_c = \lambda$ where λ may be positive or negative.

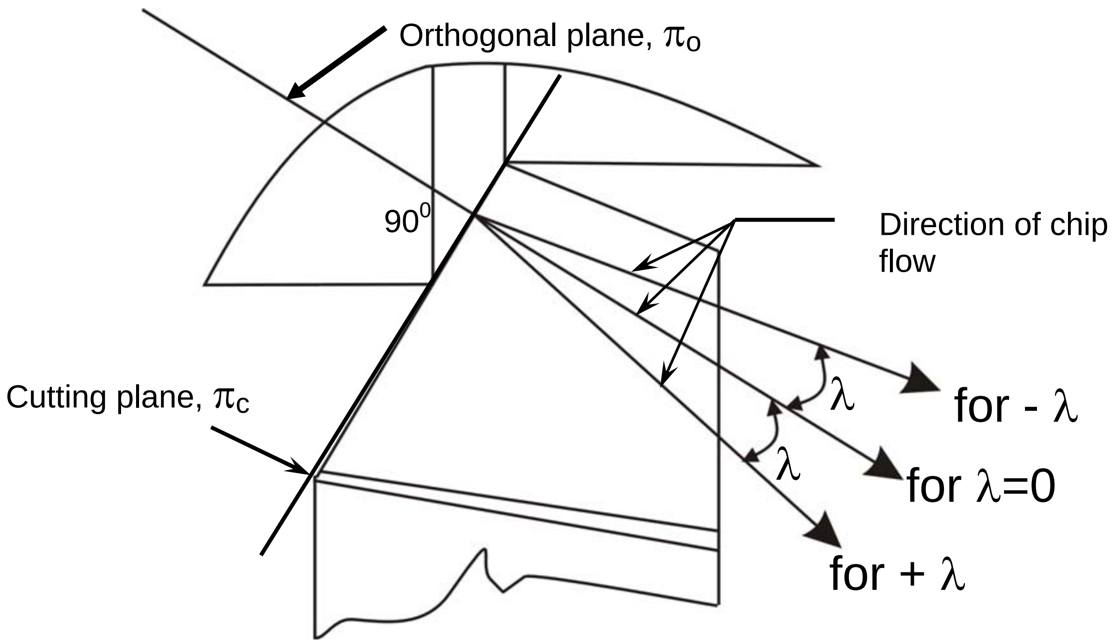


***Fig. 6.6** Role of inclination angle on chip flow direction*

(iii) Effective Rake, γ_e

It has already been realized that the value of rake angle plays vital roles on both mechanism and mechanics of machining. There are different rake angles but that rake angle is obviously the most significant which is taken in the direction of actual chip flow. This rake is called Effective Rake (γ_e)

Definition of γ_e: The angle of inclination of the rake surface from π_R and is measured on that plane which is perpendicular to the reference plane and is taken in the direction of actual chip flow as shown in Fig. 6.7.

In Fig. 6.7, OC is the deviation of apparent chip flow but OD represents the actual direction of chip flow which is deviated from OC by the chip flow angle, ρ_c. Z_o, AB and DE are perpendicular to π_R. Y_o' is parallel to Y_o and Y_n' is taken parallel to the axis Y_n.

In this figure, DOE represents effective rake angle, γ_e.

From Fig. 6.7,

$$\sin\gamma_e = \frac{DE}{OD} = \frac{DF + EF}{\dfrac{OC}{\cos\rho_c}} \tag{6.10}$$

where, $DF = AB = \dfrac{AC}{\cos\lambda}$

$EF = AF\sin\lambda$

$$AF = BD = CD - BD$$
$$AC = OC \sin \gamma_n$$
$$CD = OC \tan \rho_c$$

Combining all those equations, it appears that,

$\sin\gamma_e = \cos\lambda\cos\rho_c\lambda\sin\gamma_n + \sin\lambda.\sin\rho_c$ (6.11)

Assuming [stabler] $\lambda = \rho_c$

$\sin\gamma_e = \cos^2\lambda\sin\gamma_n + \sin^2\lambda$ (6.12)

where,

$\tan\gamma_n = \tan\gamma_o.\cos\lambda$

it is again to be noted that

if $\lambda = 0$; $\gamma_e \cong \gamma_n = \gamma_o$ (6.13)

In case of oblique cutting, which is practically more common, the actual direction of chip flow and the corresponding rake angle, i.e., effective rake should be used for more reasonably accurate analysis and assessment of cutting forces, friction and tool wear.

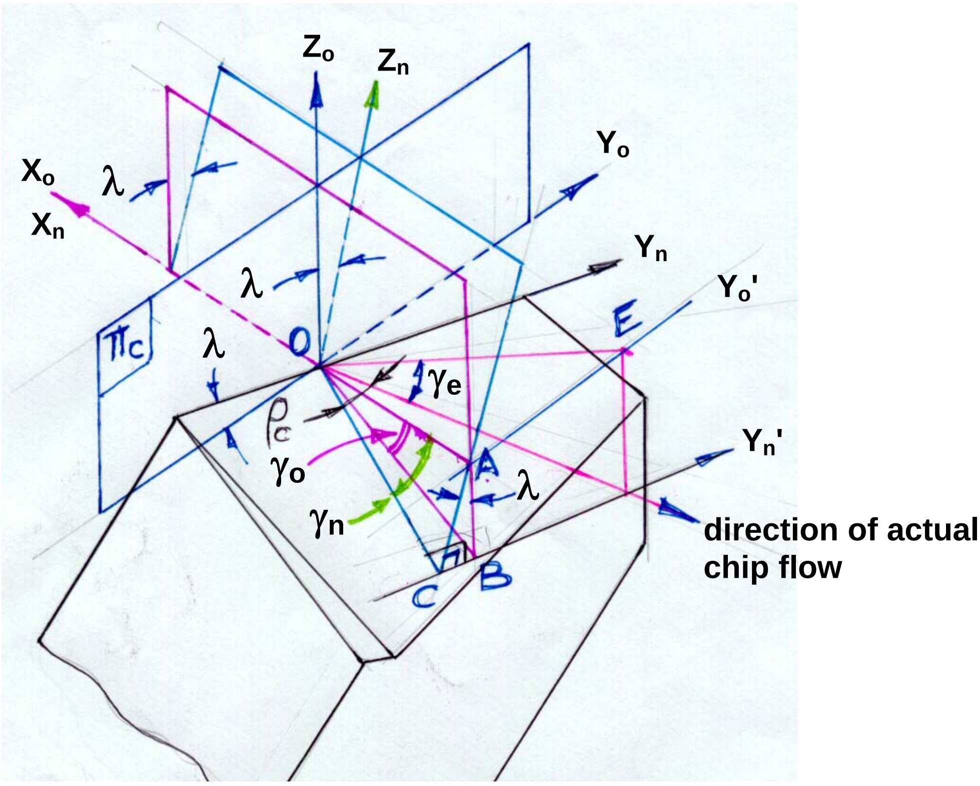


Fig. 6.7 Effective rake angle, γ_e

(iv) Effects of oblique cutting

In contrary to simpler orthogonal cutting, oblique cutting causes the following effects on chip formation and mechanics of machining:

- Chip does not flow along the orthogonal plane;
  Positive λ causes

- Chip flow deviation away from the finished surface, which may result
  - lesser further damage to the finished surface
  - but more inconvenience to the operator
- reduction of mechanical strength of the tool tip
- increase in temperature at the tool tip
- more vibration in turning slender rods due to increase in P_Y (transverse force)

On the other hand, negative λ may enhance tool life by increasing mechanical strength and reducing temperature at the tool tip but may impair the finished surface.

- The chip cross-section may change from rectangle (ideal) to skewed trapezium
- The ductile metals(materials) will produce more compact helical chips if not broken by chip breaker
- Analysis of cutting forces, chip-tool friction etc. becomes more complex.

NOTE: For specifying angles stick to ISO standards,

for ex:

shear angle is ϕ

Inclination angle is ***i***

Exercise - 6

A. Quiz test

Select the correct answer from the given four options

1.Cutting will be called orthogonal when

(a) $\lambda = 0$
(b) $\lambda = 0$ and $\phi = 90^o$
(c) chip flows along π_O plane
(d) $\lambda = 0$ and r (nose radius) = 0

2.In turning, chip will flow along π_O only when

(a) RCE is absent
(b) nose radius is zero
(c) $\lambda = 0$
(d) all of the above conditions

3.Deviation of chip flow from p_O (?)does not depend upon

(a) cutting velocity
(b) feed
(c) depth of cut
(d) nose radius

4.Effective rake in any turning process is measured on
(a) π_X
(b) π_O
(c) π_n
(d) none of the above

B. Problem

1. Under what geometrical condition the values of γ_e, γ_n, γ_o and γ_x (suffix properly) of a turning tool will be same ?

2. Estimate the value of γ_e for turning a rod at s_o= 0.24 mm/rev and t = 4.0 mm by a tool of geometry 10^o, 8^o, 7^o, 6^o, 15^o, 75^o, 1.2 (mm) – NRS

A. Quiz Test - answers
1 – (c)
2 – (d)
3 – (a)
4 – (d)

Q. 1 When γ_e, γ_n, γ_o and γ_x become same ?

Ans

- $\gamma_o = \gamma_x$ when $\phi = 90^o$ i.e., $\pi_o = \pi_x$
- $\gamma_n = \gamma_o$ when $\lambda = 0^o$ i.e., $\pi_n = \pi_o$
- $\gamma_e = \gamma_n$ when $\lambda = 0^o$ & $\rho_C = \psi \pm \lambda = 0$ i.e., $\psi = 0$
- $\psi = 0$ when nose radius, r = 0,
  i.e. $\phi_{avg} = \phi$ and RCE is absent i.e., $\phi_1 > 20^o$

Q. 2 Given : t = 4.0, s_o = 0.24 mm/rev and $\lambda = 10^o$, $\gamma_n = 8^o$, $\phi = 75^o$, $\phi_1 = 15^o$, r = 1.2 mm. Determine γ_e

Ans.

- $\sin\gamma_e = \cos\lambda\cos\rho_c\sin\gamma_n + \sin\lambda\sin\rho_c$ (1)
- $\rho_c = \psi + \lambda$ [Stabler's rule] (2)

$$\tan\psi = \frac{\sin(\phi_{avg} + \phi_1)}{\dfrac{2t}{s_o \sin\phi_{avg}} + \cos(\phi_{avg} + \phi_1)}$$

- ϕ_{avg}= [ϕ/2+(t/r-cosϕ+1)/sinϕ] / [1+(t/r–cosϕ+1)/ϕsinϕ = 62.71^o
- Put the values, get ψ = 1.65^o
- Hence ρ_c = 1.65^o + 10^o= 11.65^o
- Put values of λ, ρ_c and γ_n in equation 1;

get γ_e = 5.69^o Ans

Module
2
Mechanics of Machining

Lesson
7
Use of chip breaker in machining

Instructional Objectives

At the end of this lesson the students would be able to

(i) identify the need and purposes of chip breaking
(ii) illustrate the various principles of chip breaking
(iii) design simple chip breakers
(iv) demonstrate configuration and working principle of some common type chip breakers
(v) state the overall effects of chip breaking.

(i) 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

- safety of the working people
- prevention of damage of the product
- 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..

(ii) 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 :

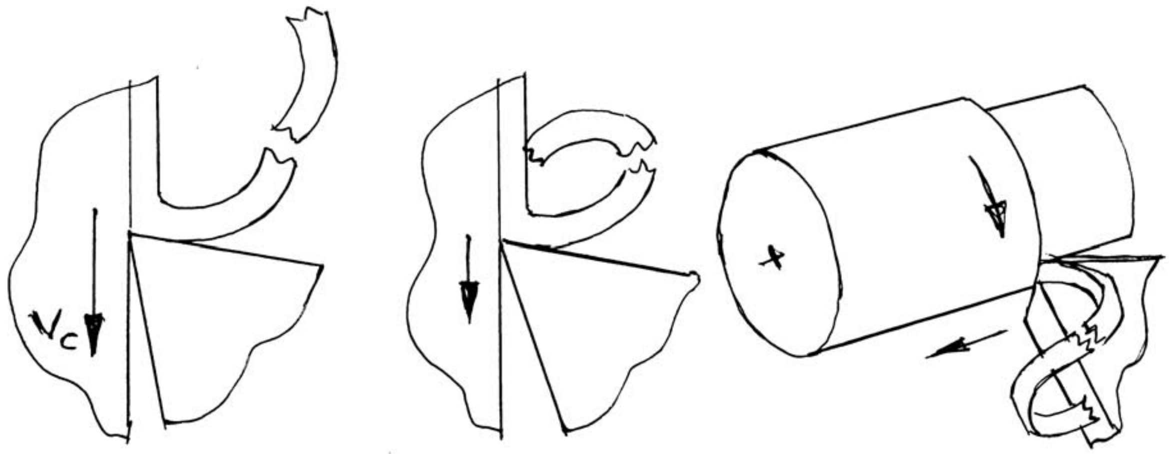
- Self breaking
  This is accomplished without using a separate chip-breaker either as an attachment or an additional geometrical modification of the tool.
- Forced chip breaking by additional tool geometrical features or devices.

(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.7.1 (a). This kind of chip breaking is generally observed under the condition close to that which favours formation of jointed or segmented chips
- By striking against the cutting surface of the job, as shown in Fig. 7.1 (b), mostly under pure orthogonal cutting
- By striking against the tool flank after each half to full turn as indicated in Fig. 7.1 (c).



(a) natural (b) striking on job (c) striking at tool flank

Fig. 7.1 *Principles of self breaking of chips.*

The possibility and pattern of self chip-breaking depend upon the work material, tool material and tool geometry (γ, λ, ϕ and r), levels of the process parameters (V_C and s_o) and the machining environment (cutting fluid application) which are generally selected keeping in view the overall machinability.

(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.

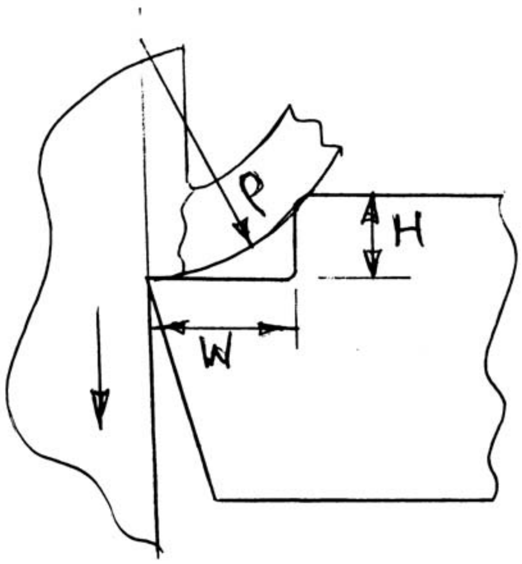
Chip breakers are basically of two types :

- 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

- Δ after their manufacture – in case of HSS tools like drills, milling cutters, broaches etc and brazed type carbide inserts
- Δ 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. 7.2 when the strain hardened and brittle running chip strikes the heel, the cantilever chip gets forcibly bent and then breaks.



W = width, H = height, β = shear angle

Fig. 7.2 *Principle of forced chip breaking.*

Fig. 7.3 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.

Groove type in-built chip breaker may be of

- Circular groove or
- Tilted Vee groove

as schematically shown in Fig. 7.4

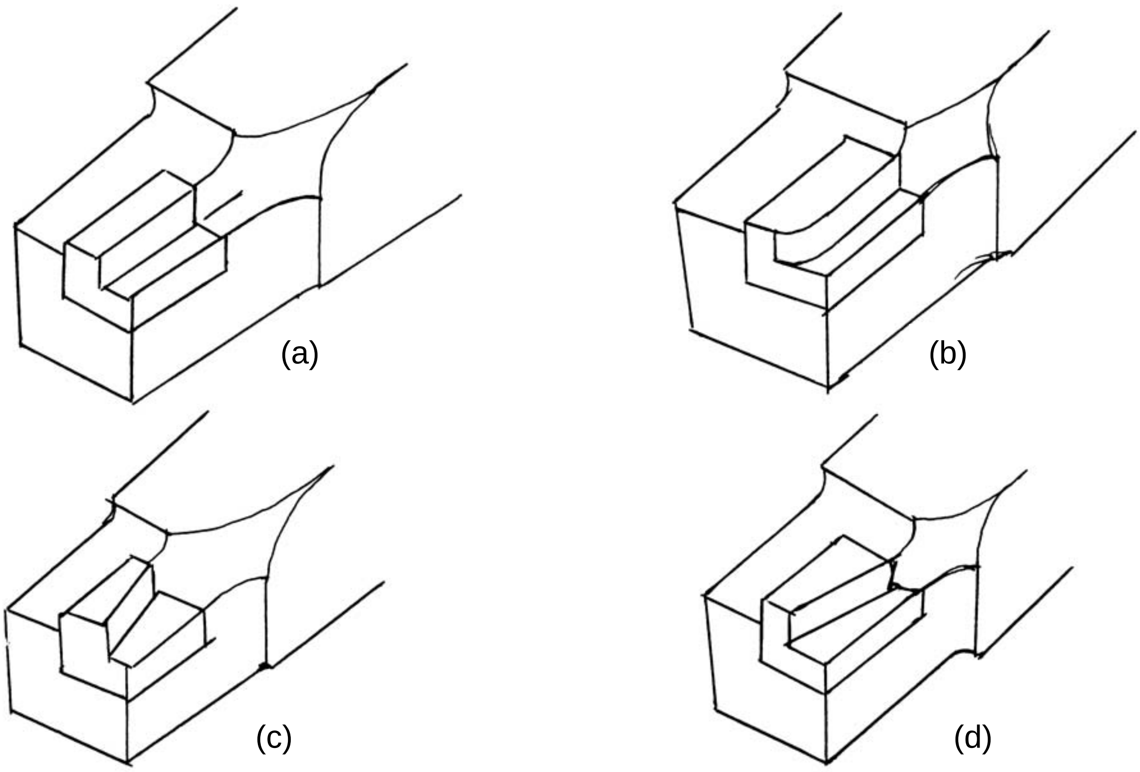
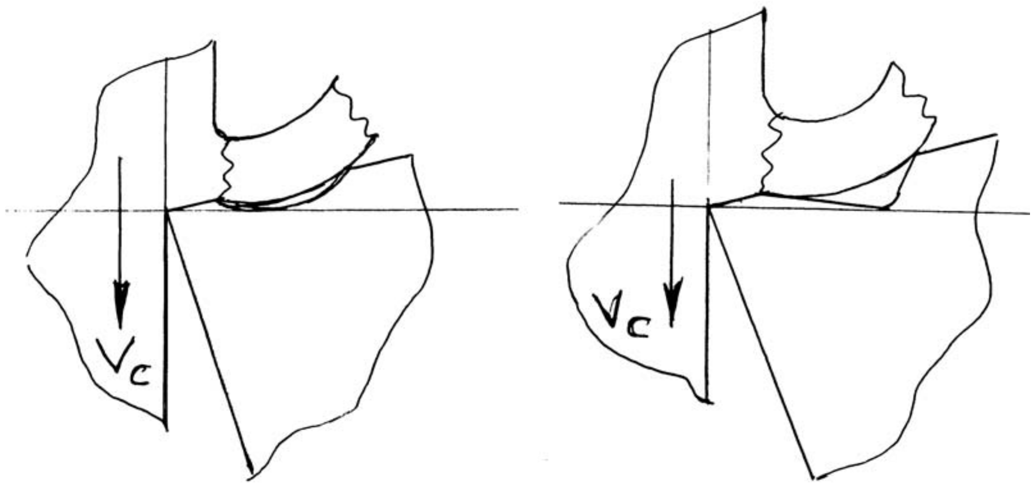


Fig. 7.3 *Step type in-built chip breaker (a) parallel step (b) parallel and radiused (c) positive angular (d) negative angular*



(a) circular groove (b) tilted Vee-groove

Fig. 7.4 *Groove type in-built chip breaker*

The unique characteristics of in-built chip breakers are :

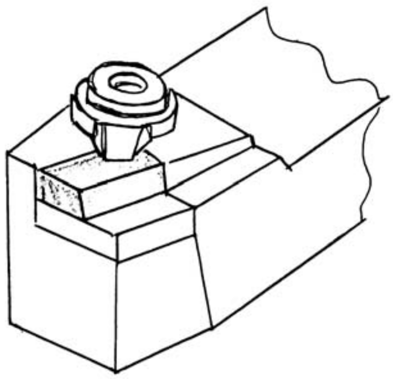
- The outer end of the step or groove acts as the heel that forcibly bend and fracture the running chip
- Simple in configuration, easy manufacture and inexpensive
- The geometry of the chip-breaking features are fixed once made (i.e., cannot be controlled)
- Effective only for fixed range of speed and feed for any given tool-work combination.

(c) clamped type chip-breaker

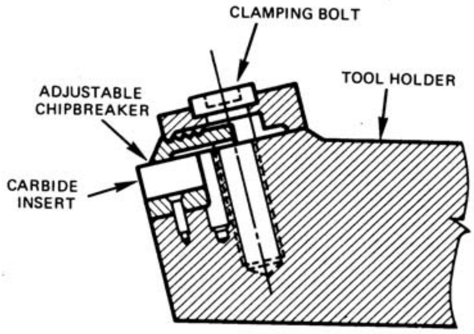
Clamped type chip breakers work basically in the principle of stepped type chip-breaker but have the provision of varying the width of the step and / or the angle of the heel.

Fig. 7.5 schematically shows three such chip breakers of common use :

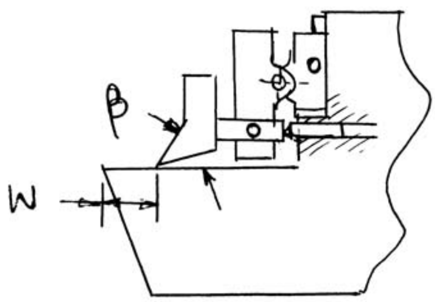
- With fixed distance and angle of the additional strip – effective only for a limited domain of parametric combination
- With variable width (W) only – little versatile
- With variable width (W), height (H) and angle (β) – quite versatile but less rugged and more expensive.



(a) fixed geometry



(b) variable width



(c) variable width and angle

Fig. 7.5 *Clamped type chip breakers.*

(iii) Design principle of simple step type chip breaker.

- **Parallel step type in-built chip breaker**

In machining like turning of ductile material the chip first leaves the hot plastic zone and then comes out as an elastic cantilever beam. The chip breaker (heel) forcibly bends the chip to shorter radius of curvature and raises the strain, resulting chip breaking as shown in Fig. 7.2.

Lot of study had been done on chip breaking and the results, briefly shown in Fig. 7.6 indicates that for a given value of uncut chip thickness, a_1, the chip effectively breaks when the radius of curvature (ρ) is brought to or slightly below some critical value.

From Fig. 7.2,

$$W^2 = (2\rho - H).H \qquad (7.1)$$

where,

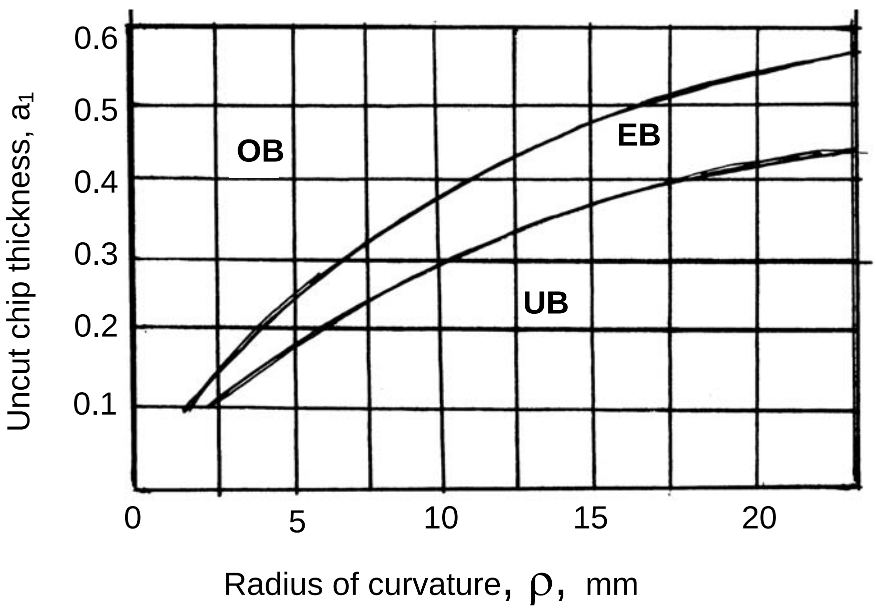
W = width of the step
H = height of the step
ρ = radius of curvature of the chip

Example : Design step type integrated chip breaker for plain turning of a mild steel rod at feed s_o = 0.24 mm/rev. with a tool whose PCEA (ϕ) = 60^o

Solution :

Here, $a_1 = s_o \sin\phi = 0.24 x \sin 60^o = 0.2$ mm
From the graph (a_1 vs ρ),
For a_1= 0.2 mm, the value of ρ is taken 5 for effective chip breaking
Assuming H = 2

$$W = \sqrt{(2x5-2).2} = 4.0 \text{ mm} \quad \text{Ans.}$$



OB – over breaking, EB – effective breaking, UB – under breaking

***Fig. 7.6** Critical radius of curvature for chip breaking.*

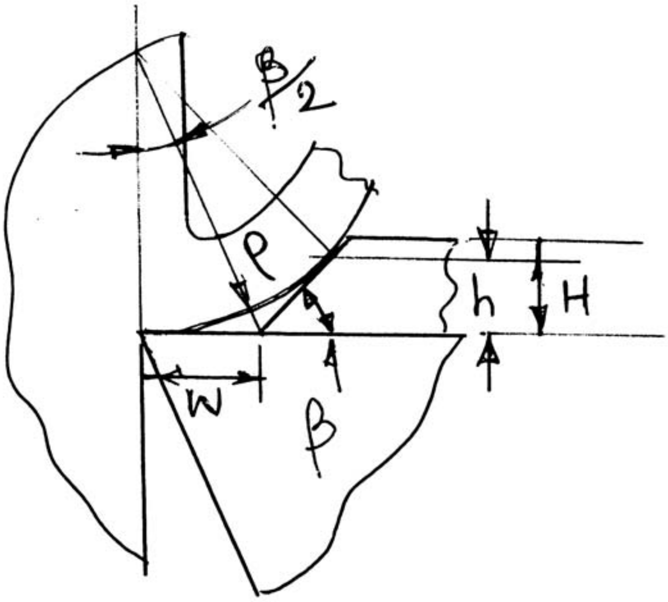


Fig. 7.7 *Design of clamped type chip breaker.*

- **Clamped type chip breaker**

From the geometry of Fig. 7.7,

$$W = \rho \tan\frac{\beta}{2} \qquad (7.2)$$

and

$$h = W \sin\beta \qquad (7.3)$$

where, β = angle of the chip-breaking strip

H is taken 1 ~ 2 mm greater than h.

For the same condition of previous problem, i.e., a_1 = 0.2 mm and ρ_c = 5 mm and assuming $\beta = 60^o$ (varies from 45^o to 90^o)

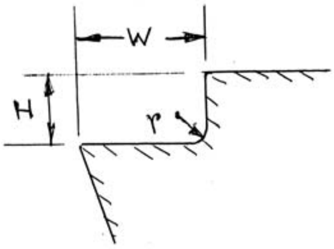
$W = 5x\tan30^o \cong 3$ mm, $h = 3x\sin60^o = 2.5$ mm

$\therefore$ H = 2.5 + 1.0 = 3.5 mm Ans.

Previous researchers prepared a chart recommending the dimensions of step type chip breaker for different conditions under the following assumptions :

- ideally plastic chip, i.e., no work hardening
- chip flows straight if chip breaker does not exist
- plane sections remain plane
- heel of breaker exerts bending force on chip.

Chip breaker



step – type

Table 1 In-built chip breaker design

Depth of cut	Feed	0.15 ~ 0.3 mm	0.3 ~ 0.4 mm	0.4 ~ 0.6 mm	0.6 ~ 1.0 mm	> 1.0 mm
	r	0.25 ~ 0.6	1.0 ~ 2.0	1.0 ~ 2.0	1.0 ~ 2.0	1.0 ~ 2.0
	H	0.25	0.4	0.5	0.75	0.75
0.4 ~ 1.2 mm	W	1.6	2.0	2.8	3.2	-
1.6 ~ 6.4 mm	W	2.4	3.2	4.0	5.0	5.0
2.0 ~ 12.8 mm	W	3.2	4.0	5.0	5.0	5.0
3.6 ~ 20 mm	W	4.0	5.0	5.0	5.0	5.0
> 20 mm	W	5.0	5.0	5.0	5.0	6.4

(iv) Configuration and working principle of some chip breakers in practice

In-built type chip breakers once made are of fixed geometry and hence are effectively applicable for particular situations or materials but are very simple in construction and easy to handle. While designing the overall geometry of the tool inserts, several factors, in addition to chip-breaking, need to be considered, such as ;

- imparting mechanical strength to the cutting edge by its rounding and / or bevelling
- reduction of cutting forces having favourable (positive) rake
- controlled contact (chip-tool) cutting effect for lesser friction and wear
- better heat dissipation

Incorporation of all such aspects through integrated tool geometry require proper design and manufacture which fortunately have become now-a-days, quite easy and fast due to advent of CAD and processes like EDM, ECM etc. for manufacturing complex shaped die and punch. In-built type chip breakers with integrated tool geometry have been much popular and are getting widely used.
Fig. 7.8 shows the typical form of the modern cutting tool inserts with in-built chip-breaker. The curved portion BC is the edge radiusing, CD is the land with negative rake, DEF is the groove with positive rake and the point F acts as the heel to break the chip by fracturing. The actual length and angle of those features and their apportionment are decided and some special features are further incorporated to that geometry (Fig. 7.8) depending upon the operations like bulk machining or finishing and the characteristics of the work materials.

The configurations of some industrially used uncoated and coated carbide tool inserts with compound rake including chip-breaking feature are typically shown in Fig. 7.9. [Cutting Tools for Productive Machining – T.A.Sadanivan and D. Sarathy, WIDIA (I) Ltd.]

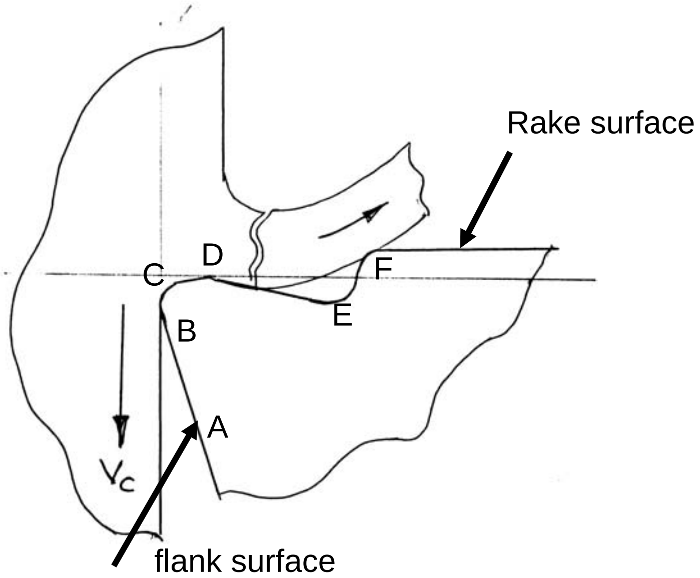


Fig. 7.8 *Schematic view of the typical form of inserts (cutting edge) with integrated chip-breaker.*

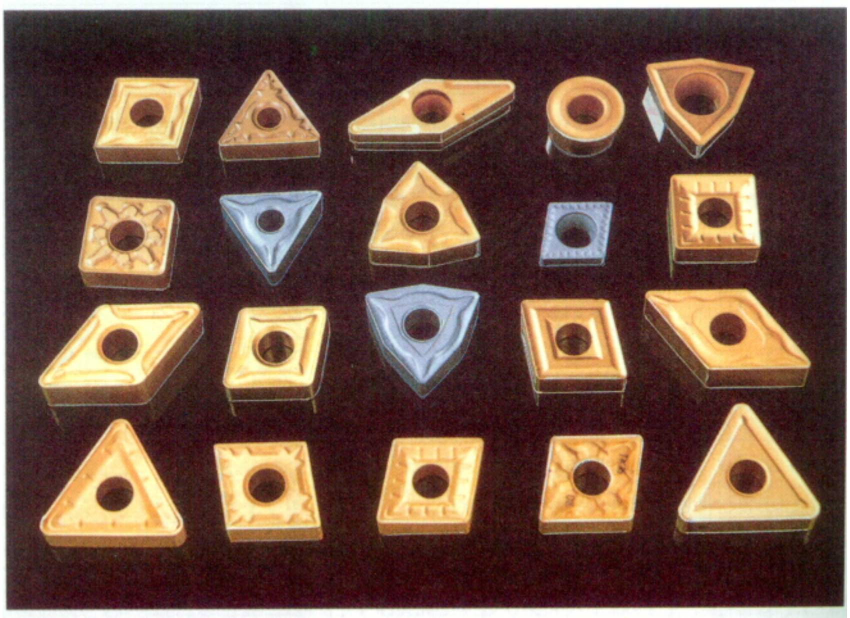


Fig. 7.9 *Various groove type inserts*

Throw away type indexable tool inserts are also widely used for drilling, milling, broaching etc. where the inserts of suitable geometry are mechanically clamped in the steel shank of the tools. The geometry of some of those uncoated and coated carbide inserts also essentially incorporates the chip-breaking feature.

Chip breakers in solid HSS tools

Despite advent of several modern cutting tool materials, HSS is still used for its excellent TRS (transverse rupture strength) and toughness, formability, grindability and low cost.
The cutting tools made of solid HSS blanks, such as form tools, twist drills, slab milling cutters, broaches etc, are also often used with suitable chip breakers for breaking the long or wide continuous chips.
The handling of wide and long chips often become difficult particularly while drilling large diameter and deep holes. Grooves, either on the rake faces or on the flanks as shown in Fig. 7.10 help break the chips both along the length and breadth in drilling ductile metals. The locations of the grooves are offset in the two cutting edges.

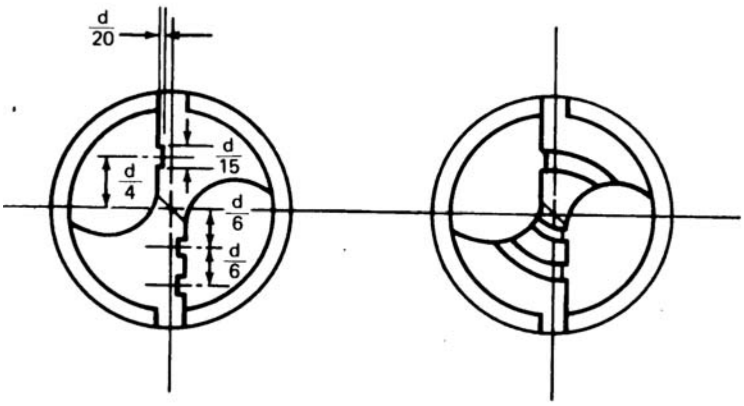
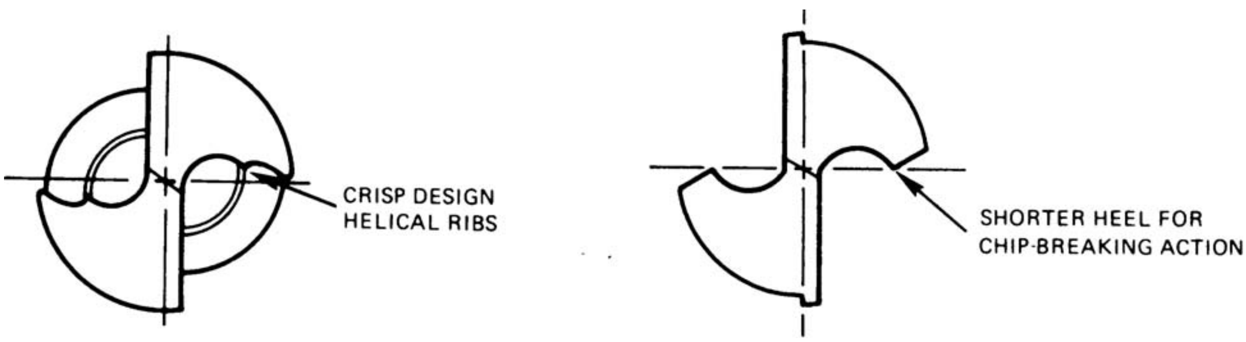


Fig. 7.10 *Chip breaking grooves.*

Fig. 7.11 schematically shows another principle of chip-breaking when the drilling chips are forced to tighter curling followed by breaking of the strain hardened chips into pieces.



(a) Crisp design of chip-breaking drill (b) US industrial design of chip-breaking drill

Fig. 7.11 *Designs of chip-breaking drill*

Plain milling and end milling inherently produces discontinuous ‘coma’ shaped chips of favourably shorter length. But the chips become very wide while milling wide surfaces and may offer problem of chip disposal. To reduce this problem, the milling cutters are provided with small peripheral grooves on the cutting edges as shown in Fig. 7.12. Such in-built type chip breakers break the wide chips into a number of chips of much shorter width. Similar groove type chip-breakers are also often provided along the teeth of broaches, for breaking the chips to shorter width and ease of disposal.

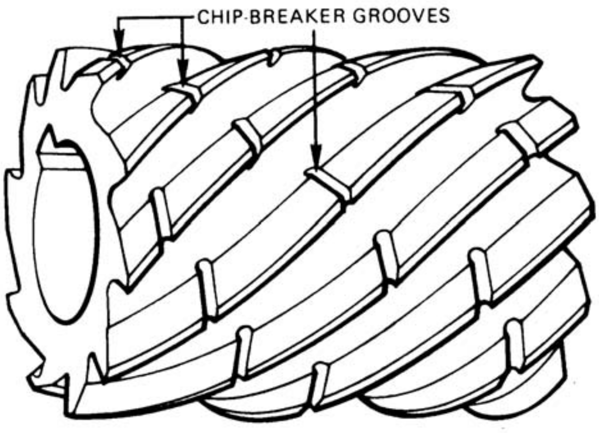


Fig. 7.12 *Chip breaking grooves on a plain helical milling cutter.*

Dynamic chip breaker

Dynamic turning is a special technique, where the cutting tool is deliberately vibrated along the direction of feed as indicated in Fig. 7.13 at suitable frequency and amplitude. Such additional controlled tool oscillation caused by mechanical, hydraulic or electro-magnetic (solenoid) shaker improves surface finish. This also reduces the cutting forces and enhances the tool life due to more effective cooling and lubrication at the chip tool and work tool interfaces for intermittent break of the tool-work contact. Such technique, if further slightly adjusted, can also help breaking the chips. When the two surfaces of the chip will be waved by phase difference of about 90^o, the chip will either break immediately or will come out in the form of bids, which will also break with slight bending or pressure as indicated in Fig. 7.13. This technique of chip breaking can also be accomplished in dynamic drilling and dynamic boring.
Fig. 7.14 schematically shows another possible dynamic chip-breaking device suitable for radially fed type lathe operations, e.g., facing, grooving and parting.

(v) Overall effects of chip breaking

- Favourable effects
    - safety of the operator(s) from the hot, sharp continuous chip flowing out at high speed
    - convenience of collection and disposal of chips

- chances of damage of the finished surface by entangling or rubbing with the chip is eliminated
- more effective cutting fluid action due to shorter and varying chip tool contact length.

- Unfavourable effects
  - chances of harmful vibration due to frequent chip breaking and hitting at the heel or flank of the tool bit
  - more heat and stress concentration near the sharp cutting edge and hence chances of its rapid failure.
  - Surface finish may deteriorate

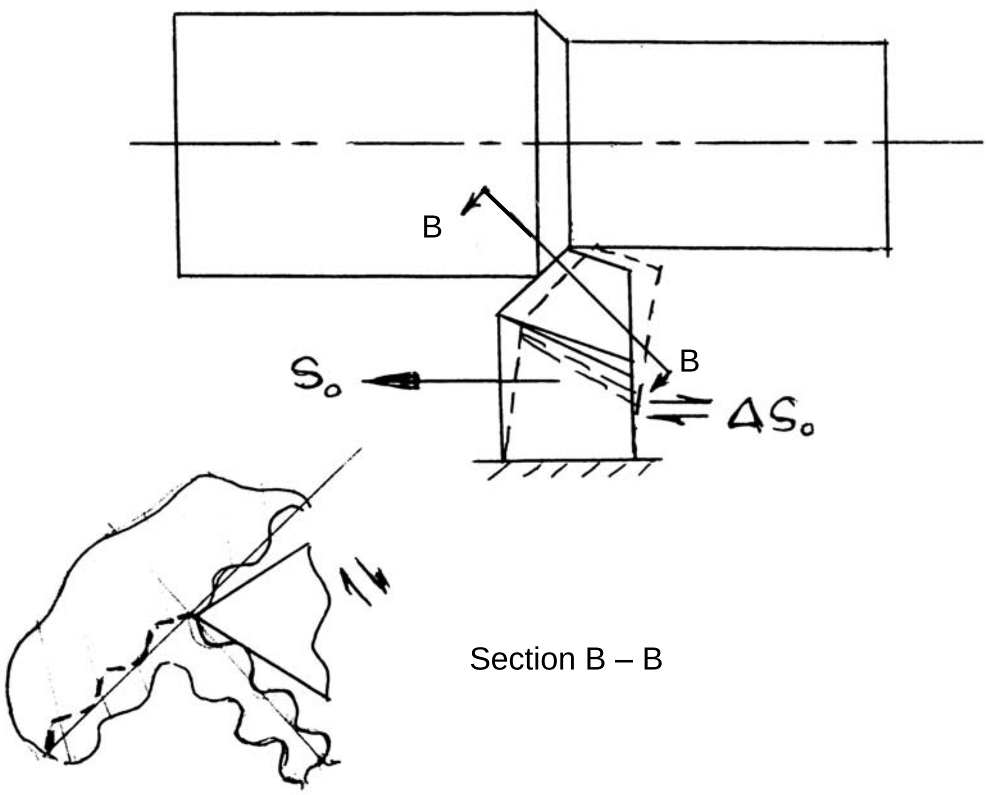


Fig. 7.13 *Self chip breaking in dynamic turning.*

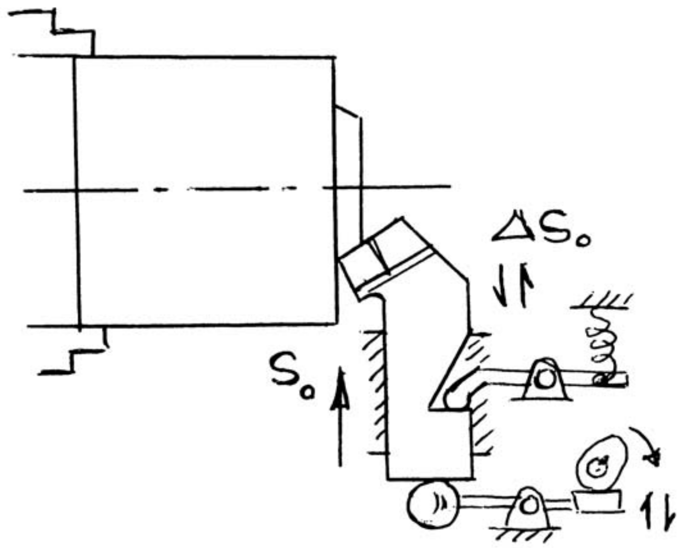


Fig. 7.14 *Dynamic chip breaking in radial operations in lathe.*

Exercise – 7

Q. 1 What factors are considered while designing the rake surface / cutting edge of carbide turning inserts ?

Q. 2 In which direction is the cutting tool vibrated and why in dynamic turning ?

Q. 3 Why are step type integrated chip breakers made angular ?

Q. 4 When is forced chip breaking necessary and why ?

Answers of the questions given in Exercise – 7

Ans. to Q. 1

- enhance thermal and mechanical strength at the sharp edge
- reduction of the cutting forces
- more effective cutting fluid action
- chip-breaking

Ans. to Q. 2

The tool is vibrated in feed direction only

- vibration in transverse direction will enhance surface roughness
- vibration in tangential direction is less effective and more difficult also.

Ans. to Q. 3

To produce close curling of chips which is safe and easy to collect and dispose.

Positive angle – shifts the coil away from the job

Negative angle – shifts the chip away from the operator

Ans. to Q. 4

When chips continuously form and come out very hot, sharp and at quite high speed – under the condition :

- soft ductile work material
- flat rake surface with positive or near zero rake

for

- safety and convenience of the operator
- easy collection and disposal of chips.

Module
2
Mechanics of Machining

Lesson
8
Machining forces and Merchant's Circle Diagram (MCD)

Instructional Objectives

At the end of this lesson, the student would be able to

(i) Ascertain the benefits and state the purposes of determining cutting forces
(ii) Identify the cutting force components and conceive their significance and role
(iii) Develop Merchant's Circle Diagram and show the forces and their relations
(iv) Illustrate advantageous use of Merchant's Circle Diagram

(i) Benefit of knowing and purpose of determining cutting forces.

The aspects of the cutting forces concerned :

- Magnitude of the cutting forces and their components
- Directions and locations of action of those forces
- Pattern of the forces : static and / or dynamic.

Knowing or determination of the cutting forces facilitate or are required for :

- Estimation of cutting power consumption, which also enables selection of the power source(s) during design of the machine tools
- Structural design of the machine – fixture – tool system
- Evaluation of role of the various machining parameters (process – V_C, s_o, t, tool – material and geometry, environment – cutting fluid) on cutting forces
- Study of behaviour and machinability characterisation of the work materials
- Condition monitoring of the cutting tools and machine tools.

(ii) Cutting force components and their significances

The single point cutting tools being used for turning, shaping, planing, slotting, boring etc. are characterised by having only one cutting force during machining. But that force is resolved into two or three components for ease of analysis and exploitation. Fig. 8.1 visualises how the single cutting force in turning is resolved into three components along the three orthogonal directions; X, Y and Z.

The resolution of the force components in turning can be more conveniently understood from their display in 2-D as shown in Fig. 8.2.

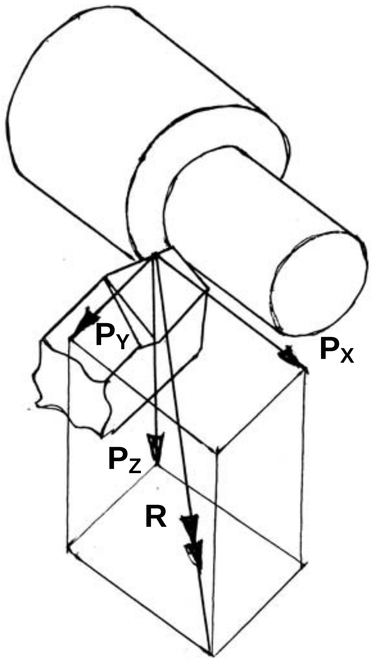


Fig. 8.1 *Cutting force R resolved into P_X, P_Y and P_Z*

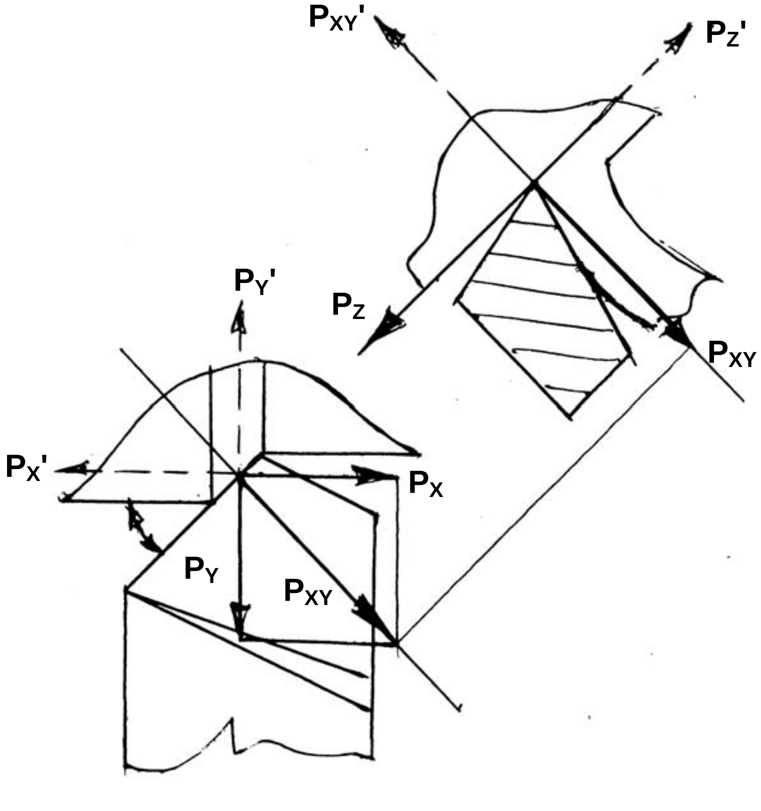


Fig. 8.2 *Turning force resolved into P_Z, P_X and P_Y*

The resultant cutting force, R is resolved as,

$$\overline{R} = \overline{P_Z} + \overline{P}_{XY} \quad (8.1)$$

and $$\overline{P}_{XY} = \overline{P}_X + \overline{P}_Y \quad (8.2)$$

where, $P_X = P_{XY}\sin\phi$ and $P_Y = P_{XY}\cos\phi$ (8.3)

where, P_Z = tangential component taken in the direction of Z_m axis
P_X = axial component taken in the direction of longitudinal feed or X_m axis
P_Y = radial or transverse component taken along Y_m axis.

In Fig. 8.1 and Fig. 8.2 the force components are shown to be acting on the tool. A similar set of forces also act on the job at the cutting point but in opposite directions as indicated by P_Z', P_{XY}', P_X' and P_Y' in Fig. 8.2

Significance of P_Z, P_X and P_Y

P_Z : called the main or major component as it is the largest in magnitude. It is also called power component as it being acting along and being multiplied by V_C decides cutting power ($P_Z.V_C$) consumption.
P_y : may not be that large in magnitude but is responsible for causing dimensional inaccuracy and vibration.
P_X : It, even if larger than P_Y, is least harmful and hence least significant.

Cutting forces in drilling

In a drill there are two main cutting edges and a small chisel edge at the centre as shown in Fig. 8.3.
The force components that develop (Fig. 8.3) during drilling operation are :

- a pair of tangential forces, P_{T1} and P_{T2} (equivalent to P_Z in turning) at the main cutting edges
- axial forces P_{X1} and P_{X2} acting in the same direction
- a pair of identical radial force components, P_{Y1} and P_{Y2}
- one additional axial force, P_{Xe} at the chisel edge which also removes material at the centre and under more stringent condition.

P_{T1} and P_{T2} produce the torque, T and causes power consumption P_C as,

$$T = P_T \times ½ (D) \quad (8.3)$$

and $$P_C = 2\pi TN \quad (8.4)$$

where, D = diameter of the drill
and N = speed of the drill in rpm.
The total axial force P_{XT} which is normally very large in drilling, is provided by

$$P_{XT} = P_{X1} + P_{X2} + P_{Xe} \quad (8.5)$$

But there is no radial or transverse force as P_{Y1} and P_{Y2}, being in opposite direction, nullify each other if the tool geometry is perfectly symmetrical.

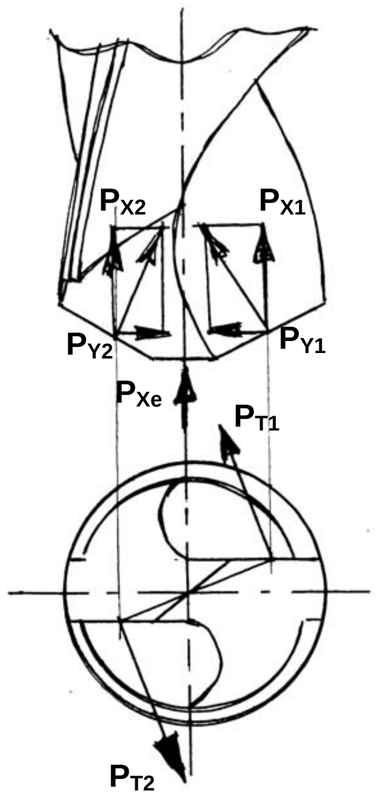


Fig. 8.3 *Cutting forces in drilling.*

Cutting forces in milling

The cutting forces (components) developed in milling with straight fluted slab milling cutter under single tooth engagement are shown in Fig. 8.4.
The forces provided by a single tooth at its angular position, ψ_I are :

- Tangential force P_{Ti} (equivalent to P_Z in turning)
- Radial or transverse force, P_{Ri} (equivalent to P_{XY} in turning)
- R is the resultant of P_T and P_R
- R is again resolved into P_Z and P_Y as indicated in Fig. 8.4 when Z and Y are the major axes of the milling machine.

Those forces have the following significance:

- o P_T governs the torque, T on the cutter or the milling arbour as

$$T = P_T \times D/2 \tag{8.5}$$

and also the power consumption, P_C as

$$P_C = 2\pi TN \tag{8.6}$$

where, N = rpm of the cutter.

The other forces, P_R, P_Z, P_Y etc are useful for design of the Machine – Fixture – Tool system.

In case of multitooth engagement;

Total torque will be $D/2.\sum P_{Ti}$ and total force in Z and Y direction will be $\sum P_Z$ and $\sum P_Y$ respectively.

One additional force i.e. axial force will also develop while milling by helical fluted cutter

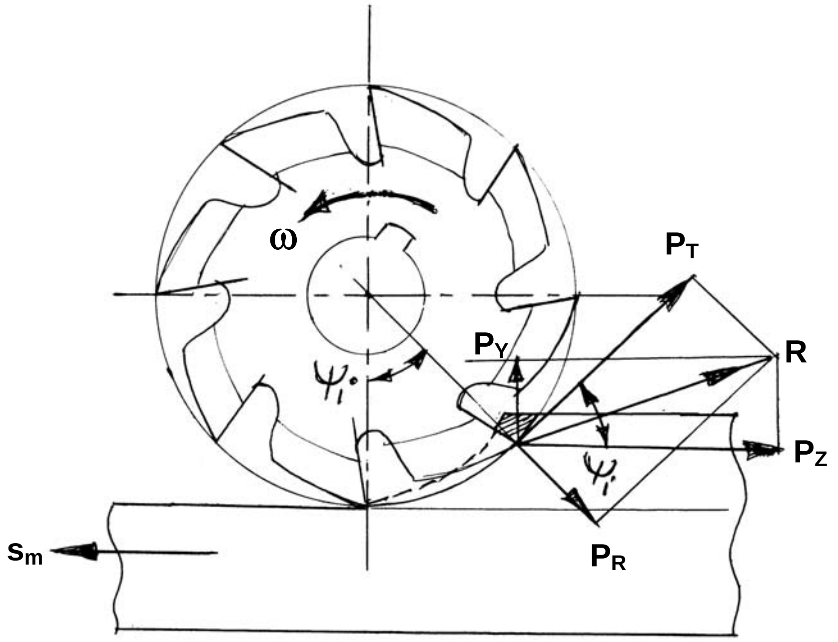


Fig. 8.4 *Cutting forces developed in plain milling (with single tooth engagement)*

(iii) Merchant's Circle Diagram and its use

In orthogonal cutting when the chip flows along the orthogonal plane, π_O, the cutting force (resultant) and its components P_Z and P_{XY} remain in the orthogonal plane. Fig. 8.5 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.

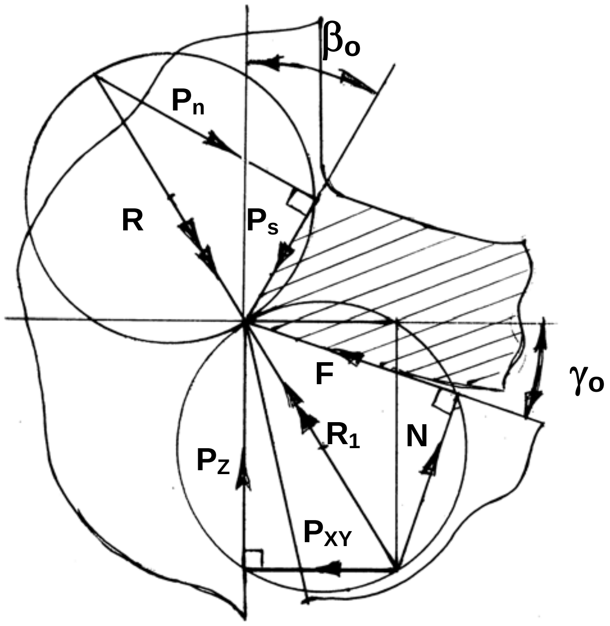


Fig. 8.5 *Development of Merchants Circle Diagram.*

The forces in the chip segment are :

- From job-side :
  - P_S – shear force and
  - P_n – force normal to the shear force

  where, $\overline{P_s} + \overline{P_n} = \overline{R}$ (resultant)
- From tool side :
  - $\overline{R_1} = \overline{R}$ (in state of equilibrium)
  - where $\overline{R_1} = \overline{F} + \overline{N}$
  - 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

$$\overline{R_1} = \overline{P_Z} + \overline{P_{XY}}$$

where, P_Z = force along the velocity vector

and 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. 8.6

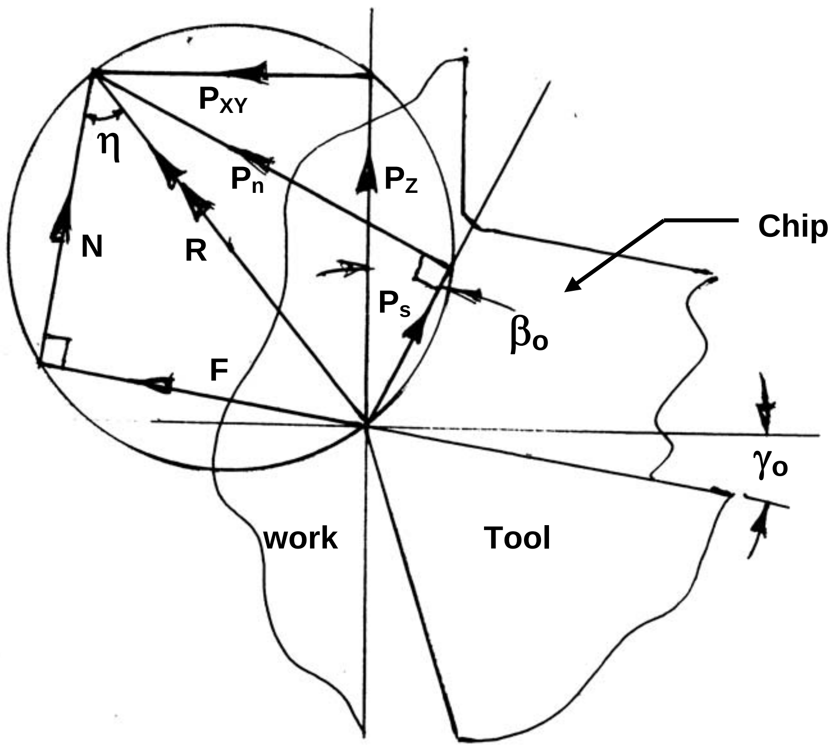


Fig. 8.6 *Merchant' s Circle Diagram with cutting forces.*

The significance of the forces displayed in the Merchant's Circle Diagram are :

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 – main force or power component acting in the direction of cutting velocity

P_{XY} – $\overline{P}_X + \overline{P}_Y$

The magnitude of P_S provides the yield shear strength of the work material under the cutting condition.

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.

(iv) Advantageous use of Merchant's Circle Diagram (MCD)

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 valid only 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.

The advantages of constructing and using MCD has been illustrated as by an example as follows ;

Suppose, in a simple straight turning under orthogonal cutting condition with given speed, feed, depth of cut and tool geometry, the only two force components P_Z and P_X are known by experiment i.e., direct measurement, then how can one determine the other relevant forces and machining characteristics easily and quickly without going into much equations and calculations but simply constructing a circle-diagram. This can be done by taking the following sequential steps :

- Determine P_{XY} from $P_X = P_{XY}\sin\phi$, where P_X and ϕ are known.
- Draw the tool and the chip in orthogonal plane with the given value of γ_o as shown in Fig. 8.4
- Choose a suitable scale (e.g. 100 N = 1 cm) for presenting P_Z and P_{XY} in cm
- Draw P_Z and P_{XY} along and normal to $\overline{V_C}$ as indicated in Fig. 8.6
- Draw the cutting force R as the resultant of P_Z and P_{XY}
- Draw the circle (Merchant's circle) taking R as diameter

- Get F and N as intercepts in the circle by extending the tool rake surface and joining tips of F and R
- Divide the intercepts of F and N by the scale and get the values of F and N
- For determining P_s (and P_n) the value of the shear angle β_o has to be evaluated from

  $$\tan\beta_o = \frac{\cos\gamma_o}{\zeta - \sin\gamma_o}$$

  where γ_o is known and ζ has to be obtained from

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

  s_o and ϕ are known and a_2 is either known, if not, it has to be measured by micrometer or slide calliper
- Draw the shear plane with the value of β_o and then P_s and P_n as intercepts shown in Fig. 8.6.
- Get the values of P_s and P_n by dividing their corresponding lengths by the scale
- Get the value of apparent coefficient of friction, μ_a at the chip tool interface simply from the ratio, $\mu_a = \frac{F}{N}$
- Get the friction angle, η, if desired, either from $\tan\eta = \mu_a$ or directly from the MCD drawn as indicated in Fig. 8.6.
- Determine dynamic yield shear strength (τ_s) of the work material under the cutting condition using the simple expression

  $$\tau_s = \frac{P_s}{A_s}$$

  where, A_s = shear area as indicated in Fig. 8.7

  $$= \frac{a_1 b_1}{\sin\beta_o} = \frac{ts_o}{\sin\beta_o}$$

  t = depth of cut (known)

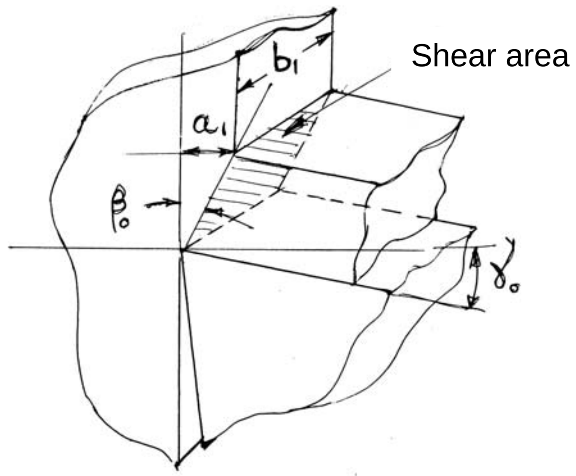


Fig. 8.7 *Shear area in orthogonal turning*

Evaluation of cutting power consumption and specific energy requirement

Cutting power consumption is a quite important issue and it should always be tried to be reduced but without sacrificing MRR.

Cutting power consumption, P_C can be determined from,

$$P_C = P_Z.V_C + P_X.V_f \qquad (8.4)$$

where, V_f = feed velocity

= $Ns_o/1000$ m/min [N=rpm]

Since both P_X and V_f, specially V_f are very small, $P_X.V_f$ can be neglected and then $P_C \cong P_Z.V_C$

Specific energy requirement, which means amount of energy required to remove unit volume of material, is an important machinability characteristics of the work material. Specific energy requirement, U_s, which should be tried to be reduced as far as possible, depends not only on the work material but also the process of the machining, such as turning, drilling, grinding etc. and the machining condition, i.e., V_C, s_o, tool material and geometry and cutting fluid application.

Compared to turning, drilling requires higher specific energy for the same work-tool materials and grinding requires very large amount of specific energy for adverse cutting edge geometry (large negative rake).

Specific energy, U_s is determined from

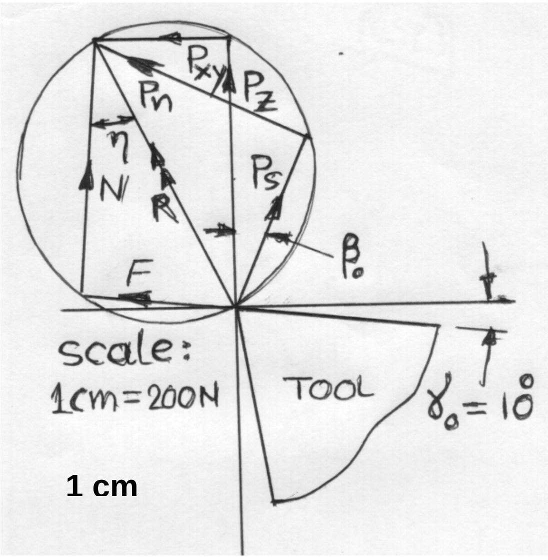
$$U_s = \frac{P_Z.V_C}{MRR} = \frac{P_Z}{ts_o}$$

Exercise - 8
Solution of some Problems

Problem 1

During turning a ductile alloy by a tool of $\gamma_o = 10^o$, it was found P_Z= 1000 N, P_X= 400 N, P_Y= 300 N and ζ = 2.5. Evaluate, using MCD, the values of F, N and μ as well as P_S and P_n for the above machining.

Solution :



—

- force, $P_{XY} = \sqrt{P_X^2 + P_Y^2} = \sqrt{(400)^2 + (300)^2}$ = 500 N
- Select a scale: 1 cm=200N
- Draw the tool tip with $\gamma_o = 10^o$
  In scale, P_Z=1000/200= 5 cm and P_{XY}=500/200=2.5cm

- Draw P_Z and P_{XY} in the diagram
- Draw R and then the MCD
- Extend the rake surface and have F and N as shown
- Determine shear angle, β_o

  $\tan \beta_o = \cos\gamma_o / (\zeta - \sin\gamma_o)$

  $= \cos 10^o/(2.5 - \sin 10^o) = 0.42$

  $\beta_o = \tan^{-1}(0.42) = 23^o$
- Draw P_S and P_n in the MCD
- From the MCD, find F = 3x200 = 600 N; N = 4.6x200 = 920 N;
  μ = F/N = 600/920 = 0.67
  P_S = 3.4x200 = 680; P_n= 4.3x200 = 860 N

Problem 2

During turning a steel rod of diameter 160 mm at speed 560 rpm, feed 0.32 mm/rev. and depth of cut 4.0 mm by a ceramic insert of geometry

0^o, —10^o, 6^o, 6^o, 15^o, 75^o, 0 (mm)

The followings were observed :

P_Z =1600 N, P_X=800 N and chip thickness=1mm. Determine with the help of MCD the possible values of F, N, m_a, P_S, P_n, cutting power and specific energy consumption.

Solution

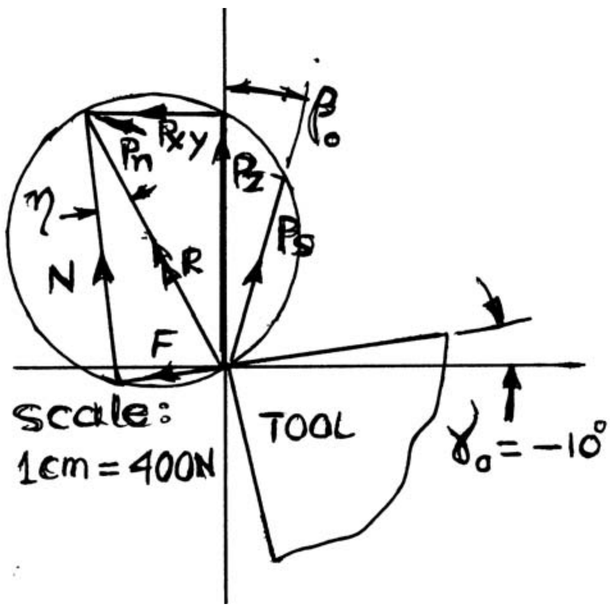
- $P_{XY} = P_X/\sin\phi$ = 800/sin75^o = 828 N
- Select a scale: 1cm = 400N
- Draw the tool tip with $\gamma_o = -10^o$
- Draw P_Z and P_{XY} in scale as shown
- Draw resultant and MCD

  shear angle, β_o

  $\tan \beta_o = \cos\gamma_o / (\zeta - \sin \gamma_o)$

  where, $\zeta = a_2/a_1 = a_2/(s_o \sin\phi) = 3.2$

  $\beta_o = \tan^{-1}(\cos(-10^o))/\{(3.2 - \sin(-10^o))\} = 16.27^o$

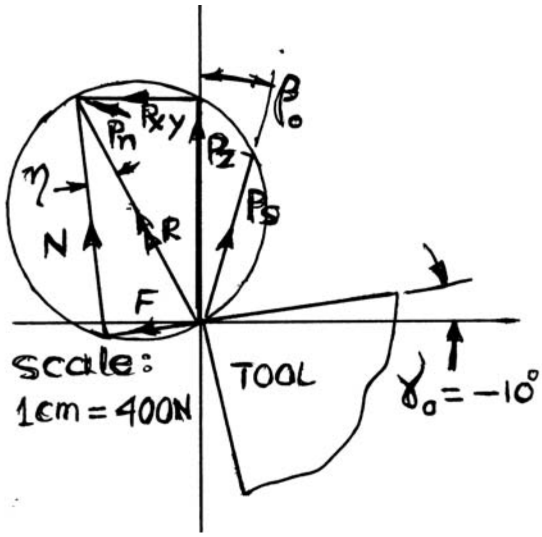


- Draw P_S and P_n as shown
- Using the scale and intercepts determine
  F = 1.75xscale = 700 N
  N = 4.40xscale = 1760 N
  μ_a = F/N = 700/1760 = 0.43
  P_S = 3.0 x scale = 1200 N
  P_n = 3.3 x scale = 1320 N
- Cutting Power, P_C $P_C = P_Z.V_C$ where
  $V_C = \pi DN/1000 = \pi \times 160 \times 560/1000 = 281.5$ m/min
  So, P_C = 8 KW.
- Specific energy = $P_Z/(ts_o)$ = 1600/(4 x 0.32)= 1250 N-mm/mm^3

Problem 3
For turning a given steel rod by a tool of given geometry if shear force P_S, frictional force F and shear angle γ_o could be estimated to be 400N and 300N respectively, then what would be the possible values of P_X P_Y and P_Z?
[use MCD]

Solution:
- tool geometry is known. Let rake angle be γ_o and principal cutting edge angle be ϕ.
- Draw the tool tip with the given value of $\boldsymbol{\gamma_o}$ as shown.
- Draw shear plane using the essential value of β_o
- using a scale (let 1cm=400N) draw shear force P_S and friction force F in the respective directions.
- Draw normals on P_S and F at their tips as shown and let the normals meet at a point.
- Join that meeting point with tool tip to get the resultant force

- Based on resultant force R draw the MCD and get intercepts for P_Z and P_{xy}
- Determine P_Z and P_{xy} from the MCD
- P_Z= __ x scale = ____
- P_{xy} = __ x scale = ___
- P_Y= P_{XY} cosϕ
- P_X= P_{XY} sinϕ



Problem - 4

During shaping like single point machining/turning) a steel plate at feed, 0.20 mm/stroke and depth 4 mm by a tool of $\lambda = \gamma = 0^o$ and $\phi = 90^o$ P_Z and P_X were found (measured by dynamometer) to be 800 N and 400 N respectively, chip thickness, a_2 is 0.4 mm. From the aforesaid conditions and using Merchant's Circle Diagram determine the yield shear strength of the work material in the machining condition?

Solution

- It is orthogonal (λ= 0^o) cutting \ MCD is valid
- draw tool with $\gamma_o = 0^o$ as shown
- P_{XY}= P_X/sinϕ = 400/sin90^o = 400 N
- Select a scale : 1 cm= 200N
- Draw P_Z and P_{XY} using that scale

  P_Z = 800/200 = 4 cm,

  P_{XY} = 400/200 = 2 cm
- Get R and draw the MCD
- Determine shear angle, β_o from

  $\tan\beta_o = \cos\gamma_o/(\zeta - \sin\gamma_o)$, γ_o= 0^o and

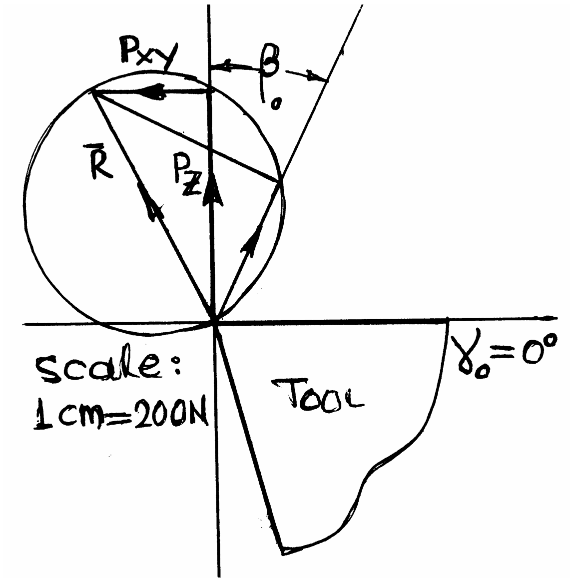
  $\zeta = a_2/a_1$ $a_1 = (s_o\sin\phi) = 0.2 \times \sin 90^o = 0.2$

  $\beta_o = \tan^{-1}(0.2/0.4) = 26^o$
- Draw P_S along the shear plane and find P_S= 2.5 x 200 = 500 N
- Now, $\tau_S = P_S/A_S$;

$A_S = (ts_O)/\sin\beta_o = 4 \times 0.2/\sin26^0 = 1.82\ mm^2$

or, $\tau_S = 500/1.82$

$= 274.7\ N/mm^2$



Module
2
Mechanics of Machining

Lesson
9
Analytical and Experimental determination of cutting forces

Instructional Objectives

At the end of this lesson, the student would be able to

(i) Develop and use equations for estimation of major cutting force components in turning under
   - Orthogonal cutting
   - Oblique cutting

(ii) Evaluate analytically the major cutting forces in
   - Drilling
   - Plain milling

(iii) Identify the needs and purposes of measurement of cutting forces

(iv) State the possible methods of measurement of cutting forces.

(i) Development of equations for estimation of cutting forces

The two basic methods of determination of cutting forces and their characteristics are :

(a) Analytical method : enables estimation of cutting forces
characteristics : -
- easy, quick and inexpensive
- very approximate and average
- effect of several factors like cutting velocity, cutting fluid action etc. are not revealed
- unable to depict the dynamic characteristics of the forces.

(b) Experimental methods : direct measurement characteristics : -
- quite accurate and provides true picture
- can reveal effect of variation of any parameter on the forces
- depicts both static and dynamic parts of the forces
- needs measuring facilities, expertise and hence expensive.

The equations for analytical estimation of the salient cutting force components are conveniently developed using Merchant's Circle Diagram (MCD) when it is orthogonal cutting by any single point cutting tool like, in turning, shaping, planning, boring etc.

Development of mathematical expressions for cutting forces under orthogonal turning.

- **Tangential or main component, P_Z**

This can be very conveniently done by using Merchant's Circle Diagram, MCD, as shown in Fig. 9.1

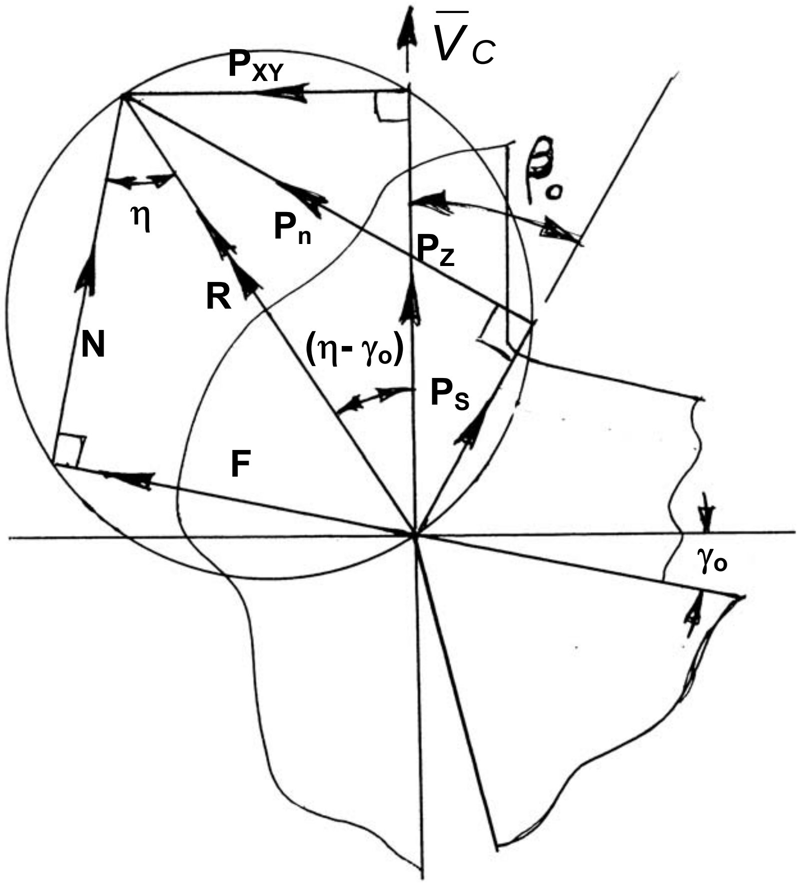


Fig. 9.1 *Forces involved in machining and contained in Merchant's Circle.*

From the diagram in Fig. 9.1,

$$P_Z = R\cos(\eta - \gamma_o) \quad (9.1)$$

$$P_s = R\cos(\beta_o + \eta - \gamma_o) \quad (9.2)$$

Dividing Eqn. 9.1 by Eqn. 9.2,

$$P_Z = \frac{P_s \cos(\eta - \gamma_o)}{\cos(\beta_o + \eta - \gamma_o)} \quad (9.3)$$

It was already shown that,

$$P_s = \frac{ts_o\tau_s}{\sin\beta_o} \quad (9.4)$$

where, τ_s = dynamic yield shear strength of the work material.

Thus, $$P_Z = \frac{ts_o\tau_s\cos(\eta - \gamma_o)}{\sin\beta_o\cos(\beta_o + \eta - \gamma_o)} \quad (9.5)$$

For brittle work materials, like grey cast iron, usually, $2\beta_o + \eta - \gamma_o = 90^o$ and τ_s remains almost unchanged.
Then for turning brittle material,

$$P_Z = \frac{ts_o \tau_s \cos(90^o - 2\beta_o)}{\sin\beta_o \cos(90^o - \beta_o)}$$

$$\text{or, } P_Z = 2ts_o \tau_s \cot\beta_o \qquad (9.6)$$

where, $\cot\beta_o = \zeta - \tan\gamma_o$ (9.7)

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

It is difficult to measure chip thickness and evaluate the values of ζ while machining brittle materials and the value of τ_s is roughly estimated from

$$\tau_s = 0.175 \text{ BHN} \qquad (9.8)$$

where, BHN = Brinnel Hardness number.
But most of the engineering materials are ductile in nature and even some semi-brittle materials behave ductile under the cutting condition.
The angle relationship reasonably accurately applicable for ductile metals is

$$\beta_o + \eta - \gamma_o = 45^o \qquad (9.9)$$

and the value of τ_s is obtained from,

$$\tau_s = 0.186 \text{ BHN (approximate)} \qquad (9.10)$$

$$\text{or } = 0.74\sigma_u\varepsilon^{0.6\Delta} \text{ (more suitable and accurate)} \qquad (9.11)$$

where, σ_u = ultimate tensile strength of the work material
ε = cutting strain
$\cong \zeta - \tan\gamma_o$
and Δ = % elongation

Substituting Eqn. 9.9 in Eqn. 9.5,

$$P_Z = ts_o \tau_s (\cot\beta_o + 1) \qquad (9.12)$$

Again $\cot\beta_o \cong \zeta - \tan\gamma_o$
So, $\mathbf{P_Z = ts_o\tau_s(\zeta - \tan\gamma_o + 1)}$ (9.13)

- **Axial force, P_X and transverse force, P_Y**

From MCD in Fig. 9.1,

$$P_{XY} = P_Z \tan(\eta - \gamma_o) \qquad (9.14)$$

Combining Eqn. 9.5 and Eqn. 9.14,

$$P_{XY} = \frac{ts_o \tau_s \sin(\eta - \gamma_o)}{\sin\beta_o \cos(\beta_o + \eta - \gamma_o)} \qquad (9.15)$$

Again, using the angle relationship $\beta_o + \eta - \gamma_o = 45^o$, for ductile material

$$P_{XY} = ts_o\tau_s(\cot\beta_o - 1) \qquad (9.16)$$

or $\mathbf{P_{XY} = ts_o\tau_s(\zeta - \tan\gamma_o - 1)}$ (9.17)

where, $\tau_s = 0.74\sigma_u\varepsilon^{0.6\Delta}$ or 0.186 BHN

It is already known,

$P_X = P_{XY}\sin\phi$
and $P_Y = P_{XY}\cos\phi$

Therefore, $\mathbf{P_X = ts_o\tau_s(\zeta - \tan\gamma_o - 1)\sin\phi}$ (9.18)
and $\mathbf{P_Y = ts_o\tau_s(\zeta - \tan\gamma_o - 1)\cos\phi}$ (9.19)

- **Friction force, F, normal force, N and apparent coefficient of friction μ_a**

Again from the MCD in Fig. 9.1

$$F = P_Z \sin\gamma_o + P_{XY} \cos\gamma_o \quad (9.20)$$

and $$N = P_Z \cos\gamma_o - P_{XY} \sin\gamma_o \quad (9.21)$$

and, $$\mu_a = \frac{F}{N} = \frac{P_Z \sin\gamma_o + P_{XY} \cos\gamma_o}{P_Z \cos\gamma_o - P_{XY} \sin\gamma_o} \quad (9.22)$$

or, $$\boldsymbol{\mu_a = \frac{P_Z \tan\gamma_o + P_{XY}}{P_Z - P_{XY} \tan\gamma_o}} \quad (9.23)$$

Therefore, if P_Z and P_{XY} are known or determined either analytically or experimentally the values of F, N and μ_a can be determined using equations only.

- **Shear force P_s and P_n**

Again from the MCD in Fig. 9.1

$$P_s = P_Z \cos\beta_o - P_{XY} \sin\beta_o \quad (9.24)$$

and $$P_n = P_Z \sin\beta_o + P_{XY} \cos\beta_o \quad (9.25)$$

From P_s, the dynamic yield shear strength of the work material, τ_s can be determined by using the relation,

$$P_s = A_s \tau_s$$

where, A_s = shear area $= \frac{ts_o}{\sin\beta}$

Therefore, $$\tau_s = \frac{P_s \sin\beta_o}{ts_o}$$

$$= \frac{(P_Z \cos\beta_o - P_{XY} \sin\beta_o)\sin\beta_o}{ts_o} \quad (9.26)$$

- **Cutting forces in turning under oblique cutting**

In orthogonal cutting, the chip flows along the orthogonal plane, π_o and all the forces concerned, i.e., P_Z, P_{XY}, F, N, P_S and P_n are situated in π_o and contained in the MCD. But in oblique cutting the chip flow is deviated from the orthogonal plane and a force develops along the cutting edge and hence MCD (drawn in π_o) is not applicable. However, since it is a single point tool, only one force will really develop which will have one component along the cutting edge in oblique cutting.

Fig. 9.2 shows how the only cutting force, R can be resolved into

Either, P_X, P_Y and P_Z; which are useful for the purpose of measurement and Design of the M – F – T system

or, P_l, P_m and P_n; which are useful for the purpose of design and stress analysis of the tool and determination of chip-tool interaction in oblique cutting when the chip does not flow along π_o.

For convenience of analysis, the set of force components are shown again in Fig. 9.3 where the cutting force R is resolved into two components R_C and R_r as

$$\overline{R} = \overline{R}_C + \overline{R}_r \qquad (9.27)$$

where, R_C is taken in cutting plane, π_C and R_r in reference plane, π_R.
From Fig. 9.3, the forces in π_C are related as,

$$P_n = P_Z\cos\lambda - P_h\sin\lambda \qquad (9.28)$$

$$P_l = P_Z\sin\lambda + P_h\cos\lambda \qquad (9.29)$$

Where, P_n is acting normal to the cutting edge and P_l is acting along the cutting edge. P_h is an imaginary component along Y_o axis.
Similarly the forces on π_R in Fig. 9.3 are related as,

$$P_m = P_X\sin\phi + P_Y\cos\phi \qquad (9.30)$$

and $$P_h = - P_X\cos\phi + P_Y\sin\phi \qquad (9.31)$$

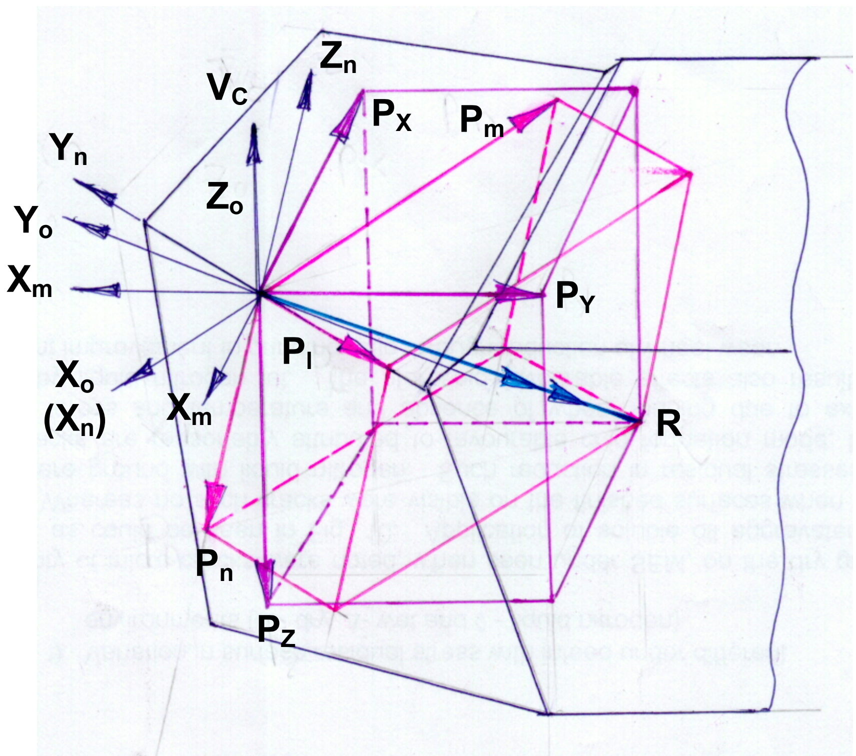


Fig. 9.2 Resolving the cutting force in oblique cutting (turning)

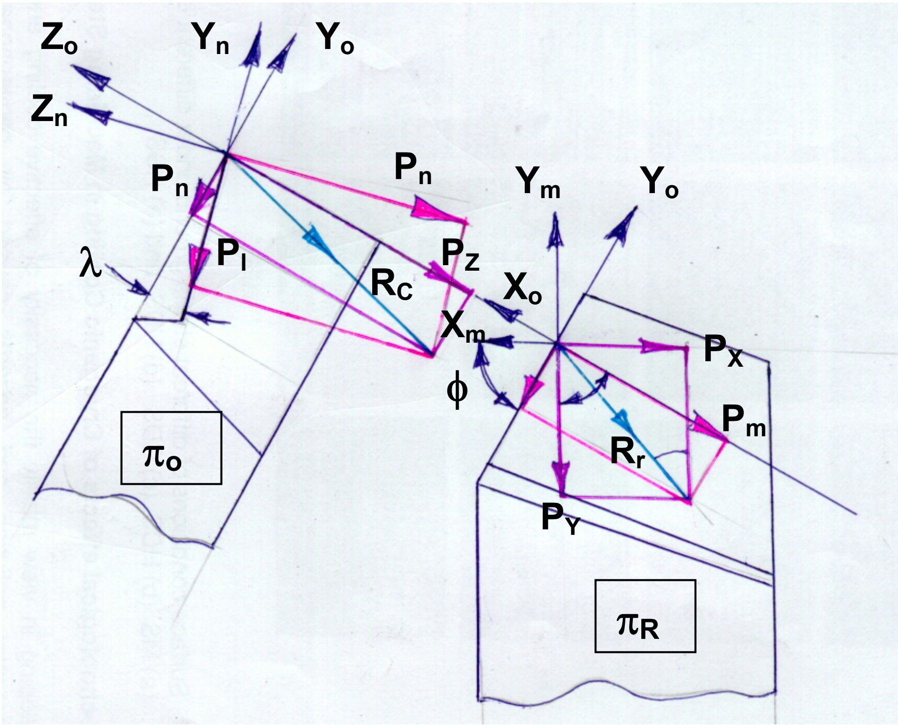


Fig. 9.3 *Resolved components of the cutting force in oblique cutting.*

From equations 9.28 to 9.31, the following three expressions are attained.

$$P_l = -P_X \cos\phi \cos\lambda + P_y \sin\phi \cos\lambda + P_Z \sin\lambda \quad (9.32)$$

$$P_m = P_X \sin\phi + P_y \cos\phi \quad (9.33)$$

and $$P_n = P_X \cos\phi \sin\lambda - P_Y \sin\phi \sin\lambda + P_Z \cos\lambda \quad (9.34)$$

The equations 9.32, 9.33 and 9.34 may be combined and arranged in matrix form as

$$\begin{bmatrix} P_l \\ P_m \\ P_n \end{bmatrix} = \begin{bmatrix} -\cos\phi\cos\lambda & \sin\phi\cos\lambda & \sin\lambda \\ \sin\phi & \cos\phi & 0 \\ \cos\phi\sin\lambda & -\sin\phi\sin\lambda & \cos\lambda \end{bmatrix} \begin{bmatrix} P_X \\ P_Y \\ P_Z \end{bmatrix} \quad (9.35)$$

The equation 9.35 is very important and useful for evaluating the force components P_l, P_m and P_n from the measured or known force components P_X, P_Y and P_Z in case of oblique cutting.

By inversion of the Eqn. 9.35, another similar matrix form can be developed which will enable evaluation of P_X, P_Y and P_Z, if required, from P_l, P_m and P_n if known other way.

Under oblique cutting, the coefficient of friction, μ_a is to be determined from

$$\mu_a = \frac{F''}{N'} = \frac{\dfrac{F'}{\cos\rho_c}}{N'}$$; ρ_c = chip flow deviation angle $\cong \lambda$

where, F′ and N′ are to be determined from the values of P_n and P_m as,

$$F' = P_n \sin\gamma_n + P_m \cos\gamma_n \quad (9.36)$$

and $$N' = P_n \cos\gamma_n - P_m \sin\gamma_n \quad (9.37)$$

Therefore, under oblique cutting,

$$\mu_a = \frac{P_n \tan\gamma_n + P_m}{\cos\lambda(P_n - P_m \tan\gamma_n)} \quad (9.38)$$

(iii) Analytical Estimation of cutting forces in drilling and milling.

(a) Cutting forces in drilling.

In drilling ductile metals by twist drills, the thrust force, P_X and torque, T can be evaluated using the following equations (Shaw and Oxford) :

$$P_X = K_{x1}.H_B.s_o^{0.8}d^{0.8} + K_{x2}.H_B.d^2 \quad \text{kg} \quad (9.39)$$

and $$T = K_t.H_B.s_o^{0.8}d^{1.8} \quad \text{kg – mm} \quad (9.40)$$

Where, K_{x1}, K_{x2} and K_t are constants depending upon the work material. H_B is Brinnel Hardness and d is drill diameter (mm).

As for example, for steels of $H_B \le 250$ and $d_c/d = 0.18$ [d_c = chisel edge diameter, mm]

Eqn. 9.39 and 9.40 become

$$P_X = 0.195 H_B s_o^{0.8} d^{0.8} + 0.0022 H_B d^2 \quad (9.41)$$

and $$T = 0.087 H_B s_o^{0.8} d^{1.8} \quad (9.42)$$

The drilling torque and thrust can also be roughly evaluated using following simpler equations:

$$T = C_1 d^x s_o^y \quad \text{(kg – mm)} \quad (9.43)$$

and $$P_X = C_2 d^{x'} s_o^{y'} \quad \text{(kg)} \quad (9.44)$$

Table 9.1 typically shows the approximate values of the constants C_1 and C_2 and the exponents x, y, x′ and y′ for some common engineering materials (Fe-based):

Table 9.1 Constant and exponents in drilling.

Work material	C_1	C_2	x	y	x′	y′
Plain carbon and low alloy steels	35 ~ 55	85 ~ 160	2.0	0.6 ~ 0.8	1.0	0.7
Cast iron BHN 150 ~ 190	20 ~ 23	50	1.9	0.8	1.0	0.8

(b) Cutting forces in Plain milling

In plain or slab milling, the average tangential force, P_{Tavg}, torque, T and cutting power, P_C can be roughly determined irrespective of number of teeth engaged and helix angle, by using the following expressions :

$$P_{Tavg} = \frac{C_p}{\pi} . \frac{B.s_o^x.d^y.Z_C}{D_C^z} \quad \text{kg} \quad (9.45)$$

$$T = P_{Tavg} x \frac{D_C}{2} \quad \text{kg – mm} \quad (9.46)$$

and $P_C = P_{Tavg} x V_C$ kg-m/min (9.47)

$$= \frac{9.81.P_{Tavg} x V_C}{60x1000} \quad \text{kW}$$

There are several other equations available (developed by researchers) for evaluating milling forces approximately under given cutting conditions.

(iv) Needs and Purposes of Measurement of Cutting Forces

In machining industries and R & D sections the cutting forces are desired and required to be measured (by experiments)

- for determining the cutting forces accurately, precisely and reliably (unlike analytical method)
- for determining the magnitude of the cutting forces directly when equations are not available or adequate
- to experimentally verify mathematical models
- to explore and evaluate role or effects of variation of any parameters, involved in machining, on cutting forces, friction and cutting power consumption which cannot be done analytically
- to study the machinability characteristics of any work – tool pair
- to determine and study the shear or fracture strength of the work material under the various machining conditions
- to directly assess the relative performance of any new work material, tool geometry, cutting fluid application and special technique in respect of cutting forces and power consumption
- to predict the cutting tool condition (wear, chipping, fracturing, plastic deformation etc.) from the on-line measured cutting forces.

(v) General methods of measurement of cutting forces

(a) Indirectly

- from cutting power consumption
- by calorimetric method

Characteristics

- o inaccurate
- o average only
- o limited application possibility

(b) Directly

Using tool force dynamometer(s)

Characteristics

- o accurate
- o precise / detail
- o versatile
- o more reliable

Exercise – 9

[Problems and solutions]

Q.1 If, in orthogonal turning a tool of $\gamma_o = 0^o$ and $\phi = 90^o$, the force components, P_X and P_Z are measured to be 400 N and 800 N respectively then what will be the value of the apparent coefficient (μ_a) of friction at the chip tool interface at that condition?

[solve using equations only]

Solution :

It is known that, $\mu_a = F/N$

where, $F = P_Z \sin\gamma_o + P_{xy}\cos\gamma_o$ and $N = P_Z\cos\gamma_o - P_{xy}\sin\gamma_o$

Now, $P_{xy} = P_X/\sin\phi = 400/\sin 90^0 = 400N.$

$\sin\gamma_o = \sin 0^0 = 0$

$\cos\gamma_o = \cos 0^0 = 1.$

$\mu_a = P_{xy}/P_Z = 400/800 = 0.5$ Ans.

Q.2 Determine without using MCD, the values of P_S (shear force) and P_N using the following given values associated with a turning operation :

$P_Z = 1000$ N, $P_X = 400$ N $P_Y = 200$ N, $\gamma_o = 15^o$ and $\zeta = 2.0$

Solution :

The known relations are:

$$P_S = P_Z\cos\beta_o - P_{XY}\sin\beta_o$$

$$P_n = P_Z\sin\beta_o + P_{XY}\cos\beta_o$$

Let b_0(shear angle) from

$$\tan\beta_o = \cos\gamma_o/(\zeta - \sin\gamma_o)$$

$$= \cos 15^0/(2.0 - \sin 15^0) = 0.554$$

$\therefore$ $\beta_o = 29^0$; $\cos\beta_o = 0.875$

and $\sin\beta_o = 0.485$

$$P_{XY} = \sqrt{(P_X)^2 + (P_Y)^2} = \sqrt{(400)^2 + (200)^2} = 445 \text{ N}$$

So, $P_S = 1000\text{x}0.875 - 445\text{x}0.485 = 659$ N

and $P_n = 1000\text{x}0.485 + 445\text{x}0.875 = 874$ N

Q. 3 During turning a steel rod of diameter 150 mm by a carbide tool of geometry;

0^o, —12^o, 8^o, 6^o, 15^o, 60^o, 0 (mm)

at speed 560 rpm, feed 0.32 mm/rev. and depth of cut 4.0 mm the followings were observed :

P_Z= 1000 N, P_Y= 200 N, a_2=0.8 mm

Determine, without using MCD, the expected values of F, N, μ, P_S, P_n, τ_s, cutting power and specific energy requirement for the above mentioned machining operation.

Solution :

- $P_{XY} = P_X/\sin\phi = 200/\cos 60^o = 400$ N
- $F = P_Z \sin\gamma_o + P_{XY}\cos\gamma_o$;

  Here $\gamma_o = -12^o$ \ $\sin\gamma_o = -0.208$ and $\cos\gamma_o = 0.978$

  F = 1000(-0.208) + 400(0.978) = 600 N ans.

and $N = P_Z\cos\gamma_o — P_{XY}\sin\gamma_o$

= 1000(0.978) — 400(-0.208)

= 1060 N answer

So, μ_a = F/N = 600/1060 = 0.566 answer

- $P_S = P_Z\cos\beta_o — P_{XY}\cos\beta_o$

  where $\beta_o = \tan^{-1}(\cos\gamma_o/(\zeta—\sin\gamma_o))$

Here, $\zeta = a_2/(s_o\sin\phi) = 0.8/(0.32x\sin 60^o) = 2.88$

$\beta_o = \tan^{-1}\{(0.978/(2.88+0.208)\} = 17.6^o$

So, P_S= 1000xcos(17.6^o) – 400xsin(17.6^o) = 832 N **answer**

and P_N= 1000sin(17.6^o) + 400cos(17.6^o) = 683 N **answer**

- $P_S = (ts_o\ \tau_s)/\sin\gamma_o$

  $\therefore \tau_s = P_S\sin\gamma_o /(ts_o)$ = 832sin(17.6^o)/(4x0.32)

  = 200 N/mm^2 answer

- Cutting power, $P_C = P_Z.V_C$

  where $V_C = \pi DN/1000 = \pi x150x560/1000$ = 263 m/min

  $\therefore P_C$ = 1000x263 N-m/min = 4.33 KW **answer**

- Specific energy consumption, E_C

  E_C= power/MRR = $(P_Z.V_C)/(V_C.s_o.t)$ N-m/m-mm^2

  = 1000x263 (Joules/min)/{263x0.32x4x1000(mm^3/min)}

  = 0.78 Joules/mm^3 **answer**

Q.4 During turning a steel rod of diameter 100 mm by a ceramic tool of geometry:

0^o, $—10^o$, 8^o, 7^o, 15^o, 75^o, 0.5 (mm)

at speed 625 rpm, feed 0.36 mm/rev. and depth of cut 5.0 mm the average chip thickness was found to be 1.0 mm. Roughly how much power will be consumed in the above mentioned machining work if;

(i) the work material is semi-ductile

(ii) Brinnel hardness number of the work material is 240 (kg/mm^2)

Solution :

Cutting power, $P_C = P_Z . V_C$ N.m/min.

V_C= Cutting Velocity = πDN/1000 m/min.

= (π x100x625)/1000 =196 m/min.

$P_Z = ts_o\tau_s\cos(\eta - \gamma_o)/\{\sin\beta_o.\cos(\beta_o + \eta - \gamma_o)\}$

For semi-ductile materials, the angle relationships that may be taken

$2\beta_o + \eta - \gamma_o = \pi/2$ [Earnst & Merchant]

Then, $P_Z = 2ts_o\cot\beta_o$

Get shear angle, β_o from,

$\tan\beta_o = (\cos\gamma_o) / (\zeta - \sin\gamma_o)$

where, $\zeta = a_2/a_1 = a_2/s_o\sin\phi = 1.0/(0.36.\sin75^0) = 2.87$

$\beta_o = \tan^{-1}\{\cos(-10^0)/(2.87-\sin(-10^0))\} = 17.9^0$

$\therefore$Shear strength, τ_s = 0.186 BHN

= 0.186x240x9.81 N/mm^2

= 424N/mm^2

So, P_Z= 2 x5x0.36x424xcot(17.9^0) = 4697 N. **Ans.**

Module 2

Mechanics of Machining

Lesson
10
Dynamometers for measuring cutting forces

Instructional objectives

At the end of this lesson, the students would be able to

- (i) show the general principle of measurement
- (ii) classify and apply different transducers for converting cutting forces into suitable signals
- (iii) state the design requirements of tool-force dynamometers
- (iv) develop and use strain gauge type dynamometer for
  - turning
  - drilling
  - milling
  - grinding

(i) General principle of measurement.

The existence of some physical variables like force, temperature etc and its magnitude or strength cannot be detected or quantified directly but can be so through their effect(s) only. For example, a force which can neither be seen nor be gripped but can be detected and also quantified respectively by its effect(s) and the amount of those effects (on some material) like elastic deflection, deformation, pressure, strain etc. These effects, called signals, often need proper conditioning for easy, accurate and reliable detection and measurement. The basic principle and general method of measurement is schematically shown in Fig. 10.1.

The measurement process is comprised of three stages:

Stage – 1 : The target physical variable (say force) is converted proportionally into another suitable variable (say voltage) called signal, by using appropriate sensor or transducer.

Stage – 2 : The feeble and noisy signal is amplified, filtered, rectified (if necessary) and stabilized for convenience and accuracy of measurement.

Stage – 3 : where the conditioned signal (say voltage) is quantitatively determined and recorded by using some read out unit like galvanometer, oscilloscope, recorder or computer.

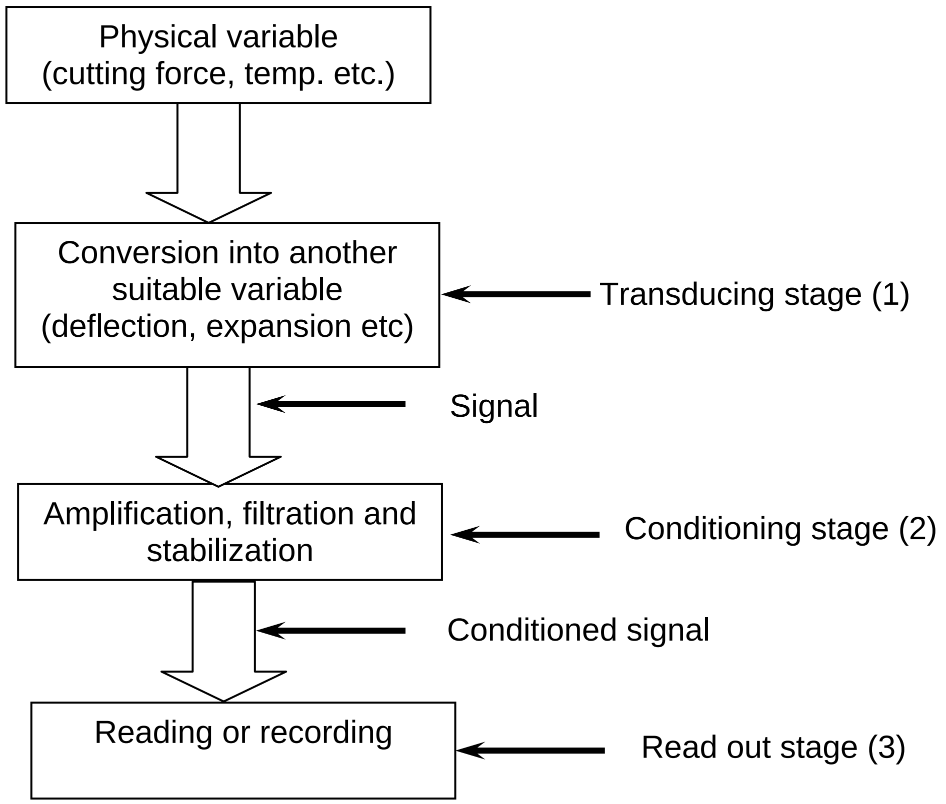


Fig. 10.1 *General principle of measurement.*

(ii) Different types of transducers used in dynamometers for measuring machining forces.

Measurement of cutting force(s) is based on three basic principles :

- (a) measurement of elastic deflection of a body subjected to the cutting force
- (b) measurement of elastic deformation, i.e. strain induced by the force
- (c) measurement of pressure developed in a medium by the force.

The type of the transducer depends upon how that deflection, strain or pressure is detected and quantified.

(a) Measuring deflection caused by the cutting force(s)

Under the action of the cutting force, say P_Z in turning, the tool or tool holder elastically deflects as indicated in Fig. 10.2. Such tool deflection, δ is proportional to the magnitude of the cutting force, P_Z, simply as,

$$\delta = P_Z\left(\frac{L^3}{3EI}\right) \tag{10.1}$$

where, L = overhang or equivalent projected length of the cantilever type tool (holder)

E = physical property (Young's modulus of elasticity of the beam)

I = size (plane moment of inertia) of the beam section.

Since for a given cutting tool and its holder, E and I are fixed and the equation 10.1 becomes,

$$\delta \;\alpha\; P_Z \quad \text{or,} \quad \delta = kP_Z \qquad (10.2)$$

where, k is a constant of proportionality.

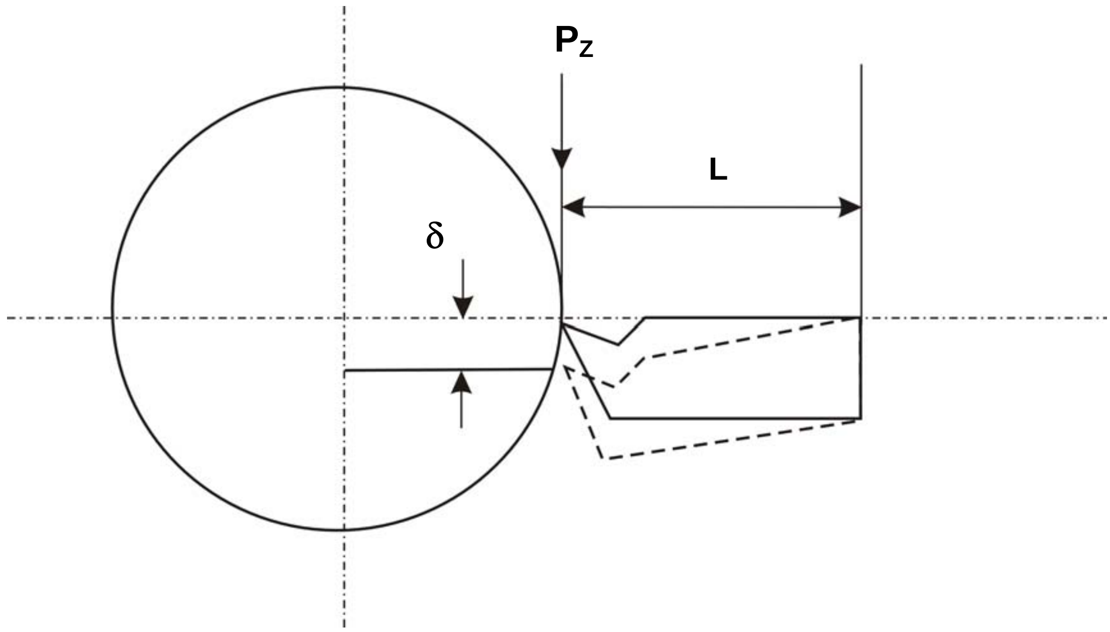


Fig. 10.2** Cutting tool undergoing deflection, δ due to cutting force, **P_Z

The deflection, δ, can be measured

- mechanically by dial gauge (mechanical transducer)
- electrically by using several transducers like;
  - — potentiometer; linear or circular
  - — capacitive pickup
  - — inductive pickup
  - — LVDT

as schematically shown in Fig. 10.3.

- opto-electronically by photocell where the length of the slit through which light passes to the photocell changes proportionally with the tool – deflection

All such transducers need proper calibration before use.

In case of mechanical measurement of the tool deflection by dial gauge, calibration is done by employing known loads, W and the corresponding tool deflections, δ are noted and then plotted as shown in Fig. 10.4. Here the slope of the curve represents the constant, k of the equation (10.2). Then while actual measurement of the cutting force, P_Z, the δ***** is noted and the corresponding force is assessed from the plot as shown.

In capacitive pick up type dynamometer, the cutting force causes proportional tool deflection, δ , which causes change in the gap (d) and hence capacitance, C as

$$C = \frac{\varepsilon . A}{3.6\pi d} \qquad (10.3)$$

The change in C is then measured in terms of voltage, ∆V which becomes proportional to the force. The final relation between P_Z and ∆V is established by calibration.

In case of LVDT, the linear movement of the core, (coupled with the tool), inside the fixed coil produces proportional voltage across the secondary coil.

Fig. 10.3 Electrical transducers working based on deflection measurement

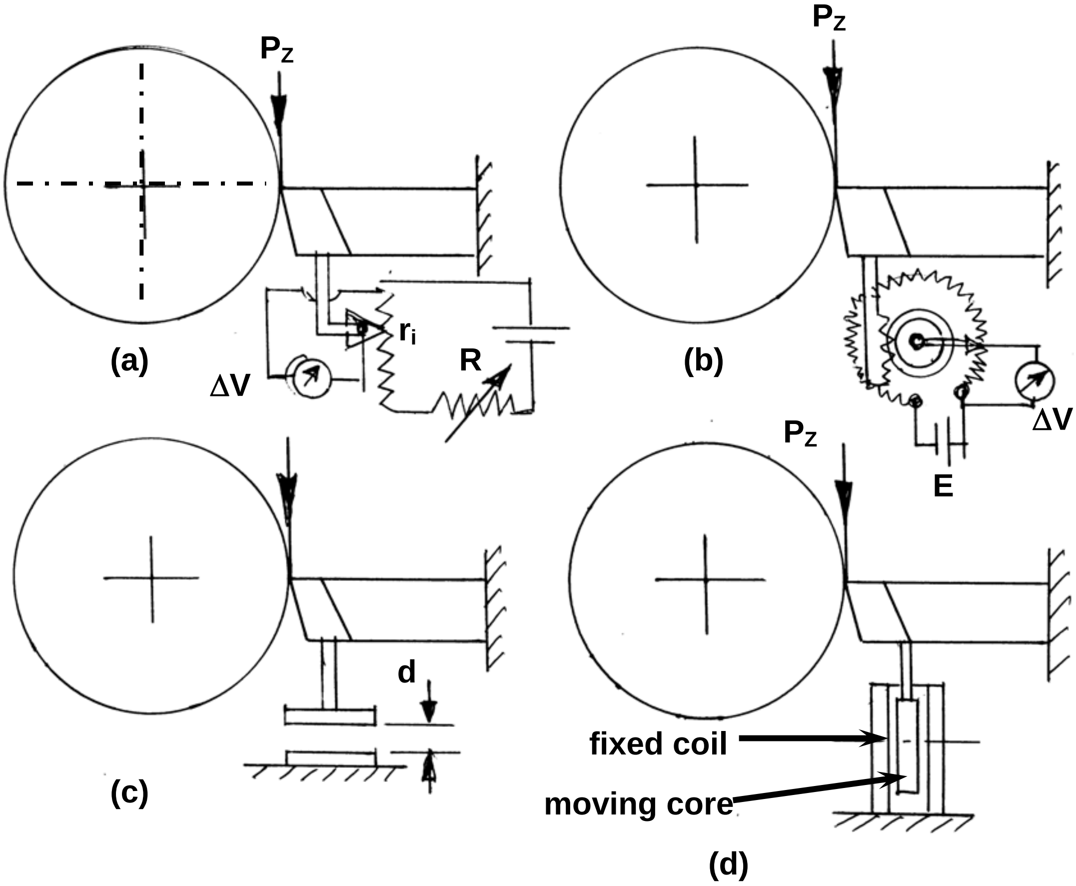


Fig. 10.3 *Electrical transducers working based on deflection measurment*
(a) linear pot (b) circular pot (c) capacitive pick up (d) LVDT type

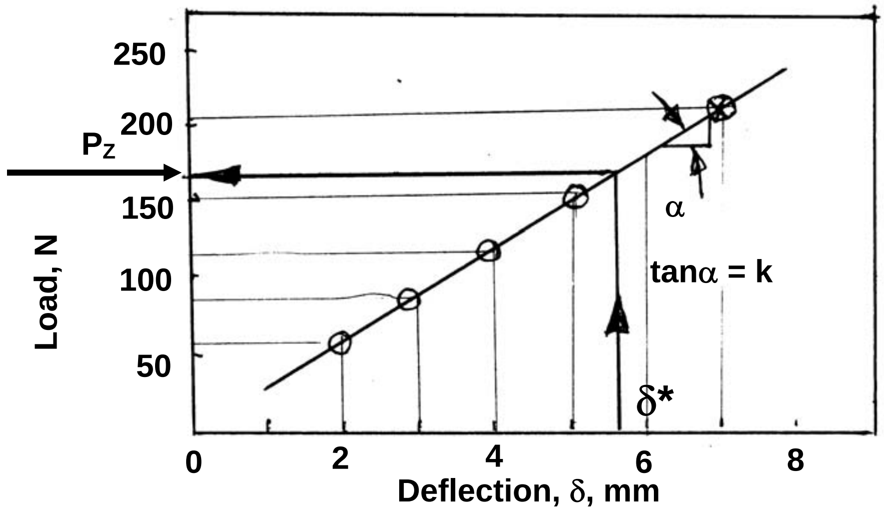


Fig. 10.4 *Calibration of mechanical measurement system (dial gauge)*

(b) Measuring cutting force by monitoring elastic strain caused by the force.

Increasing deflection, δ enhances sensitivity of the dynamometer but may affect machining accuracy where large value of δ is restricted, the cutting forces are suitably measured by using the change in strain caused by the force. Fig. 10.5 shows the principle of force measurement by measuring strain, ε, which would be proportional with the magnitude of the force, F (say P_Z) as,

$$\varepsilon = \frac{\sigma}{E} = \frac{M/Z}{E} = \frac{P_Z.l}{Z.E} = k_1 P_Z \qquad (10.4)$$

where, M = bending moment
Z = sectional modulus (I/y) of the tool section
I = plane moment of inertia of the plane section
y = distance of the straining surface from the neutral plane of the beam (tool)

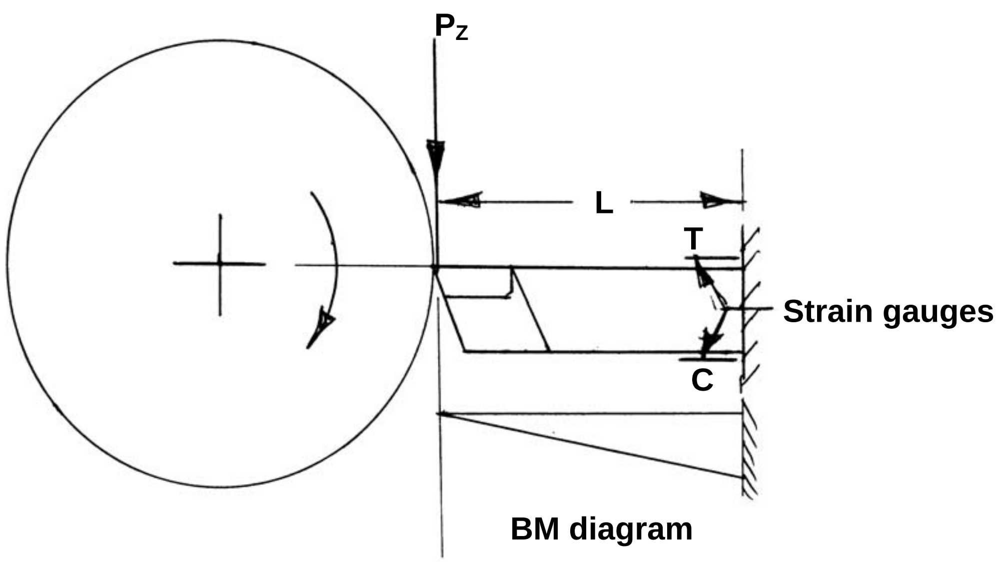


Fig. 10.5 *Measuring cutting forces by strain gauges*

The strain, ε induced by the force changes the electrical resistance, R, of the strain gauges which are firmly pasted on the surface of the tool-holding beam as

$$\frac{\Delta R}{R} = G\varepsilon \qquad (10.5)$$

where, G = gauge factor (around 2.0 for conductive gauges)

The change in resistance of the gauges connected in a wheatstone bridge produces voltage output ΔV, through a strain measuring bridge (SMB) as indicated in Fig. 10.6.

Out of the four gauges, R_1, R_2, R_3 and R_4, two are put in tension and two in compression as shown in Fig. 10.6. The output voltage, ΔV, depends upon the constant, G and the summation of strains as,

$$\Delta V = \frac{GE}{4}\left[\varepsilon_1 - (-\varepsilon_2) + \varepsilon_3 - (-\varepsilon_4)\right] \qquad (10.6)$$

where, ε_1 and ε_2 are in tension and - ε_3 and - ε_4 are in compression

The gauge connections may be

- full bridge (all 4 gauges alive) – giving full sensitivity
- half bridge (only 2 gauges alive) – half sensitive
- quarter bridge (only 1 gauge alive) – ¼ th sensitivity

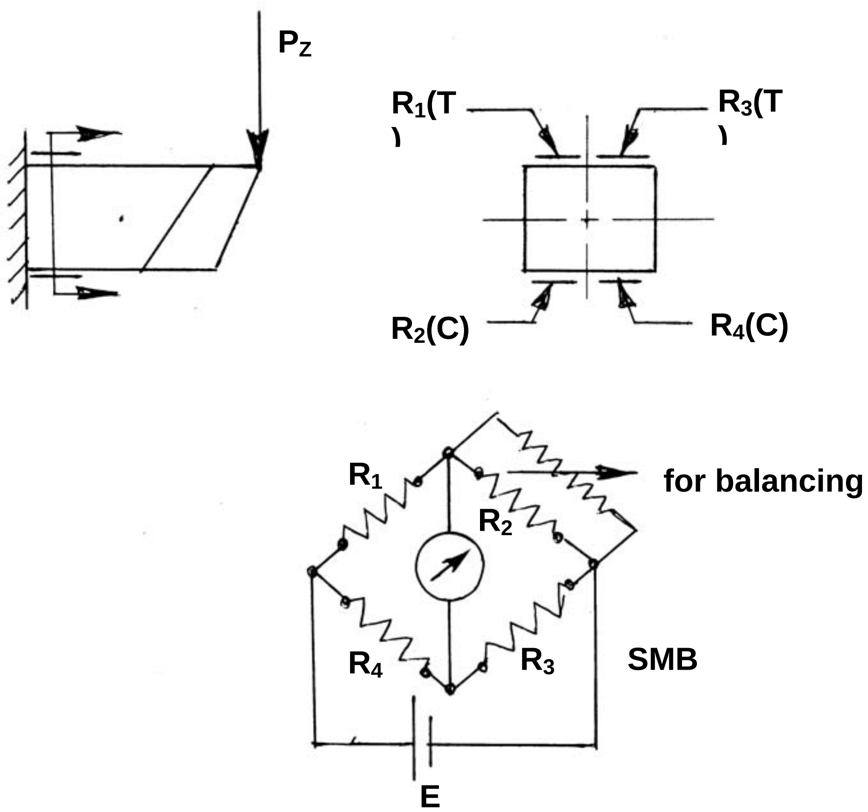


Fig. 10.6 *Force measurement by strain gauge based transducer.*

(c) Measuring cutting forces by pressure caused by the force

This type of transducer functions in two ways :

- the force creates hydraulic pressure (through a diaphragm or piston) which is monitored directly by pressure gauge
- the force causes pressure on a piezoelectric crystal and produces an emf proportional to the force or pressure as indicated in Fig. 10.7.

Here, $$\text{emf} = \lambda t p \qquad (10.7)$$

where λ = voltage sensitivity of the crystal
t = thickness of the crystal
p = pressure

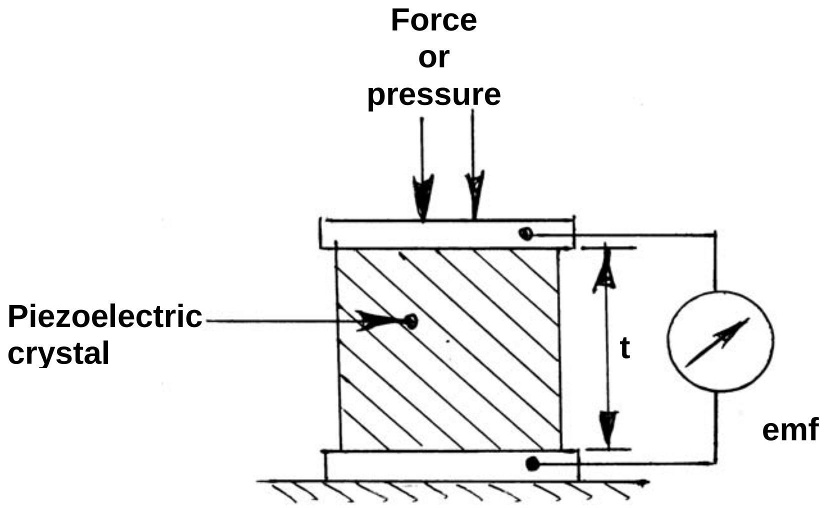


Fig. 10.7 *Piezoelectric transducer for measuring force or pressure*.

(iii) Design requirements for Tool – force Dynamometers

For consistently accurate and reliable measurement, the following requirements are considered during design and construction of any tool force dynamometers :

- **Sensitivity** : the dynamometer should be reasonably sensitive for precision measurement
- **Rigidity** : the dynamometer need to be quite rigid to withstand the forces without causing much deflection which may affect the machining condition
- **Cross sensitivity** : the dynamometer should be free from cross sensitivity such that one force (say P_Z) does not affect measurement of the other forces (say P_X and P_Y)
- Stability against humidity and temperature
- Quick time response
- High frequency response such that the readings are not affected by vibration within a reasonably high range of frequency
- Consistency, i.e. the dynamometer should work desirably over a long period.

(iv) Construction and working principle of some common tool – force dynamometers.

The dynamometers being commonly used now-a-days for measuring machining forces desirably accurately and precisely (both static and dynamic characteristics) are

either • strain gauge type

or • piezoelectric type

Strain gauge type dynamometers are inexpensive but less accurate and consistent, whereas, the piezoelectric type are highly accurate, reliable and consistent but very expensive for high material cost and stringent construction.

- **Turning Dynamometer**

Turning dynamometers may be strain gauge or piezoelectric type and may be of one, two or three dimensions capable to monitor all of P_X, P_Y and P_Z.

For ease of manufacture and low cost, strain gauge type turning dynamometers are widely used and preferably of 2 – D (dimension) for simpler construction, lower cost and ability to provide almost all the desired force values.

Design and construction of a strain – gauge type 2 – D turning dynamometer are shown schematically in Fig. 10.8 and photographically in Fig. 10.9 Two full bridges comprising four live strain gauges are provided for P_Z and P_X channels which are connected with the strain measuring bridge for detection and measurement of strain in terms of voltage which provides the magnitude of the cutting forces through calibration. Fig. 10.10 pictorially shows use of 3 – D turning dynamometer having piezoelectric transducers inside.

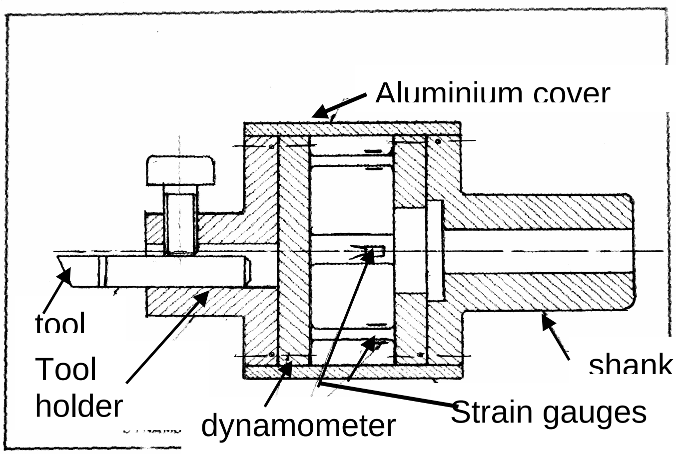
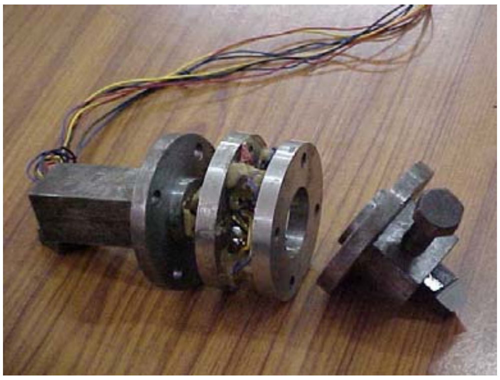


Fig. 10.8 *Schematic view of a strain gauge type 2 – D turning dynamometer.*



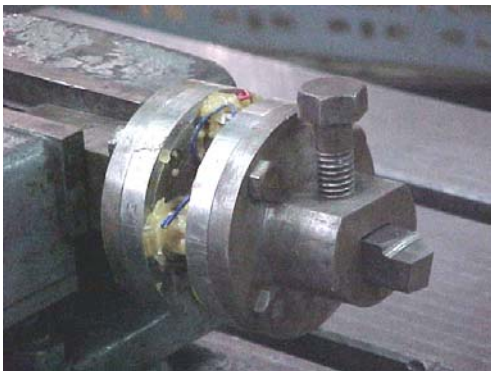


Fig. 10.9 *Photographs of a strain gauge type 2 – D turning dynamometer and its major components.*

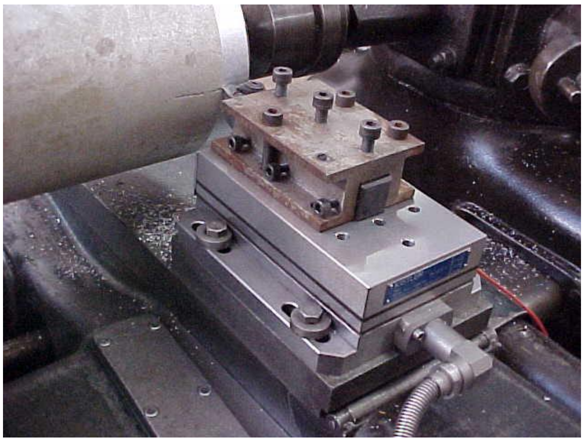


Fig. 10.10 *Use of 3 – D piezoelectric type turning dynamometer.*

- **Drilling dynamometer**

Physical construction of a strain gauge type 2 – D drilling dynamometer for measuring torque and thrust force is typically shown schematically in Fig. 10.11 and pictorially in Fig. 10.12. Four strain gauges are mounted on the upper and lower surfaces of the two opposite ribs for P_X – channel and four on the side surfaces of the other two ribs for the torque channel. Before use, the dynamometer must be calibrated to enable determination of the actual values of T and P_X from the voltage values or reading taken in SMB or PC.

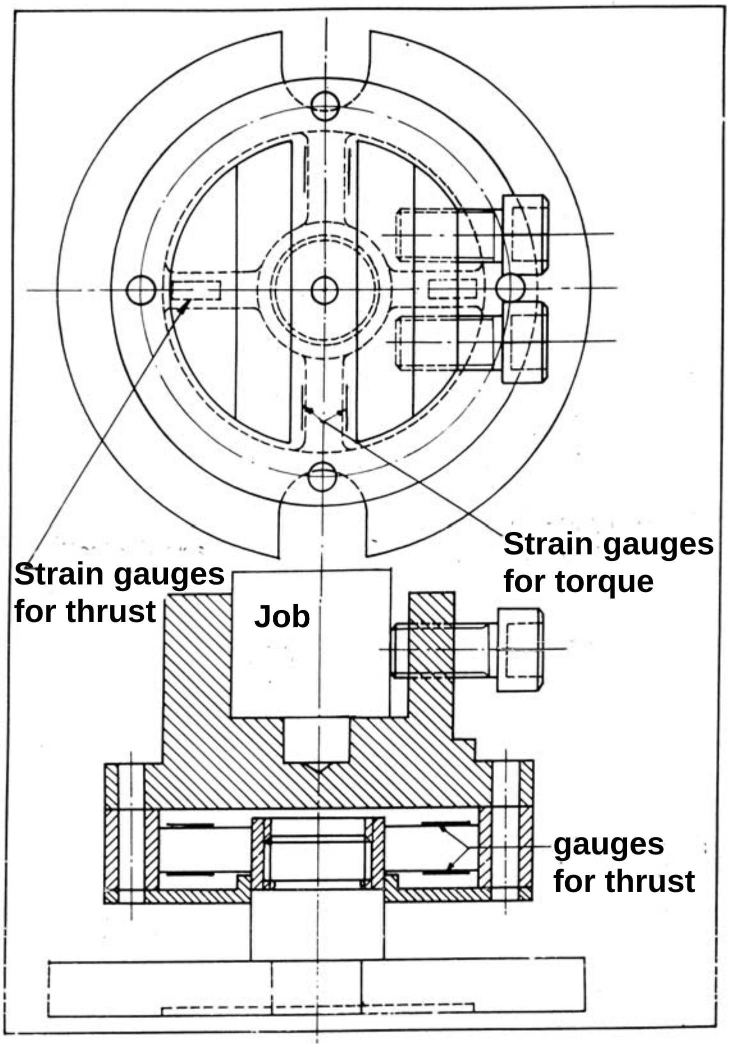
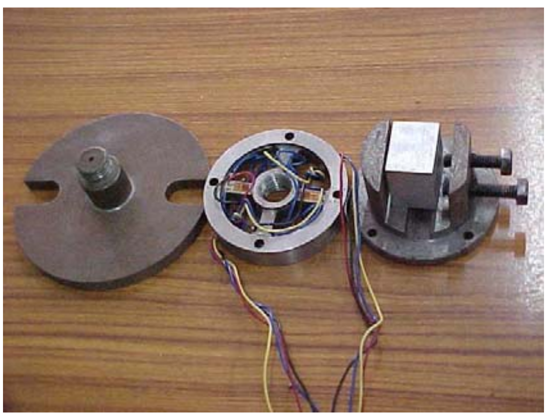


Fig. 10.11 *Schematic view of construction of a strain gauge type drilling dynamometer.*



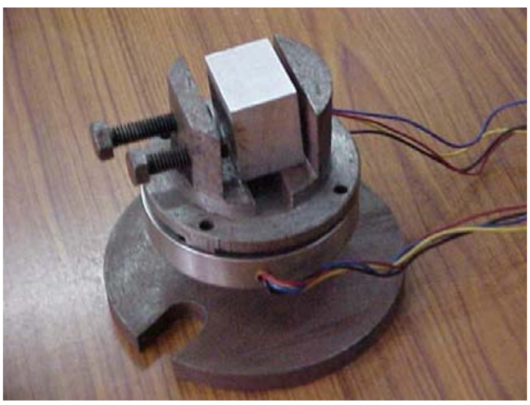
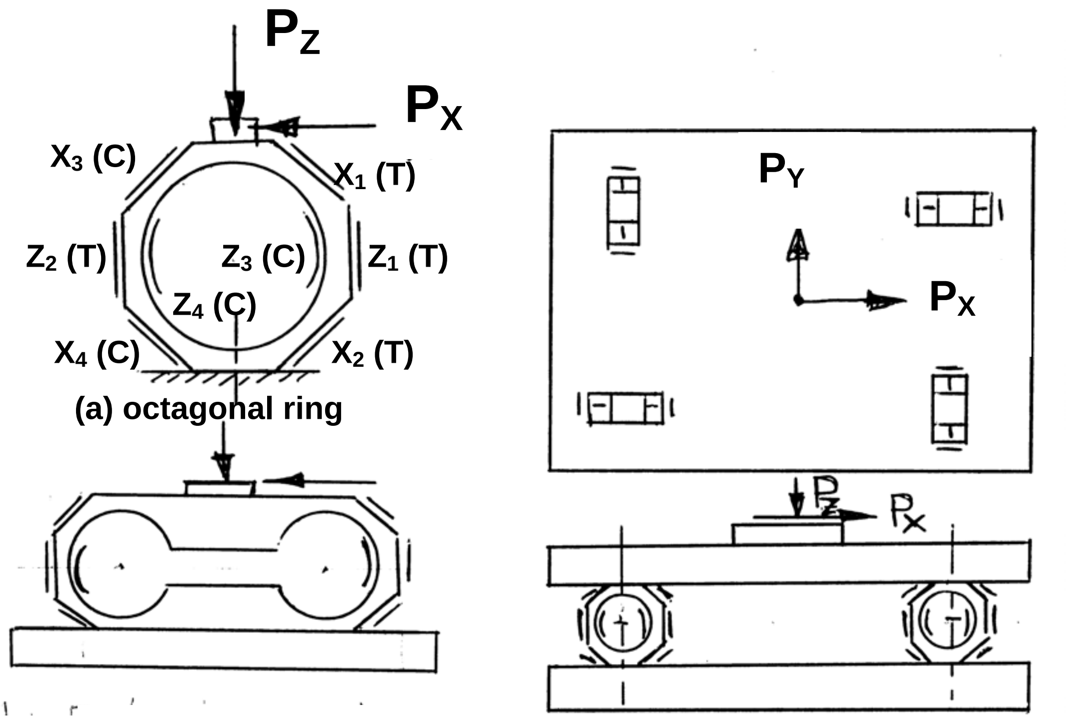


Fig. 10.12 *A strain gauge type drilling dynamometer and its major components.*

- **Milling dynamometer**

Since the cutting or loading point is not fixed w.r.t. the job and the dynamometer, the job platform rests on four symmetrically located supports in the form of four O-rings. The forces on each O-ring are monitored and summed up correspondingly for getting the total magnitude of all the three forces in X, Y and Z direction respectively.
Fig. 10.13 shows schematically the principle of using O-ring for measuring two forces by mounting strain gauges, 4 for radial force and 4 for transverse force.



(b) Extended O-ring (c) Four O-rings for P_X, P_Y and P_Z

Fig. 10.13 *Scheme of strain gauge type 3 – D milling dynamometer*

Fig. 10.14 typically shows configuration of a strain gauge type 3 – D milling dynamometer having 4 octagonal rings. Piezoelectric type 3 – D dynamometers are also available and used for measuring the cutting forces in milling (plain, end and face)

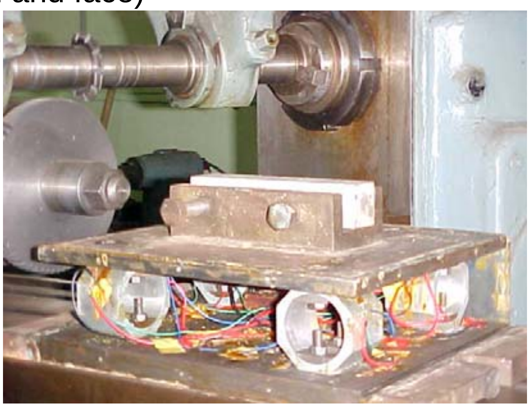


Fig. 10.14 *A typical strain gauge type 3 – D milling dynamometer*

- **Grinding dynamometer**

The construction and application of a strain gauge type (extended O-ring) grinding surface dynamometer and another piezoelectric type are typically shown in Fig. 10.15 and Fig. 10.16 respectively.

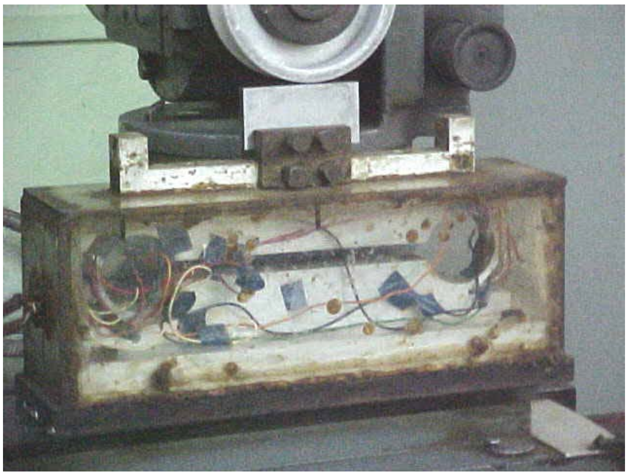


Fig. 10.15 *A typical strain – gauge type 2 – D grinding dynamometer*

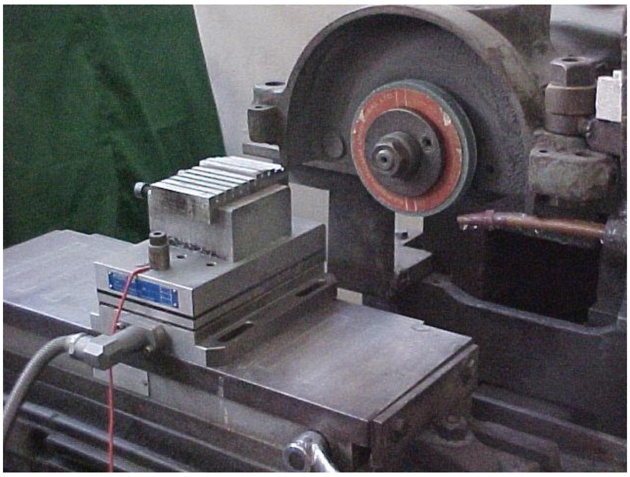


Fig. 10.16 *Piezoelectric type grinding dynamometer in operation.*

Unlike strain gauge type dynamometers, the sophisticated piezoelectric type (KISTLER) dynamometers can be used directly more accurately and reliably even without calibration by the user.

Module 2

Mechanics of Machining

Lesson
11
Cutting temperature – causes, effects, assessment and control

Instructional Objectives

At the end of this lesson, the students would be able to

(i) Identify the causes of development of heat and temperature in machining
(ii) State the effects of cutting temperature on cutting tool and job
(iii) Determine the value of cutting temperature
- Analytical methods
- Experimental methods

(iv) Evaluate the roles of variation of the different machining parameters on cutting temperature.
(v) Point out the general methods of controlling cutting temperature.

(i) Sources and causes of heat generation and development of temperature in machining

During machining heat is generated at the cutting point from three sources, as indicated in Fig. 2.7.1. Those sources and causes of development of cutting temperature are:

- Primary shear zone (1) where the major part of the energy is converted into heat
- Secondary deformation zone (2) at the chip – tool interface where further heat is generated due to rubbing and / or shear
- At the worn out flanks (3) due to rubbing between the tool and the finished surfaces.

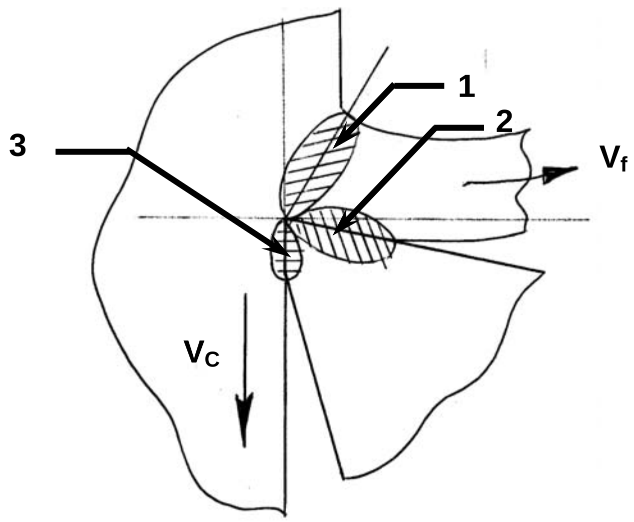


Fig. 2.7.1 *Sources of heat generation in machining*

The heat generated is shared by the chip, cutting tool and the blank. The apportionment of sharing that heat depends upon the configuration, size and thermal conductivity of the tool – work material and the cutting condition. Fig. 2.7.2 visualises that maximum amount of heat is carried away by the flowing chip. From 10 to 20% of the total heat goes into the tool and some heat is absorbed in the blank. With the increase in cutting velocity, the chip shares heat increasingly.

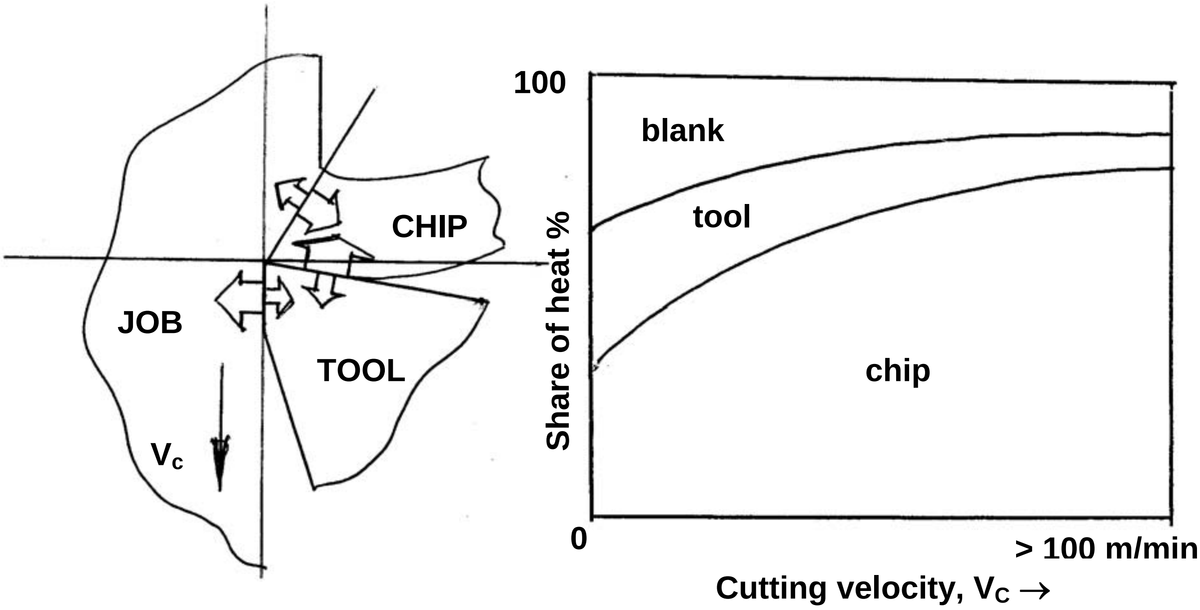


Fig. 2.7.2 *Apportionment of heat amongst chip, tool and blank.*

(ii) Effects of the high cutting temperature on tool and job.

The effect of the cutting temperature, particularly when it is high, is mostly detrimental to both the tool and the job. The major portion of the heat is taken away by the chips. But it does not matter because chips are thrown out. So attempts should be made such that the chips take away more and more amount of heat leaving small amount of heat to harm the tool and the job.
The possible detrimental effects of the high cutting temperature on cutting tool (edge) are

- rapid tool wear, which reduces tool life
- plastic deformation of the cutting edges if the tool material is not enough hot-hard and hot-strong
- thermal flaking and fracturing of the cutting edges due to thermal shocks
- built-up-edge formation

The possible detrimental effects of cutting temperature on the machined job are:

Δ dimensional inaccuracy of the job due to thermal distortion and expansion-contraction during and after machining

Δ surface damage by oxidation, rapid corrosion, burning etc.

Δ induction of tensile residual stresses and microcracks at the surface / subsurface

However, often the high cutting temperature helps in reducing the magnitude of the cutting forces and cutting power consumption to some extent by softening or reducing the shear strength, τ_s of the work material ahead the cutting edge. To attain or enhance such benefit the work material ahead the cutting zone is often additionally heated externally. This technique is known as Hot Machining and is beneficially applicable for the work materials which are very hard and hardenable like high manganese steel, Hadfield steel, Ni-hard, Nimonic etc.

(iii) Determination of cutting temperature

The magnitude of the cutting temperature need to be known or evaluated to facilitate

- assessment of machinability which is judged mainly by cutting forces and temperature and tool life
- design and selection of cutting tools
- evaluate the role of variation of the different machining parameters on cutting temperature
- proper selection and application of cutting fluid
- analysis of temperature distribution in the chip, tool and job.

The temperatures which are of major interests are:

θ_s : average shear zone temperature
θ_i : average (and maximum) temperature at the chip-tool interface
θ_f : temperature at the work-tool interface (tool flanks)
θ_{avg} : average cutting temperature

Cutting temperature can be determined by two ways :

- analytically – using mathematical models (equations) if available or can be developed. This method is simple, quick and inexpensive but less accurate and precise.
- Experimentally – this method is more accurate, precise and reliable.

- **Analytical estimation of cutting temperature, θ_s**

(a) Average shear zone temperature, θ_s

Equation(s) have to be developed for the purpose. One simple method is presented here.

The cutting energy per unit time, i.e., P_ZV_C gets used to cause primary shear and to overcome friction at the rake face as,

$$P_Z.V_C = P_S.V_S + F.V_f \qquad (2.7.1)$$

where, V_S = slip velocity along the shear plane

and V_f = average chip – velocity

So, $P_S.V_S = P_Z.V_C – F.V_f$

Equating amount of heat received by the chip in one minute from the shear zone and the heat contained by that chip, it appears,

$$\frac{A.q_1(P_Z.V_C - F.V_f)}{J} = c_v a_1 b_1 V_C(\theta_S - \theta_a) \quad (2.7.2)$$

where, A = fraction (of shear energy that is converted into heat)
q_1 = fraction (of heat that goes to the chip from the shear zone)
J = mechanical equivalent of heat of the chip / work material
C_v= volume specific heat of the chip
θ_a = ambient temperature
$a_1.b_1$ = cross sectional area of uncut chip
= ts_o

Therefore, $$\theta_s = \frac{Aq_1(P_Z.V_C - F.V_f)}{Jts_oV_C} + \theta_a \quad (2.7.3)$$

or, $$\theta_s \cong \frac{Aq_1(P_Z - F/\zeta)}{Jts_o} \quad (2.7.4)$$

Generally A varies from 0.95 to 1.0 and q from 0.7 to 0.9 in machining like turning.

(b) Average chip – tool interface temperature, θ_i

Using the two dimensionless parameters, Q_1 and Q_2 and their simple relation (Buckingham),

$$Q_1 = C_1.Q_2^n \quad (2.7.5)$$

where, $$Q_1 = \left(\frac{c_v\theta_i}{E_c}\right) \text{ and } Q_2 = \left(\frac{V_C c_v a_1}{\lambda}\right)^{0.5}$$

E_C = specific cutting energy
c_v = volume specific heat
λ = thermal conductivity
c_1 = a constant
n = an index close to 0.25

Therefore, $$\theta_i = c_1 E_C\sqrt{V_c a_1/\lambda c_v} \quad (2.7.6)$$

Using equation 2.7.6 one can estimate the approximate value of average θ_I from the known other machining parameters.
[There are several other models available for the cutting temperatures – see in books and journals]

- **Experimental methods of determination of cutting temperature**

Amongst θ_S, θ_i, and θ_f, θ_i is obviously the highest one and its value is maximum almost at the middle of the chip – tool contact length. Experimental methods generally provide the average or maximum value of θ_i. Some techniques also enable get even distribution of temperature in the chip, tool and job at the cutting zone.
The feasible experimental methods are :

- Calorimetric method – quite simple and low cost but inaccurate and gives only grand average value
- Decolourising agent – some paint or tape, which change in colour with variation of temperature, is pasted on

the tool or job near the cutting point; the as such colour of the chip (steels) may also often indicate cutting temperature

- Tool-work thermocouple – simple and inexpensive but gives only average or maximum value
- Moving thermocouple technique
- Embedded thermocouple technique
- Using compound tool
- Indirectly from Hardness and structural transformation
- Photo-cell technique
- Infra ray detection method

The aforesaid methods are all feasible but vary w.r.t. accuracy, preciseness and reliability as well as complexity or difficulties and expensiveness.
Some of the methods commonly used are briefly presented here.

- **Tool work thermocouple technique**

Fig. 2.7.3 shows the principle of this method.

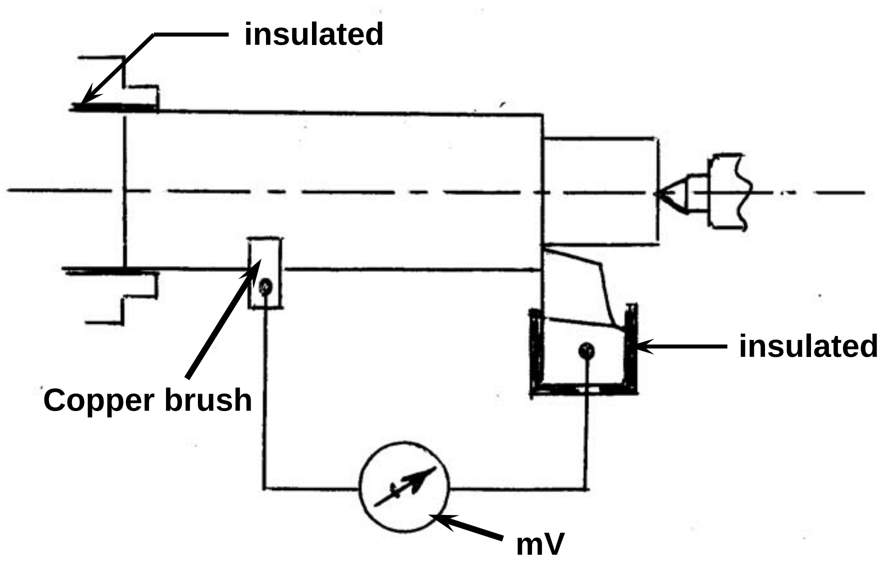


Fig. 2.7.3 *Tool-work thermocouple technique of measuring cutting temperature.*

In a thermocouple two dissimilar but electrically conductive metals are connected at two junctions. Whenever one of the junctions is heated, the difference in temperature at the hot and cold junctions produce a proportional current which is detected and measured by a milli-voltmeter. In machining like turning, the tool and the job constitute the two dissimilar metals and the cutting zone functions as the hot junction. Then the average cutting temperature is evaluated from the mV after thorough calibration for establishing the exact relation between mV and the cutting temperature.
Fig. 2.7.4 typically shows a method of calibration for measuring average cutting temperature, θ_{avg}, in turning steel rod by uncoated carbide tool.

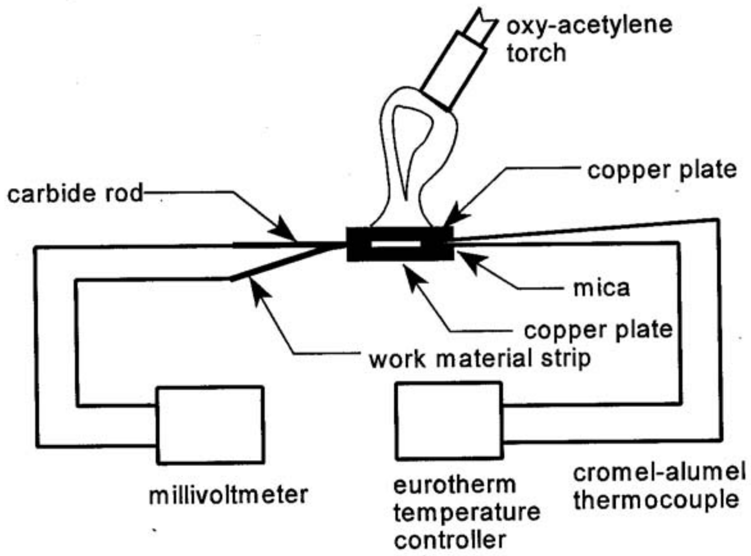


Fig. 2.7.4 *Calibration for tool – work thermocouple.*

- Moving thermocouple technique

This simple method, schematically shown in Fig. 2.7.5, enables measure the gradual variation in the temperature of the flowing chip before, during and immediately after its formation. A bead of standard thermocouple like chrome-alumel is brazed on the side surface of the layer to be removed from the work surface and the temperature is attained in terms of mV.

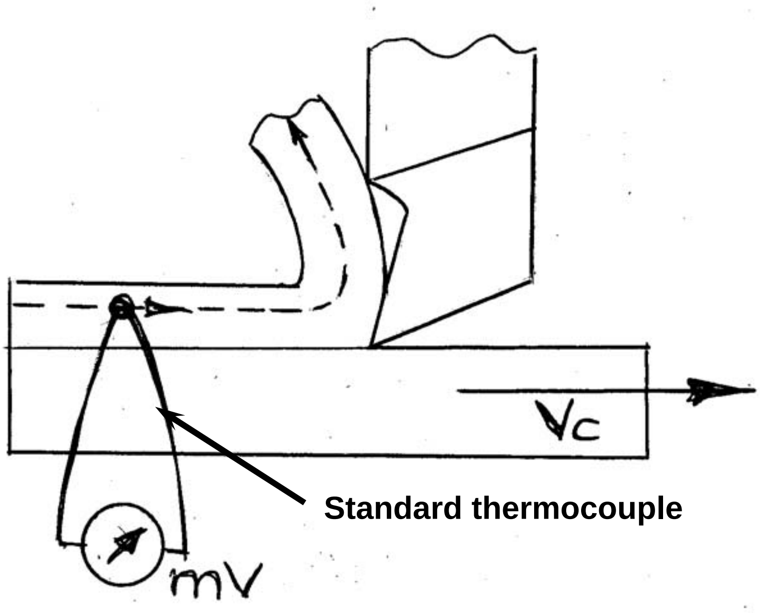


Fig. 2.7.5 *Moving thermocouple technique*

- Embedded thermocouple technique

In operations like milling, grinding etc. where the previous methods are not applicable, embedded thermocouple can serve the purpose. Fig. 2.7.6 shows the principle. The standard thermocouple monitors the job temperature at a certain depth, h_i from the cutting zone. The temperature recorded in oscilloscope or strip chart recorder becomes maximum when the thermocouple bead comes nearest (slightly offset) to the grinding zone. With the progress of grinding the depth, h_i gradually decreases after each grinding pass and the value of temperature, θ_m also rises as has been indicated in Fig. 2.7.6. For getting the temperature exactly at the surface i.e., grinding zone, h_i has to be zero, which is not possible. So the θ_m vs h_i curve has to be extrapolated upto $h_i = 0$ to get the actual grinding zone temperature. Log – log plot helps such extrapolation more easily and accurately.

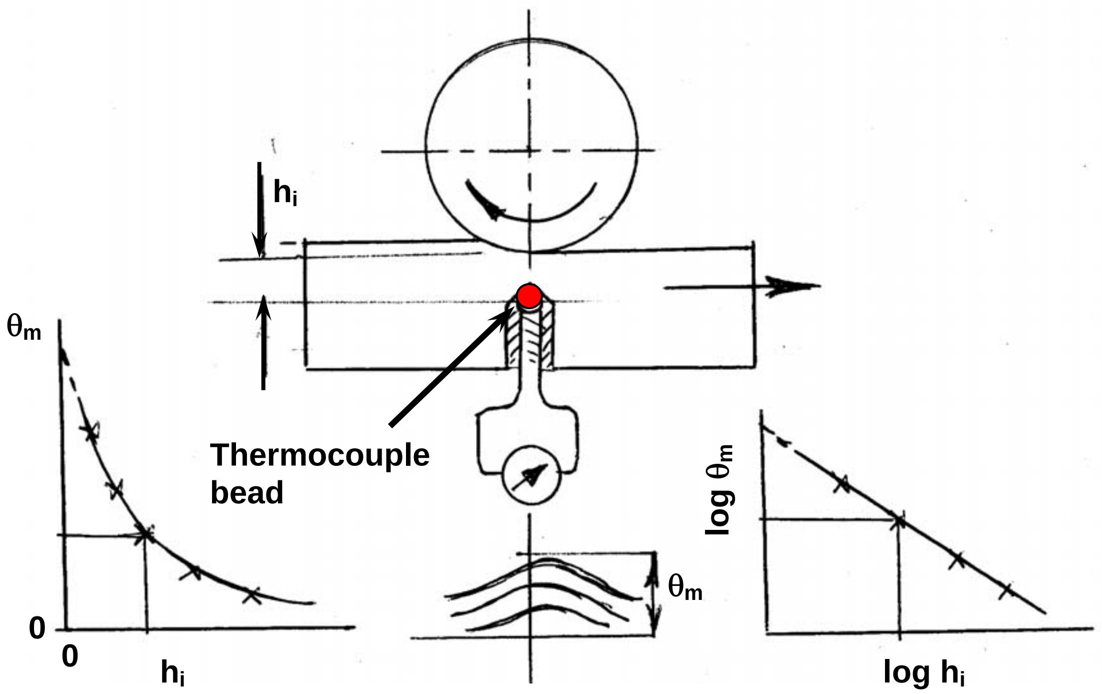


Fig. 2.7.6 *Embedded thermocouple technique*

- Measurement of chip-tool interface temperature by compound tool

In this method a conducting tool piece (carbide) is embedded in a non conducting tool (ceramic). The conducting piece and the job form the tool-work thermocouple as shown in Fig. 2.7.7 which detects temperature θ_i at the location (L_i) of the carbide strip. Thus θ_i can be measured along the entire chip-tool contact length by gradually reducing L_i by grinding the tool flank. Before that calibration has to be done as usual.

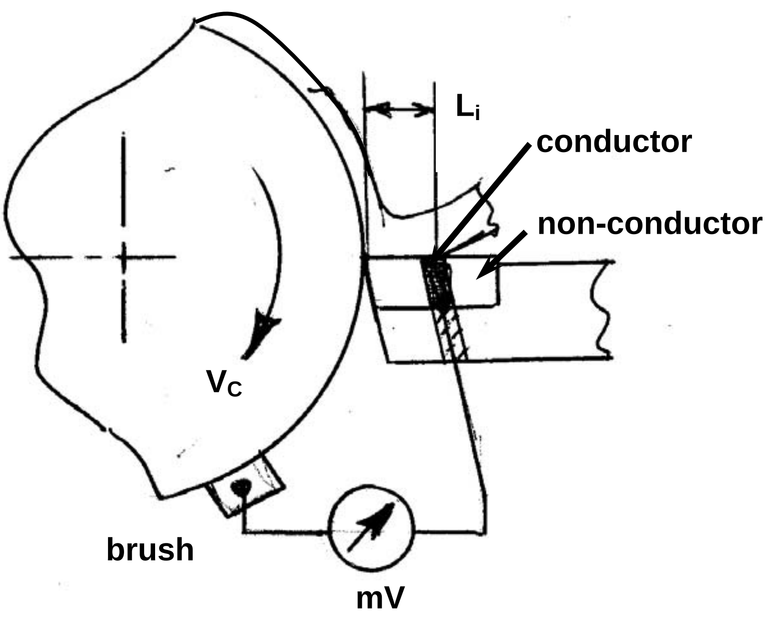


***Fig. 2.7.7** Compound rake used for measuring cutting temperature along rake surface*

- Photo-cell technique

This unique technique enables accurate measurement of the temperature along the shear zone and tool flank as can be seen in Fig. 2.7.8. The electrical resistance of the cell, like PbS cell, changes when it is exposed to any heat radiation. The amount of change in the resistance depends upon the temperature of the heat radiating source and is measured in terms of voltage, which is calibrated with the source temperature. It is evident from Fig. 2.7.8 that the cell starts receiving radiation through the small hole only when it enters the shear zone where the hole at the upper end faces a hot surface. Receiving radiation and measurement of temperature continues until the hole passes through the entire shear zone and then the tool flank.

- Infra-red photographic technique

This modern and powerful method is based on taking infra-red photograph of the hot surfaces of the tool, chip, and/or job and get temperature distribution at those surfaces. Proper calibration is to be done before that. This way the temperature profiles can be recorded in PC as indicated in Fig. 2.7.9. The fringe pattern readily changes with the change in any machining parameter which affect cutting temperature.

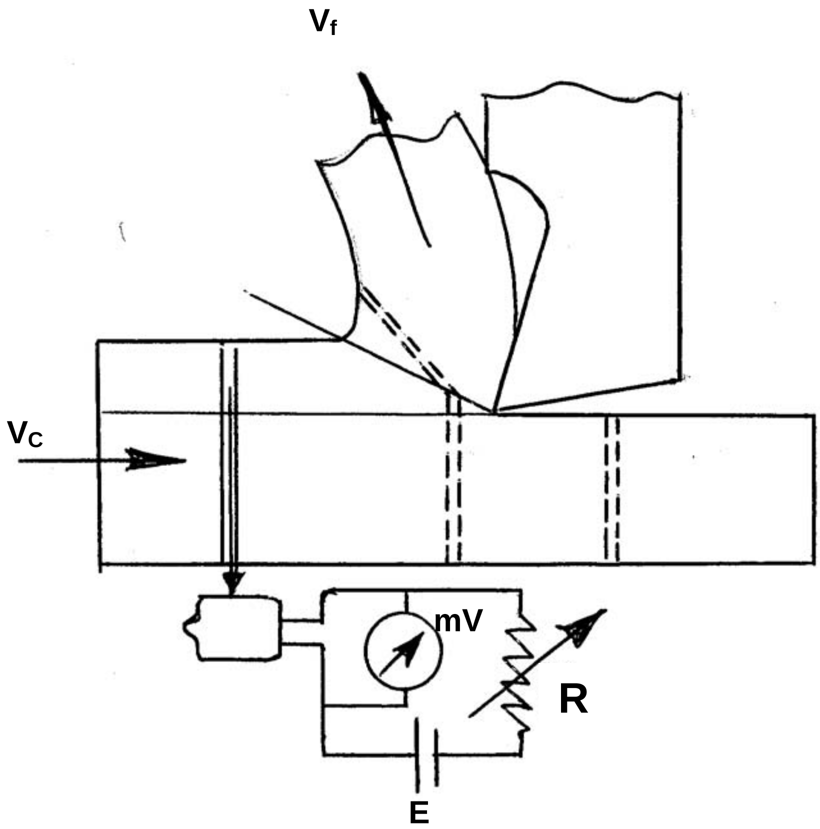


Fig. 2.7.8 *Measuring temperature at shear plane and tool flank by photocell technique*

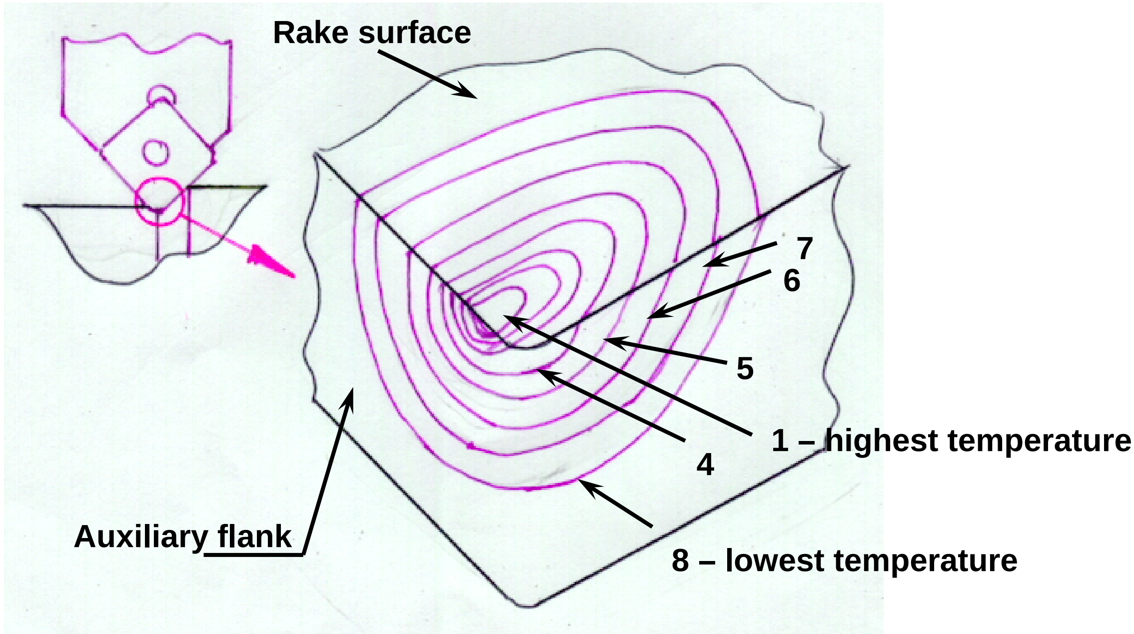


Fig. 2.7.9 *Temperature distribution at the tool tip detected by Infra ray technique*

(iv) Role of variation of the various machining parameters on cutting temperature

The magnitude of cutting temperature is more or less governed or influenced by all the machining parameters like :

- Work material : - specific energy requirement
  - ductility
  - thermal properties (λ, c_v)
- process parameters : - cutting velocity (V_C)
  - feed (s_o)
  - depth of cut (t)
- cutting tool material : - thermal properties
  - wear resistance
  - chemical stability
- tool geometry : - rake angle (γ)
  - cutting edge angle (ϕ)
  - clearance angle (α)
  - nose radius (r)
- cutting fluid : - thermal and lubricating properties
  - method of application

Many researchers studied, mainly experimentally, on the effects of the various parameters on cutting temperature. A well established overall empirical equation is,

$$\theta_i = \frac{C_\theta (V_C)^{0.4} (s_o \sin\phi)^{0.24} (t)^{0.105}}{(\frac{t}{s_o})^{0.086} (r)^{0.11} (ts_o)^{0.054}} \qquad (2.7.7)$$

where, C_θ = a constant depending mainly on the work-tool materials

Equation 2.7.7 clearly indicates that among the process parameters V_C affects θ_i most significantly and the role of t is almost insignificant. Cutting temperature depends also upon the tool geometry. Equation 2.7.7 depicts that θ_i can be reduced by lowering the principal cutting edge angle, ϕ and increasing nose radius, r. Besides that the tool rake angle, γ and hence inclination angle, λ also have significant influence on the cutting temperature. Increase in rake angle will reduce temperature by reducing the cutting forces but too much increase in rake will raise the temperature again due to reduction in the wedge angle of the cutting edge.

Proper selection and application of cutting fluid help reduce cutting temperature substantially through cooling as well as lubrication.

(v) Control of cutting temperature

It is already seen that high cutting temperature is mostly detrimental in several respects. Therefore, it is necessary to control or reduce the cutting temperature as far as possible.

Cutting temperature can be controlled in varying extent by the following general methods:

- proper selection of material and geometry of the cutting tool(s)
- optimum selection of V_C – s_o combination without sacrificing MRR
- proper selection and application of cutting fluid
- application of special technique, if required and feasible.

Exercise 2.7

Problem 1

Analytically estimate the average shear zone Temperature, θ_S for plain turning of a mild steel rod of diameter 100 mm by a carbide tool of geometry

–6°, -6°, 6°, 6°, 15°, 75°, 1.2 (mm) NRS at speed 400 rpm, feed 0.12 mm/rev and depth of cut 3.0 mm under dry condition when the followings were noted:

Main cutting force component, P_Z= 1200 N

Frictional force at the rake surface, F = 500 N

Chip thickness, a_2= 0.6 mm

Assume : 80% of mechanical energy gets converted into heat, 90% of the heat generated at the shear zone goes into the chips, Mechanical equivalent of heat, J = 4.2 J/Cal, Volume specific heat of mild steel,ρ_V=3554KJ/m^3 ^{o}C

Ambient temperature,θ_a = 25°

Solution :

• The general expression for average shear zone temperature, θ_S is,

$\theta_S = Aq(P_Z V_C — FV_f)/(Jr_V V_c t s_o) + q_a$

• where given,

A = 0.8 s_o = 0.12 mm/rev

q = 0.9 t = 3.0 mm

P_Z = 1000 N $V_C = \pi DN/ 1000$ m/min=125.6m/min

J = 4.2 J/Cal ρ_V = 825 Kcal/m^3/^{0}C

• chip velocity, $V_f = V_C/\zeta$

where $\zeta = a_2/a_1 = a_2/s_o\sin\phi$

given a_2 = 0.6 and $\phi = 75^o$ / $\zeta = 0.6/(0.12x\sin75^o) = 5.176$

Hence, V_f = = V_C / ζ = 125.6 / 5.176 =24.264 m/min

Thus,

$$\theta_S = \frac{0.8x0.9(1200x125.6 - 500x24.264)}{4.2x825x125.6x0.12x3x10^{-6}} + 25 = 643^oC$$ **answer**

Problem 2

From dimensional analysis,

$Q_1 = \rho_V \theta_I / E_C$ and

$Q_2 = (Va_1/ \rho_V \lambda)^2$

where $Q_1 = C_1.Q_2^{0.25}$ and C_1 is a constant, = 121.

Material-A is machined at 150m/min and feed of 0.2 mm/rev under orthogonal turning with principal cutting edge angle, $\phi = 90^{o}$. Determine the interface temp. θ_i for this material?

Given:

Properties	λ Kcal/m-hr-sec	ρ_v Kcal/m^3/^{o}C	σ_u Kg/mm^2	Δ- % elong.	ζ -chip red. Coeff.
	40	800	40	0.2	2.5

- Given the relations :

$$Q_1 = \rho_v\, \theta_I / E_c$$

$$Q_2 = (V_C a_1 / \rho_v \lambda)^2$$

and $$Q_1 = C_1 . Q_2^{0.25}$$

- Combining those equations :

$\theta_I = C_1 E_c (V_c a_1/\rho_v\, \lambda\,)^{0.5}$ where

θ_I = average chip-tool interface temp.

C_1 = constant = 121

E_c = specific cutting energy of the work material by a given tool in a given environment

V_c = cutting velocity, m/min

a_1 = uncut chip thickness = $s_o \sin\phi$ mm

- $E_c = (P_z.V_c/ts_oV_c) = (ts_o\tau_s fV_c)/(ts_oV_c)$

$= \tau_s f$ N/mm^2 where, τ_s = dynamic yield shear strength of the work material

and f = form factor

- For material A

$\tau = 0.74\Delta\sigma_u 6^{0.6\Delta}$; σ_{UA}= 40 kg/mm^2

$\Delta = 0.2$ and $f = \zeta_A - \tan\gamma + 1 \cong \zeta_A + 1 = 2.5+1 = 3.5$

- Hence for material A

$E_c = (0.74 \times 40 \times 6^{0.6 \times 0.2}) \times 3.75$ kg/mm^2

- $\theta_{iA} = C_1 \times E_{CA}(V_c a_1/\rho_{vA}\, \lambda_A)$

given c_v = 800, λ_A = 40 and C_1=121

$\theta_{iA} = 121\,\{E_{CA}(V_c a_1/ c_{vA}\, \lambda_A)^{0.5}\} = 500^oC$ answer

Module
2
Mechanics of Machining

Lesson
12
Control of cutting temperature and cutting fluid application

Instructional objectives

At the end of this lesson, the students would be able to

(i) State the possible ways of controlling cutting temperature
(ii) Identify the purposes of application of cutting fluid in machining
(iii) Ascertain the essential properties of cutting fluids
(iv) Illustrate the principle of cutting fluid action
(v) Classify the types of cutting fluids and state their application
(vi) Demonstrate the methods of application of cutting fluid in machining and grinding.

(i) Basic methods of controlling cutting temperature

It is already realised that the cutting temperature, particularly when it is quite high, is very detrimental for both cutting tools and the machined jobs and hence need to be controlled, i.e., reduced as far as possible without sacrificing productivity and product quality.
The methods generally employed for controlling machining temperature and its detrimental effects are :

- Proper selection of cutting tools; material and geometry
- Proper selection of cutting velocity and feed
- Proper selection and application of cutting fluid

- **Selection of material and geometry of cutting tool for reducing cutting temperature and its effects**

Cutting tool material may play significant role on reduction of cutting temperature depending upon the work material.
As for example,

- PVD or CVD coating of HSS and carbide tools enables reduce cutting temperature by reducing friction at the chip-tool and work-tool interfaces.
- In high speed machining of steels lesser heat and cutting temperature develop if machined by cBN tools which produce lesser cutting forces by retaining its sharp geometry for its extreme hardness and high chemical stability.
- The cutting tool temperature of ceramic tools decrease further if the thermal conductivity of such tools is enhanced (by adding thermally conductive materials like metals, carbides, etc in Al_2O_3 or Si_3N_4)

Cutting temperature can be sizeably controlled also by proper selection of the tool geometry in the following ways;

- large positive tool–rake helps in reducing heat and temperature generation by reducing the cutting forces, but too much increase in rake mechanically and thermally weakens the cutting edges
- compound rake, preferably with chip–breaker, also enables reduce heat and temperature through reduction in cutting forces and friction

- even for same amount of heat generation, the cutting temperature decreases with the decrease in the principal cutting edge angle, ϕ as

$$\theta_C \,\alpha\, [V_C^{0.5}(s_o \sin\phi)^{0.25}] \qquad (2.8.1)$$

- nose radiusing of single point tools not only improves surface finish but also helps in reducing cutting temperature to some extent.

o **Selection of cutting velocity and feed**

Cutting temperature can also be controlled to some extent, even without sacrificing MRR, by proper or optimum selection of the cutting velocity and feed within their feasible ranges. The rate of heat generation and hence cutting temperature are governed by the amount of cutting power consumption, P_C where;

$$P_C = P_Z.V_C = ts_o\tau_s fV_C \qquad (2.8.2)$$

So apparently, increase in both s_o and V_C raise heat generation proportionately. But increase in V_C, though further enhances heat generation by faster rubbing action, substantially reduces cutting forces, hence heat generation by reducing τ_s and also the form factor f. The overall relative effects of variation of V_C and s_o on cutting temperature will depend upon other machining conditions. Hence, depending upon the situation, the cutting temperature can be controlled significantly by optimum combination of V_C and s_o for a given MRR.

o **Control of cutting temperature by application of cutting fluid**

Cutting fluid, if employed, reduces cutting temperature directly by taking away the heat from the cutting zone and also indirectly by reducing generation of heat by reducing cutting forces

(ii) Purposes of application of cutting fluid in machining and grinding.

The basic purposes of cutting fluid application are :

- Cooling of the job and the tool to reduce the detrimental effects of cutting temperature on the job and the tool
- Lubrication at the chip–tool interface and the tool flanks to reduce cutting forces and friction and thus the amount of heat generation.
- 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
- 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_2, O_2, H_2S, N_xO_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.

(iii) Essential properties of cutting fluids

To enable the cutting fluid fulfil 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.

(iv) 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. 2.8.1

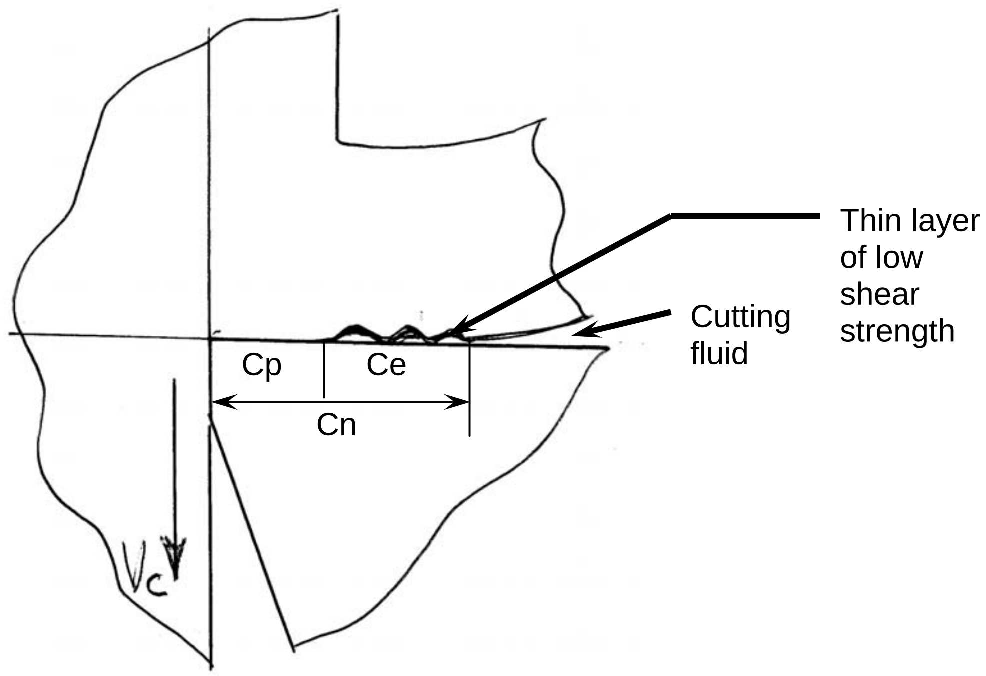


Fig. 2.8.1 Cutting fluid action in machining.

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. 2.8.2. Therefore, at high speed machining, the cutting fluid becomes unable to lubricate and cools the tool and the job only by bulk external cooling .

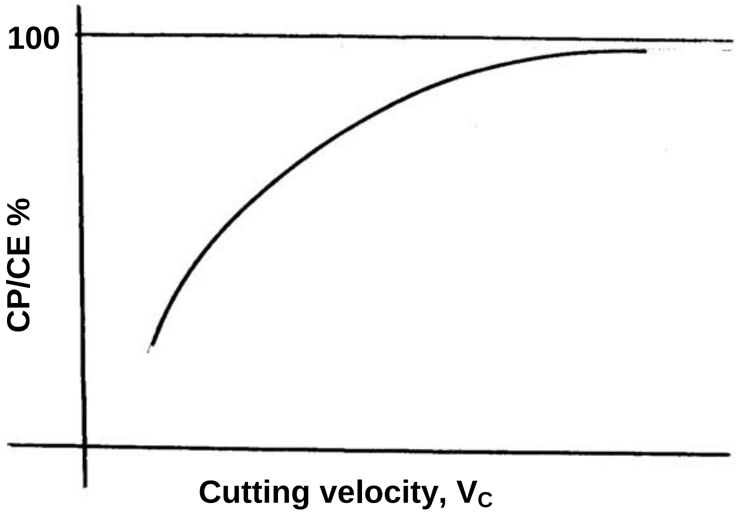


Fig. 2.8.2 *Apportionment of plastic and elastic contact zone with increase in cutting velocity.*

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 ($200^oC \sim 350^oC$), high ($350^oC \sim 500^oC$) and very high ($500^oC \sim 800^oC$) respectively.

(v) 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

- **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.
- **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.
- **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 depends 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. Selection of cutting fluids for machining some common engineering materials and operations are presented as follows :

- Grey cast iron :
  - ∆ Generally dry for its self lubricating property
  - ∆ Air blast for cooling and flushing chips

- Steels :
  - ∆ Soluble oil for cooling and flushing chips in high speed machining and grinding
  - ∆ If machined by HSS tools, sol. Oil (1: 20 ~30) for low carbon and alloy steels and neat oil with EPA for heavy cuts
  - ∆ If machined by carbide tools thinner sol. Oil for low strength steel, thicker sol. Oil (1:10 ~ 20) for stronger steels and staright sulphurised oil for heavy and low speed cuts and EP cutting oil for high alloy steel.
  - ∆ Often steels are machined dry by carbide tools for preventing thermal shocks.
- Aluminium and its alloys:
  - ∆ Preferably machined dry
  - ∆ Light but oily soluble oil
  - ∆ Straight neat oil or kerosene oil for stringent cuts.
- Copper and its alloys :
  - ∆ Water based fluids are generally used
  - ∆ Oil with or without inactive EPA for tougher grades of Cu-alloy.
- Stainless steels and Heat resistant alloys:
  - ∆ High performance soluble oil or neat oil with high concentration with chlorinated EP additive.

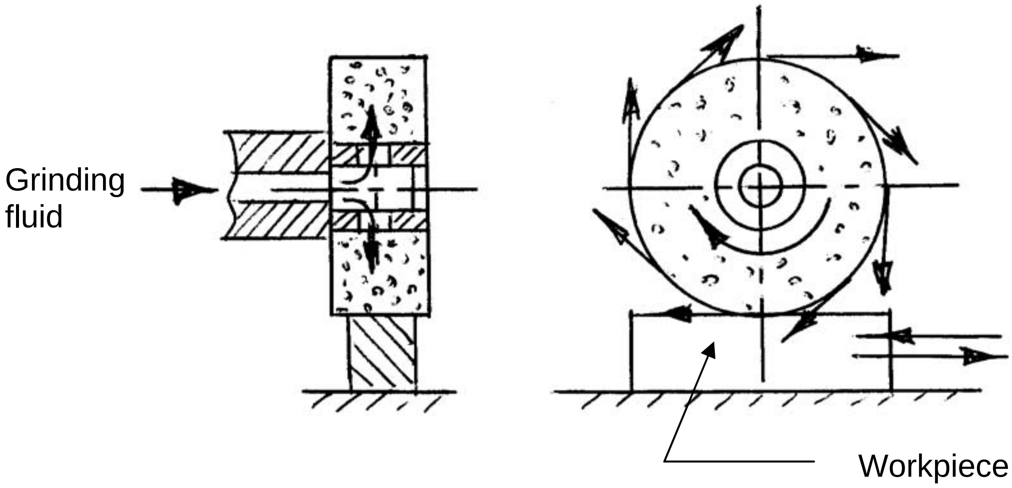
The brittle ceramics and cermets should be used either under dry condition or light neat oil in case of fine finishing.
Grinding at high speed needs cooling (1: 50 ~ 100) soluble oil. For finish grinding of metals and alloys low viscosity neat oil is also used.

(vi) Methods of application of cutting fluid

The effectiveness and expense of cutting fluid application significantly depend also on how it is applied in respect of flow rate and direction of application.
In machining, depending upon the requirement and facilities available, cutting fluids are generally employed in the following ways (flow) :

- Drop-by-drop under gravity
- Flood under gravity
- In the form of liquid jet(s)
- Mist (atomised oil) with compressed air
- Z-Z method – centrifugal through the grinding wheels (pores) as indicated in Fig. 2.8.3.

The direction of application also significantly governs the effectiveness of the cutting fluid in respect of reaching at or near the chip-tool and work-tool interfaces. Depending upon the requirement and accessibility the cutting fluid is applied from top or side(s). in operations like deep hole drilling the pressurised fluid is often sent through the axial or inner spiral hole(s) of the drill. For effective cooling and lubrication in high speed machining of ductile metals having wide and plastic chip-tool contact, cutting fluid may be pushed at



high pressure to the chip-tool interface through hole(s) in the cutting tool, as schematically shown in Fig. 2.8.4.

Fig. 2.8.3 *Z-Z method of cutting fluid application in grinding.*

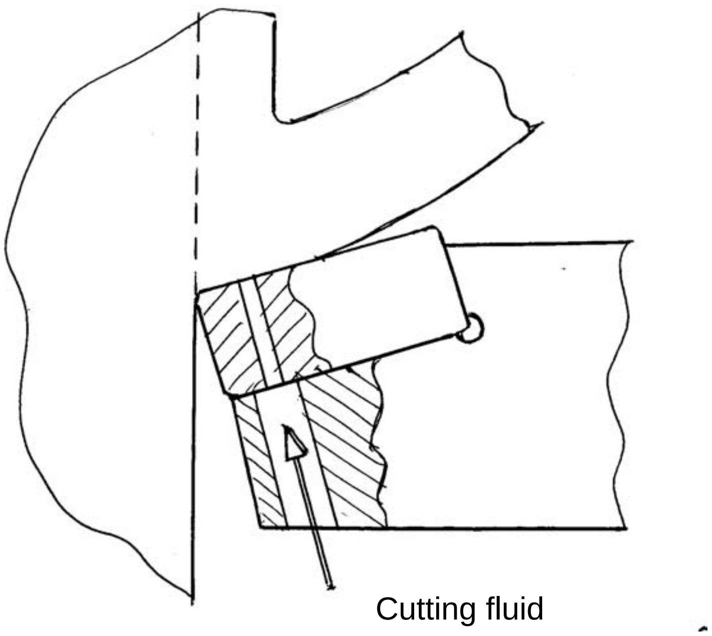


Fig. 2.8.4 *Application of cutting fluid at high pressure through the hole in the tool.*

Exercise – 2.8

Identify the correct answer from the given four options:

1. Cutting fluid is employed in machining for
   (a) cooling the tool and the job
   (b) lubricate at the rubbing surfaces
   (c) cleaning the machining zone
   (d) all of the above

2. For same tool-work materials and speed, feed and depth of cut, the average cutting temperature will decrease
   (a) with the increase in principal cutting edge angle (ϕ)
   (b) with the decrease in principal cutting edge angle (ϕ)
   (c) with the increase in auxiliary cutting edge angle (ϕ_1)
   (d) with the decrease in the auxiliary cutting edge angle (ϕ_1)

3. The work material, which is machined by HSS tool generally in dry condition, is
   (a) grey cast iron
   (b) mild steel
   (c) stainless steel
   (d) low alloy steel

4. Extreme pressure additive (EPA) is mixed with cutting fluid for improving its power of
   (a) cooling
   (b) lubrication
   (c) cleaning of the cutting zone
   (d) protection of the machined surface

5. More lubricating type cutting fluid should be used while machining
   (a) easily machinable material at high speed
   (b) grey cast iron at low speed
   (c) high alloy steels at low speed
   (d) aluminium at high speed

6. In Z-Z method of cooling in surface grinding, the cutting fluid is employed
   (a) in the form of flood under gravity
   (b) in the form of jet at the grinding zone
   (c) drop by drop
   (d) none of the above

7. In machining copper under heavy cut one should use
   (a) light soluble oil
   (b) active type chemical fluid

(c) inactive type chemical fluid
(d) compound oil

Answers

1 – (d)
2 – (b)
3 – (a)
4 – (b)
5 – (c)
6 – (d)
7 – (b)

Module
3
Machinability

Lesson
13
Concept of Machinability and its Improvement

Instructional objectives

At the end of this lesson, the students would be able to

(i) Conceptualise machinability and state its
- Definition
- Criteria of judgement

(ii) Illustrate how machinability is governed or influenced by several factors,
- Chemical and physical properties of work material
- Processing parameters
- Cutting tool parameters
- Environmental factors

(iii) Suggest various methods of improvement of machinability

(i) Concept, Definition And Criteria Of Judgement Of Machinability

It is already known that preformed components are essentially machined to impart dimensional accuracy and surface finish for desired performance and longer service life of the product. It is obviously attempted to accomplish machining effectively, efficiently and economically as far as possible by removing the excess material smoothly and speedily with lower power consumption, tool wear and surface deterioration. But this may not be always and equally possible for all the work materials and under all the conditions. The machining characteristics of the work materials widely vary and also largely depend on the conditions of machining. A term; 'Machinability' has been introduced for gradation of work materials w.r.t. machining characteristics.

But truly speaking, there is no unique or clear meaning of the term machinability. People tried to describe "Machinability" in several ways such as:
- It is generally applied to the machining properties of work material
- It refers to material (work) response to machining
- It is the ability of the work material to be machined
- It indicates how easily and fast a material can be machined.

But it has been agreed, in general, that it is difficult to clearly define and quantify Machinability. For instance, saying 'material A is more machinable than material B' may mean that compared to 'B',
- 'A' causes lesser tool wear or longer tool life
- 'A' requires lesser cutting forces and power
- 'A' provides better surface finish

where, surface finish and tool life are generally considered more important in finish machining and cutting forces or power in bulk machining.

Machining is so complex and dependant on so many factors that the order of placing the work material in a group, w.r.t. favourable behaviour in machining, will change if the consideration is changed from tool life to cutting power or surface quality of the product and vice versa. For instance, the machining behaviour of work materials are so affected by the cutting tool; both material and geometry, that often machinability is expressed as "operational characteristics of the work-tool combination". Attempts were made to measure or quantify machinability and it was done mostly in terms of :

- tool life which substantially influences productivity and economy in machining
- magnitude of cutting forces which affects power consumption and dimensional accuracy
- surface finish which plays role on performance and service life of the product.

Often cutting temperature and chip form are also considered for assessing machinability.

But practically it is not possible to use all those criteria together for expressing machinability quantitatively. In a group of work materials a particular one may appear best in respect of, say, tool life but may be much poor in respect of cutting forces and surface finish and so on. Besides that, the machining responses of any work material in terms of tool life, cutting forces, surface finish etc. are more or less significantly affected by the variation; known or unknown, of almost all the parameters or factors associated with machining process. Machining response of a material may also change with the processes, i.e. turning, drilling, milling etc. therefore, there cannot be as such any unique value to express machinability of any material, and machinability, if to be used at all, has to be done for qualitative assessment.

However, earlier, the relative machining response of the work materials compared to that of a standard metal was tried to be evaluated quantitatively only based on tool life ($V_B^* = 0.33$ mm) by an index,

Machinability rating (MR)

$$= \frac{\text{speed (fpm) of machining the work giving 60 min tool life}}{\text{speed (fpm) of machining the standard metal giving 60 min tool life}} \text{x}100$$

Fig. 3.1.1 shows such scheme of evaluating Machinability rating (MR) of any work material.

The free cutting steel, AISI – 1112, when machined (turned) at 100 fpm, provided 60 min of tool life. If the work material to be tested provides 60 min of tool life at cutting velocity of 60 fpm (say), as indicated in Fig. 3.1.1, under the same set of machining condition, then machinability (rating) of that material would be,

$MR = \frac{60}{100} \text{x}100 = 60\%$ or simply 60 (based on 100% for the standard material)

or, simply the value of the cutting velocity expressed in fpm at which a work material provides 60 min tool life was directly considered as the MR of that work material. In this way the MR of some materials, for instance, were evaluated as,

Metal	MR
Ni	200
Br	300
Al	200
CI	70
Inconel	30

But usefulness and reliability of such practice faced several genuine doubts and questions :

- tool life cannot or should not be considered as the only criteria for judging machinability
- under a given condition a material can yield different tool life even at a fixed speed (cutting velocity); exact composition, microstructure, treatments etc. of that material may cause significant difference in tool life
- the tool life - speed relationship of any material may substantially change with the variation in
  - o material and geometry of the cutting tool
  - o level of process parameters (V_c, s_o, t)
  - o machining environment (cutting fluid application)
  - o machine tool condition

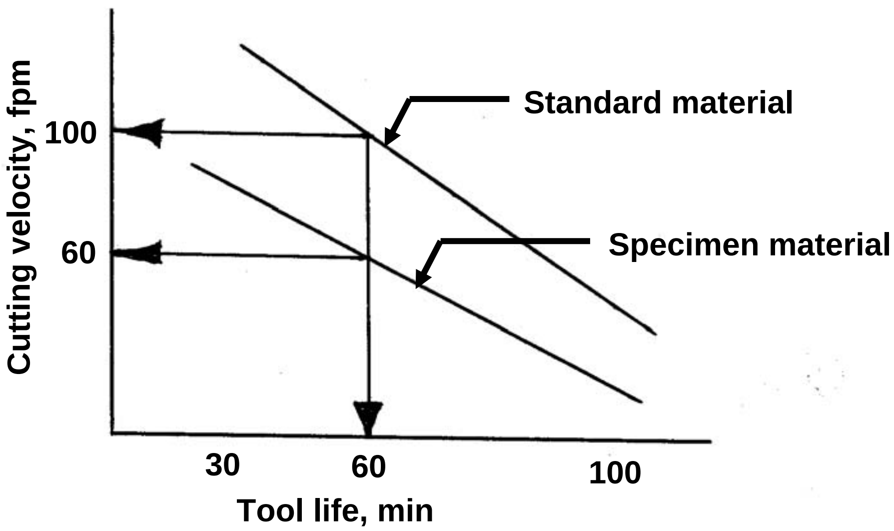


Fig. 3.1.1 *Machinability rating in terms of cutting velocity giving 60 min tool life.*

Keeping all such factors and limitations in view, Machinability can be tentatively defined as “ability of being machined” and more reasonably as “ ease of machining”.
Such ease of machining or machinability characteristics of any tool-work pair is to be judged by :

- magnitude of the cutting forces
- tool wear or tool life
- surface finish
- magnitude of cutting temperature
- chip forms

Machinability will be considered desirably high when cutting forces, temperature, surface roughness and tool wear are less, tool life is long and chips are ideally uniform and short enabling short chip-tool contact length and less friction.

(ii) Role Of Variation Of The Different Machining Parameters Or Factors On Machinability Of Work Materials.

The machinability characteristics and their criteria, i.e., the magnitude of cutting forces and temperature, tool life and surface finish are governed or influenced more or less by all the variables and factors involved in machining such as,

(a) properties of the work material
(b) cutting tool; material and geometry
(c) levels of the process parameters
(d) machining environments (cutting fluid application etc)

Machinability characteristics of any work – tool pair may also be further affected by,

- strength, rigidity and stability of the machine
- kind of machining operations done in a given machine tool
- functional aspects of the special techniques, if employed.

(a) Role of the properties of the work material on machinability.

The work material properties that generally govern machinability in varying extent are:

- the basic nature – brittleness or ductility etc.
- microstructure
- mechanical strength – fracture or yield
- hardness
- hot strength and hot hardness
- work hardenability
- thermal conductivity
- chemical reactivity
- stickiness / self lubricity.

- **Machining of brittle and ductile materials**

In general, brittle materials are relatively more easily machinable for :

- the chip separation is effected by brittle fracture requiring lesser energy of chip formation
- shorter chips causing lesser frictional force and heating at the rake surface

For instance, compared to even mild steel, grey cast iron jobs produce much lesser cutting forces and temperature. Smooth and continuous chip formation is likely to enable mild steel produce better surface finish but BUE, if formed, may worsen the surface finish.

For machining, like turning of ductile metals, the expression

$$P_Z = ts_o\tau_s f \qquad (3.1.1)$$

Indicates that cutting forces increase with the increase in yield shear strength, τ_s of the work material. The actual value of τ_s of any material, again, changes with the condition of machining and also on the ductility of the work material as,

$$\tau_s = 0.74\sigma_U\varepsilon^{0.6\Delta} \qquad (3.1.2)$$

where,

σ_u = ultimate tensile strength which is a classical property of the material

Δ = percentage elongation indicating ductility of the work material

ε = cutting strain

Role of microstructure

The value of τ_s of a given material depends sizeably on its microstructure. Coarse microstructure leads to lesser value of τ_s. Therefore, τ_s can be desirably reduced by

- proper heat treatment like annealing of steels
- controlled addition of materials like sulphur (S), lead (Pb), Tellerium etc leading to free cutting of soft ductile metals and alloys.

Free Cutting steels

Addition of lead in low carbon steels and also in aluminium, copper and their alloys help reduce their τ_s. The dispersed lead particles act as discontinuity and solid lubricants and thus improve machinability by reducing friction, cutting forces and temperature, tool wear and BUE formation. Addition of sulphur also enhances machinability of low carbon steels by enabling its free cutting. The added sulphur reacts with Mn present in the steels and forms MnS inclusions which being very soft act almost as voids and reduce friction at the tool – work interfaces resulting reduction of cutting forces and temperature and their consequences. The degree of ease of machining of such free cutting steels depend upon the morphology of the MnS inclusions which can be made more favourable by addition of trace of Tellurium.

Effects of hardness, hot strength and hot hardness and work hardening of work materials.

Harder materials are obviously more difficult to machine for increased cutting forces and tool damage.
Usually, with the increase in cutting velocity the cutting forces decrease to some extent making machining easier through reduction in τ_s and also chip thickness. τ_s decreases due to softening of the work material at the shear zone due to elevated temperature. Such benefits of increased temperature and cutting velocity are not attained when the work materials are hot strong and hard like Ti and Ni based superalloys and work hardenable like high manganese steel, Ni- hard, Hadfield steel etc.
Sticking of the materials (like pure copper, aluminium and their alloys) and formation of BUE at the tool rake surface also hamper machinability by increasing friction, cutting forces, temperature and surface roughness. Lower thermal conductivity of the work material affects their machinability by raising the cutting zone temperature and thus reducing tool life.
Sticking of the materials (like pure copper, aluminium and their alloys) and formation of BUE at the tool rake surface also hamper machinability by increasing friction, cutting forces, temperature and surface roughness.

(b) Role of cutting tool material and geometry on machinability of any work material.

- **Role of tool materials**

In machining a given material, the tool life is governed mainly by the tool material which also influences cutting forces and temperature as well as accuracy and finish of the machined surface. The composition, microstructure, strength, hardness, toughness, wear resistance, chemical stability and thermal conductivity of the tool material play significant roles on the machinability characteristics though in different degree depending upon the properties of the work material.
Fig. 3.1.2 schematically shows how in turning materials like steels, the tool materials affect tool life at varying cutting velocity.
High wear resistance and chemical stability of the cutting tools like coated carbides, ceramics, cubic Boron nitride (cBN) etc also help in providing better surface integrity of the product by reducing friction, cutting temperature and BUE formation in high speed machining of steels. Very soft, sticky and chemically reactive material like pure aluminium attains highest machinability when machined by diamond tools.

- **Role of the geometry of cutting tools on machinability.**

The geometrical parameters of cutting tools (say turning tool) that significantly affect the machinability of a given work material (say mild steel) under given machining conditions in terms of specific energy requirement, tool life, surface finish etc. are:

- tool rake angles (γ)
- clearance angle (α)
- cutting angles (ϕ and ϕ_1)

- nose radius (r)

The other geometrical (tool) parameters that also influence machinability to some extent directly and indirectly are:

— inclination angle (λ)
— edge bevelling or rounding (r′)
— depth, width and form of integrated chip breaker

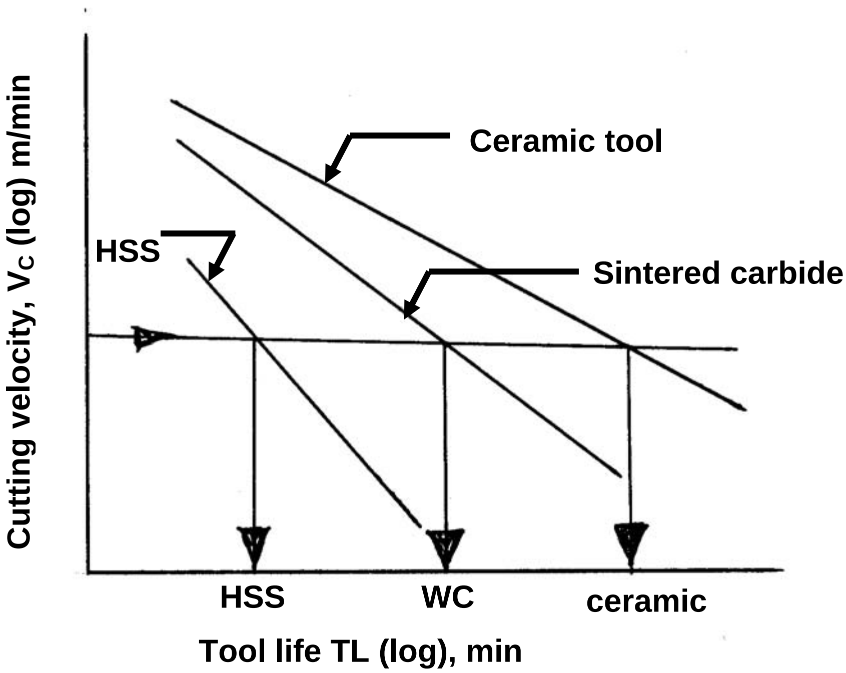


Fig. 3.1.2 *Role of cutting tool material on machinability (tool life)*

Effects of tool rake angle(s) on machinability

In machining like turning ductile material, the main cutting force, P_Z decreases as typically shown in Fig. 3.1.3 mainly due to,

$$P_Z = ts_o\tau_s f \qquad (3.1.3)$$

where, $f = \zeta - \tan\gamma + 1$

$$\zeta = e^{\mu(\pi/2-\gamma)}$$

$$\tau_s = 0.74\sigma_U\varepsilon^{0.6\Delta}$$

$$\varepsilon \cong \zeta - \tan\gamma$$

The expressions clearly show that increase in γ reduces P_Z through reduction in cutting strain (ε), chip reduction coefficient (ζ) and hence τ_s and the form factor, f.

With P_Z, P_{XY} also decreases proportionally.

But too much increase in rake weakens the cutting edge both mechanically and thermally and may cause premature failure of the tool.

Presence of inclination angle, λ enhances effective rake angle and thus helps in further reduction of the cutting forces.

However, the tool rake angle does not affect surface finish that significantly.

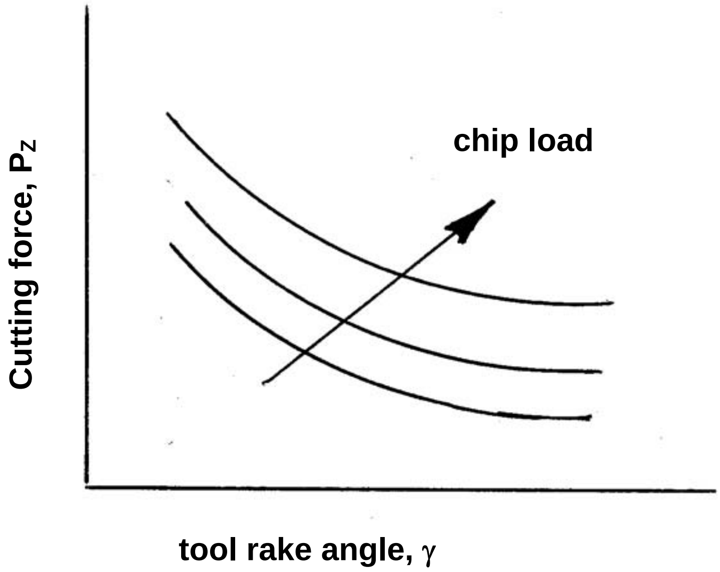


Fig. 3.1.3 *Effect of tool rake angle on machinability (cutting force, P_Z)*

Role of cutting angles (ϕ and ϕ₁) on machinability

The variation in the principal cutting edge angle, ϕ does not affect P_Z or specific energy requirement but influences P_Y and the cutting temperature (θ_C) quite significantly as indicated in Fig. 3.1.4 mainly for,

$$P_Y = P_{XY}\cos\phi \quad \text{i.e.,} \ \alpha\ P_Z \cos\phi \qquad (3.1.4)$$

and

$$\theta_C \ \alpha \ \sqrt{V_C s_o \sin\phi} \qquad (3.1.5)$$

The force, P_Y, if large, may impair the product quality by dimensional deviation and roughening the surface due to vibration.
Reduction in both ϕ and ϕ_1 improves surface finish sizeably in continuous chip formation, as

$$h_{max} = \frac{s_o}{\cot\phi + \cot\phi_1} \qquad (3.1.6)$$

where h_{max} (define h_{max} ?) is the maximum surface roughness due to feed marks alone.

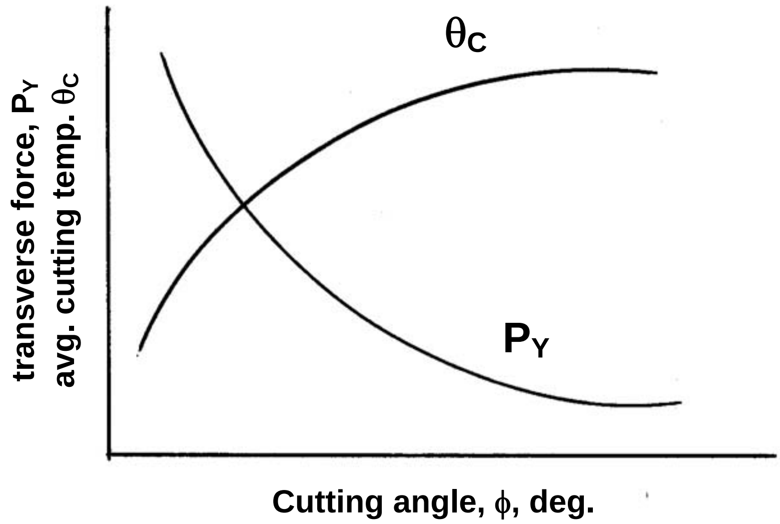


Fig. 3.1.4 *Effects of variation in cutting angle on machinability (θ_C and P_y)*

Effects of clearance angle (α)

Fig. 3.1.5 schematically shows how clearance angle, α affects tool life.

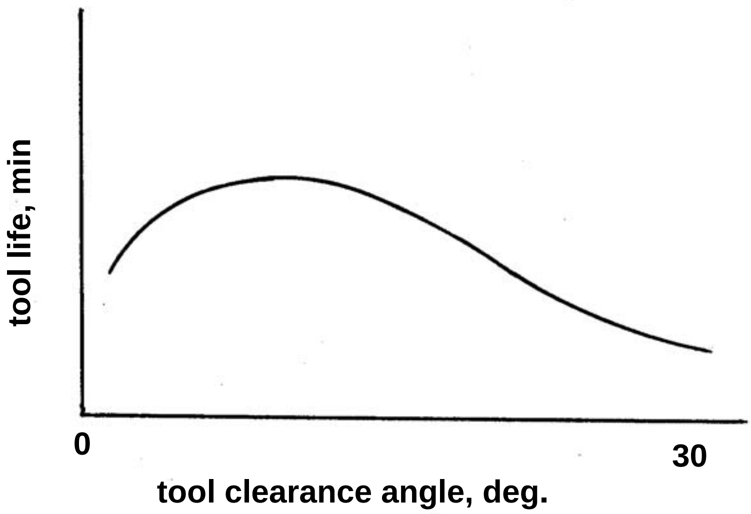


Fig. 3.1.5 *Influence of tool clearance angle on tool life.*

Inadequate clearance angle reduces tool life and surface finish by tool - work rubbing, and again too large clearance reduces the tool strength and hence tool life.

Role of tool nose radius (r) on machinability

Proper tool nose radiusing improves machinability to some extent through

- increase in tool life by increasing mechanical strength and reducing temperature at the tool tip
- reduction of surface roughness, h_{max}

  as $$h_{max} = \frac{(s_o)^2}{8r} \quad (3.1.7)$$

Proper edge radiusing (r′) also often enhances strength and life of the cutting edge without much increase in cutting forces

(c) Role of the process parameters on machinability

Proper selection of the levels of the process parameters (V_C, s_o and t) can provide better machinability characteristics of a given work – tool pair even without sacrificing productivity or MRR.
Amongst the process parameters, depth of cut, t plays least significant role and is almost invariable. Compared to feed (s_o) variation of cutting velocity (V_C) governs machinability more predominantly. Increase in V_C, in general, reduces tool life but it also reduces cutting forces or specific energy requirement and improves surface finish through favourable chip-tool interaction. Some cutting tools, specially ceramic tools perform better and last

longer at higher V_C within limits. Increase in feed raises cutting forces proportionally but reduces specific energy requirement to some extent. Cutting temperature is also lesser susceptible to increase in s_o than V_C. But increase in s_o, unlike V_C raises surface roughness. Therefore, proper increase in V_C, even at the expense of s_o often can improve machinability quite significantly.

(d) Effects of machining environment (cutting fluids) on machinability

The basic purpose of employing cutting fluid is to improve machinability characteristics of any work – tool pair through :

- improving tool life by cooling and lubrication
- reducing cutting forces and specific energy consumption
- improving surface integrity by cooling, lubricating and cleaning at the cutting zone

The favourable roles of cutting fluid application depend not only on its proper selection based on the work and tool materials and the type of the machining process but also on its rate of flow, direction and location of application.

(iii) Possible Ways Of Improving Machinability Of Work Materials

The machinability of the work materials can be more or less improved, without sacrificing productivity, by the following ways :

- Favourable change in composition, microstructure and mechanical properties by mixing suitable type and amount of additive(s) in the work material and appropriate heat treatment
- Proper selection and use of cutting tool material and geometry depending upon the work material and the significant machinability criteria under consideration
- Optimum selection of V_C and s_o based on the tool – work materials and the primary objectives.
- Proper selection and appropriate method of application of cutting fluid depending upon the tool – work materials, desired levels of productivity i.e., V_C and s_o and also on the primary objectives of the machining work undertaken
- Proper selection and application of special techniques like dynamic machining, hot machining, cryogenic machining etc, if feasible, economically viable and eco-friendly.

Module 3

Machinability

Lesson
14
Failure of cutting tools and tool life

Instructional objectives

At the end of this lesson, the students will be able to

(i) State how the cutting tools fail
(ii) Illustrate the mechanisms and pattern of tool wear
(iii) Ascertain the essential properties of cutting tool materials
(iv) Define and assess tool life
(v) Develop and use tool life equation.

(i) Failure of cutting tools

Smooth, safe and economic machining necessitate

- prevention of premature and catastrophic 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 :

i) Mechanical breakage due to excessive forces and shocks. Such kind of tool failure is random and catastrophic in nature and hence are extremely detrimental.
ii) Quick dulling by plastic deformation due to intensive stresses and temperature. This type of failure also occurs rapidly and are quite detrimental and unwanted.
iii) 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.

(ii) 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 :

i) Mechanical wear
   - thermally insensitive type; like abrasion, chipping and delamination
   - thermally sensitive type; like adhesion, fracturing, flaking etc.

ii) Thermochemical wear
   - macro-diffusion by mass dissolution
   - micro-diffusion by atomic migration

iii) Chemical wear

iv) Galvanic wear

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 wear increases with the increase in temperature at the cutting zone.
Diffusion wear becomes predominant when the cutting temperature becomes very high due to high cutting velocity and high strength of the work material.
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.
Galvanic wear, based on electrochemical dissolution, seldom occurs when both the work tool materials are electrically conductive, cutting zone temperature is high and the cutting fluid acts as an electrolyte.
The usual pattern or geometry of wear of turning and face milling inserts are typically shown in Fig. 3.2.1 (a and b) and Fig. 3.2.2 respectively.

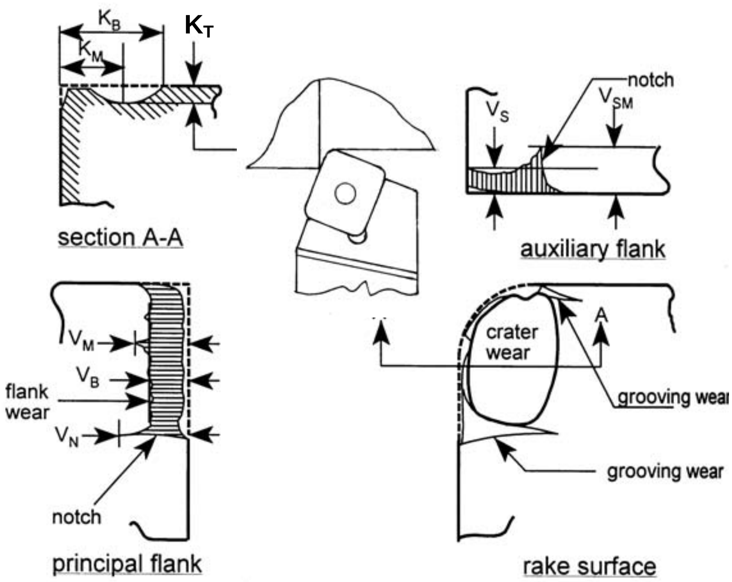


***Fig. 3.2.1 (a)** Geometry and major features of wear of turning tools*

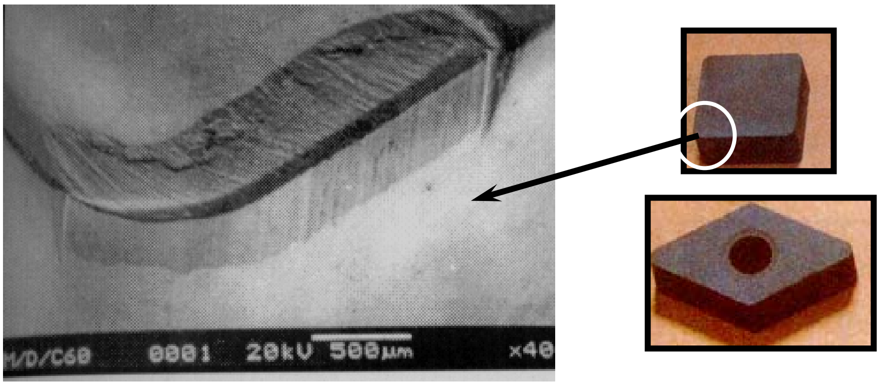


Fig. 3.2.1 (b) Photographic view of the wear pattern of a turning tool insert

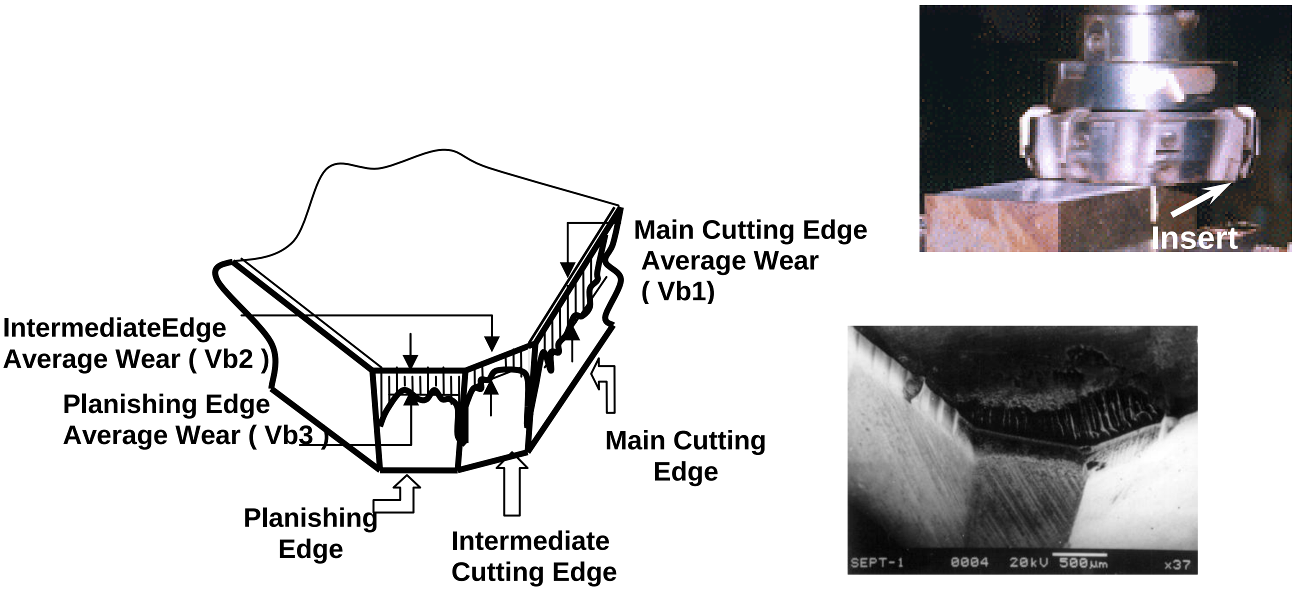


Fig. 3.2.2 *Schematic (a) and actual view (b) of wear pattern of face milling insert*

In addition to ultimate failure of the tool, the following effects are also caused by the growing tool-wear :

- increase in cutting forces and power consumption mainly due to the principal flank wear
- increase in dimensional deviation and surface roughness mainly due to wear of the tool-tips and auxiliary flank wear (V_s)
- odd sound and vibration
- worsening surface integrity
- mechanically weakening of the tool tip.

(iii) Essential properties for 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 :

i) high mechanical strength; compressive, tensile, and TRA
ii) fracture toughness – high or at least adequate
iii) high hardness for abrasion resistance
iv) high hot hardness to resist plastic deformation and reduce wear rate at elevated temperature
v) chemical stability or inertness against work material, atmospheric gases and cutting fluids
vi) resistance to adhesion and diffusion
vii) thermal conductivity – low at the surface to resist incoming of heat and high at the core to quickly dissipate the heat entered
viii) high heat resistance and stiffness
ix) manufacturability, availability and low cost.

iv) 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

- no. of pieces of work machined
- total volume of material removed
- total length of cut.

Measurement of tool wear

The various methods are :

i) 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.

ii) 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

iii) using optical microscope fitted with micrometer – very common and effective method

iv) using scanning electron microscope (SEM) – used generally, for detailed study; both qualitative and quantitative

v) Talysurf, specially for shallow crater wear.

(v) 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, (s_o) 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.3.2.3.

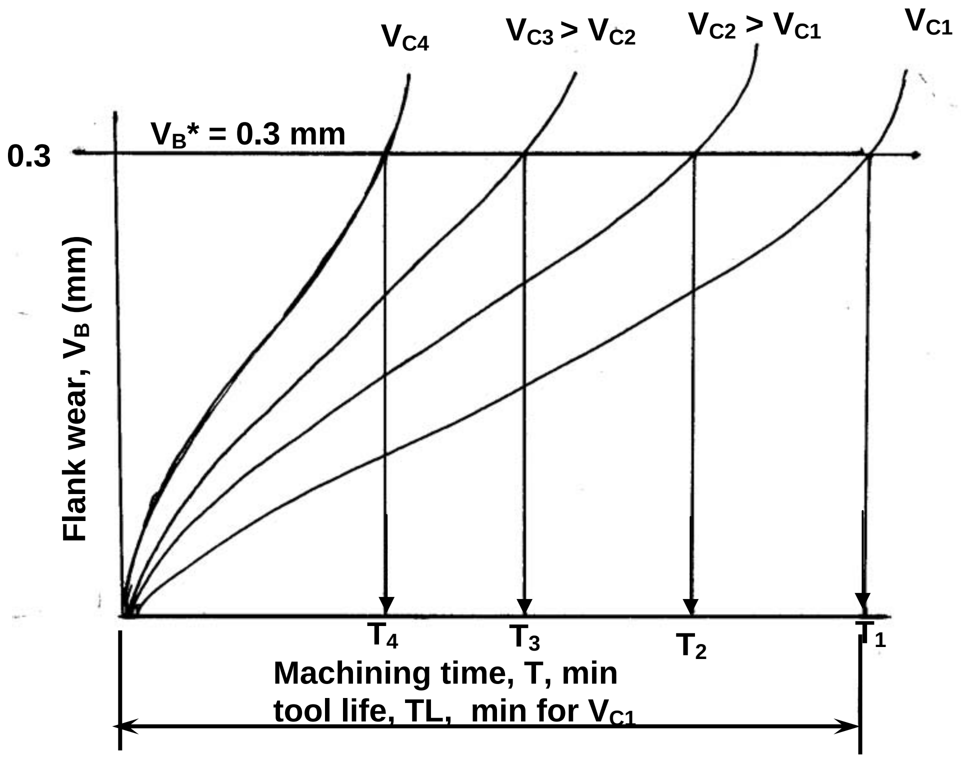


Fig. 3.2.3 *Growth of flank wear and assessment of tool life*

The tool life obviously decreases with the increase in cutting velocity keeping other conditions unaltered as indicated in Fig. 3.2.3.

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. 3.2.4, 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. 3.2.5.

With the slope, n and intercept, c, Taylor derived the simple equation as

$$VT^n = C$$

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.)

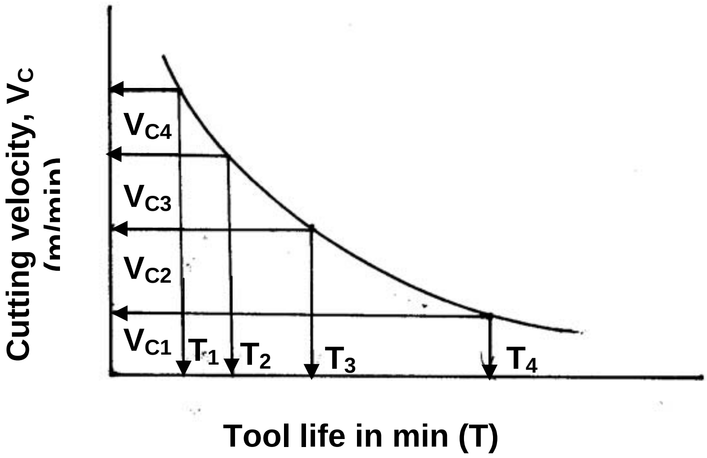


Fig. 3.2.4 *Cutting velocity – tool life relationship*

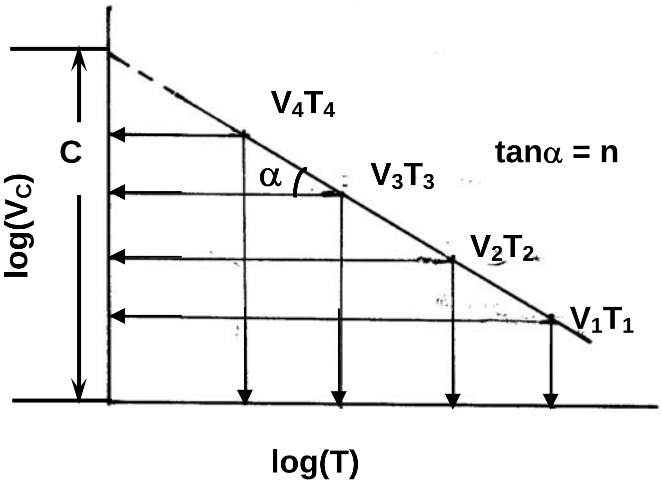


Fig. 3.2.5 *Cutting velocity vs tool life on a log-log scale*

Example of use of Taylor's tool life equation

Problem :

If in turning of a steel rod by a given cutting tool (material and geometry) at a given machining condition (s_o and t) under a given environment (cutting fluid application), the tool life decreases from 80 min to 20 min. due to increase in cutting velocity, V_C from 60 m/min to 120 m/min., then at what cutting velocity the life of that tool under the same condition and environment will be 40 min.?

Solution :

Assuming Taylor's tool life equation, $VT^n = C$

$V_1T_1 = V_2T_2 = V_3T_3 = ... = C$

Here, V_1 = 60 m/min; T_1 = 80 min.

V_2 = 120 m/min; T_2 = 20 min.

V_3 = ? (to be determined); T_3 = 40 min.

Taking,

$$V_1T_1^n = V_2T_2^n$$

i.e,

$$\left(\frac{T_1}{T_2}\right)^n = \left(\frac{V_2}{V_1}\right)$$

or

$$\left(\frac{80\min}{20\min}\right)^n = \left(\frac{120m/\min}{60m/\min}\right)$$

from which, n = 0.5

Again

$$V_3T_3^n = V_1T_1^n$$

i.e,

$$\left(\frac{V_3}{V_1}\right) = \left(\frac{T_1}{T_3}\right)^n$$

or

$$V_3 = \left(\frac{80}{40}\right)^{0.5} x60 = 84.84m/\min \qquad \textbf{\textit{Ans}}$$

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 (s_o) 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,

$$TL = \frac{C_T}{V_c^x s_o^y t^z}$$

where, TL = tool life in min

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.

Exercise – 3.2

Quiz Test

Identify the correct answer from the given four options.

1. In high speed machining of steels the teeth of milling cutters may fail by
   (a) mechanical breakage
   (b) plastic deformation
   (c) wear
   (d) all of the above
2. Tool life in turning will decrease by maximum extent if we double the
   (a) depth of cut
   (b) feed
   (c) cutting velocity
   (d) tool rake angle
3. In cutting tools, crater wear develops at
   (a) the rake surface
   (b) the principal flank
   (c) the auxiliary flank
   (d) the tool nose
4. To prevent plastic deformation at the cutting edge, the tool material should possess
   (a) high fracture toughness
   (b) high hot hardness
   (c) chemical stability
   (d) adhesion resistance

Problems

Problem – 1

During turning a metallic rod at a given condition, the tool life was found to increase from 25 min to 50 min. when V_C was reduced from 100 m/min to 80 m/min. How much will be the life of that tool if machined at 90 m/min ?

Problem – 2

While drilling holes in steel plate by a 20 mm diameter HSS drill at a given feed, the tool life decreased from 40 min. to 24 min. when speed was raised from 250 rpm to 320 rpm. At what speed (rpm) the life of that drill under the same condition would be 30 min.?

Answers of the questions of Exercise – 3.2

Quiz Test

Q. 1 : (d)
Q. 2 : (c)
Q. 3 : (a)
Q. 4 : (b)

Solution to Problem 1.

Ans. 34.6 min

Solution to Problem 2

Ans. 287 rpm.

Module
3
Machinability

Lesson
15
Cutting Tool Materials of common use

Instructional Objectives

At the end of this lesson, the students will be able to

(i) Identify the needs and cite the chronological development of cutting tool materials.
(ii) Describe the characteristics and state the applications of the commonly used cutting tool materials;
  (a) High speed steel
  (b) Stellite
  (c) Sintered carbides
  (d) Plain ceramics

(i) 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 that 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,

- the cutting tool materials
- the cutting tool geometry
- proper selection and use of those tools
- 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. 3.3.1

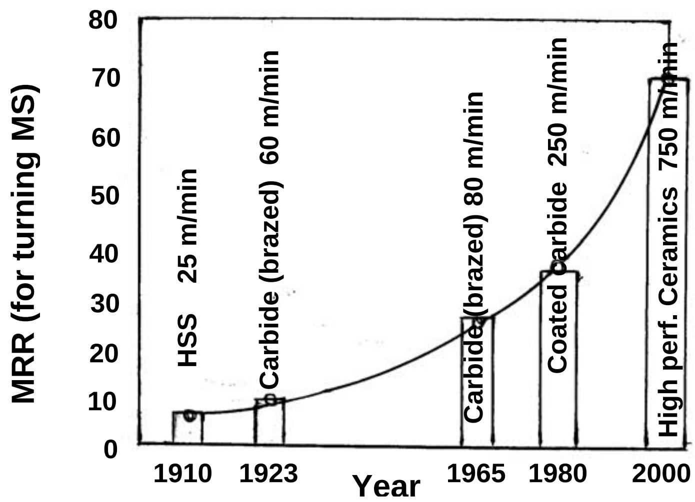


Fig. 3.3.1 *Productivity raised by cutting tool materials.*

The chronological development of cutting tool materials is briefly indicated in Fig. 3.3.2

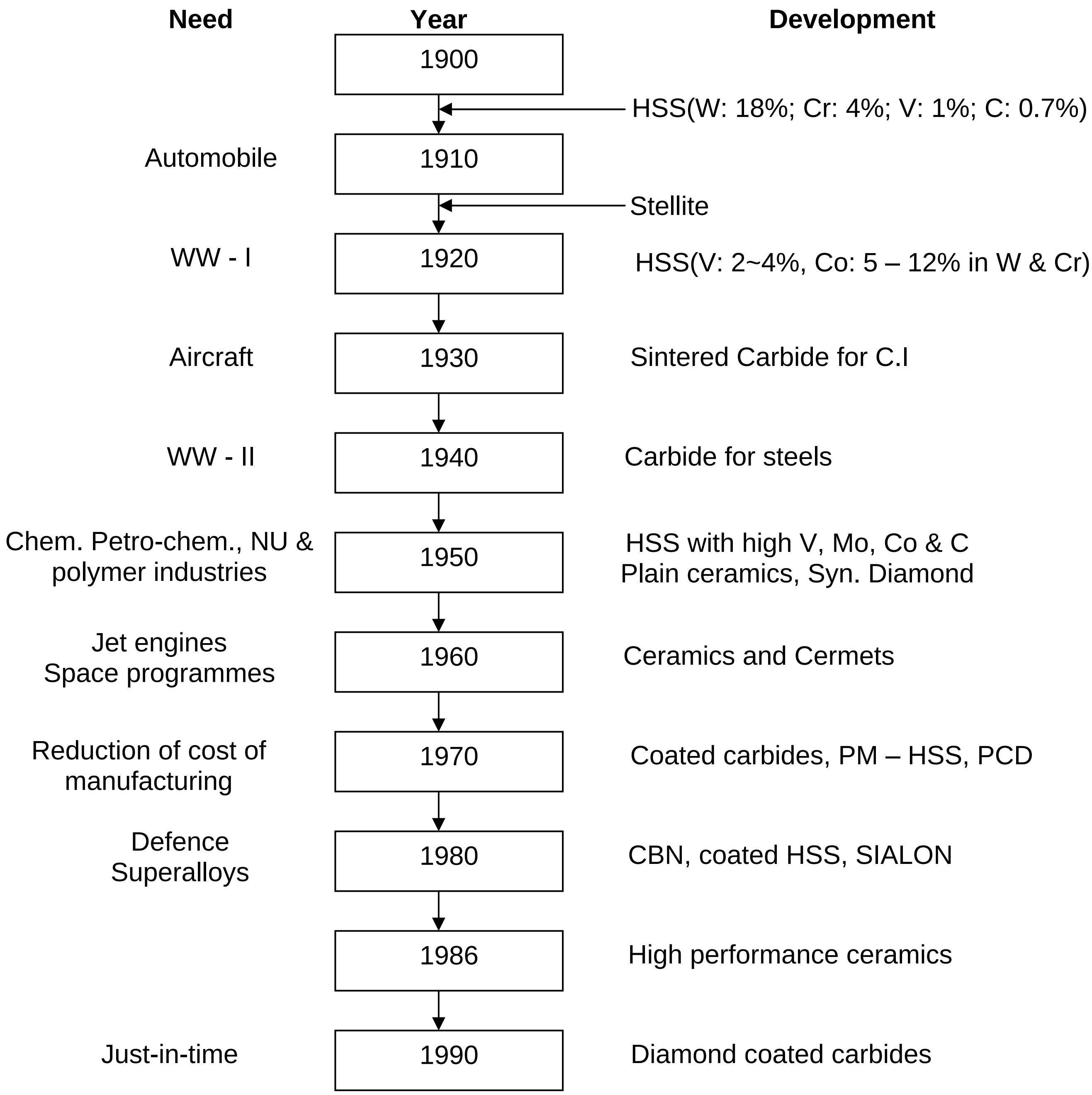


Fig. 3.3.2 *Chronological development of cutting tool materials.*

(ii) Characteristics And Applications Of The Primary 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 upto 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 -

- Refinement of microstructure
- Addition of large amount of cobalt and Vanadium to increase hot hardness and wear resistance respectively
- Manufacture by powder metallurgical process
- 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 3.3.1.

Table 3.3.1 Compositions and types of popular high speed steels

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

Addition of large amount of Co and V, refinement of microstructure and coating increased strength and wear resistance and thus enhanced productivity and life of the HSS tools remarkably.

(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 specially 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.

- **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.

- **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.

- **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 upto 25% TiC are used and for heavy roughing work at lower speeds lesser amount (5 to 10%) of TiC is suitable.

- **Gradation of cemented carbides and their applications**

The standards developed by ISO for grouping of carbide tools and their application ranges are given in Table 3.3.2.

Table 3.3.2 Broad classification of carbide tools.

ISO Code	Colour Code	Application
P		For machining long chip forming common materials like plain carbon and low alloy steels
M		For machining long or short chip forming ferrous materials like Stainless steel
K		For machining short chipping, ferrous and non-ferrous material and non-metals like Cast Iron, Brass etc.

K-group is suitable for machining short chip producing ferrous and non-ferrous metals and also some non metals.

P-group is suitably used for machining long chipping ferrous metals i.e. plain carbon and low alloy steels

M-group is generally recommended for machining more difficult-to-machine materials like strain hardening austenitic steel and manganese steel etc.

Each group again is divided into some subgroups like P_{10}, P_{20} etc., as shown in Table 3.3.3 depending upon their properties and applications.

Table 3.3.3 Detail grouping of cemented carbide tools

ISO Application group	Material	Process
P01	Steel, Steel castings	Precision and finish machining, high speed
P10	Steel, steel castings	Turning, threading and milling high speed, small chips
P20	Steel, steel castings, malleable cast iron	Turning, milling, medium speed with small chip section
P30	Steel, steel castings, malleable cast iron forming long chips	Turning, milling, low cutting speed, large chip section
P40	Steel and steel casting with sand inclusions	Turning, planning, low cutting speed, large chip section
P50	Steel and steel castings of medium or low tensile strength	Operations requiring high toughness turning, planning, shaping at low cutting speeds
K01	Hard grey C.I., chilled casting, Al. alloys with high silicon	Turning, precision turning and boring, milling, scraping
K10	Grey C.I. hardness > 220 HB. Malleable C.I., Al. alloys containing Si	Turning, milling, boring, reaming, broaching, scraping
K20	Grey C.I. hardness up to 220 HB	Turning, milling, broaching, requiring high toughness
K30	Soft grey C.I. Low tensile strength steel	Turning, reaming under favourable conditions
K40	Soft non-ferrous metals	Turning milling etc.
M10	Steel, steel castings, manganese steel, grey C.I.	Turning at medium or high cutting speed, medium chip section
M20	Steel casting, austentic steel, manganese steel, spherodized C.I., Malleable C.I.	Turning, milling, medium cutting speed and medium chip section
M30	Steel, austenitic steel, spherodized C.I. heat resisting alloys	Turning, milling, planning, medium cutting speed, medium or large chip section
M40	Free cutting steel, low tensile strength steel, brass and light alloy	Turning, profile turning, specially in automatic machines.

The smaller number refers to the operations which need more wear resistance and the larger numbers to those requiring higher toughness for the tool.

(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 3.3.4 shows the advantages and limitations of alumina ceramics in contrast to sintered carbide. Alumina (Al_2O_3) is preferred to silicon nitride (Si_3N_4) for higher hardness and chemical stability. Si_3N_4 is tougher but again more difficult to process. The plain ceramic tools are brittle in nature and hence had limited applications.

Table 3.3.4 Cutting tool properties of alumina ceramics.

Advantages	**Shortcoming**
very high hardness	poor toughness
very high hot hardness	poor tensile strength
chemical stability	poor TRS
antiwelding	low thermal conductivity
less diffusivity	less density
high abrasion resistance	
high melting point	
very low thermal conductivity*	
very low thermal expansion coefficient	

* Cutting tool should resist penetration of heat but should disperse the heat throughout the core.

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 V_C = 150 to 250 m/min
- Carbide ceramic (Al_2O_3 + 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 then existing tool materials in some application areas like high speed machining of softer steels mainly for higher hot hardness as indicated in Fig. 3.3.3

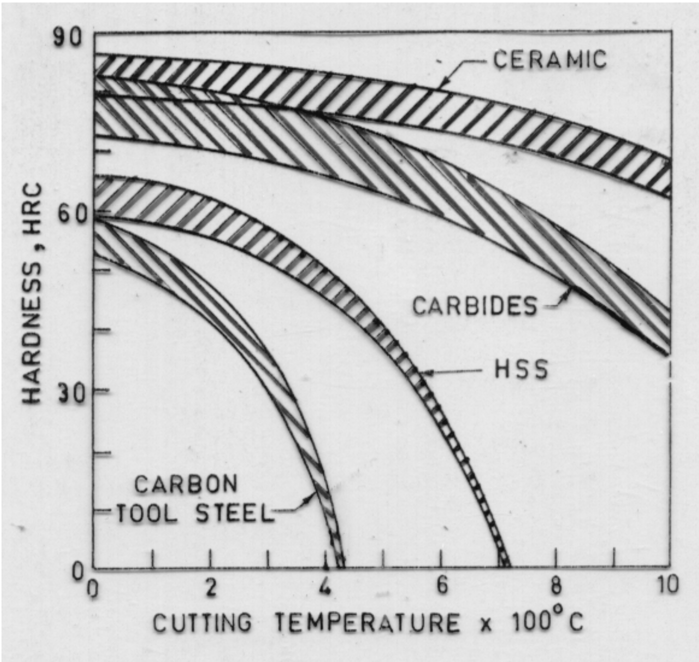


Fig. 3.3.3 *Hot hardness of the different commonly used tool materials.*
(Ref. Book by A.Bhattacharya)

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

Advent of coated carbide capable of machining cast iron and steels at high velocity made the then ceramics almost obsolete.

Module
3
Machinability

Lesson
16
Advanced Cutting Tool Materials

Instructional Objectives

At the end of this lesson, the students will be able to

(i) Classify, illustrate the properties and suggest the applications of the advanced cutting tool materials
- (a) Coated carbides
- (b) Cermets
- (c) Coronite
- (d) High Performance Ceramics (HPC)
- (e) Cubic Boron Nitride (cBN)
- (f) Diamond

(i) Development And Application Of Advanced Tool Materials

(a) Coated carbides

The properties and performance of carbide tools could be substantially improved by

- Refining microstructure
- Manufacturing by casting – expensive and uncommon
- Surface coating – made remarkable contribution.

Thin but hard coating of single or multilayers of more stable and heat and wear resistive materials like TiC, TiCN, TiOCN, TiN, Al_2O_3 etc on the tough carbide inserts (substrate) (Fig. 3.3.4) by processes like chemical Vapour Deposition (CVD), Physical Vapour Deposition (PVD) etc at controlled pressure and temperature enhanced MRR and overall machining economy remarkably enabling,

- reduction of cutting forces and power consumption
- increase in tool life (by 200 to 500%) for same V_C or increase in V_C (by 50 to 150%) for same tool life
- improvement in product quality
- effective and efficient machining of wide range of work materials
- pollution control by less or no use of cutting fluid

through

- reduction of abrasion, adhesion and diffusion wear
- reduction of friction and BUE formation
- heat resistance and reduction of thermal cracking and plastic deformation

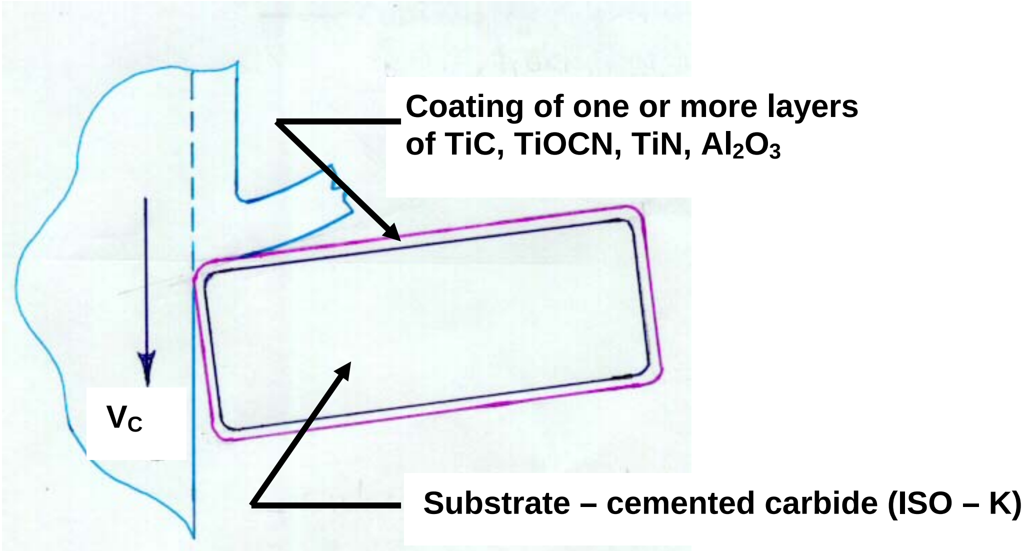


Fig. 3.3.4 *Machining by coated carbide insert.*

The contributions of the coating continues even after rupture of the coating as indicated in Fig. 3.3.5.

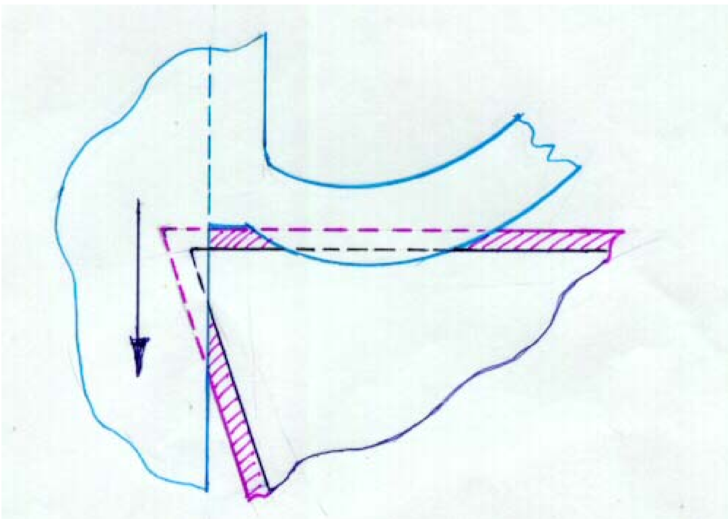


Fig. 3.3.5 *Role of coating even after its wear and rupture*

The cutting velocity range in machining mild steel could be enhanced from 120 ~ 150 m/min to 300 ~ 350 m/min by properly coating the suitable carbide inserts.

About 50% of the carbide tools being used at present are coated carbides which are obviously to some extent costlier than the uncoated tools.

Different varieties of coated tools are available. The appropriate one is selected depending upon the type of the cutting tool, work material and the desired productivity and product quality.

The properties and performances of coated inserts and tools are getting further improved by;

- Δ Refining the microstructure of the coating
- Δ Multilayering (already upto 13 layers within 12 ~ 16 μm)

- ∆ Direct coating by TiN instead of TiC, if feasible
- ∆ Using better coating materials.

(b) Cermets

These sintered hard inserts are made by combining 'cer' from ceramics like TiC, TiN orn (or)TiCN and 'met' from metal (binder) like Ni, Ni-Co, Fe etc. Since around 1980, the modern cermets providing much better performance are being made by TiCN which is consistently more wear resistant, less porous and easier to make. The characteristic features of such cermets, in contrast to sintered tungsten carbides, are :

- The grains are made of TiCN (in place of WC) and Ni or Ni-Co and Fe as binder (in place of Co)
- Harder, more chemically stable and hence more wear resistant
- More brittle and less thermal shock resistant
- Wt% of binder metal varies from 10 to 20%
- Cutting edge sharpness is retained unlike in coated carbide inserts
- Can machine steels at higher cutting velocity than that used for tungsten carbide, even coated carbides in case of light cuts.

Application wise, the modern TiCN based cermets with bevelled or slightly rounded cutting edges are suitable for finishing and semi-finishing of steels at higher speeds, stainless steels but are not suitable for jerky interrupted machining and machining of aluminium and similar materials. Research and development are still going on for further improvement in the properties and performance of cermets.

(c) Coronite

It is already mentioned earlier that the properties and performance of HSS tools could have been sizeably improved by refinement of microstructure, powder metallurgical process of making and surface coating. Recently a unique tool material, namely Coronite has been developed for making the tools like small and medium size drills and milling cutters etc. which were earlier essentially made of HSS. Coronite is made basically by combining HSS for strength and toughness and tungsten carbides for heat and wear resistance. Microfine TiCN particles are uniformly dispersed into the matrix.
Unlike a solid carbide, the coronite based tool is made of three layers;

- the central HSS or spring steel core
- a layer of coronite of thickness around 15% of the tool diameter
- a thin (2 to 5 μm) PVD coating of TiCN.

Such tools are not only more productive but also provides better product quality.
The coronite tools made by hot extrusion followed by PVD-coatring of TiN or TiCN outperformed HSS tools in respect of cutting forces, tool life and surface finish.

(d) High Performance ceramics (HPC)

Ceramic tools as such are much superior to sintered carbides in respect of hot hardness, chemical stability and resistance to heat and wear but lack in fracture toughness and strength as indicated in Fig. 3.3.6.

Through last few years remarkable improvements in strength and toughness and hence overall performance of ceramic tools could have been possible by several means which include;

- Sinterability, microstructure, strength and toughness of Al_2O_3 ceramics were improved to some extent by adding TiO_2 and MgO
- Transformation toughening by adding appropriate amount of partially or fully stabilised zirconia in Al_2O_3 powder
- Isostatic and hot isostatic pressing (HIP) – these are very effective but expensive route

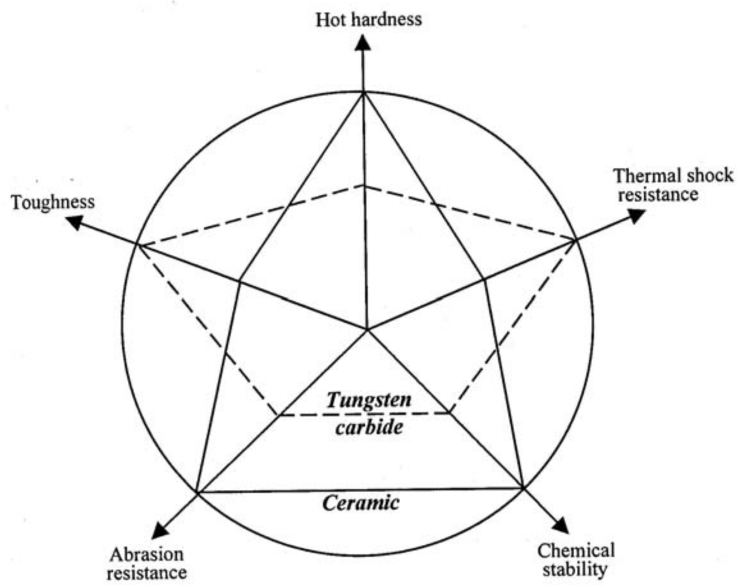


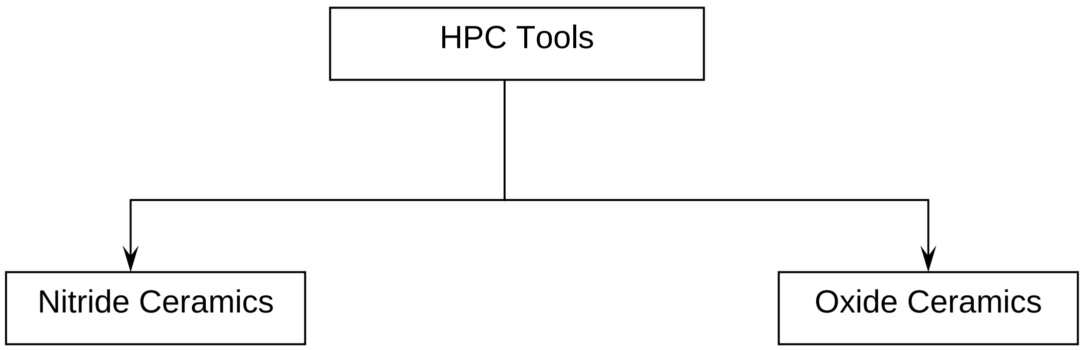
Fig. 3.3.6 *Comparison of important properties of ceramic and tungsten carbide tools*

- Introducing nitride ceramic (Si_3N_4) with proper sintering technique – this material is very tough but prone to built-up-edge formation in machining steels
- Developing SIALON – deriving beneficial effects of Al_2O_3 and Si_3N_4
- Adding carbide like TiC (5 ~ 15%) in Al_2O_3 powder – to impart toughness and thermal conductivity
- Reinforcing oxide or nitride ceramics by SiC whiskers, which enhanced strength, toughness and life of the tool and thus productivity spectacularly. But manufacture and use of this unique tool need specially careful handling
- Toughening Al_2O_3 ceramic by adding suitable metal like silver which also impart thermal conductivity and self lubricating property; this novel and inexpensive tool is still in experimental stage.

The enhanced qualities of the unique high performance ceramic tools, specially the whisker and zirconia based types enabled them machine structural steels at speed even beyond 500 m/min and also intermittent cutting at reasonably high speeds, feeds and depth of cut. Such tools are also found to machine relatively harder and stronger steels quite effectively and economically.

The successful and commonly used high performance ceramic tools have been discussed here :

The HPC tools can be broadly classified into two groups as :



Silicon Nitride

(i) Plain
(ii) SIALON
(iii) Whisker toughened

Alumina toughned by

(i) Zirconia
(ii) SiC whiskers
(iii) Metal (Silver etc)

Nitride based ceramic tools

Plain nitride ceramics tools

Compared to plain alumina ceramics, Nitride (Si_3N_4) ceramic tools exhibit more resistance to fracturing by mechanical and thermal shocks due to higher bending strength, toughness and higher conductivity. Hence such tool seems to be more suitable for rough and interrupted cutting of various material excepting steels, which cause rapid diffusional wear and BUE formation. The fracture toughness and wear resistance of nitride ceramic tools could be further increased by adding zirconia and coating the finished tools with high hardness alumina and titanium compound.
Nitride ceramics cannot be easily compacted and sintered to high density. Sintering with the aid of ‘reaction bonding’ and ‘hot pressing’ may reduce this problem to some extent.

SIALON tools

Hot pressing and sintering of an appropriate mix of Al_2O_3 and Si_3N_4 powders yielded an excellent composite ceramic tool called SIALON which are very hot hard, quite tough and wear resistant. These tools can machine steel and cast irons at high speeds (250 – 300 m/min). But machining of steels by such tools at too high speeds reduces the tool life by rapid diffusion.

SiC reinforced Nitride tools

The toughness, strength and thermal conductivity and hence the overall performance of nitride ceramics could be increased remarkably by adding SiC whiskers or fibers in 5 – 25 volume%. The SiC whsikers add fracture toughness mainly through crack bridging, crack deflection and fiber pull-out.

Such tools are very expensive but extremely suitable for high production machining of various soft and hard materials even under interrupted cutting.

Zirconia (or Partially stabilized Zirconia) toughened alumina (ZTA) ceramic

The enhanced strength, TRS and toughness have made these ZTAs more widely applicable and more productive than plain ceramics and cermets in machining steels and cast irons. Fine powder of partially stabilised zirconia (PSZ) is mixed in proportion of ten to twenty volume percentage with pure alumina, then either cold pressed and sintered at 1600 – 1700^{o}C or hot isostatically pressed (HIP) under suitable temperature and pressure. The phase transformation of metastable tetragonal zirconia (t-Z) to monoclinic zirconia (m-Z) during cooling of the composite (Al_2O_3 + ZrO_2) inserts after sintering or HIP and during polishing and machining imparts the desierd strength and fracture toughness through volume expansion (3 – 5%) and induced shear strain (7%). The mechanisms of toughening effect of zirconia in the basic alumina matrix are stress induced transformation toughening as indicated in Fig. 3.3.7 and microcrack nucleation toughening.

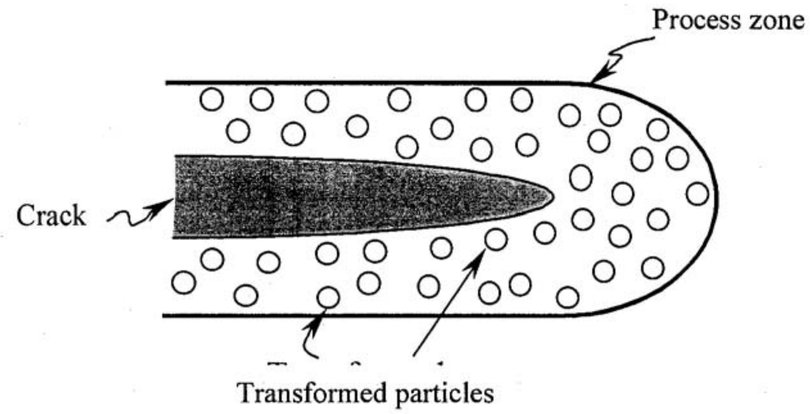


Fig. 3.3.7 *The method of crack shielding by a transformation zone.*

Their hardness have been raised further by proper control of particle size and sintering process. Hot pressing and HIP raise the density, strength and hot hardness of ZTA tools but the process becomes expensive and the tool performance degrades at lower cutting speeds. However such ceramic tools can machine steel and cast iron at speed range of 150 – 500 m/min.

Alumina ceramic reinforced by SiC whiskers

The properties, performances and application range of alumina based ceramic tools have been improved spectacularly through drastic increase in fracture toughness (2.5 times), TRS and bulk thermal conductivity, without sacrificing hardness and wear resistance by mechanically reinforcing the brittle alumina matrix with extremely strong and stiff silicon carbide whiskers. The randomly oriented, strong and thermally conductive whsikers enhance the strength and toughness mainly by crack deflection and crack-bridging and also by reducing the temperature gradient within the tool. After optimization of the composition, processing and the tool geometry, such tools have been found to effectively and efficiently machine wide range of materials, over wide speed range (250 – 600 m/min) even under large chip loads. But manufacturing of whiskers need very careful handling and precise control and these tools are costlier than zirconia toughned ceramic tools.

Silver toughened alumina ceramic

Toughening of alumina with metal particle became an important topic since 1990 though its possibility was reported in 1950s. Alumina-metal composites have been studied primarily using addition of metals like aluminium, nickel, chromium, molybdenum, iron and silver. Compared to zirconia and carbides, metals were found to provide more toughness in alumina ceramics. Again compared to other metal-toguhened ceramics, the silver-toguhned ceramics can be manufactured by simpler and more economical process routes like pressureless sintering and without atmosphere control. All such potential characteristics of silver-toughened alumina ceramic have already been exploited in making some salient parts of automobiles and similar items. Research is going on to develop and use silver-toguhened alumina for making cutting tools like turning inserts.. The toughening of the alumina matrix by the addition of metal occurs mainly by crack deflection and crack bridging by the metal grains as schematically shown in Fig. 3.3.8. Addition of silver further helps by increasing thermal conductivity of the tool and self lubrication by the traces of the silver that oozes out through the pores and reaches at the chip-tool interface. Such HPC tools can suitably machine with large MRR and V_C (250 – 400 m/min) and long tool life even under light interrupted cutting like milling. Such tools also can machine steels at speed from quite low to very high cutting velocities (200 to 500 m/min).

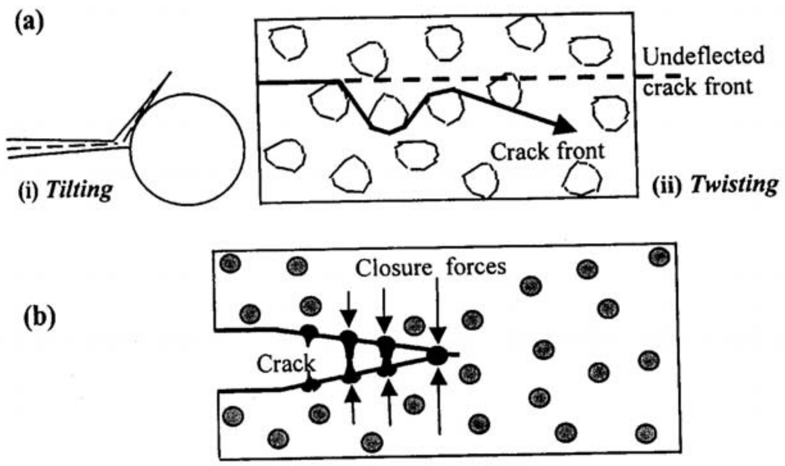


Fig. 3.3.8 *Toughening mechanism of alumina by metal dispersion.*

(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 toguhness 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 upto 1400^o 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 R_C) : 80 – 140 m/min
- Hardened steels (> 45 R_C) : 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 crytal 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
- Drill bits for mining, oil exploration, etc.
- Tool for cutting and drilling in glasses, stones, ceramics, FRPs etc.
- Wire drawing and extrusion dies
- Superabrasive 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.

Polycrystalline Diamond (PCD)

The polycrystalline diamond (PCD) tools consist of a layer (0.5 to 1.5 mm) of fine grain size, randomly oriented diamond particles sintered with a suitable binder (ususally cobalt) and then metallurgically bonded to a suitable substrate like cemented carbide or Si_3N_4 inserts. PCD exhibits excellent wear resistance, hold sharp edge, generates little friction in the cut, provide high fracture strength, and had good thermal conductivity. These properties contribute to PCD tooling's long life in conventional and high speed machining of soft, non-ferrous materials (aluminium, magnesium, copper etc), advanced composites and metal-matrix composites, superalloys, and non-metallic materials. PCD is particularly well suited for abrasive materials (i.e. drilling and reaming metal matrix composites) where it provides 100 times the life of carbides. PCD is not ususally recommended for ferrous metals because of high solubility of diamond (carbon) in these materials at elevated temperature. However, they can be used to machine some of these materials under special conditions; for example, light cuts are being successfully made in grey cast iron. The main advanatage of such PCD tool is the greater toughness due to finer microstructure with random orientation of the grains and reduced cleavage. But such unique PCD also suffers from some limitations like :

- High tool cost
- Presence of binder, cobalt, which reduces wear resistance and thermal stability
- Complex tool shapes like in-built chip breaker cannot be made
- Size restriction, particularly in making very small diameter tools

The above mentioned limitations of polycrystalline diamond tools have been almost overcome by developing Diamond coated tools.

Diamond coated carbide tools

Since the invention of low pressure synthesis of diamond from gaseous phase, continuous effort has been made to use thin film diamond in cutting tool field. These are normally used as thin (<50 μm) or thick (> 200 μm) films of diamond synthesised by CVD method for cutting tools, dies, wear surfaces and even abrasives for Abrasive Jet Machining (AJM) and grinding. Thin film is directly deposited on the tool surface. Thick film (> 500 μm) is grown on an easy substrate and later brazed to the actual tool substrate and the primary substrate is removed by dissolving it or by other means. Thick film diamond finds application in making inserts, drills, reamers, end mills, routers. CVD coating has been more popular than single diamond crystal and PCD mainly for :

- Free from binder, higher hardness, resistance to heat and wear more than PCD and properties close to natural diamond
- Highly pure, dense and free from single crystal cleavage
- Permits wider range of size and shape of tools and can be deposited on any shape of the tool including rotary tools
- Relatively less expensive

However, achieving improved and reliable performance of thin film CVD diamond coated tools; (carbide, nitride, ceramic, SiC etc) in terms of longer tool life, dimensional accuracy and surface finish of jobs essentially need :

1. good bonding of the diamond layetr
2. adequate properties of the film, e.g. wear resistance, micro-hardness, edge coverage, edge sharpness and thickness uniformity
3. ability to provide work surface finish required for specific applications.

While cBN tools are feasible and viable for high speed machining of hard and strong steels and similar materials, Diamond tools are extreemly useful for machining stones, slates, glass, ceramics, composites, FRPs and non ferrous metals specially which are sticky and BUE former such as pure aluminium and its alloys.

CBN and Diamond tools are also essentially used for ultraprecision as well as micro and nano machining.

Module
4
General Purpose Machine Tools

Lesson
17
Kinematic systems and operations of lathes

Instructional objectives

At the end of this lesson, the students will be able to

(i) Name the general purpose machine tools of common use
(ii) Classify the different types of lathes
(iii) Illustrate the kinematic system of centre lathe and explain its method of working
(iv) State the different machining operations that are usually done in centre lathes.

(i) General Purpose Machine Tools Of Common Use

The basic machine tools which are commonly used for general purposes, are :

- Lathes
- Drilling machines
- Shaping machines
- Planning machines
- Slotting machines
- Milling machines
- Boring machines
- Hobbing machines
- Gear shaping machines
- Broaching machines
- Grinding machines

Each one of the machine tools, mentioned above, can be further classified into several types depending upon size, shape, automation, etc.

(ii) Classification Of Lathes

Lathes are very versatile of wide use and are classified according to several aspects:

(a) According to configuration

- Horizontal
  - Most common for ergonomic conveniences
- Vertical
  - Occupies less floor space, only some large lathes are of this type.

(b) According to purpose of use

- General purpose
  - Very versatile where almost all possible types of operations are carried out on wide ranges of size, shape and materials of jobs; example : centre lathes
- Single purpose

- Only one (occasionally two) type of operation is done on limited ranges of size and material of jobs; example – facing lathe, roll turning lathe etc.

- Special purpose
  - Where a definite number and type of operations are done repeatedly over long time on a specific type of blank; example: gear blank machining lathe etc.

(c) According to size or capacity

- Small (low duty)
  - In such light duty lathes (upto 1.1 kW), only small and medium size jobs of generally soft and easily machinable materials are machined
- Medium (medium duty)
  - These lathes of power nearly upto 11 kW are most versatile and commonly used
- Large (heavy duty)
- Mini or micro lathe
  - These are tiny table-top lathes used for extremely small size jobs and precision work; example : swiss type automatic lathe

(d) According to degree of automation

- Non-automatic
  - Almost all the handling operations are done manually; example: centre lathes
- Semi-automatic
  - Nearly half of the handling operations, irrespective of the processing operations, are done automatically and rest manually; example : capstan lathe, turret lathe, copying lathe relieving lathe etc.
- Automatic
  - Almost all the handling operations (and obviously all the processing operations) are done automatically; example – single spindle automat (automatic lathe), swiss type automatic lathe, etc.

(e) According to type of automation

- Fixed automation
  - Conventional; example – single spindle automat, swiss type automatic lathe etc.
- Flexible automation
  - Modern; example CNC lathe, turning centre etc.

(f) According to configuration of the jobs being handled

- Bar type
  - Slender rod like jobs being held in collets
- Chucking type
  - Disc type jobs being held in chucks

- Housing type

- Odd shape jobs, being held in face plate

(g) According to precision

- Ordinary
- Precision (lathes)
  - These sophisticated lathes meant for high accuracy and finish and are relatively more expensive.

(h) According to number of spindles

- Single spindle
  - Common
- Multispindle (2, 4, 6 or 8 spindles)
  - Such uncommon lathes are suitably used for fast and mass production of small size and simple shaped jobs.

(iii) Kinematic System And Working Principle Of Lathes

Amongst the various types of lathes, centre lathes are the most versatile and commonly used.

Fig. 4.1.1 schematically shows the typical kinematic system of a 12 speed centre lathe.

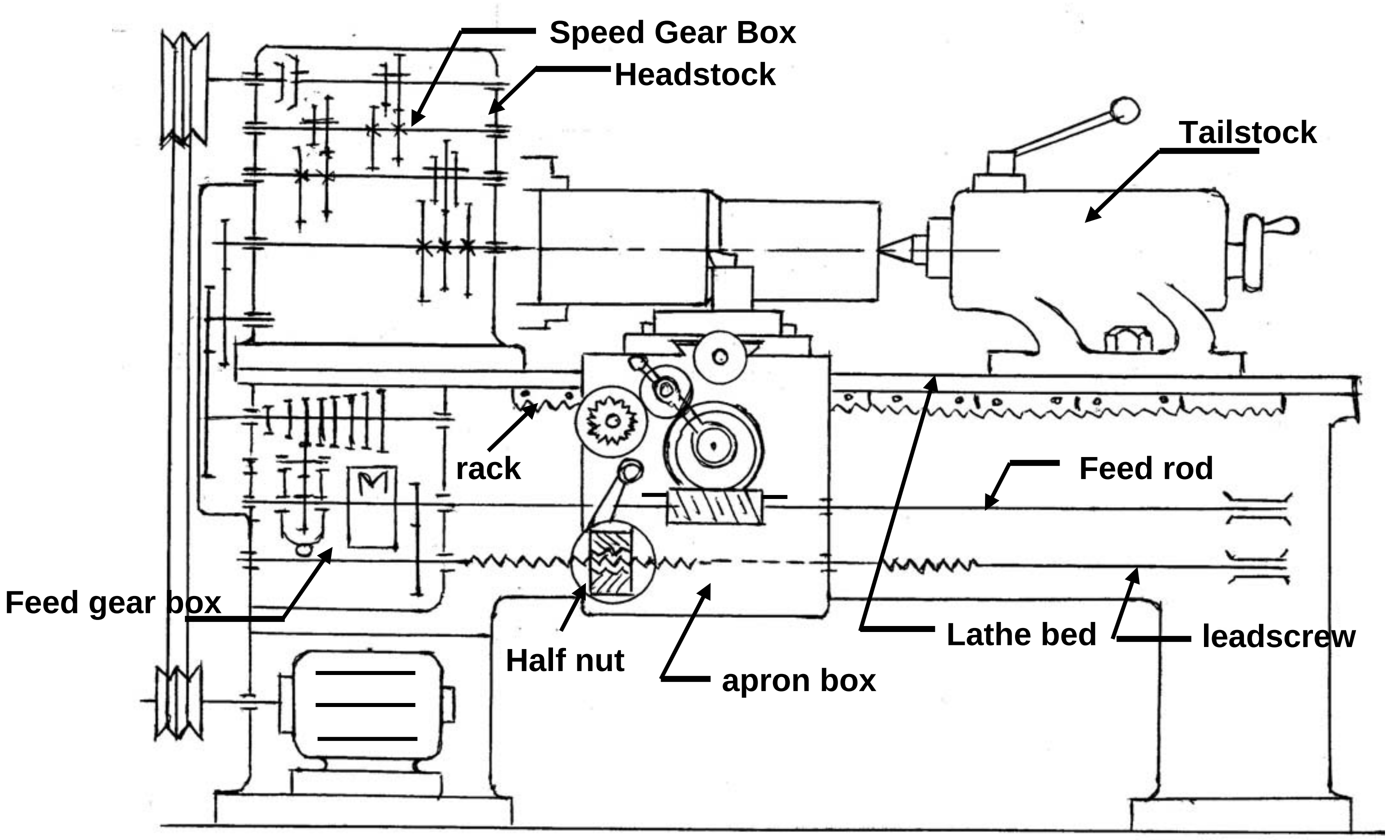


***Fig. 4.1.1** Schematic diagram of a centre lathe.*

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 etc

In lathes

- o Cutting motion is attained by rotating the job
- o Feed motion by linear travel of the tool
  - either axially for longitudinal feed
  - or radially for cross feed

It is noted, in general, from Fig. 4.1.1

- 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 appron 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 leadscrew 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 (FGR). 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 quil 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 attachments like
  - Taper turning attachment
  - Thread milling attachment
  - Copying attachment

(iv) Machining Operations Usually Done In Centre Lathes

The machining operations generally carried out in centre lathes are :

- Facing
- Centering
- Rough and finish turning
- Chamfering, shouldering, grooving, recessing etc
- Axial drilling and reaming by holding the cutting tool in the tailstock barrel

- Taper turning by

- offsetting the tailstock
- swivelling 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
- Forming; external and internal
- Cutting helical threads; external and internal
- Parting off
- Knurling

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, such as,

- Grinding, both external and internal by mounting a grinding attachment on the saddle
- Copying (profiles) by using hydraulic copying attachment
- Machining long and large threads for leadscrews, power-screws, worms etc. by using thread milling attachment.

Module
4
General Purpose Machine Tools

Lesson
18
Kinematic system and operations of drilling machines

Instructional Objectives

At the end of this lesson, the students will be able to :

(i) State the basic purposes of use of drilling machines
(ii) Classify the types of drilling machines
(iii) Illustrate the general kinematic system of drilling machine and explain its working principle
(iv) State and visualise the various common and other possible applications of drilling machines

(i) Basic purposes of use of drilling machines

Drilling machines are generally or mainly used to originate through or blind straight cylindrical holes in solid rigid bodies and/or enlarge (coaxially) existing (premachined) holes :

- of different diameter ranging from about 1 mm to 40 mm
- of varying length depending upon the requirement and the diameter of the drill
- in different materials excepting very hard or very soft materials like rubber, polythene etc.

(ii) Classification of drilling machines.

(a) General purpose drilling machines of common use

- **Table top small sensitive drilling machine**

These small capacity ($\leq$ 0.5 kW) upright (vertical) single spindle drilling machines are mounted (bolted) on rigid table and manually operated using usually small size ($\phi \leq$ 10 mm) drills. Fig. 4.2.1 typically shows one such machine.

Fig. 4.2.1 *Table top sensitive drilling machine*

- **Pillar drilling machine**

These drilling machines, usually called pillar drills, are quite similar to the table top drilling machines but of little larger size and higher capacity (0.55 ~ 1.1 kW) and are grouted on the floor (foundation). Here also, the drill-feed and the work table movement are done manually. Fig. 4.2.2 typically shows a pillar drill. These low cost drilling machines have tall tubular columns and are generally used for small jobs and light drilling.

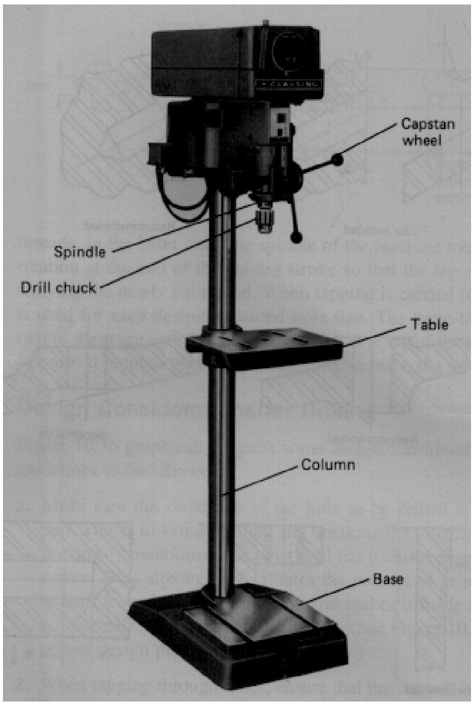


Fig. 4.2.2 *Pillar Drilling machine*

- **Column drilling machine**

These box shaped column type drilling machines as shown in Fig. 4.2.3 are much more strong, rigid and powerful than the pillar drills. In column drills the feed gear box enables automatic and power feed of the rotating drill at different feed rates as desired. Blanks of various size and shape are rigidly clamped on the bed or table or in the vice fitted on that. Such drilling machines are most widely used and over wide range (light to heavy) work.

Fig. 4.2.3 *Column drilling machine*

- **Radial drilling machine**

This usually large drilling machine possesses a radial arm which along with the drilling head can swing and move vertically up and down as can be seen in Fig. 4.2.4. The radial, vertical and swing movement of the drilling head enables locating the drill spindle at any point within a very large space required by large and odd shaped jobs. There are some more versatile radial drilling machines where the drill spindle can be additionally swivelled and / or tilted.

Fig. 4.2.4 *Radial drilling machine*

- **CNC column drilling machine**

In these versatile and flexibly automatic drilling machine having box-column type rigid structure the work table movements and spindle rotation are programmed and accomplished by Computer Numerical Control (CNC). These modern sophisticated drilling machines are suitable for piece or batch production of precision jobs.

(b) General purpose drilling machines with more specific use.

- **Hand drills**

Unlike the grouted stationary drilling machines, the hand drill is a portable drilling device which is mostly held in hand and used at the locations where holes have to be drilled as shown in Fig. 4.2.5. The small and reasonably light hand drills are run by a high speed electric motor. In fire hazardous areas the drill is often rotated by compressed air.

Fig. 4.2.5 *Hand drill in operation*

- **Gang drilling machine**

In this almost single purpose and more productive machine a number (2 to 6) of spindles with drills (of same or different size) in a row are made to produce number of holes progressively or simultaneously through the jig. Fig. 4.2.6 schematically shows a typical gang drilling machine.

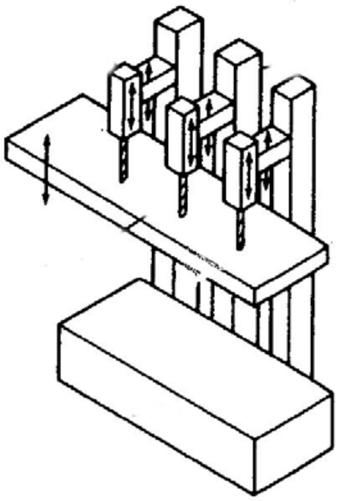


Fig. 4.2.6 Schematic view of a gang drilling machine

- **Turret (type) drilling machine**

Turret drilling machines are structurally rigid column type but are more productive like gang drill by having a pentagon or hexagon turret as shown in Fig. 4.2.7. The turret bearing a number of drills and similar tools is indexed and moved up and down to perform quickly the desired series of operations progressively. These drilling machines are available with varying degree of automation both fixed and flexible type.

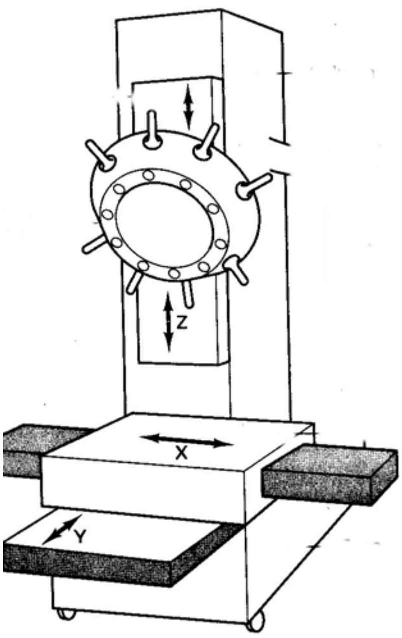


Fig. 4.2.7 *Schematic view of turret type drilling machine*

- **Multispindle drilling machine**

In these high production machine tools a large number of drills work simultaneously on a blank through a jig specially made for the particular job. The entire drilling head works repeatedly using the same jig for batch or lot production of a particular job. Fig. 4.2.8 shows a typical multispindle drilling machine. The rotation of the drills are derived from the main spindle and the central gear through a number of planetary gears in mesh with the central gear) and the corresponding flexible shafts. The positions of those parallel shafts holding the drills are adjusted depending upon the locations of the holes to be made on the job. Each shaft possesses a telescopic part and two universal joints at its ends to allow its change in length and orientation respectively for adjustment of location of the drills of varying size and length. In some heavy duty multispindle drilling machines, the work-table is raised to give feed motion instead of moving the heavy drilling head.

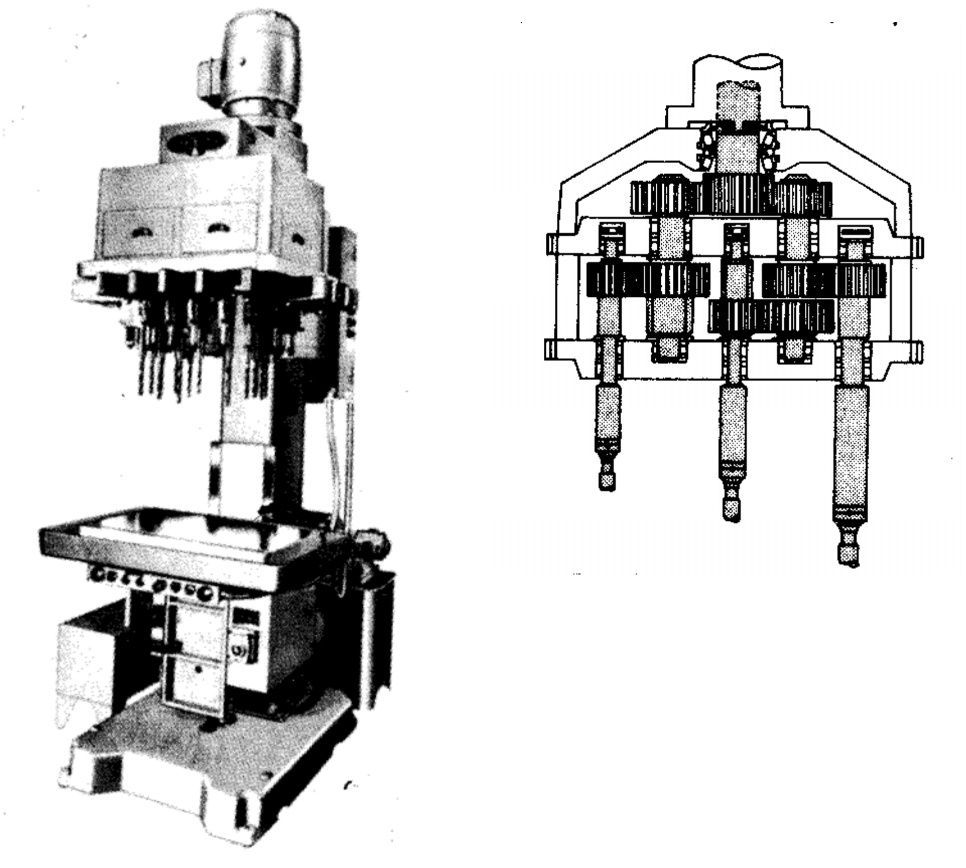


Fig. 4.2.8 *A typical multi spindle drilling machine*

- **Micro (or mini) drilling machine**

This type of tiny drilling machine of height within around 200 mm is placed or clamped on a table, as shown in Fig. 4.2.9 and operated manually for drilling small holes of around 1 to 3 mm diameter in small workpieces.

Fig. 4.2.9 *Photographic view of a micro (or mini) drilling machine*

- **Deep hole drilling machine**

Very deep holes of L/D ratio 6 to even 30, required for rifle barrels, long spindles, oil holes in shafts, bearings, connecting rods etc, are very difficult to make for slenderness of the drills and difficulties in cutting fluid application and chip removal. Such drilling cannot be done in ordinary drilling machines and b ordinary drills. It needs machines like deep hole drilling machine such as gun drilling machines with horizontal axis which are provided with

— high spindle speed
— high rigidity
— tool guide
— pressurised cutting oil for effective cooling, chip removal and lubrication at the drill tip.

Deep hole drilling machines are available with both hard automation and CNC system.

(iii) Kinematic System of general purpose drilling machine and their principle of working

Kinematic system in any machine tool is comprised of chain(s) of several mechanisms to enable transform and transmit motion(s) from the power source(s) to the cutting tool and the workpiece for the desired machining action. The kinematic structure varies from machine tool to machine tool requiring different type and number of tool-work motions. Even for the same type of machine tool, say column drilling machine, the designer may take different kinematic structure depending upon productivity, process capability, durability, compactness, overall cost etc targeted. Fig. 4.2.10 schematically shows a typical kinematic system of a very general purpose drilling machine, i.e., a column drilling machine having 12 spindle speeds and 6 feeds.
The kinematic system enables the drilling machine the following essential works;

- **Cutting motion:**

  The cutting motion in drilling machines is attained by rotating the drill at different speeds (r.p.m.). Like centre lathes, milling machines etc, drilling machines also need to have a reasonably large number of spindle speeds to cover the useful ranges of work material, tool material, drill diameter, machining and machine tool conditions. It is shown in Fig. 4.2.10 that the drill gets its rotary motion from the motor through the speed gear box (SGB) and a pair of bevel gears. For the same motor speed, the drill speed can be changed to any of the 12 speeds by shifting the cluster gears in the SGB. The direction of rotation of the drill can be changed, if needed, by operating the clutch in the speed reversal mechanism, RM-s shown in the figure.

- **Feed motion**

  In drilling machines, generally both the cutting motion and feed motion are imparted to the drill. Like cutting velocity or speed, the feed (rate) also needs varying (within a range) depending upon the tool-work materials and other conditions and requirements.
  Fig. 4.2.10 visualises that the drill receives its feed motion from the output shaft of the SGB through the feed gear box (FGA), and the clutch. The feed rate can be changed to any of the 6 rates by shifting the gears in the FGB. And the automatic feed direction can be reversed, when required, by operating the speed reversal mechanism, RM-s as shown. The slow rotation of the pinion causes the axial motion of the drill by moving the rack provided on the quil.

  The upper position of the spindle is reduced in diameter and splined to allow its passing through the gear without hampering transmission of its rotation.

- **Tool work mounting**

  The taper shank drills are fitted into the taper hole of the spindle either directly or through taper socket(s). Small straight shank drills are fitted through a drill chuck having taper shank. The workpiece is kept rigidly fixed on the bed (of the table). Small jobs are generally held in vice and large or odd shaped jobs are directly mounted on the bed by clamping tools using the T-slots made in the top and side surfaces of the bed as indicated in Fig. 4.2.10.

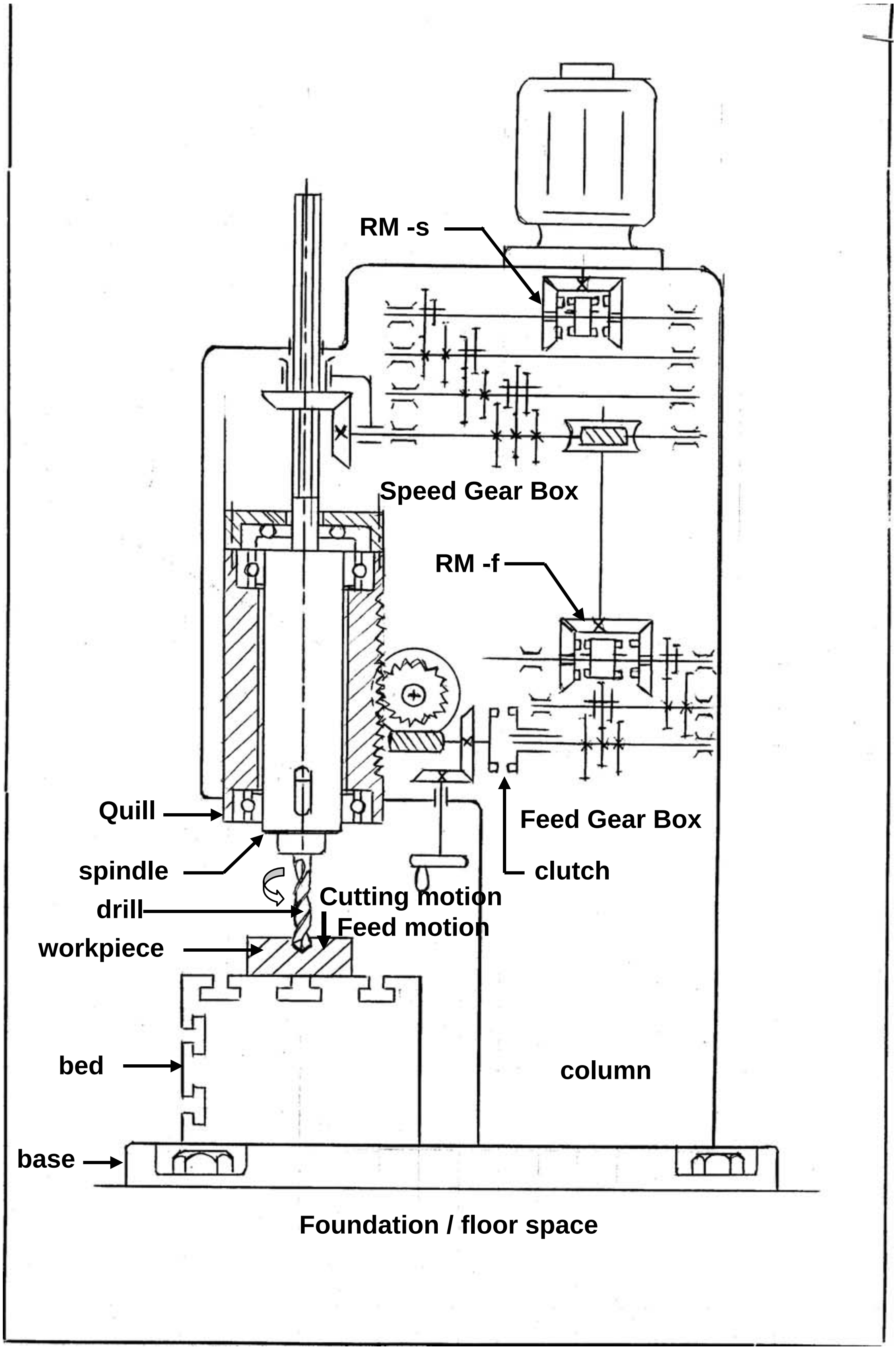


Fig. 4.2.10 *Schematic view of the drives of a drilling machine*

(iv) Application of drilling machines

Drilling machines of different capacity and configuration are basically used for originating cylindrical holes and occasionally for enlarging the existing holes to full or partial depth. But different types of drills are suitably used for various applications depending upon work material, tool material, depth and diameter of the holes.

General purpose drills may be classified as;

- **According to material :**
  - ∆ High speed steel – most common
  - ∆ Cemented carbides
    - Without or with coating
    - In the form of brazed, clamped or solid
- **According to size**
  - ∆ Large twist drills of diameter around 40 mm
  - ∆ Microdrills of diameter 25 to 500 μm
  - ∆ Medium range (most widely used) diameter ranges between 3 mm to 25 mm.

- **According to number of flutes**
  - ∆ Two fluted – most common
  - ∆ Single flute – e.g., gun drill (robust)
  - ∆ Three or four flutes – called slot drill

- **According to helix angle of the flutes**
  - ∆ Usual – 20^0 to 35^0 – most common
  - ∆ Large helix : 45^o to 60^o suitable for deep holes and softer work materials
  - ∆ Small helix : for harder / stronger materials
  - ∆ Zero helix : spade drills for high production drilling micro-drilling and hard work materials.

- **According to length – to – diameter ratio**
  - ∆ Deep hole drill; e.g. crank shaft drill, gun drill etc.
  - ∆ General type : $L/\phi \cong 6$ to 10
  - ∆ Small length : e.g. centre drill

- **According to shank**
  - ∆ Straight shank – small size drill being held in drill chuck
  - ∆ Taper shank – medium to large size drills being fitted into the spindle nose directly or through taper sockets

- **According to specific applications**
  - ∆ Centre drills (Fig. 4.2.11) : for small axial hole with 60^o taper end to accommodate lathe centre for support

∆ Step drill and subland drill (Fig. 4.2.12) : for small holes with two or three steps

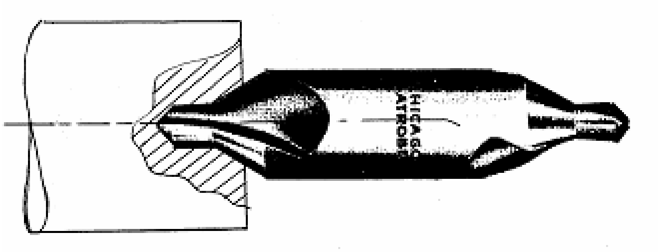


Fig. 4.2.11 *Centre Drill*

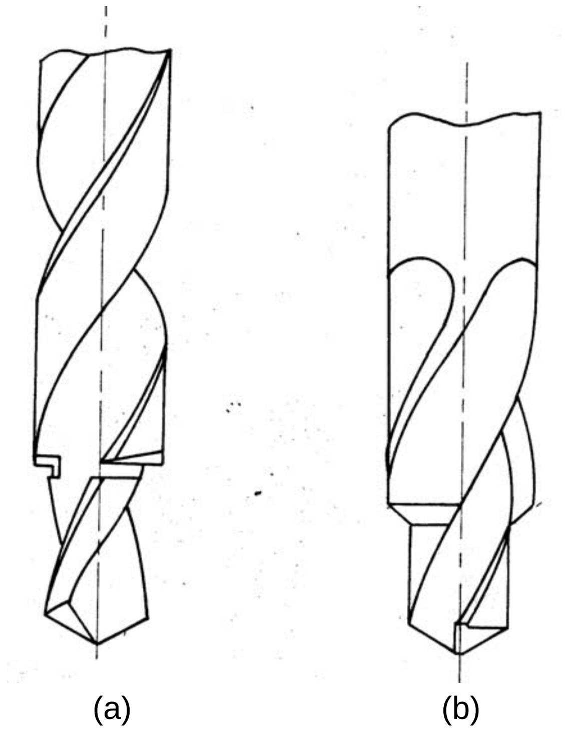


Fig. 4.2.12 *(a) Stepped drill and (b) subland drill*

∆ Half round drill, gun drill and crank shaft drill (for making oil holes) – shown in Fig. 4.2.13

∆ Ejector drill for high speed drilling of large diameter holes

∆ Taper drill for batch production

∆ Trepanning tool (Fig. 4.2.14) : for large holes in soft materials

Besides making holes, drilling machines may be used for various other functions using suitable cutting tools.

The wide range of applications of drilling machines include :

- Origination and / or enlargement of existing straight through or stepped holes of different diameter and depth in wide range of work materials – this is the general or common use of drilling machines

- Making rectangular section slots by using slot drills having 3 or four flutes and 180^0 cone angle
- Boring, after drilling, for accuracy and finish or prior to reaming
- Counterboring, countersinking, chamfering or combination using suitable tools as shown in Fig. 4.2.15

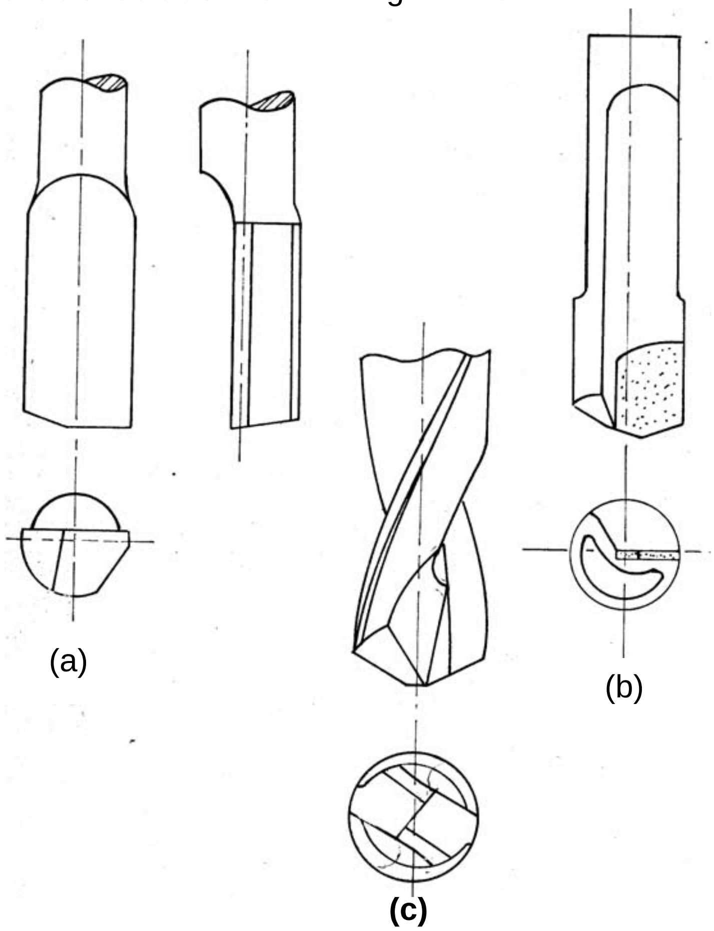


Fig. 4.2.13 *Schematic views of (a) half round drill, (b) gun drill and (c) crank shaft drill*

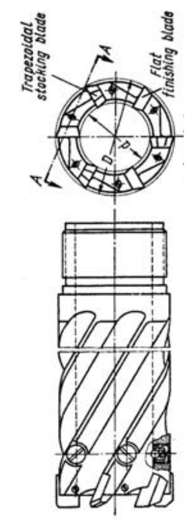


Fig. 4.2.14 *Schematic view of a trepanning tool.*

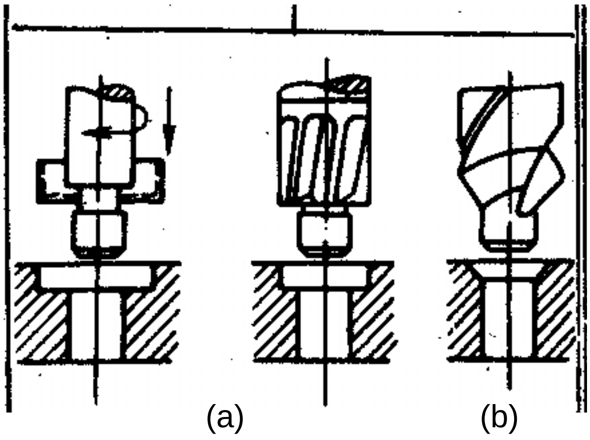


Fig. 4.2.15 *Schematic view of (a) counter boring and (b) countersinking*

- Spot facing by flat end tools (Fig. 4.2.16)
- Trepanning for making large through holes and or getting cylindrical solid core.
- Reaming is done, if necessary, after drilling or drilling and boring holes for accuracy and good surface finish. Different types of reamers of standard sizes are available as shown in Fig. 4.2.17 for different applications.

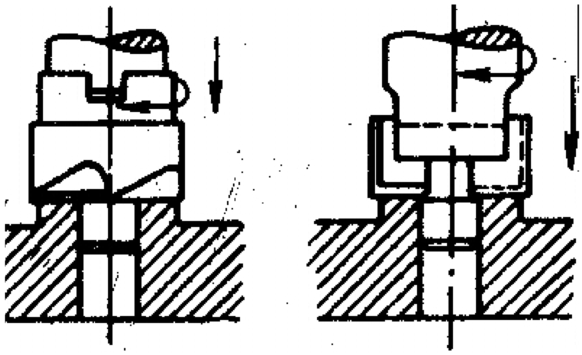


Fig. 4.2.16 Schematic view of spot facing

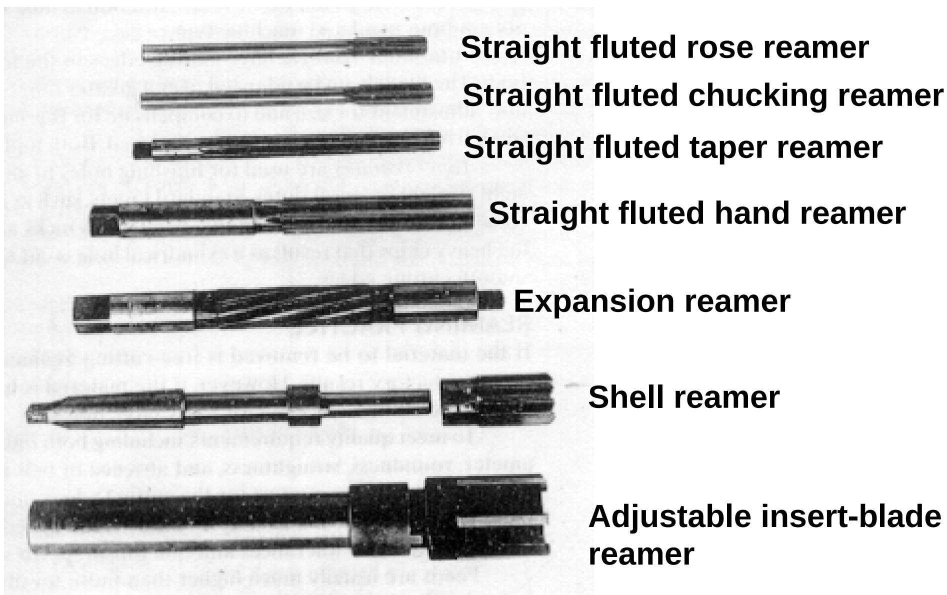


Fig. 4.2.17 *Different types of reamers.*

- Cutting internal screw threads mounting a tapping attachment in the spindle.

Several other operations can also be done, if desired, in drilling machines by using special tools and attachments.

Module
4
General purpose machine tools

Lesson
19
Kinematic system and operations of milling machines.

Instructional Objectives

(i) State the basic functions and purposes of using milling machines
(ii) Classify milling machines and illustrate their configurations
(iii) Visualise kinematic system of commonly used milling machines and explain its working principle.
(iv) Show and briefly describe the various applications of milling machines using different types of milling cutters.

(i) Basic functions and purposes of using milling machines

The basic function of milling machines is to produce flat surfaces in any orientation as well as surfaces of revolution, helical surfaces and contoured surfaces of various configurations. Such functions are accomplished by slowly feeding the workpiece into the equispaced multiedge circular cutting tool rotating at moderately high speed as indicated in Fig. 4.3.1. Upmilling needs stronger holding of the job and downmilling needs backlash free screw-nut systems for feeding.

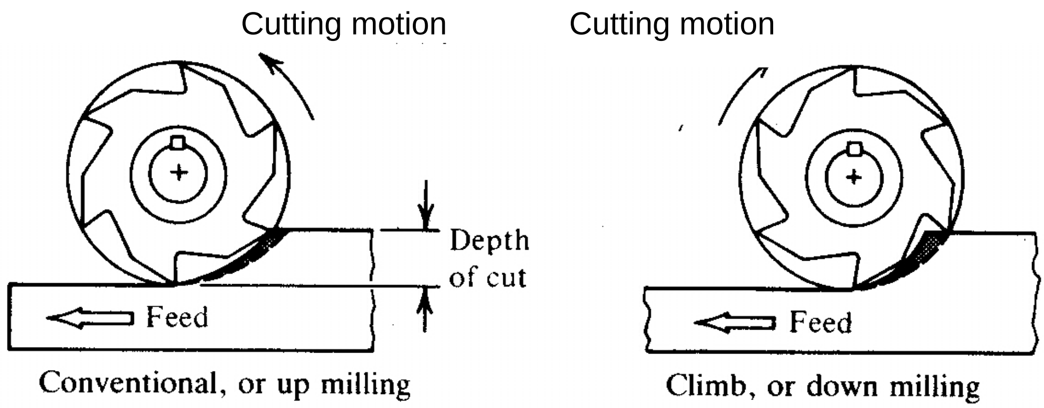


Fig. 4.3.1 *Schematic views of conventional up and down milling*

Milling machines of various type are widely used for the following purposes using proper cutting tools called milling cutters :

- Flat surface in vertical, horizontal and inclined planes
- Making slots or ribs of various sections
- Slitting or parting
- Often producing surfaces of revolution
- Making helical grooves like flutes of the drills
- Long thread milling on large lead screws, power screws, worms etc and short thread milling for small size fastening screws, bolts etc.
- 2-D contouring like cam profiles, clutches etc and 3-D contouring like die or mould cavities
- Cutting teeth in piece or batch production of spur gears, straight toothed bevel gears, worm wheels, sprockets, clutches etc.
- Producing some salient features like grooves, flutes, gushing and profiles in various cutting tools, e.g., drills, taps, reamers, hobs, gear shaping cutters etc.

(ii) Classification of milling machines

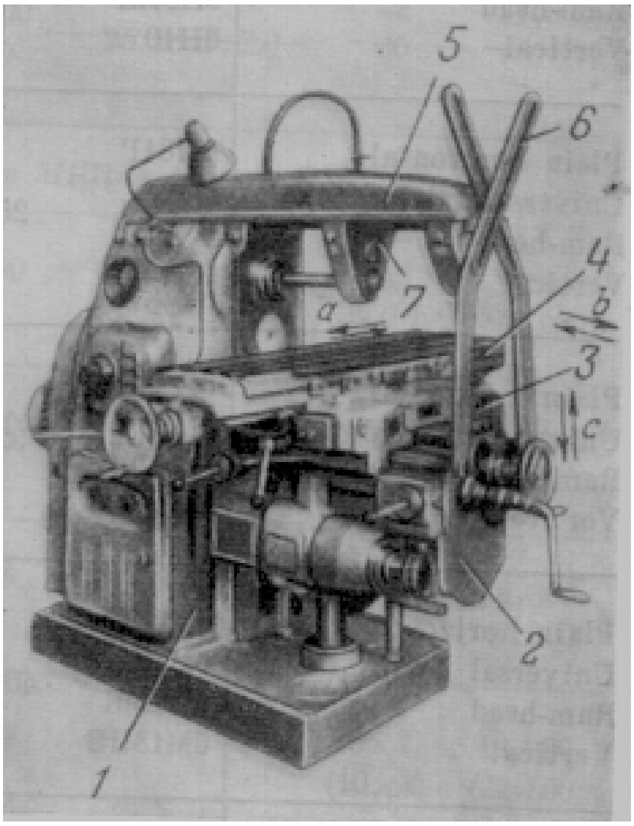
Milling machines can be broadly classified;

(a) According to nature of purposes of use :

- **general purpose** – most versatile commonly used mainly for piece or small lot production
- **single purpose** – e.g., thread milling machines, cam milling machines and slitting machine which are generally used for batch or lot production.
- **Special purpose** – these are used for lot or mass production, e.g., duplicating mills, die sinkers, short thread milling etc.

(b) According to configuration and motion of the work-holding table / bed

- **Knee type :** typically shown in Fig. 4.3.2. In such small and medium duty machines the table with the job/work travels over the bed (guides) in horizontal (X) and transverse (Y) directions and the bed with the table and job on it moves vertically (Z) up and down.



Machine parts :

1. column
2. bed
3. cross slide
4. work table
5. ram
6. ram support
7. arbour support

Table feed motions :

a. longitudinal feed
b. cross feed
c. vertical feed

Fig. 4.3.2 *Knee type milling machine*

- **Bed type (Fig. 4.3.3) :** Usually of larger size and capacity; the vertical feed is given to the milling head instead of the knee type bed

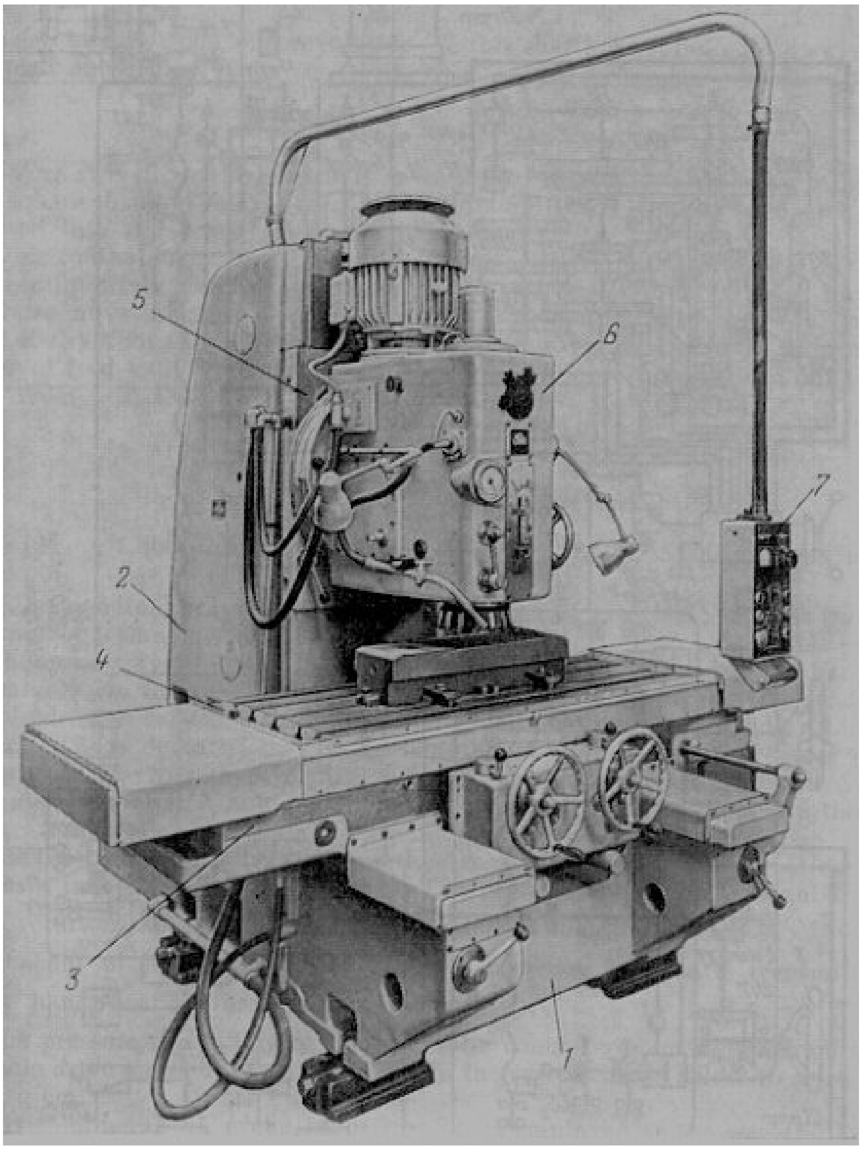


Fig. 4.3.3 *Bed type milling machine*

- **Planer type (Fig. 4.3.4) :** These heavy duty large machines, called plano-miller, look like planing machine where the single point tools are replaced by one or a number of milling heads; generally used for machining a number of longitudinal flat surfaces simultaneously, viz., lathe beds, table and bed of planning machine etc.
- **Rotary table type :** Such open or closed ended high production milling machines possess one large rotary work-table and one or two vertical spindles as typically shown in Fig. 4.3.5; the positions of the job(s) and the milling head are adjusted according to the size and shape of the job.

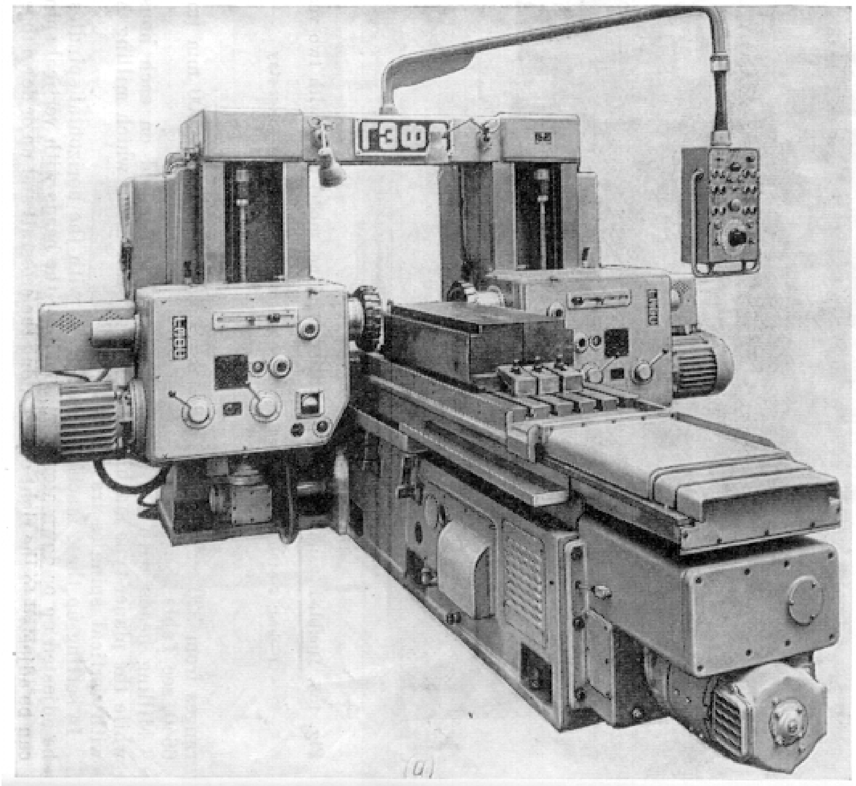


Fig. 4.3.4 *Planar type milling machine*

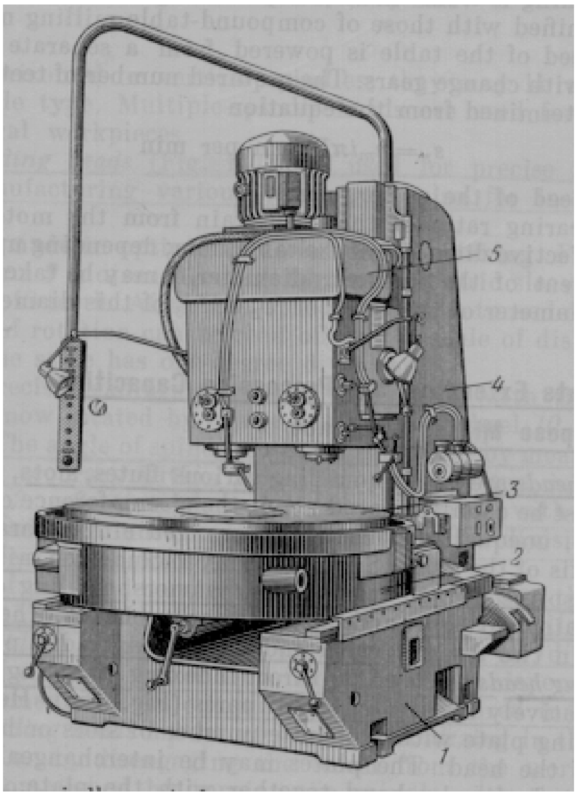


Fig. 4.3.5 *Rotary table type milling machine*

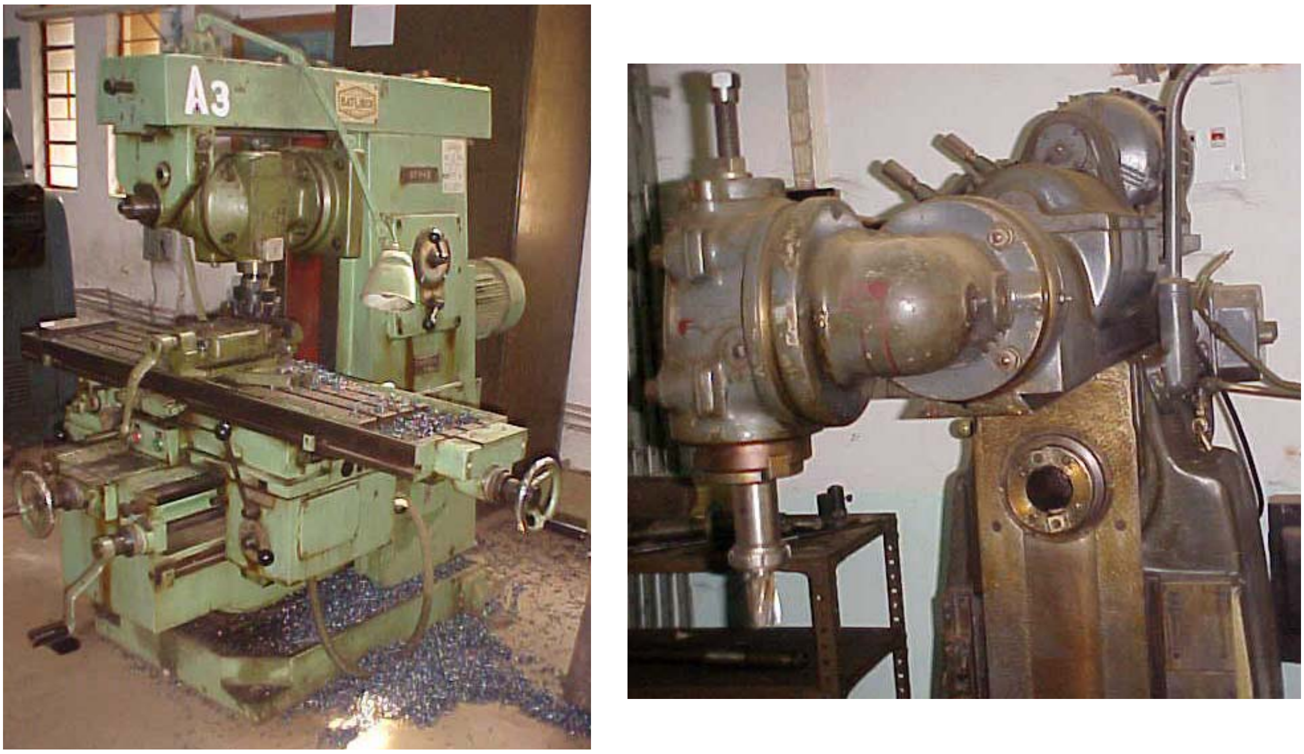
(c) According to the orientation of the spindle(s).

- **Plain horizontal knee type** (Fig. 4.3.6)
  This non-automatic general purpose milling machine of small to medium size possesses a single horizontal axis milling arbour; the work-table can be linearly fed along three axes (X,Y, Z) only; these milling machines are most widely used for piece or batch production of jobs of relatively simpler configuration and geometry

Fig. 4.3.6 *Plain horizontal knee type milling machine*

- **Horizontal axis (spindle) and swivelling bed type**
  These are very similar to the plain horizontal arbour knee type machines but possess one additional swivelling motion of the work-table
- **Vertical spindle type**
  In this machine, typically shown in Fig. 4.3.7, the only spindle is vertical and works using end mill type and face milling cutters; the table may or may not have swivelling features
- **Universal head milling machine**
  These versatile milling machines, typically shown in Fig. 4.3.8, not only possess both horizontal milling arbour and the vertical axis spindle, the latter spindle can be further tilted about one (X) or both the horizontal axes (X and Y) enabling machining jobs of complex shape.

Fig. 4.3.7 *Vertical spindle type milling machine*



(a) (b)

Fig. 4.3.8 *(a) & (b) Universal head milling machine*

(d) According to mechanisation / automation and production rate

Milling machines are mostly general purpose and used for piece or small lot production. But like other machine tools, some milling machines are also incorporated with certain type and degree of automation or mechanisation to enhance production rate and consistency of product quality. In this respect milling machines can be further classified as follows :

- **Hand mill (milling machine) -** this is the simplest form of milling machine where even the table feed is also given manually as can be seen in Fig. 4.3.9.

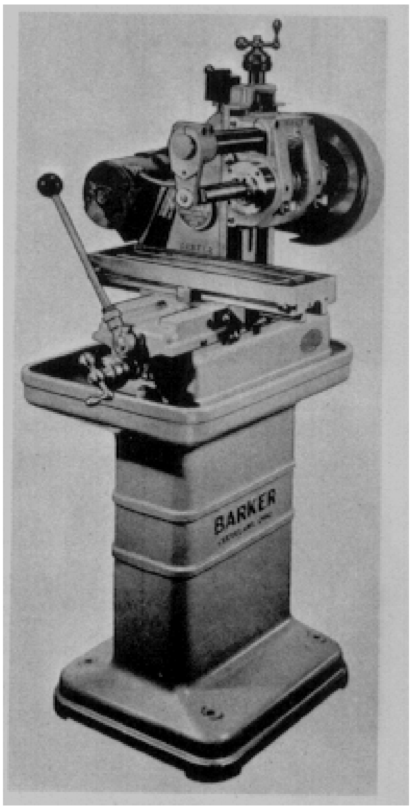


Fig. 4.3.9 *Hand mill milling machine*

- **Planer and rotary table type vertical axis milling machines** are not that automated but provide relatively higher production rate

- **Tracer controlled copy milling machine,** typically shown in Fig. 4.3.10, are mechanically or hydraulically operated semi-automatic milling machines used for lot production of cams, dies etc by copying the master piece

- **Milling machines for short thread milling** may be considered single purpose and automatic machine being used for mass production of small bolts and screws.

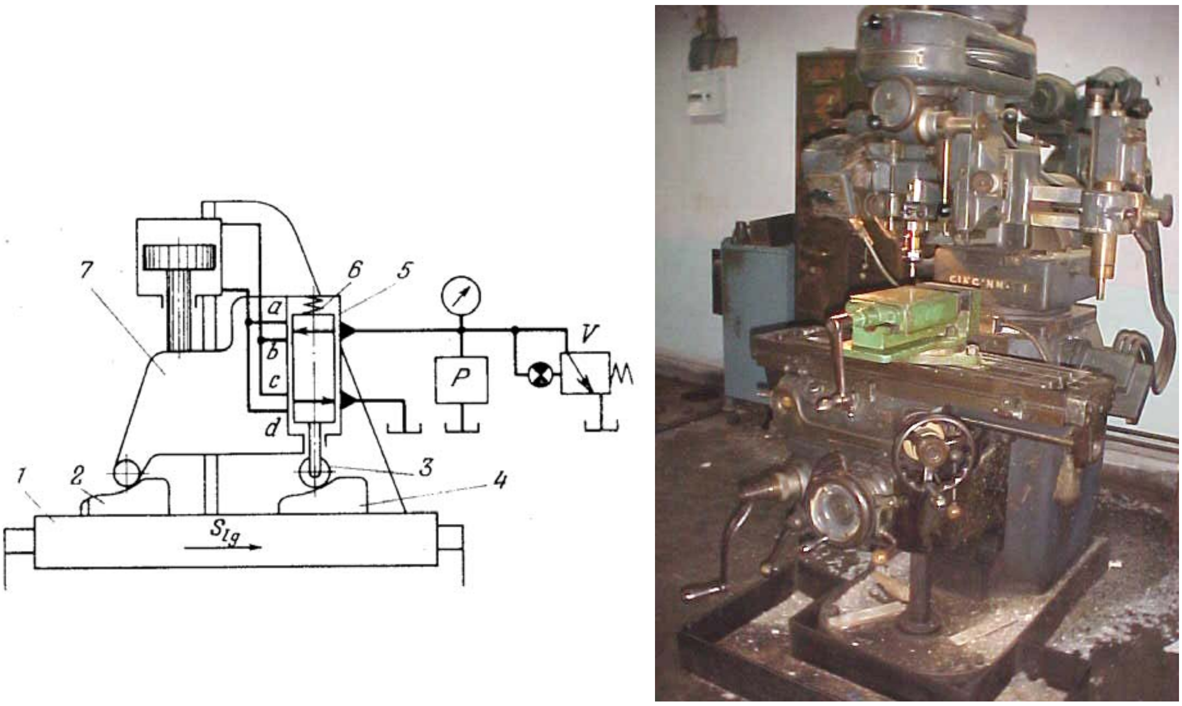


Fig. 4.3.10 *Tracer controlled milling machine*

- **Computer Numerical Controlled (CNC) milling machine**

Replacement of hard or rigid automation by Flexible automation by developing and using CNC has made a great break through since mid seventies in the field of machine tools' control. The advantageous characteristics of CNC machine tools over conventional ones are :

- flexibility in automation
- change-over (product) time, effort and cost are much less
- less or no jigs and fixtures are needed
- complex geometry can be easily machined
- high product quality and its consistency
- optimum working condition is possible
- lesser breakdown and maintenance requirement

Fig. 4.3.11 typically shows a CNC milling machine. The versatility of CNC milling machine has been further enhanced by developing what is called Machining Centre. Fig. 4.3.12 visualises one of such Machining Centres.

Fig. 4.3.11 *CNC Milling Machine*

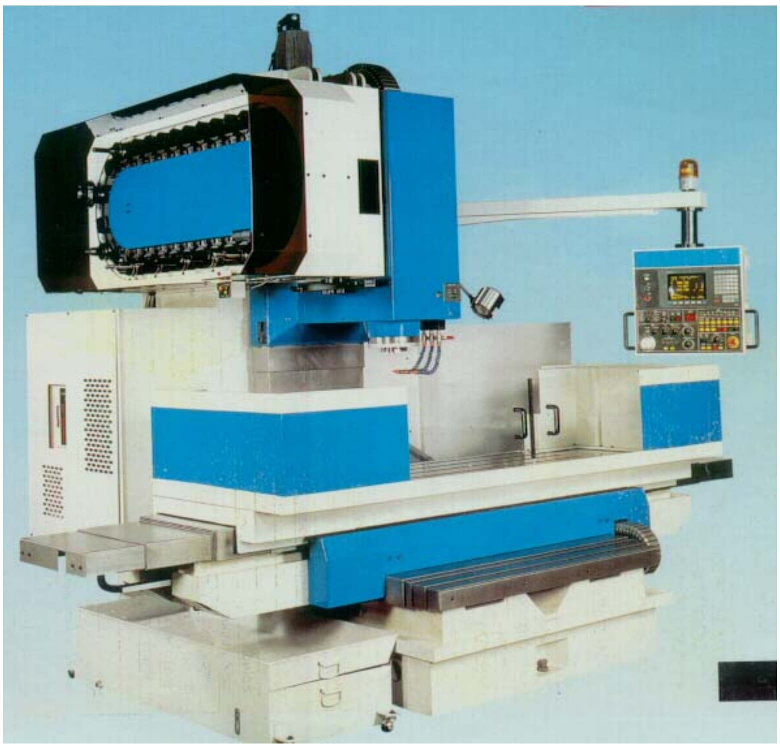


Fig. 4.3.12 *CNC Machining Centre*

(iii) Kinematic system of milling machine

The kinematic system comprising of a number of kinematic chains of several mechanisms enables transmission of motions (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. In some milling machines the vertical feed is given to the milling(cutter) head. The more versatile milling machines additionally possess the provisions of rotating the work table and tilting the vertical milling spindle about X and / or Y axes.

Fig. 4.3.13 typically shows the kinematic diagram of the most common and widely used milling machine having rotation of the single horizontal spindle or arbour and three feed motions of the work-table in X, Y and Z directions.

The milling cutter mounted on the horizontal milling arbour, receives its rotary motion at different speeds from the main motor through the speed gear box which with the help of cluster gears splits the single speed into desirably large number(12, 16, 18, 24 etc) of spindle speeds. Power is transmitted to the speed gear box through Vee-belts and a safety clutch as shown in the diagram. For the feed motions of the workpiece (mounted on the work-table) independently, the cutter speed, rotation of the input shaft of the speed gear box is transmitted to the feed gear box through reduction (of speed) by worm and worm wheels as shown. The cluster gears in the feed gear box enables provide a number of feed rates desirably. The feeds of the job can be given both manually by rotating the respective wheels by hand as well as automatically by engaging the respective clutches. The directions of the longitudinal (X), cross (Y) and vertical (Z) feeds are controlled by appropriately shifting the clutches. The system is so designed that the longitudinal feed can be combined with the cross feed or vertical feed but cross feed and vertical feed cannot be obtained simultaneously. This is done for safety purpose. A telescopic shaft with universal joints at its ends is incorporated to transmit feed motion from the fixed position of the feed gear box to the bed (and table) which moves up and down requiring change in length and orientation of the shaft. The diagram also depicts that a separate small motor is provided for quick traverse of the bed and table with the help of an over running clutch. During the slow working feeds the rotation is transmitted from the worm and worm wheel to the inner shaft through three equi-spaced rollers which get jammed into the tapering passage. During quick unworking work-traverse, the shaft is directly rotated by that motor on-line without stopping or slowing down the worm. Longer arbours can also be fitted, if needed, by stretching the over-arm. The base of the milling machine is grouted on the concrete floor or foundation.

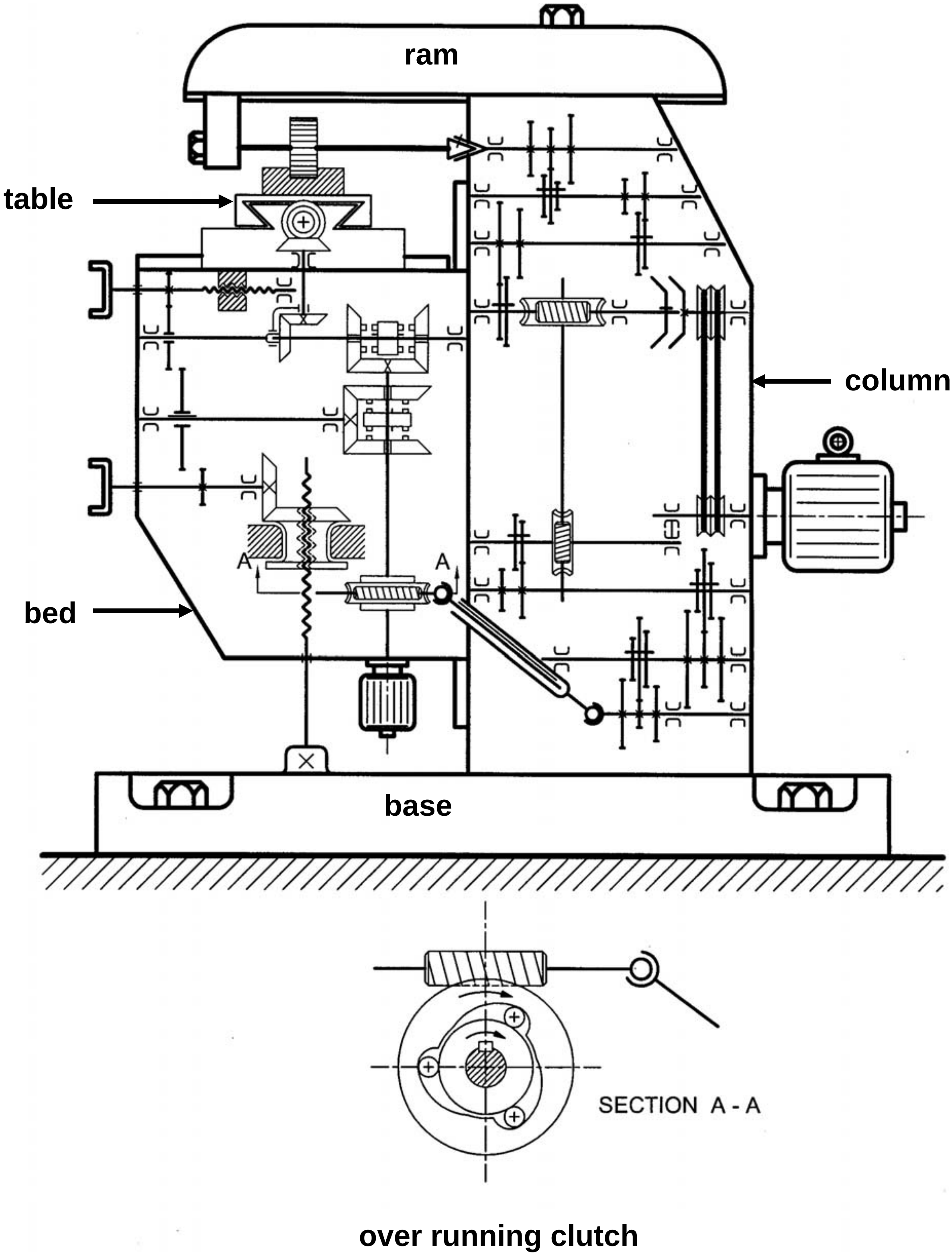


Fig. 4.3.13 Kinematic diagram of a milling machine

(iv) Various applications of milling machines using different types of milling cutters.

Milling machines are mostly general purpose and have wide range of applications requiring various types and size of milling cutters.
Intermittent cutting nature and usually complex geometry necessitate making the milling cutters mostly by HSS which is unique for high tensile and transverse rupture strength, fracture toughness and formability almost in al respects i.e. forging, rolling, powdering, welding, heat treatment, machining (in annealed condition) and grinding. Tougher grade cemented carbides are also used without or with coating, where feasible, for high productivity and product quality.

Broad classifications of milling cutters

Milling cutters are broadly classified as,

(a) Profile sharpened cutters – where the geometry of the machined surfaces are not related with the tool shape, viz;

- i. Slab or plain milling cutter : — straight or helical fluted
- ii. side milling cutters – single side or both sided type
- iii. slotting cutter
- iv. slitting or parting tools
- v. end milling cutters – with straight or taper shank
- vi. face milling cutters

(b) Form relieved cutters – where the job profile becomes the replica of the tool-form, e.g., viz.;

- i. Form cutters
- ii. gear (teeth) milling cutters
- iii. spline shaft cutters
- iv. tool form cutters
- v. T-slot cutters
- vi. Thread milling cutter

Various uses of different milling cutters and milling machines

Use of profile sharpened cutters

The profile sharpened cutters are inherently used for making flat surfaces or surface bounded by a number of flat surfaces only.

- **Slab or Plain milling cutters : -**

Plain milling cutters are hollow straight HSS cylinder of 40 to 80 mm outer diameter having 4 to 16 straight or helical equi-spaced flutes or cutting edges and are used in horizontal arbour to machine flat surface as shown in Fig. 4.3.14.

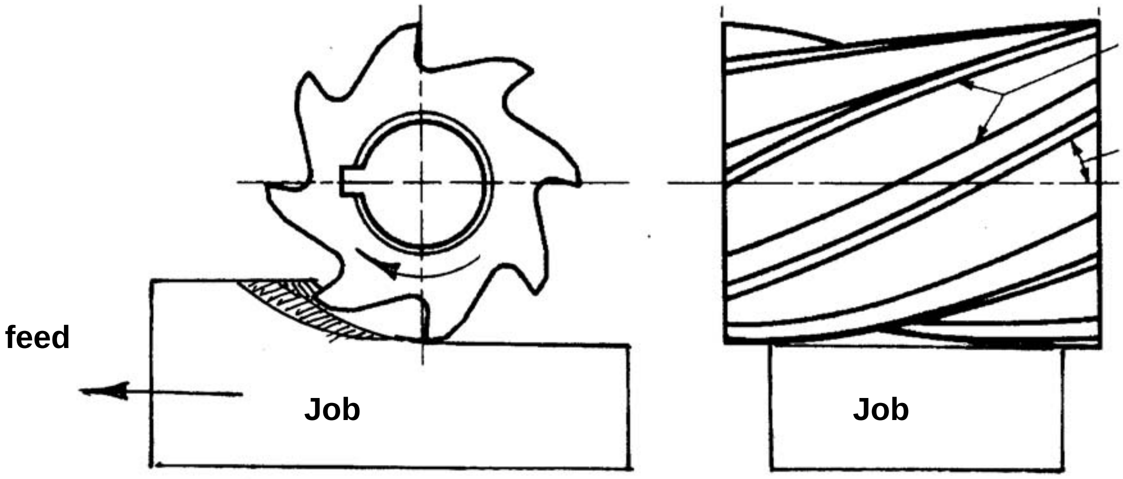


Fig. 4.3.14 *Machining flat surface by slab milling.*

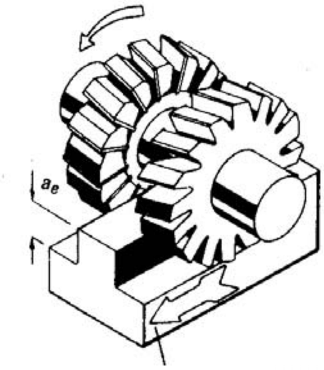
- **Side and slot milling cutters**

These arbour mounted disc type cutters have a large number of cutting teeth at equal spacing on the periphery. Each tooth has a peripheral cutting edge and another cutting edge on one face in case of single side cutter and two more cutting edges on both the faces leading to double sided cutter. One sided cutters are used to produce one flat surface or steps comprising two flat surfaces at right angle as shown in Fig. 4.3.15. Both sided cutters are used for making rectangular slots bounded by three flat surfaces. Slotting is also done by another similar cutter having only one straight peripheral cutting on each tooth. These cutters may be made from a single piece of HSS or its teeth may be of carbide blades brazed on the periphery or clamped type uncoated or coated carbide inserts for high production machining.

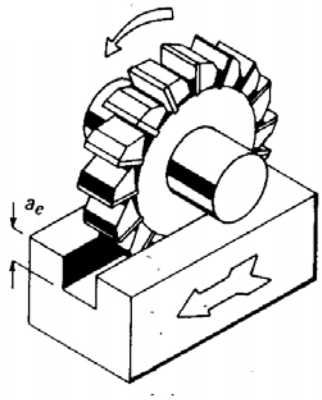
- **Slitting saw or parting tool (Fig. 4.3.15)**

These milling cutters are very similar to the slotting cutters having only one peripheral cutting edge on each tooth. However, the slitting saws

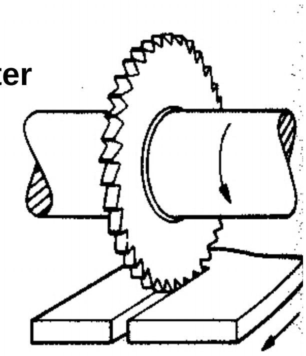
— are larger in diameter and much thin
— possess large number of cutting teeth but of small size
— used only for slitting or parting



(a) parallel facing by two side (single) cutter



(b) slotting by side (double sided) milling cutter



(c) Parting by slitting saw

Fig. 4.3.15 *Side milling cutters and slitting saw and their use.*

- **End milling cutters or End mills**

The shape and the common applications of end milling cutters (profile sharpened type) are shown in Fig. 4.3.16. The common features and characteristics of such cutters are :

— mostly made of HSS
— 4 to 12 straight or helical teeth on the periphery and face
— diameter ranges from about 1 mm to 40 mm
— very versatile and widely used in vertical spindle type milling machines
— end milling cutters requiring larger diameter are made as a separate cutter body which is fitted in the spindle through a taper shank arbour as shown in the same figure.

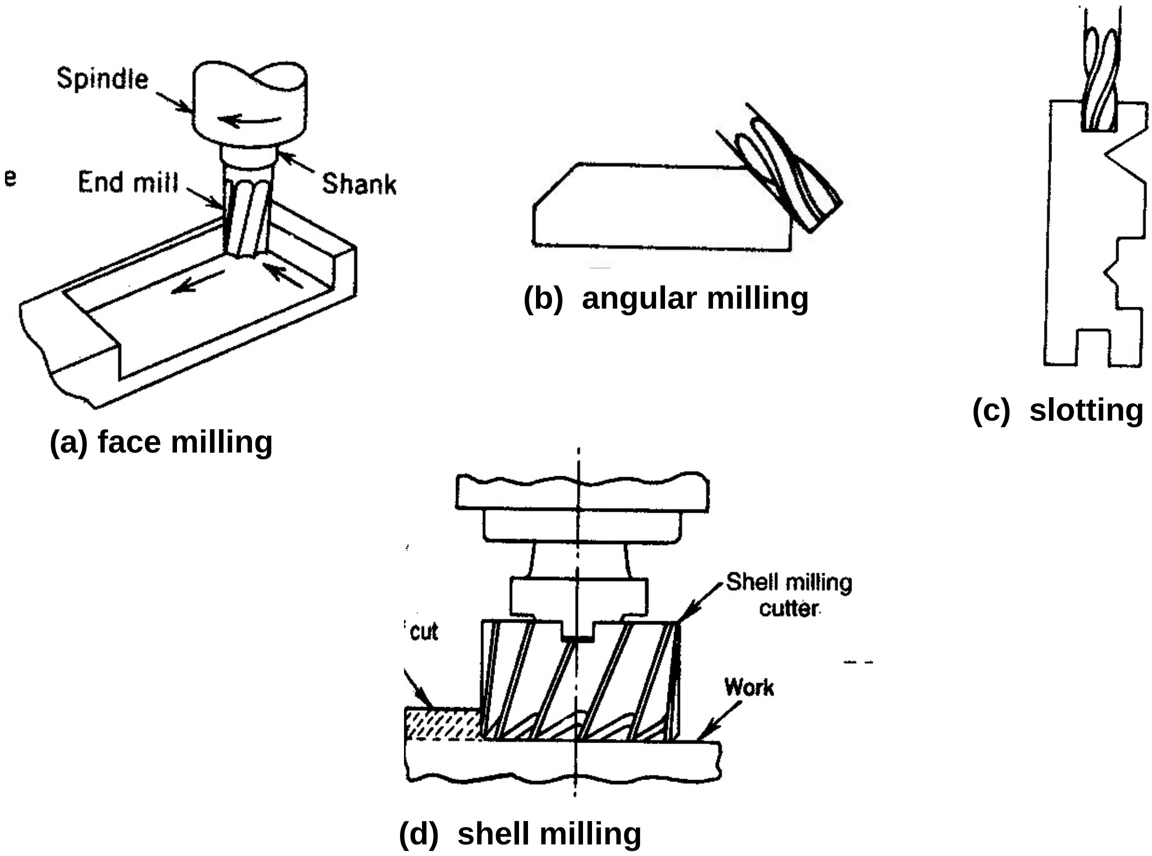


Fig. 4.3.16 *Use of end milling cutters and shell mill*

- **Face milling cutters**

The shape, geometry and typical use of face milling cutters are shown in Fig. 4.3.17.

The main features are :

- usually large in diameter (80 to 800 mm) and heavy
- used only for machining flat surfaces in different orientations
- mounted directly in the vertical and / or horizontal spindles
- coated or uncoated carbide inserts are clamped at the outer edge of the carbon steel body as shown
- generally used for high production machining of large jobs.

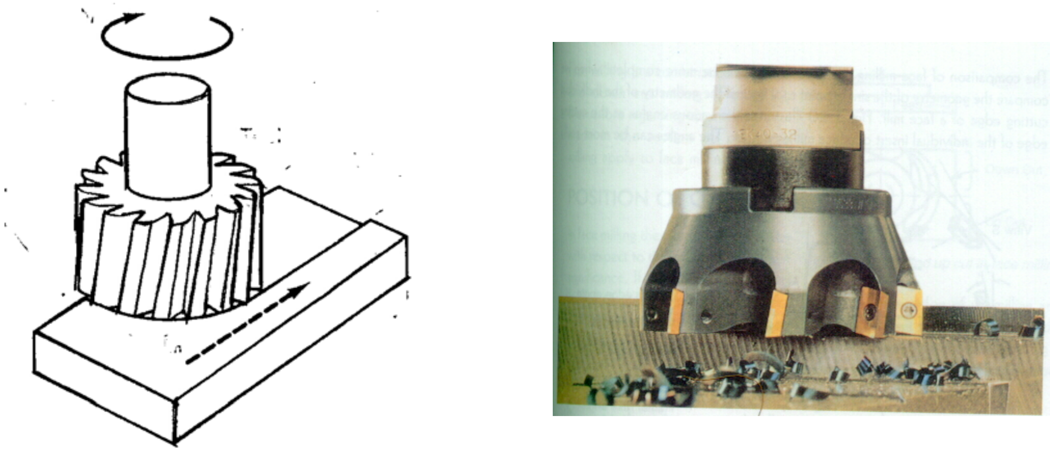


Fig. 4.3.17 *Face milling cutters and their working*

Use of form relieved cutters (milling)

The distinguishing characteristics of such cutters, in contrast to profile sharpened cutters, are ;

- form of the tool is exactly replica of the job-profile to be made
- clearance or flank surfaces of the teeth are of archemedian spiral shaped instead of flat
- teeth are sharpened by grinding the rake surface only
- used for making 2-D and 3-D contour surfaces

The configurations and applications of several form relieved type milling cutters of common use are briefly presented.

- **Form cutters**

Such disc type HSS cutters are generally used for making grooves or slots of various profiles as indicated in Fig. 4.3.18.
Form cutters may be also end mill type like T-slot cutter as shown in Fig. 4.3.19

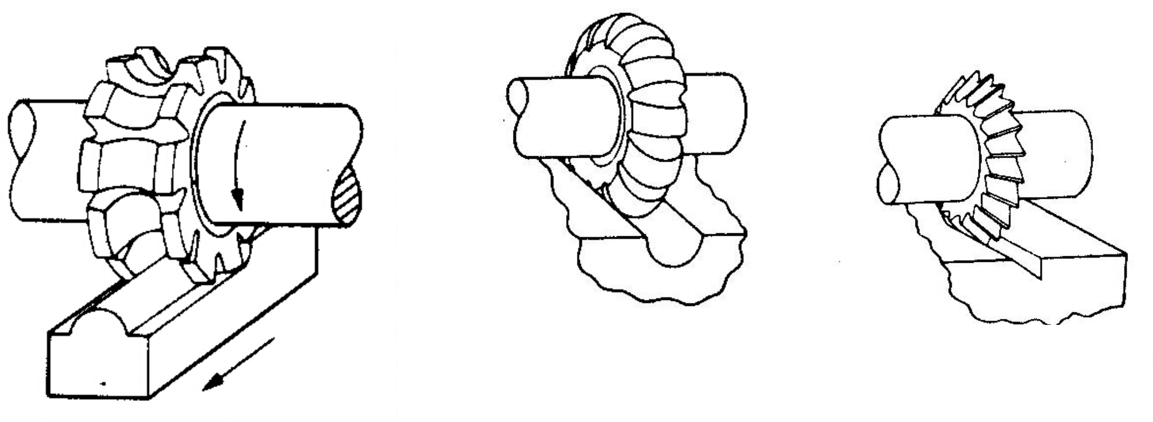


Fig. 4.3.18 *Form cutters and their use*

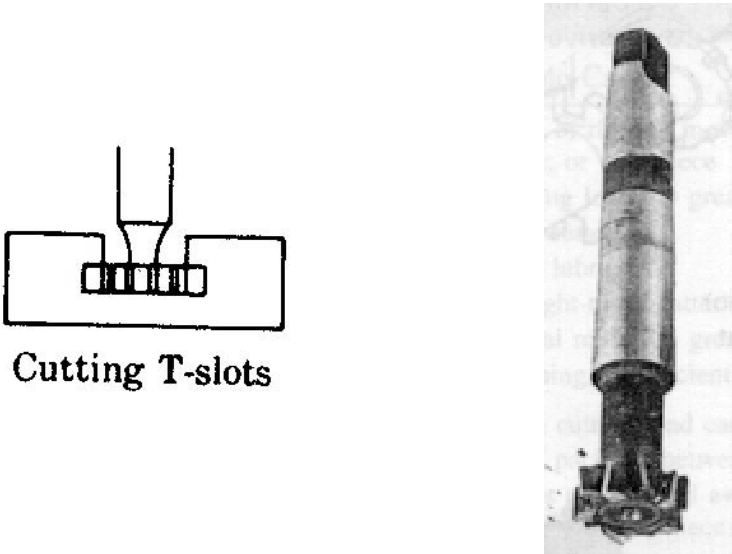


Fig. 4.3.19 *T-slot cutter*

- **Gear teeth milling cutters**

Gear milling cutters are made of HSS and available mostly in disc form like slot milling cutters and also in the form of end mill for producing teeth of large module gears. The form of these tools conform to the shape of the gear tooth-gaps bounded by two involutes as shown in Fig. 4.3.20. Such form relieved cutters can be used for producing teeth of straight and helical toothed external spur gears and worm wheels as well as straight toothed bevel gears.

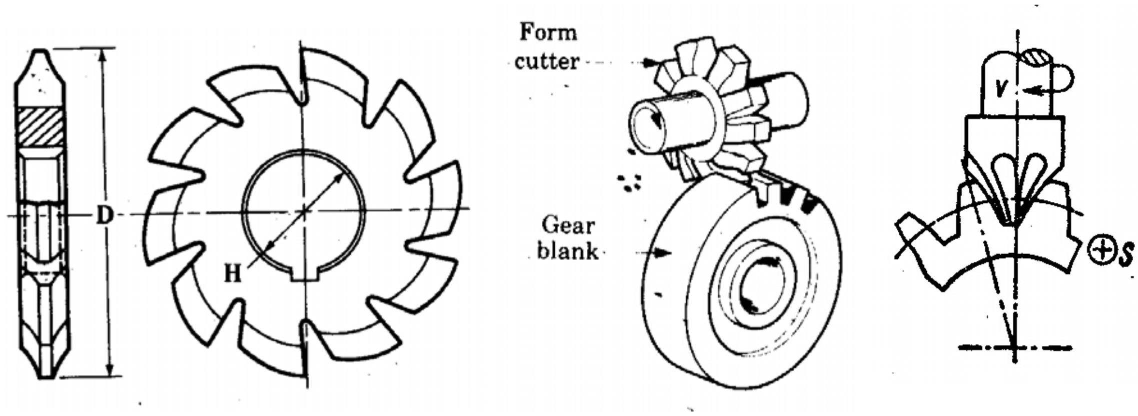


Fig. 4.3.20 *Gear milling cutters and their use*

- **Spline shaft cutters**

These disc type HSS form relieved cutters are used for cutting the slots of external spline shafts having 4 to 8 straight axial teeth. Fig. 4.3.21 typically shows such application.

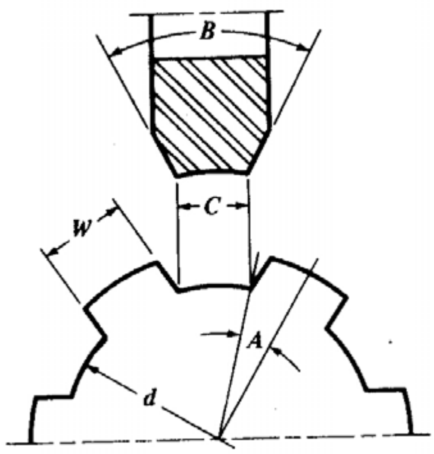


Fig. 4.3.21 *Spline shaft cutter*

- **Tool form cutters**

Form milling type cutters are also used widely for cutting slots or flutes of different cross section e.g. the flutes of twist drills (Fig. 4.3.22), milling cutters, reamers etc., and gushing of hobs, taps, short thread milling cutters etc.

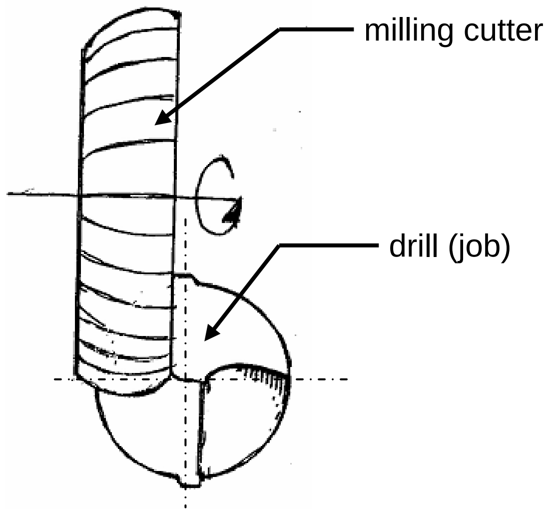


Fig. 4.3.22 *Cutting of drill flutes by form milling cutter*

- **Thread milling cutter**

Such shank type solid HSS or carbide cutters having thread like annular grooves with equi-spaced gushings are used in automatic single purpose milling machines for cutting the threads in large lot production of screws, bolts etc. Both internal and external threads are cut by the tool as shown in Fig. 4.3.23. The milling cutter and its use in long thread milling (e.g. lead screws, power screws, worms etc.) are shown in Fig. 4.3.24.

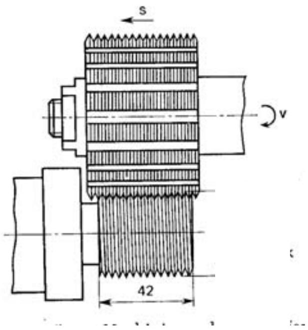


Fig. 4.3.23 *Short thread milling*

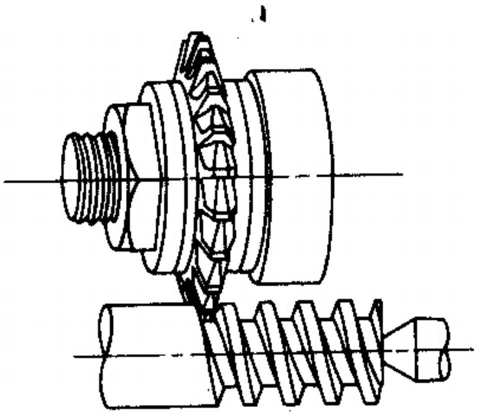


Fig. 4.3.24 *Long thread milling*

Some other applications of milling machines using suitable milling cutters

- **Straddle milling**

  For faster and accurate machining two parallel vertical surfaces at a definite distance, two separate side milling cutters are mounted at appropriate distance on the horizontal milling arbour as shown in Fig. 4.3.25.

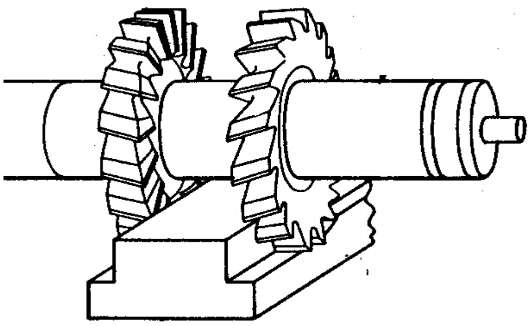


Fig. 4.3.25 *Straddle milling*

- **Gang milling**

In gang milling, being employed, where feasible, for quick production of complex contours comprising a number of parallel flat or curved surfaces a proper combination of several cutters are mounted tightly on the same horizontal milling arbour as indicated in Fig. 4.3.26

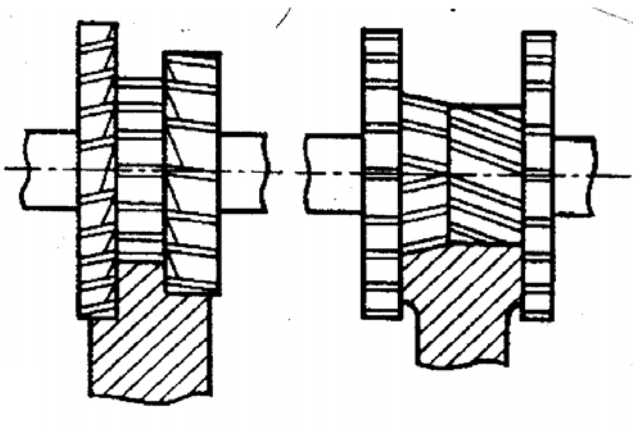


Fig. 4.3.26 *Gang milling*

- **Turning by rotary tools (milling cutters)**

During turning like operations in large heavy and odd shaped jobs, its speed (rpm) is essentially kept low. For enhancing productivity and better cutting fluid action rotary tools like milling cutters are used as shown in Fig. 4.3.27.

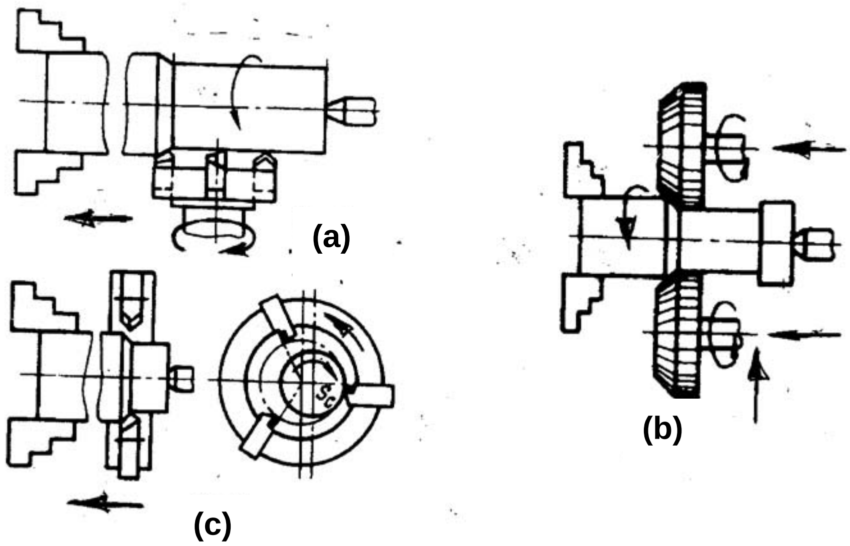


Fig. 4.3.27 *Turning by rotary milling cutters*

- **Ball-nose end mill**

Small HSS end mill with ball like hemispherical end , as shown in Fig. 4.3.28, is often used in CNC milling machines for machining free form 3-D or 2-D contoured surfaces.

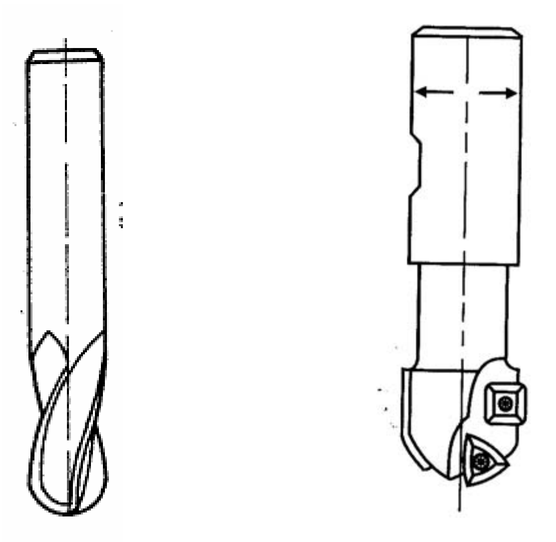


Fig. 4.3.28 *Ball nose end mills*

Ball nose end mills may be made of HSS, solid carbide or steel body with coated or uncoated carbide inserts clamped at its end as can be seen in the figure.

Beside the aforesaid applications, the versatile milling processes using several other types of milling cutters are employed for many other machining work like cam milling, keyway cutting, making hob cutter and so on. For enhancing capability range of milling work a number of attachments are fitted in the milling machines. Such milling attachments include

- universal milling and spiral milling attachment
- indexing head – simple, compound and differential type
- universal milling and spiral milling attachment
- copying attachment (mechanical and hydraulic (tracer control))
- slotting attachment

Module
4
General purpose machine tools

Lesson
20
Construction, working principle and applications of shaping, planing and slotting machines.

Instructional objectives

At the end of this lesson, the students will be able to;

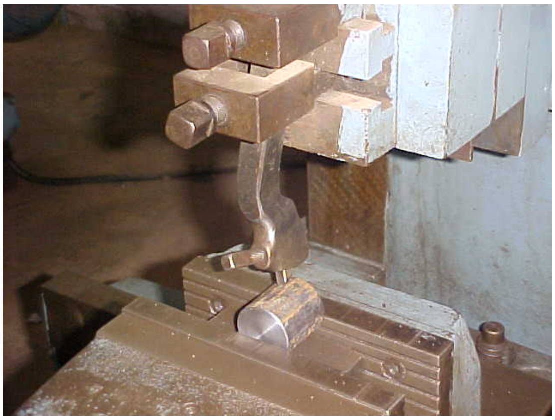
(i) Demonstrate the configurations and functions of shaping machine, planing machine and slotting machine
(ii) Illustrate the kinematic systems and explain the working principles of shaping machine, planing machine and slotting machine
(iii) Show and describe the various machining applications of shaping, planing and slotting machines.

(i) Configurations and basic functions of

- **Shaping machines**
- **Planing machines**
- **Slotting machines**

- **Shaping machine**

A photographic view of general configuration of shaping machine is shown in Fig. 4.4.1. The main functions of shaping machines are to produce flat surfaces in different planes. Fig. 4.4.2 shows the basic principle of generation of flat surface by shaping machine. The cutting motion provided by the linear forward motion of the reciprocating tool and the intermittent feed motion provided by the slow transverse motion of the job along with the bed result in producing a flat surface by gradual removal of excess material layer by layer in the form of chips. The vertical infeed is given either by descending the tool holder or raising the bed or both. Straight grooves of various curved sections are also made in shaping machines by using specific form tools. The single point straight or form tool is clamped in the vertical slide which is mounted at the front face of the reciprocating ram whereas the workpiece is directly or indirectly through a vice is mounted on the bed.



Cutting tool in action

Fig. 4.4.1 *Photographic view of a shaping machine*

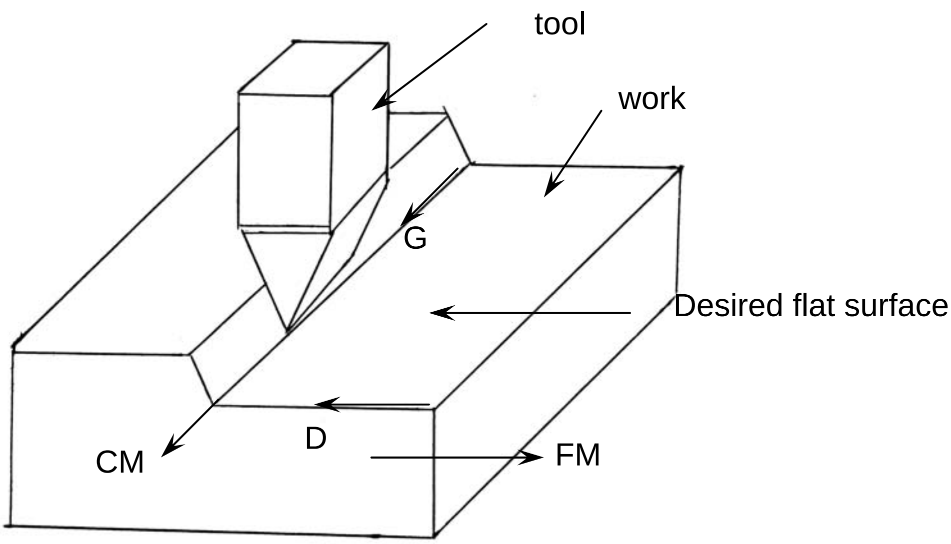


Fig. 4.4.2 *Principle of producing flat surface in shaping machine*

- **Planing machine**

The photographic view in Fig. 4.4.3 typically shows the general configuration of planing machine. Like shaping machines, planing machines are also basically used for producing flat surfaces in different planes. However, the major differences between planing machines from shaping machines are :

- o Though in principle both shaping and planing machines produce flat surface in the same way by the combined actions of the Generatrix and Directrix but in planing machine, instead of the tool, the workpiece reciprocates giving the fast cutting motion and instead of the job, the tool(s) is given the slow feed motion(s).
- o Compared to shaping machines, planing machines are much larger and more rugged and generally used for large jobs with longer stroke length and heavy cuts. In planing machine, the workpiece is mounted on the reciprocating table and the tool is mounted on the horizontal rail which, again, can move vertically up and down along the vertical rails.
- o Planing machines are more productive (than shaping machines) for longer and faster stroke, heavy cuts (high feed and depth of cut) possible and simultaneous use of a number of tools.

As in shaping machines, in planing machines also;

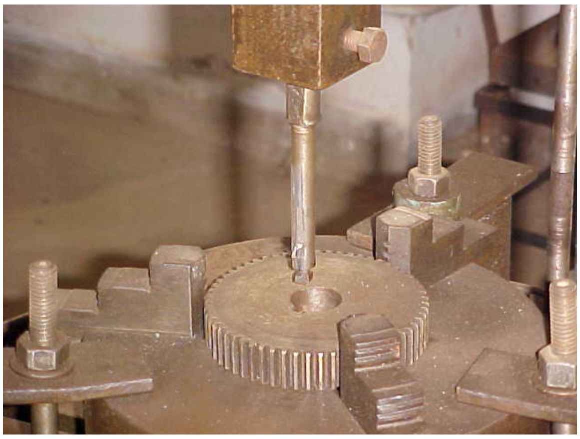
- Δ The length and position of stroke can be adjusted
- Δ Only single point tools are used
- Δ The quick return persists
- Δ Form tools are often used for machining grooves of curved section
- Δ Both shaping and planing machines can also produce large curved surfaces by using suitable attachments.

Cutting tool in action

Fig. 4.4.3 *Photographic view of a planing machine*

- **Slotting machine**

Slotting machines can simply be considered as vertical shaping machine where the single point (straight or formed) reciprocates vertically (but without quick return effect) and the workpiece, being mounted on the table, is given slow longitudinal and / or rotary feed as can be seen in Fig. 4.4.4. In this machine also the length and position of stroke can be adjusted. Only light cuts are taken due to lack of rigidity of the tool holding ram for cantilever mode of action. Unlike shaping and planing machines, slotting machines are generally used to machine internal surfaces (flat, formed grooves and cylindrical).
Shaping machines and slotting machines, for their low productivity, are generally used, instead of general production, for piece production required for repair and maintenance. Like shaping and slotting machines, planing machines, as such are also becoming obsolete and getting replaced by plano-millers where instead of single point tools a large number of large size and high speed milling cutters are used.



Cutting tool in action

Fig. 4.4.4 *Photographic view of a slotting machine*

(ii) Kinematic system and working principles of

- **Shaping machine**
- **Planing machine**
- **Slotting machine**

- **Shaping machine**

The usual kinematic system provided in shaping machine for transmitting power and motion from the motor to the tool and job at desired speeds and feeds is schematically shown in Fig. 4.4.5.

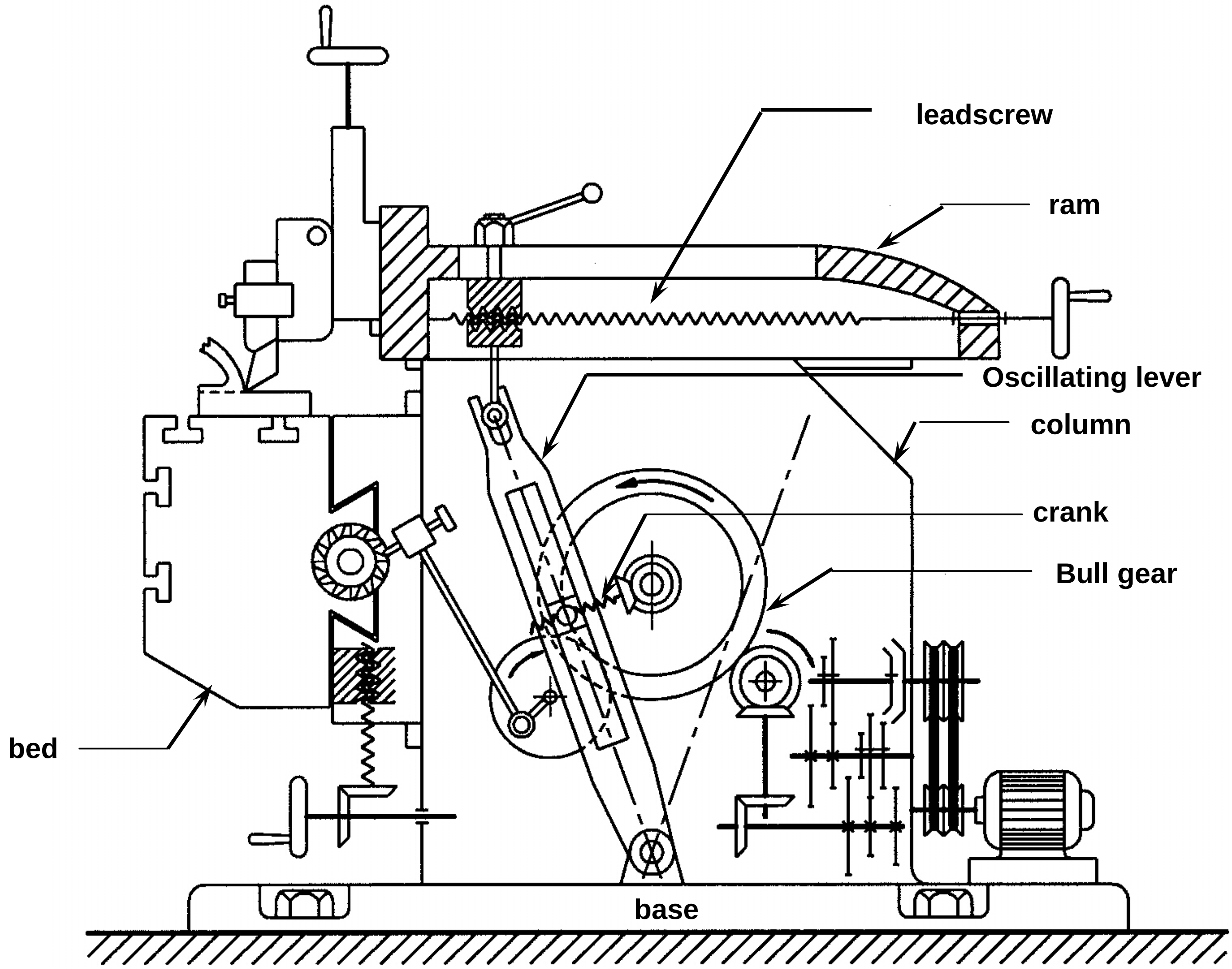


Fig. 4.4.5 *Kinematic diagram of a shaping machine.*

The central large bull gear receives its rotation from the motor through the belt-pulley, clutch, speed gear box and then 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. Cutting velocity which needs to be varied depending upon the tool-work materials, depends upon

- The stroke length, S mm
- Number of strokes per min., N_s and
- The Quick return ratio, QRR (ratio of the durations of the forward stroke and the return stroke)

As, $V_C = \frac{sxN_s}{1000}\left(1+\frac{1}{QRR}\right) m/\min$ (4.5.1)

To reduce idle time, return stroke is made faster and hence QRR > 1.0 (4.5.2)

Since $QRR = \frac{2L+s}{2L-s}$ (4.5.3)

where, L = length (fixed) of the oscillating lever
and s = stroke length

The benefit of quick return decreases when S becomes less.

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 nut by rotating the leadscrew as shown in Fig. 4.4.5.

The value of N_s is varied by operating the speed gear box.

The main (horizontal) feed motion of the work table is provided at different rate by using the ratchet – paul systen as shown in Fig. 4.4.5. The vertical feed or change in height of the tool tip from the bed can be obtained either by lowering the tool or raising the bed by rotating the respective wheel as indicated in Fig. 4.4.5.

- **Planing machine**

The simple kinematic system of the planing machine 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 tools. The reciprocation of the table, which imparts cutting motion to the job, is attained by rack-pinion mechanism. 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 which not only enables change in the number of stroke per minute but also quick return of the table.

The blocks holding the cutting tools are moved horizontally along the rail by screw-nut system and the rail is again moved up and down by another screw-nut pair as indicated in Fig. 4.4.3.

- **Slotting machine**

The schematic view of slotting machine is typically shown in Fig. 4.4.6

The vertical slide holding the cutting tool is reciprocated by a crank and connecting rod mechanism, so here quick return effect is absent. The job, to be machined, is mounted directly or in a vice on the work table. Like shaping machine, in slotting machine also the fast cutting motion is imparted to the tool and the feed motions to the job. In slotting machine, in addition to the

longitudinal and cross feeds, a rotary feed motion is also provided in the work table.
The intermittent rotation of the feed rod is derived from the driving shaft with the help of a four bar linkage as shown in the kinematic diagram.
It is also indicated in Fig. 4.4.6 how the intermittent rotation of the feed rod is transmitted to the leadsrews for the two linear feeds and to the worm – worm wheel for rotating the work table. The working speed, i.e., number of strokes per minute, N_s may be changed, if necessary by changing the belt-pulley ratio or using an additional “speed gear box”, whereas, the feed values are changed mainly by changing the amount of angular rotation of the feed rod per stroke of the tool. This is done by adjusting the amount of angle of oscillation of the paul as shown in Fig. 4.4.6. The directions of the feeds are reversed simply by rotating the tapered paul by 180^o as done in shaping machines.

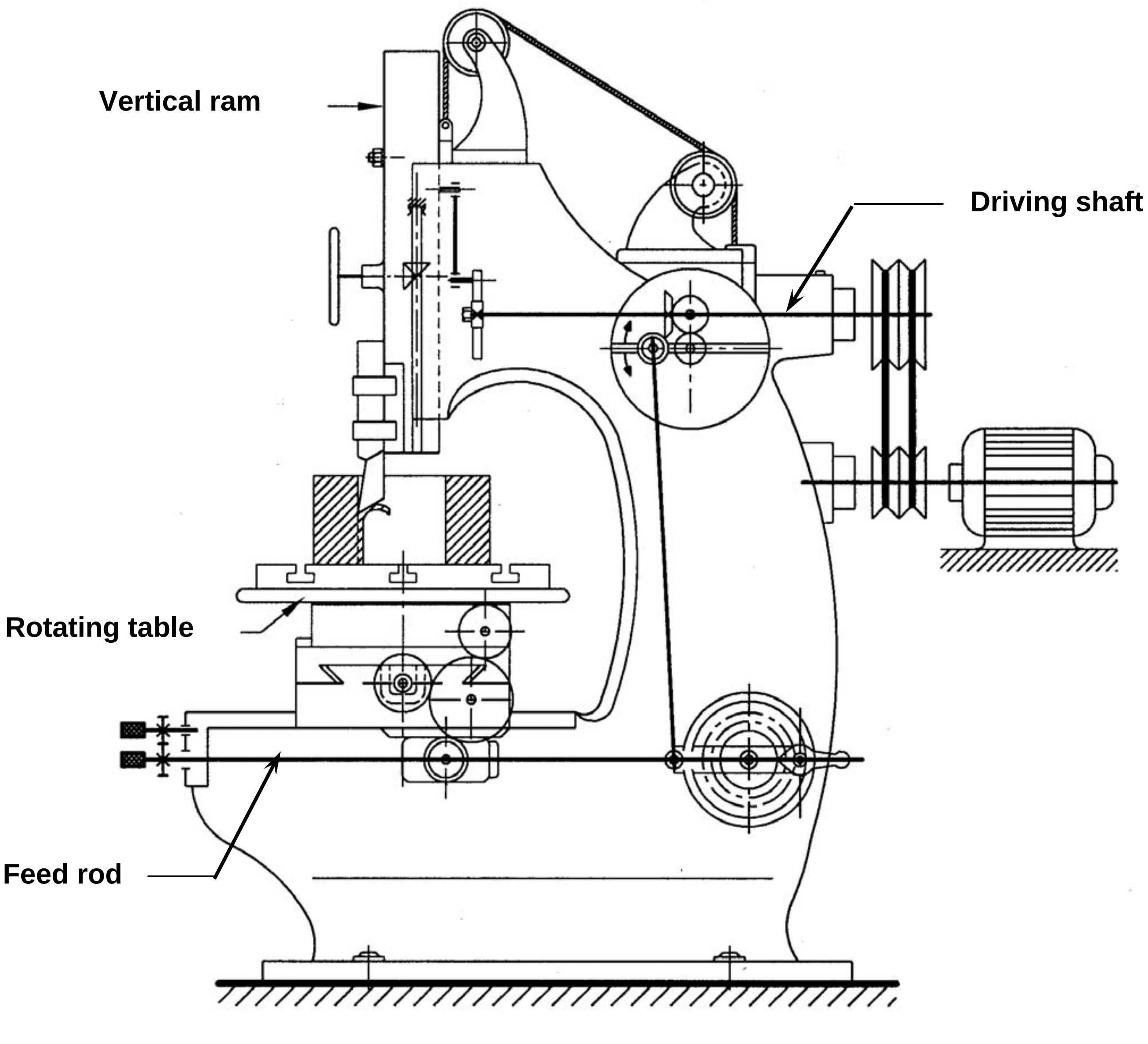


Fig. 4.4.6 *Kinematic system of a slotting machine.*

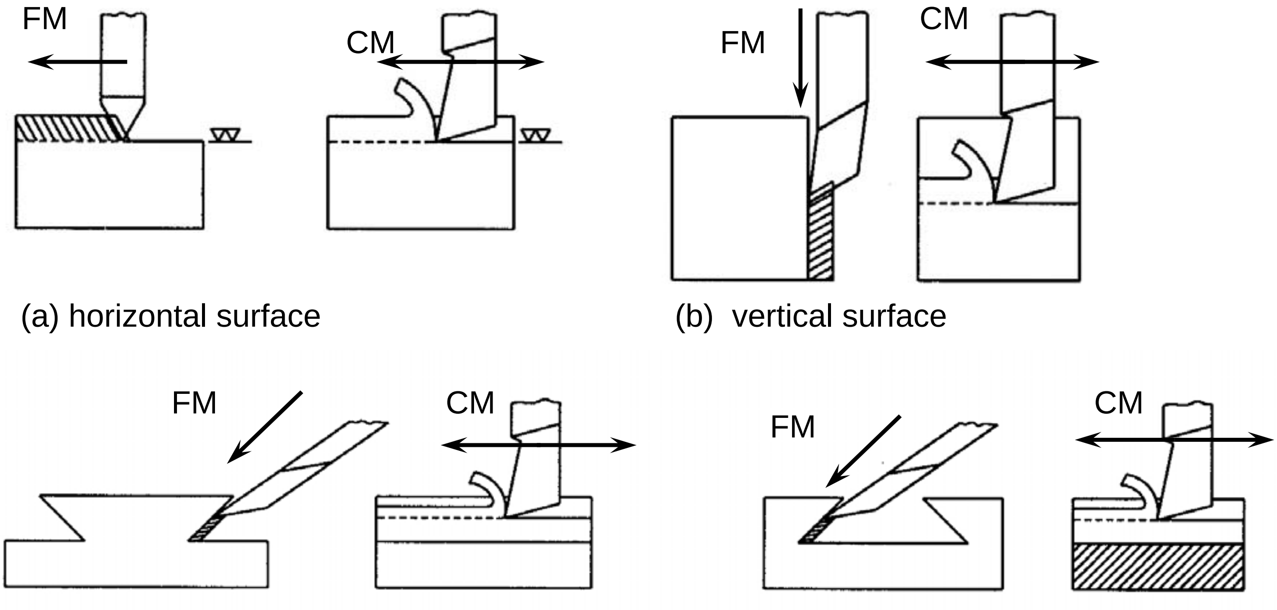
(iii) Various applications of

- **Shaping machine**
- **Planing machines**
- **Slotting machines**

- **Shaping machines**

It is already mentioned that shaping machines are neither productive nor versatile.
However, its limited applications include :

- ∆ Machining flat surfaces in different planes. Fig. 4.4.7 shows how flat surfaces are produced in shaping machines by single point cutting tools in (a) horizontal, (b) vertical and (c) inclined planes.



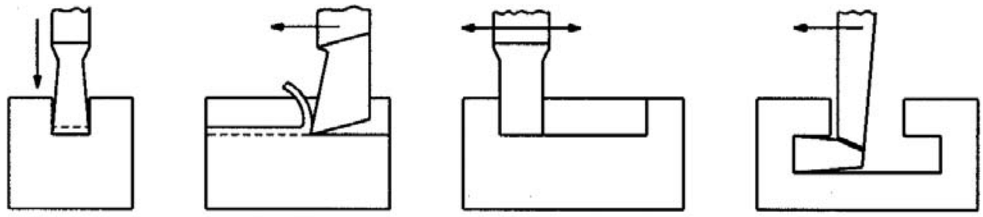
(c) inclined surfaces (dovetail slides and guides)

***Fig. 4.4.7** Machining of flat surfaces in shaping machines*

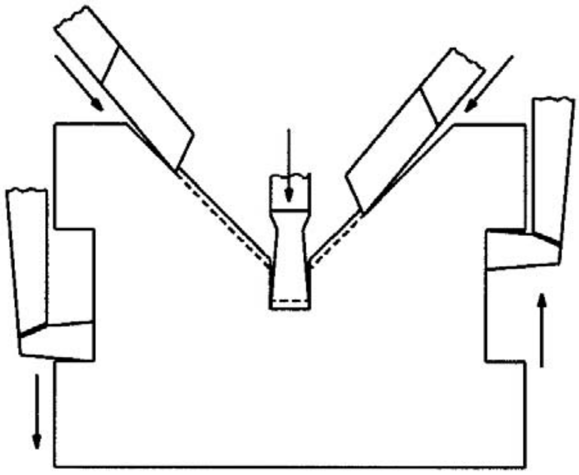
- ∆ Making features like slots, steps etc. which are also bounded by flat surfaces. Fig. 4.4.8 visualises the methods of machining (a) slot, (b) pocket (c) T-slot and (d) Vee-block in shaping machine by single point tools.
- ∆ Forming grooves bounded by short width curved surfaces by using single point but form tools. Fig. 4.4.9 typically shows how (a) oil grooves and (b) straight tooth of spur gears can be made in shaping machine
- ∆ Some other machining applications of shaping machines are cutting external keyway and splines, smooth slitting or parting, cutting teeth

of rack for repair etc. using simple or form type single point cutting tools.

Some unusual work can also be done, if needed, by developing and using special attachments.

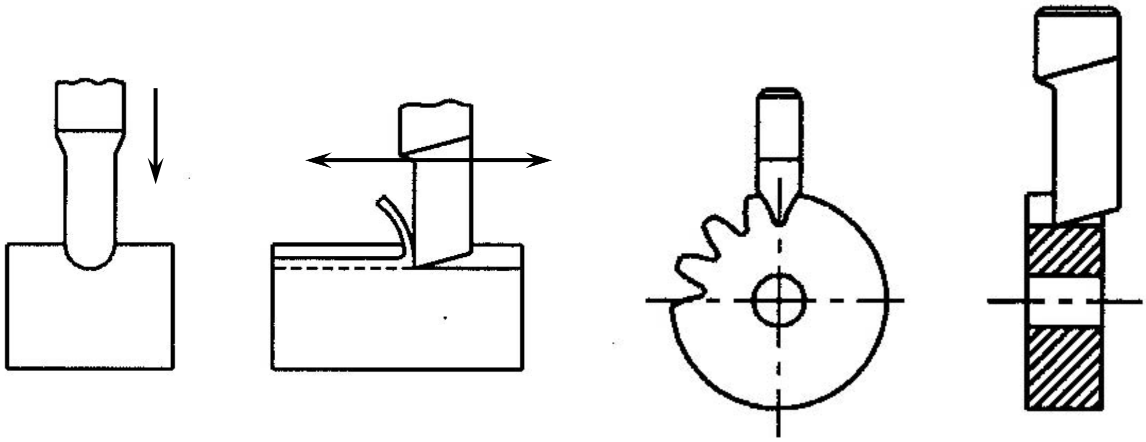


(a) slotting (b) pocketing (c) T-slot cutting



(d) Vee-block

Fig. 4.4.8 *Machining (a) slot, (b) pocket (c) T-slot and (d) Vee block in shaping machine*



(a) grooving (b) straight tooth cutting for spur gears

Fig. 4.4.9 *Making grooves and gear teeth cutting in shaping machine by form tools*.

However, due to very low productivity, less versatility and poor process capability, shaping machines are not employed for lot and even batch production. Such low cost primitive machine tools may be reasonably used only for little or few machining work on one or few pieces required for repair and maintenance work in small machine shops.

- **Planing machines**

The basic principles of machining by relative tool-work motions are quite similar in shaping machine and planing machine. The fast straight path cutting motion is provided by reciprocation of the tool or job and the slow, intermittent transverse feed motions are imparted to the job or tool. In respect of machining applications also these two machine tools are very close. All the operations done in shaping machine can be done in planing machine. But large size and stroke length and higher rigidity enable the planing machines do more heavy duty work on large jobs and their long surfaces. Simultaneous use of number of tools further enhances the production capacity of planing machines.
The usual and possible machining applications of planing machines are

- ∆ The common machining work shown in Fig. 4.4.7, Fig. 4.4.8 and Fig. 4.4.9 which are also done in shaping machines
- ∆ Machining the salient features like the principal surfaces and guideways of beds and tables of various machines like lathes, milling machines, grinding machines and planing machines itself, broaching machines etc. are the common applications of planing machine as indicated in Fig. 4.4.10 where the several parallel surfaces of typical machine bed and guideway are surfaced by a number of single point HSS or carbide tools. Besides that the long parallel T-slots, Vee and inverted Vee type guideways are also machined in planing machines.

- Δ 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.

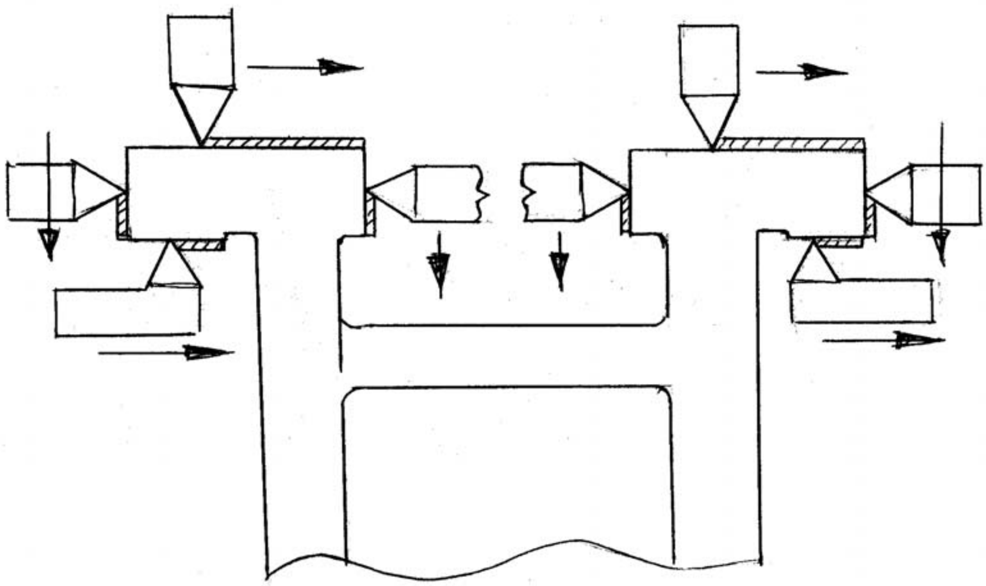


Fig. 4.4.10 *Machining of a machine bed in planing machine*

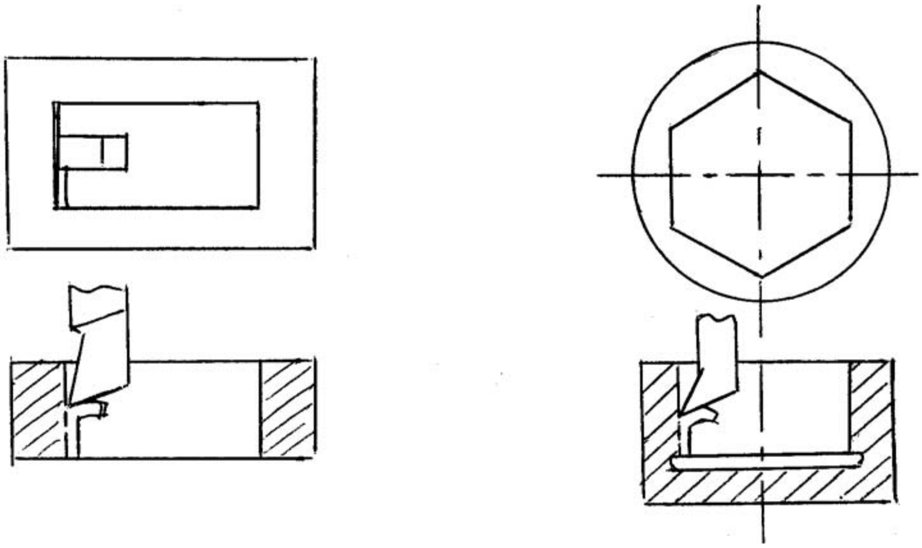
- **Slotting machine**

Slotting machines are very similar to shaping machines in respect of machining principle, tool-work motions and general applications. However, relative to shaping machine, slotting machines are characterised by :

- Δ Vertical tool reciprocation with down stroke acting
- Δ Longer stroke length
- Δ Less strong and rigid
- Δ An additional rotary feed motion of the work table
- Δ Used mostly for machining internal surfaces.

The usual and possible machining applications of slotting machines are :

- o Internal flat surfaces
- o Enlargement and / or finishing non-circular holes bounded by a number of flat surfaces as shown in Fig. 4.4.11 (a)
- o Blind geometrical holes like hexagonal socket as shown in Fig. 4.4.11 (b)
- o Internal grooves and slots of rectangular and curved sections.
- o Internal keyways and splines, straight tooth of internal spur gears, internal curved surface of circular section, internal oil grooves etc. which are not possible in shaping machines.



(a) through rectangular hole (b) hexagonal socket

Fig. 4.4.11 *Typical machining application of slotting machine.*

However, it has to be borne in mind that productivity and process capability of slotting machines are very poor and hence used mostly for piece production required by maintenance and repair in small industries. Scope of use of slotting machine for production has been further reduced by more and regular use of broaching machines.

Exercise

Identify the correct answer from the given four options.

1. Reciprocation of the cutting tool in shaping machines is accomplished by
    a. Rack pinion mechanism
    b. Crank and connecting rod mechanism
    c. Cam and cam follower mechanism
    d. Oscillating lever mechanism
2. Internal keyway in gears can be cut in
    a. Shaping machine
    b. Planing machine
    c. Slotting machine
    d. None of the above
3. The job reciprocates in
    a. Shaping machine
    b. Planing machine
    c. slotting machine
    d. All of the above
4. The T-slots in the table of planing machines are cut in
    a. Shaping machine
    b. Planing machine
    c. Slotting machine
    d. None of the above
5. Flat surface can be produced in
    a. Shaping machine only
    b. Planing machine only
    c. Slotting machine only
    d. All of the above
6. Large number of cutting tools can be simultaneously used in
    a. Shaping machine
    b. Planing machine
    c. Slotting machine
    d. None of the above

7. Heavy cuts can be given during machining in
    a. Shaping machine
    b. Planing machine
    c. Slotting machine
    d. None of the above
8. Slotting machines are used to cut internal gear teeth for
    a. Batch production
    b. Lot production
    c. Mass production
    d. None of the above
9. The work-table can rotate in
    a. Shaping machine
    b. Planing machine
    c. Slotting machine
    d. None of the above

10. Length of the stroke can be varied in
    a. Shaping machine
    b. Planing machine
    c. Slotting machine
    d. All of the above

Answers

Q.No	Answers
1	d
2	c
3	b
4	b
5	d
6	b
7	b
8	a
9	c
10	b

Module 4

General Purpose Machine Tools

Lesson 21

Methods of mounting of jobs and cutting tools in machine tools.

Instructional objectives

At the end of this lesson, the students will be able to;

(i) State the principles and conditional requirements of mounting jobs and tools in machine tools
(ii) Illustrate how the jobs (blanks) and cutting tools are mounted in
   a. Lathes
   b. Drilling machines
   c. Shaping, Planing and slotting machines
   d. Milling machine
   e. Grinding machines
(iii) Point out the special requirements and methods on mounting job and cutting tools in CNC machine tools.

(i) Principles And Conditional Requirements Of Mounting Job And Cutting Tool In Machine Tools

The job or blank and the cutting tools essentially need to be properly mounted in the machine tool for achieving desired performance of the machining system.
The following principles are generally followed and conditions are maintained;

(a) while mounting the job or blank in the machine tool

- appropriate selection of work holding device or system from the available resources depending upon;
  - Δ configuration of the machine tool
  - Δ shape, size and weight of the blank
  - Δ kind of machining work to be done
  - Δ order of dimensional accuracy desired
  - Δ volume (number of same job) of production
- correct location, strong support and rigid clamping of the blank against the cutting and other forces
- easy and quick loading and unloading to and from the machine tool or the holding device
- proper alignment like coaxiality, concentricity etc. of rotating jobs
- free flow of chips and cutting fluid

(b) while mounting the cutting tools

- appropriate selection of tool holder and the method of mounting
- proper positioning and orientation of the tool depending upon its
  - Δ type
  - Δ size and shape
  - Δ geometry
- proper alignment in respect of coaxiality, concentricity and machine tool configuration
- accurate and quick locating, strong support and rigid clamping
- minimisation of run out and deflection during cutting operation

- easy and quick mounting and change
- unobstructed chip flow and cutting fluid action.

(ii) Methods Of Mounting Job And Cutting Tool In General Purpose Machine Tools.

(a) Job and tool mounting in lathes

- **In centre lathes**

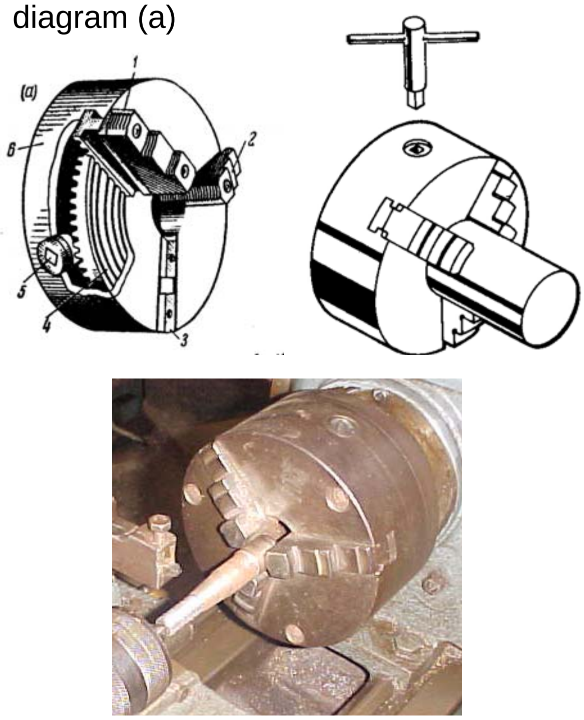
  - **Mounting of jobs**

    The general systems of holding jobs in centre lathes;

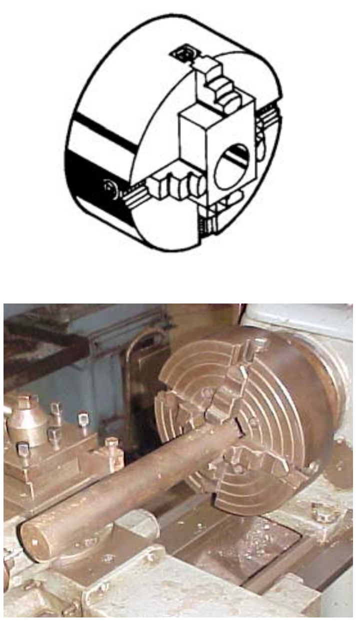
    ∆ without additional support from tailstock;

    - Chucks — 3-jaw self centering chuck
    - — 4- independent jaw chuck
    - Face plate
    - Jigs and fixture

- Fig. 4.5.1 visualises 3 – jaw and 4 – jaw chucks which are mounted at the spindle nose and firmly hold 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 (a)



(a) 3-Jaw chuck

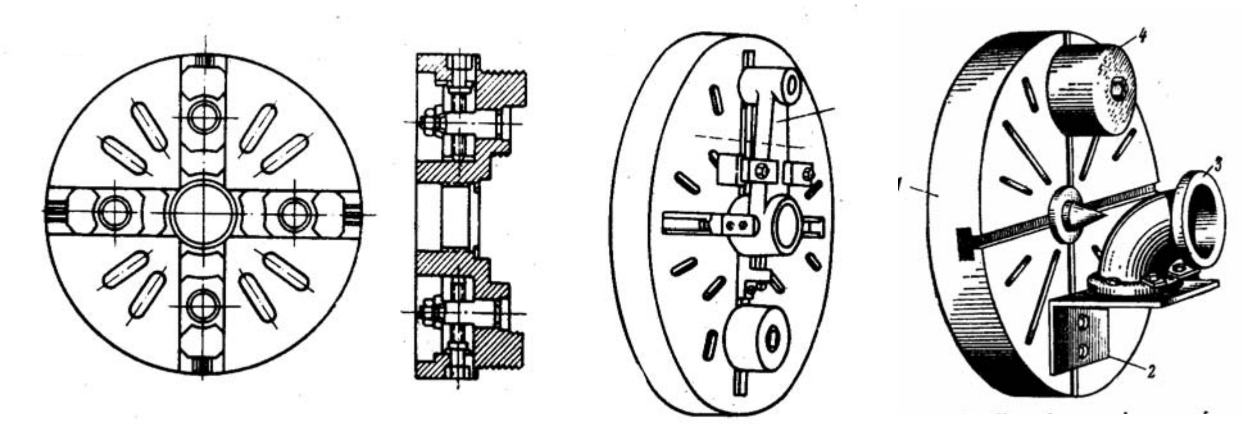


(b) 4-Jaw chuck

__Fig. 4.5.1__ Holding jobs in centre lathes by 3-jaw and 4-jaw chucks.

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 more odd 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.

- For turning, facing, boring, threading and similar operations, jobs of odd shape and size are usually mounted on large face plate (instead of chuck) being fitted on the spindle nose as shown in Fig. 4.5.2.
- The job may be (b) directly clamped on the face plate or (c) in case of batch or small lot production, in a fixture which is clamped on the face plate.



(a) (b) (c)

Fig. 4.5.2 *Mounting of odd shaped jobs on face plate in centre lathe*

Δ Job mounting in centre lathe using support from the tailstock (centre)
    - In-between centre
    - In-between chuck and centre
    - In-between headstock and tailstock with additional support of rest
  - Fig. 4.5.3 schematically shows how long slender rods are held in between the live centre fitted into the 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. 4.5.4. 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.

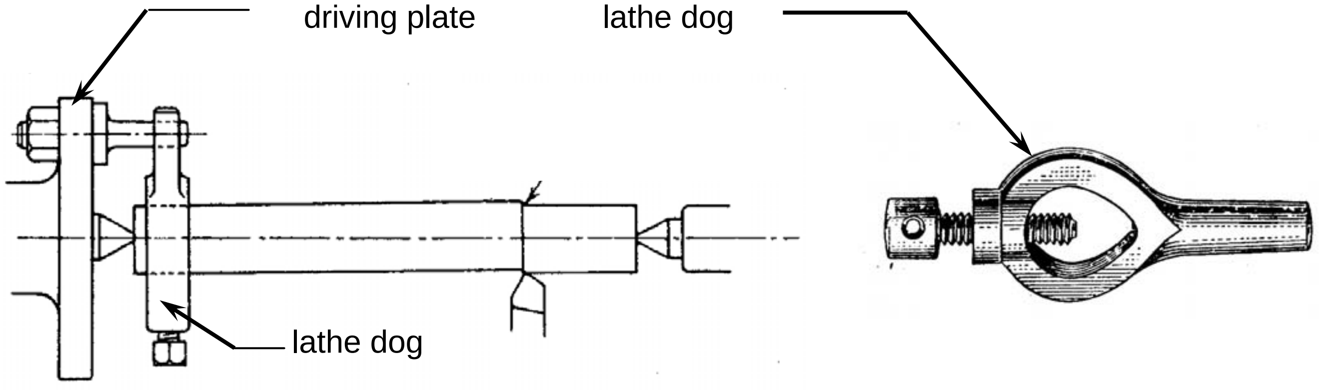
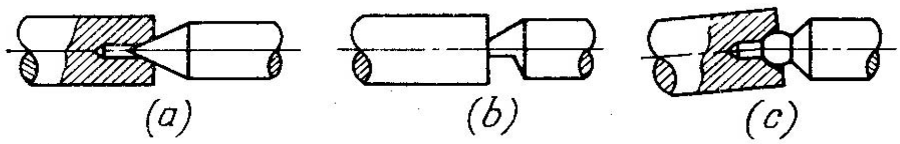
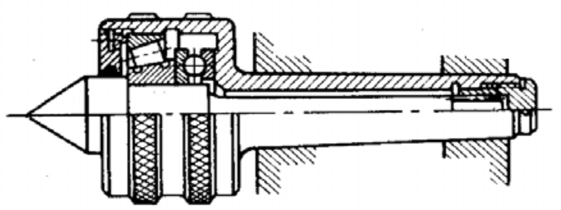


Fig. 4.5.3 *Mounting bar type job in between centres in centre lathe.*



dead centres

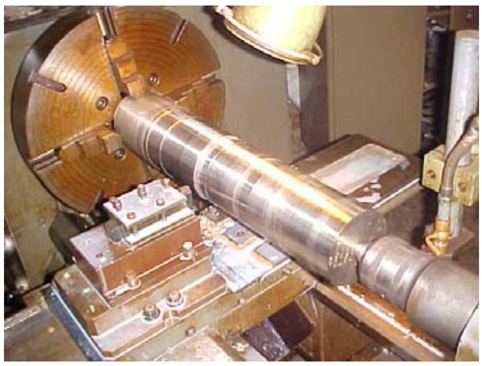


(d) revolving centre

Fig. 4.5.4 *Type of dead centres and revolving centre being fitted in the quill of the tailstock.*

Heavy and reasonably long jobs of large diameter and requiring heavy cuts (cutting forces) are essentially held strongly and rigidly in the chuck at headstock with support from the tailstock through a revolving centre as can be seen in Fig. 4.5.5.

(a) 3-jaw chuck



(b) 4-jaw chuck

Fig. 4.5.5 *Job mounted in between chuck and centre in centre lathe*

- To prevent deflection of the long slender jobs like feed rod, leadscrew etc. due to sagging and cutting forces during machining, some additional supports are provided as shown in Fig. 4.5.6. 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-diameter.

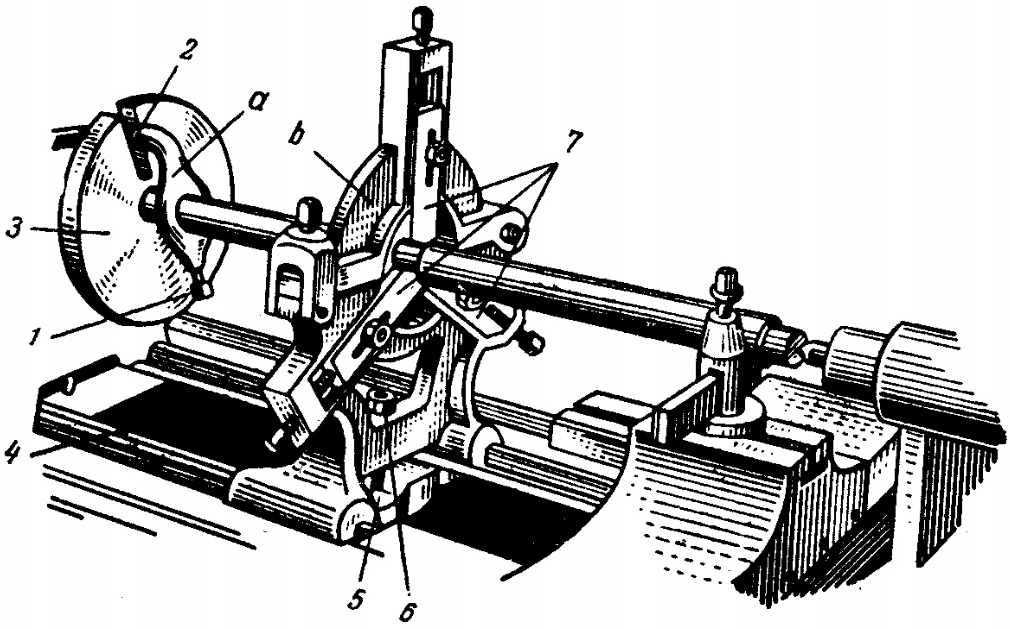
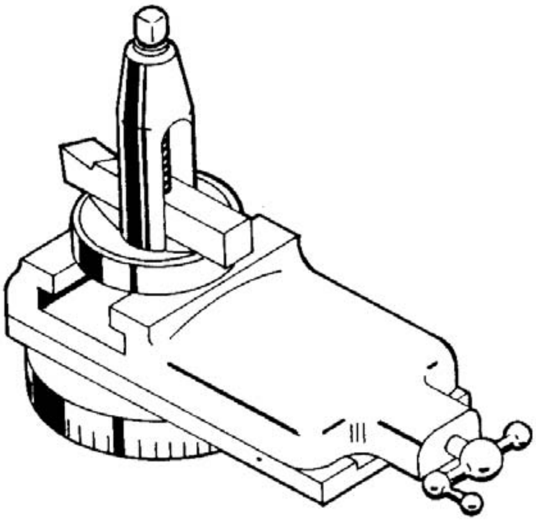


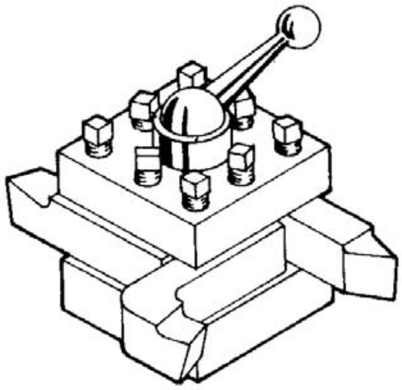
Fig. 4.5.6 *Slender job held with extra support by steady rest*

- **Mounting of tools in centre lathes**

  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. 4.5.7 is typically showing mounting of shank type HSS single point tools in rotatable (only one tool) and indexable (upto four tools) tool posts. Small tool bits are preferably fitted in a rectangular sectioned bar type tool holder which is mounted in the tool post as shown by the photograph in Fig. 4.5.5 (a).
- Fig. 4.5.8 typically shows how a circular form or thread chasing HSS tool is fitted in the tool holder which is mounted in the tool post.



(a) single tool



(b) upto four tools

Fig. 4.5.7 *Mounting of shank type lathe tools in tool posts.*

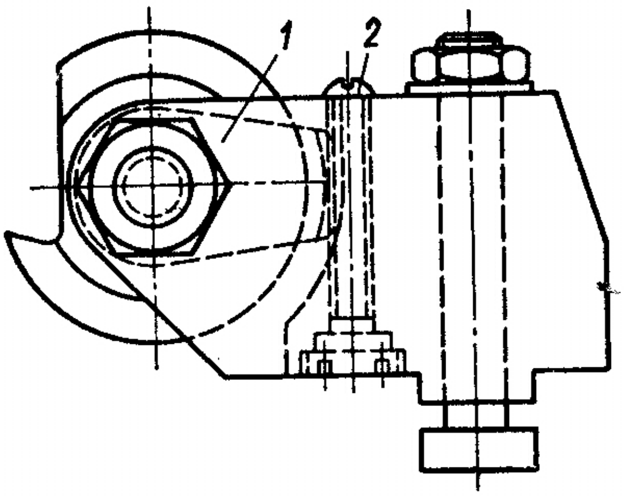
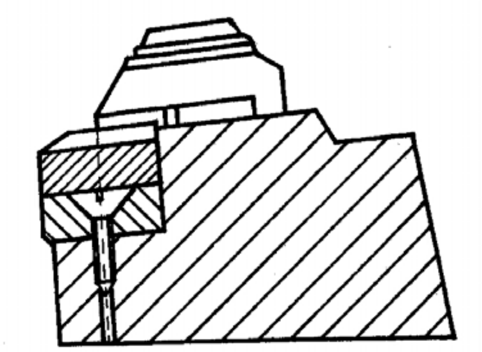
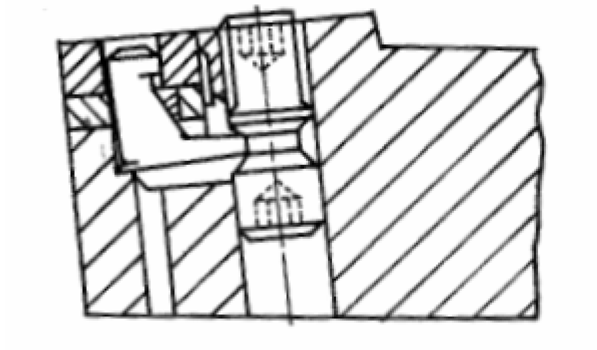


Fig. 4.5.8 *Mounting of form tool in tool post.*

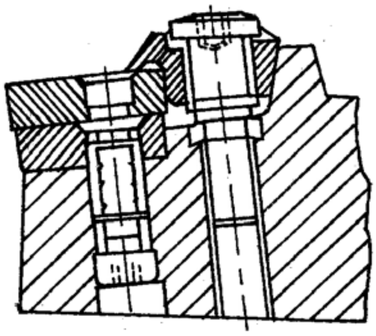
- Carbide, ceramic and cermet inserts of various size and shape are mechanically clamped in the seat of rectangular sectioned steel bars which are mounted in the tool post. Fig. 4.5.9 shows the common methods of clamping of such inserts. After wearing out of the cutting point, the insert is indexed and after using all the corner-tips the insert is thrown away.



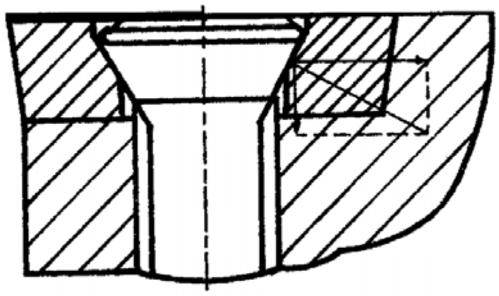
(a) clamp type



(b) lever type



(c) pin and clamp



(d) screw type

Fig. 4.5.9 *Mounting of tool inserts in tool holders by mechanical clamping.*

- For originating axial hole in centre lathe, the drill bit is fitted into the tailstock which is slowly moved forward against the rotating job as indicated in Fig. 4.5.10. Small straight shank drills are fitted in a drill chuck whereas taper shank drill is fitted directly into the tailstock quill without or with a socket.

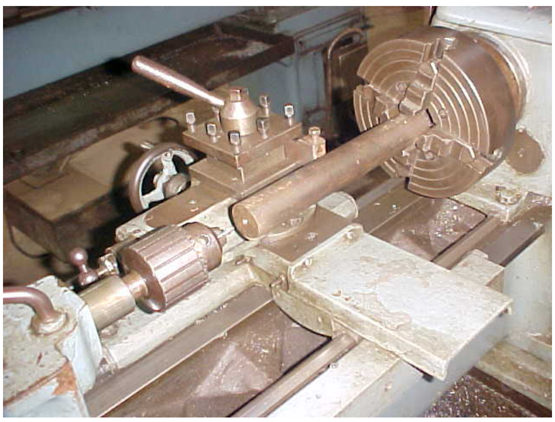


Fig. 4.5.10 *Holding drill chuck and drill in tailstock.*

- Often boring operation is done in centre lathes for enlarging and finishing holes by simple shank type HSS boring tool. The tool is mounted on the tool post and moved axially forward, along with the saddle, through the hole in the rotating job as shown in Fig. 4.5.11 (a).

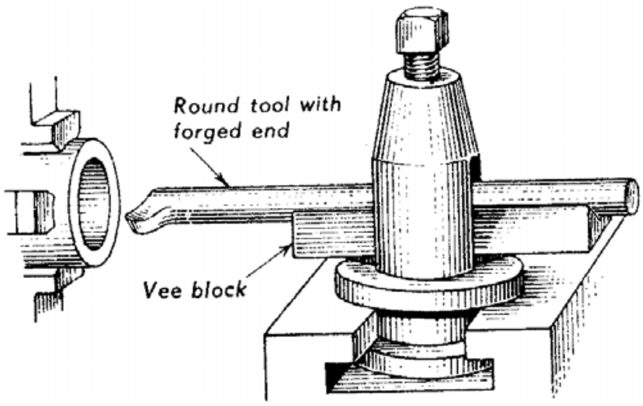


Fig. 4.5.11 *(a) Boring tool mounted in the tool post in centre lathe.*

For precision boring in centre lathe, the tool may be fitted in the tailstock quill supported by bush in the spindle as shown in Fig. 4.5.11 (b).

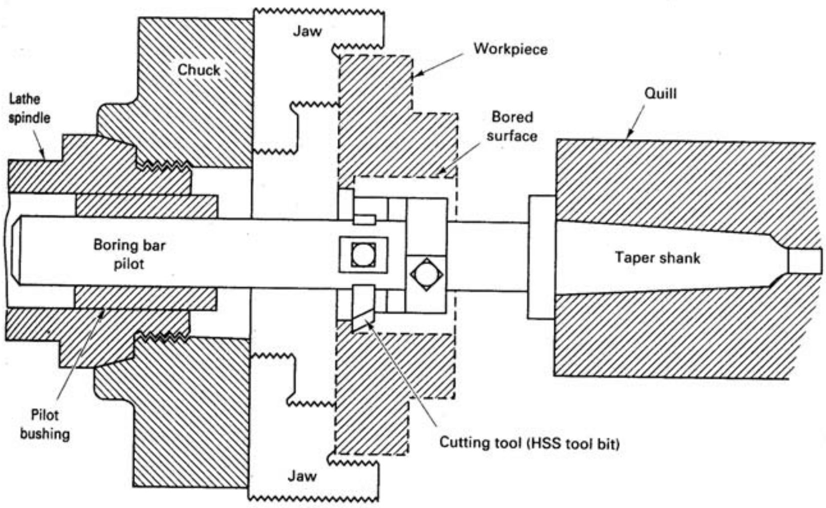


Fig. 4.5.11 *(b) Precision boring in centre lathe.*

- **In semiautomatic and automatic lathes**

Automation is incorporated in machine tool systems to enable faster and consistently accurate processing operations for increasing productivity and reducing manufacturing cost in batch and mass production. Therefore, in semiautomatic and automatic machine tools mounting and feeding of the job or blank and the tool are also done much faster but properly.

- **Mounting of job in semiautomatic and automatic lathes.**

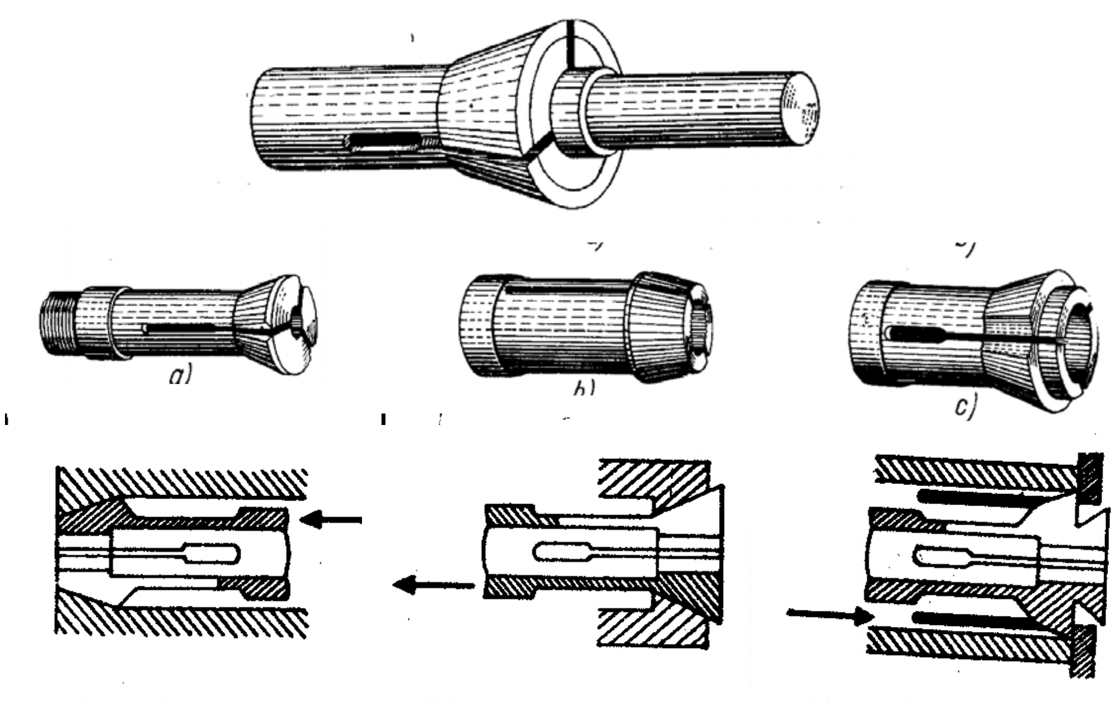
Semiautomatic lathes like capstan and turret lathes work on both chucking type (disc like) and bar type jobs. But automatic lathes like single spindle automat work on long bars of small (ϕ = 6 to 20 mm) circular or regular polygon section (square, hexagonal and octagonal). However, there is no scope of support from tailstock at all in any of such semiautomatic or automatic lathes. Only occasionally additional support is taken through a revolving centre during heavy transverse or radial cut in a turret lathe. In that case that centre is fitted into the turret head only. The devices or systems those are commonly used to hold the job or blank quickly, coaxially (with the spindle axis) strongly and rigidly in the aforesaid semiautomatic and automatic lathes are :

- Coventry concentric chuck – where the 3 jaws are actuated quickly and accurately by a ring cam
- Air operated chuck – where the jaws are moved more quickly and accurately by compressed air. Often hydraulically operated quick acting chucks are used in turret lathes for heavy jobs and cuts.
- Quick acting soft jaw chucks – preferably used where the gripping portion of the job need to be unaffected
- Collet chuck – used for holding long thin bars of regular section passing and fed through the hollow spindle.

Collet chucks inherently work at high speed with accurate location and strong grip. The collets are actuated

- Δ manually or semiautomatically in capstan and turret lathes
- Δ automatically in automatic lathes

Basically there are three types of spring collets as shown in Fig. 4.5.12. All of those collets are splitted at their gripping end to provide springiness and enable reduce the bore diameter to grip the bar by radial force.



(a) push type (b) pull type (c) stationary type

Fig. 4.5.12 *Collets used to hold bar stock in semiautomatic and automatic lathes.*

All the collet types; push, pull and stationary, have some relative advantages based on which those are selected appropriate for the application.

- **Mounting of cutting tools**
  - ∆ **In semiautomatic lathes**

In semiautomatic lathes liken capstan lathe and turret lathe, the cutting tools are mounted in the

(a) **Radial slides** – moving transverse to the job axis

- ∗ Front slide – if fixed type, holds only one tool
  - if turret type, may hold upto 4 tools
- ∗ rear slide – for only one cutting tool

The cutting tools, mounted on the radial slides, are used for the external machining operations which need radial tool feed, e.g., facing, shouldering, grooving, recessing, forming, chamfering, parting etc.

(b) **Turret (mostly hexagonal)** – moving along the spindle axis

The cutting tools to be used for external or internal work requiring axial feed motions such as turning, drilling, boring, reaming, threading etc., are mounted on the faces of the turret. The turret holding upto six different tools, as shown in Fig. 4.5.13, for different machining operations moves slowly with one acting tool in front of it at desired feed rate, then after doing the particular machining operation returns at the end of which it gets indexed, i.e., rotated by 60^o or multiple of it.

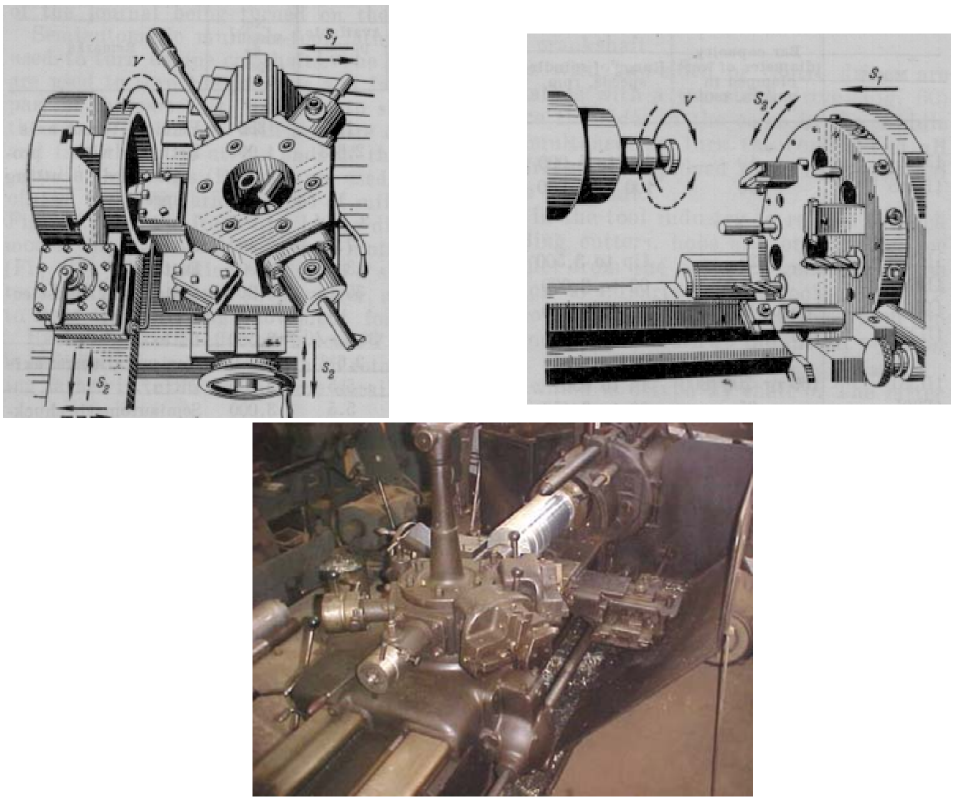


Fig. 4.5.13 *Mounting of cutting tools on the turret in semiautomatic lathe.*

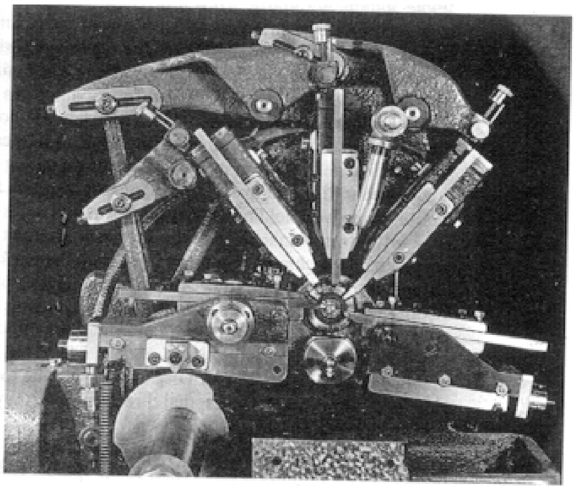
For faster production, a number of machining work, as far as feasible, are carried out simultaneously

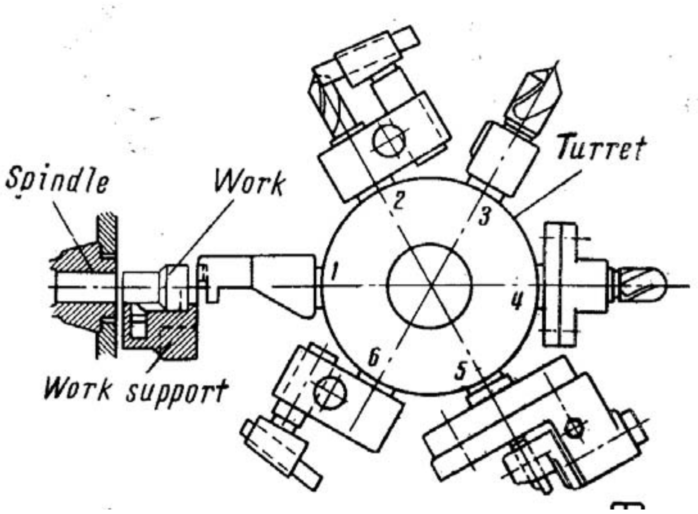
- o by compounding the cutting tool enabling more than one work
- o by partially or fully overlapping the duration of action of radially moving tool with axially moving tool

In addition to cutting tools, some other objects like stop-stock, revolving centre etc are also often need to be mounted in the turret.

∆ Mounting of tools in automatic lathes

In general purpose automatic lathes, i.e., single spindleautomats also, the tools requiring transverse feed motions are mounted in the radial slides and those requiring axial feeds are mounted in the hexagonal turret which rotates with the tools about a horizontal axis for indexing as shown in Fig. 4.5.14.





(a) radially moving tools (b) axially moving tools in turret

Fig. 4.5.14 *Mounting of tools in single spindle automatic lathe.*

(ii) (b) Mounting of jobs and tools in drilling machines

Mounting of job and tool in drilling machine are typically shown in Fig. 4.5.15 (a).

- **Mounting of job or blank**

In general purpose drilling machines like column and radial arm type, the workpiece or blank is generally mounted

- ∆ by directly clamping on the drilling machine bed particularly when the job is heavy and / or of odd shape and size
- ∆ in a vice which is clamped on the bed as shown in Fig. 4.5.15 (a)
- ∆ in a suitable jig clamped on the bed.

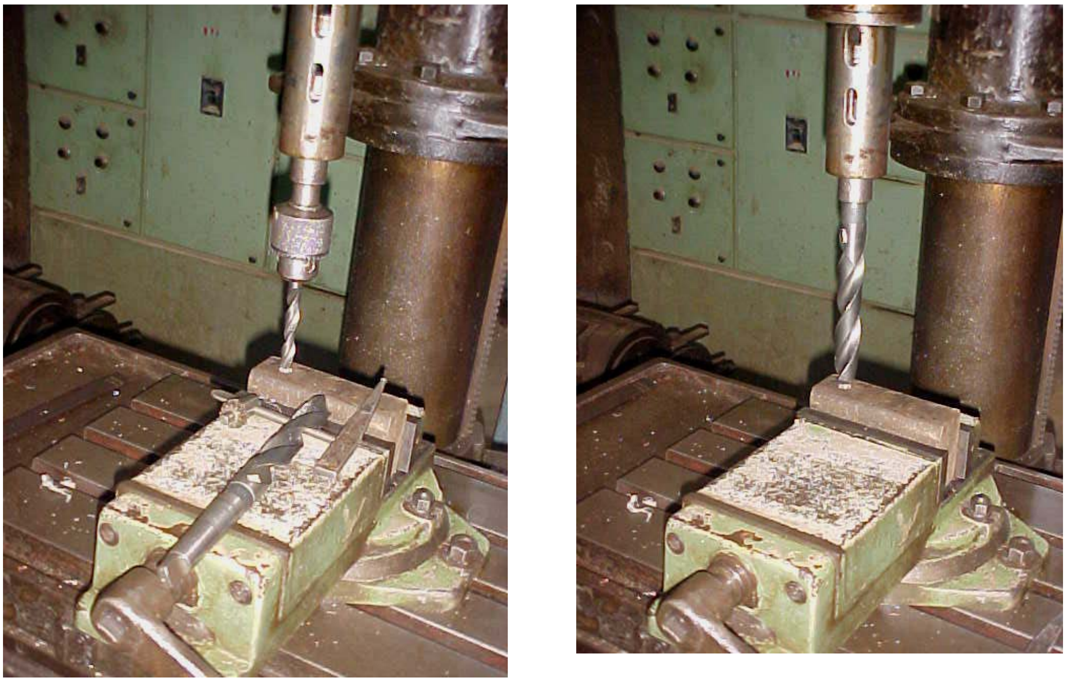


***Fig. 4.5.15** (a)   Mounting of job and tool in drilling machine*

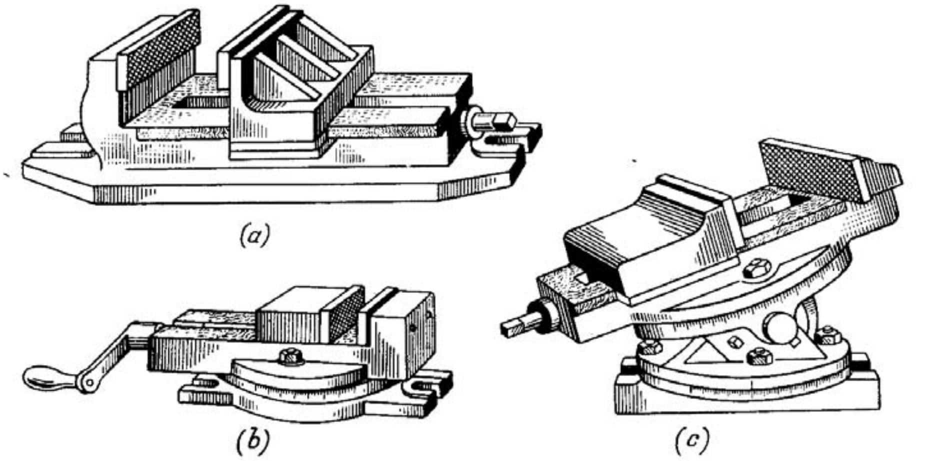


***Fig. 4.5.15** (b)   Vices to hold jobs in drilling machines*

Direct clamping of job or clamping of the vice and jig on the drilling bed are done with the help of clamp plates, T-bolts etc., as indicated in Fig. 4.5.16. Fig. 4.5.15 (b) shows the type of vices; plain, swivelling and universal type being used for holding small jobs in drilling machines. Fig. 4.5.16 also typically shows how a job is fitted in a jig for drilling in batch production

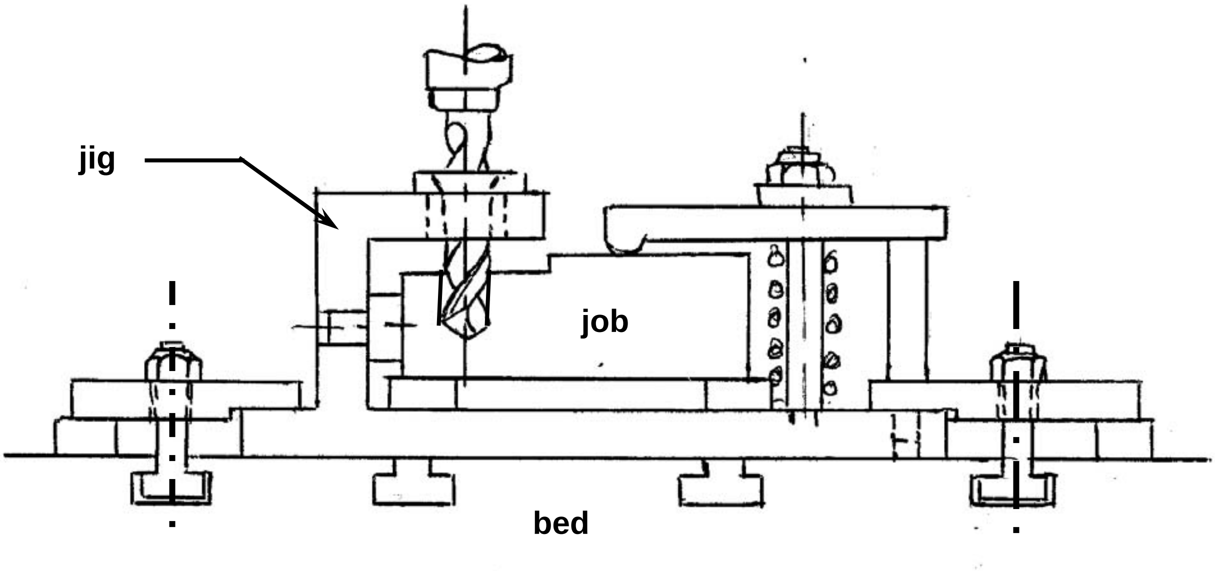


Fig. 4.5.16 *Mounting of job in a jig which is clamped on the drill - bed.*

- **Mounting of tools in drilling machines**

In drilling machines mostly drills of various type and size are used for drilling holes. Often some other tools are also used for enlarging and finishing drilled holes, counterboring, countersinking, tapping etc.

The basic methods of mounting drill bits in the spindle are simple as already has been typically shown in Fig. 4.5.15 (a).

Small straight shank type solid HSS and carbide drills are held in a drill chuck which is fitted in the drill spindle at its taper bore.

Larger taper shank drills are put straight in the spindle without drill chuck. However, for fitting the taper shank of the drill chuck and the taper shank drills in the spindle having larger taper bore, some sockets are put in between.

The sockets of varying size as shown in Fig. 4.5.17 are tapered inside to accommodate the taper shank of the drill chuck, drills and smaller sockets and tapered outside for fitting in the taper bore of the spindle :

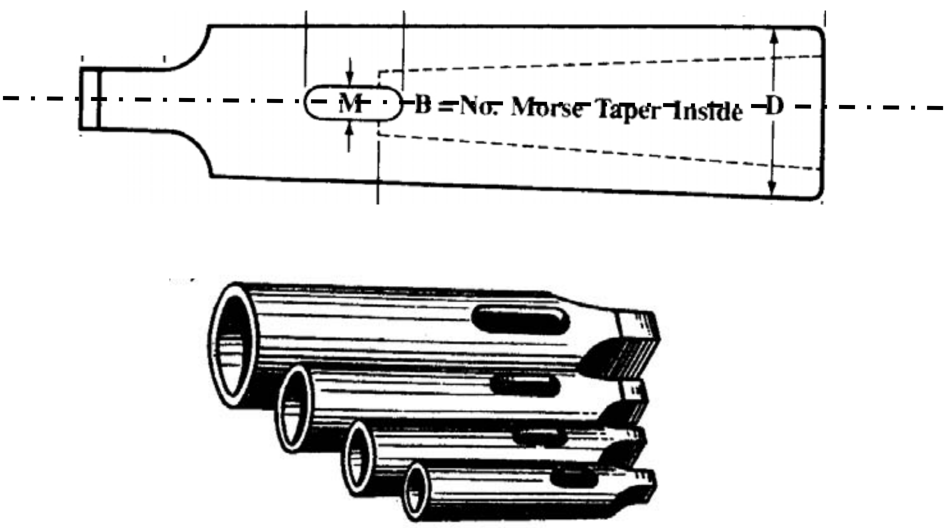


Fig. 4.5.17 *Drill socket for mounting drill chuck and taper shank drills in spindle*

Carbide drills are available in the form of;

- Solid carbide with two helical flutes – usually these drills are of small diameter (≤ 6 mm)
- Carbide tips – brazed in the steel shank
- Carbide inserts mechanically clamped in straight or helically fluted steel shank as shown in Fig. 4.5.18.

Fig. 4.5.18 *Drills with carbide inserts.*

Small solid carbide drills are generally of straight shank type and held in drill chuck. The medium size (ϕ 6 to 12 mm) spade and lug type drills having carbide tip(s) brazed at its tip are provided with taper shank and hence mounted in the drill spindle directly or through taper socket(s). Mechanically clamped type carbide tipped drills are manufactured over a wide range diameter.

- the taper shank type of such drills are as usual fitted in the taper bore of the spindle with or without taper socket
- the straight shank type are fitted in suitable collets, or may be, if of smaller size, fitted in drill chuck.

(ii) (c) Mounting of jobs and cutting tools in

- Shaping machines
- Planning machines
- Slotting machines

- **Job – tool mounting in shaping machines**

Shaping machines with their limited stroke length and rigidity are used for machining small or medium size jobs.

- Job is mounted on the bed of shaping machine in the following ways :
  - Relatively large and odd shaped blanks are generally directly clamped on the bed with the help of clamps, supports, and T-bolts being fitted in the T-slots in the bed. Some odd shaped jobs are often clamped on the side surfaces of the bed.
  - Blanks of small size and geometric shape are gripped in a vice which is firmly clamped on the bed as shown in Fig. 4..5.19. For locating and supporting the blank in the vice parallel blocks and Vee-blocks are used.
  - In case of batch or small lot production, the blank is mounted in the fixture designed and used for that purpose. The fixture remains rigidly clamped on the bed.

- Machining is done in shaping machines only by single point tools, even if it is a form tool. And only one tool is used at a time. That shank type tool is mounted, as can be seen in Fig. 4.5.19,

    - ∆ either directly in the clapper box
    - ∆ or in a tool holder which is fitted in the clapper box.

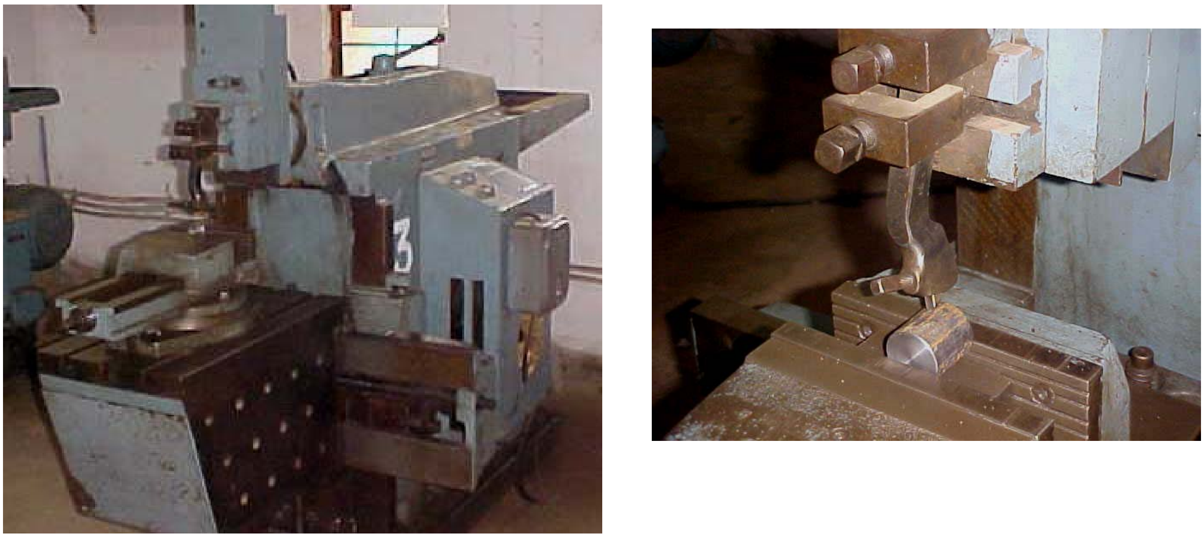


Fig. 4.5.19 *Mounting of job and tool in shaping machine.*

- **Job-tool mounting in planing machine**

Planing machines are used for machining large and heavy jobs requiring large work table, large stroke length and reasonable productivity.

- **Mounting of job in Planing machine**

    - o For conventional machining the large and heavy job is directly mounted on the work table and rigidly clamped with the help of number of clamps, angle plates, and T-bolts.
    - o Occasionally, some rod like jobs are mounted in between centres for some special work requiring rotation of the rod.

- **Mounting of tools in planing machines**

In planning machines also, only single point cutting tools are used but usually more than one tool is used simultaneously from different planes and angles. Fig. 4.5.20 typically shows the method of tool mounting in planning machine.

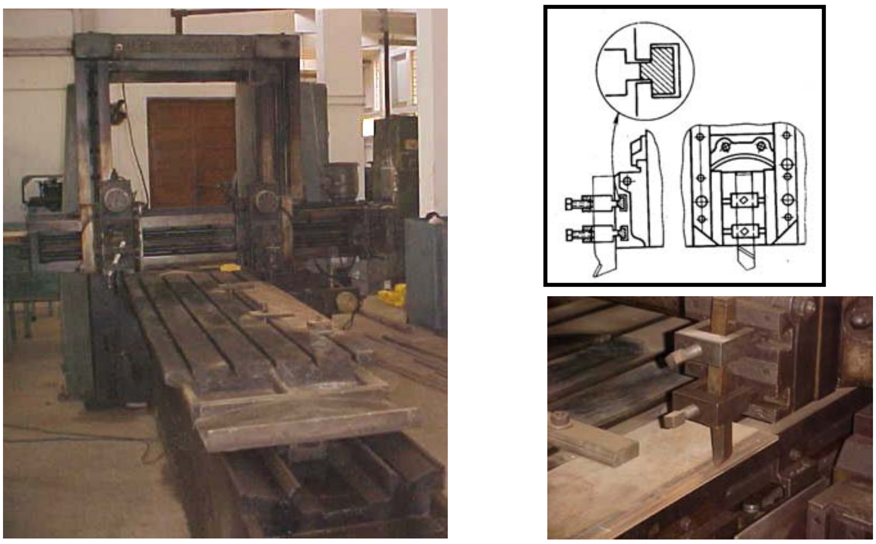


Fig. 4.5.20 *Mounting of cutting tools in planning machine*

- **Job-tool mounting in slotting machine**

Vertical shaper like but less rigid slotting machines are used for less volume of machining work with light cuts and lower MRR using only one single point tool at a time.

- **Job mounting on slotting machine**

It is already known that in slotting machine the flat work table can linearly slide along X and Y directions over the guides. In addition to that there is a rotary table fitted on the top of the sliding bed. On the rotary table chuck, face plate and even small fixtures can be mounted.

Depending on the types of the job and machining work required, the blank is mounted

- Δ directly on the top of the sliding bed with the help of clamps etc.
- Δ on the rotary table or in the chuck as shown in Fig. 4.5.21.
- Δ occasionally in the fixture which is clamped on the flat bed or face plate.

- **Tool mounting in slotting machine**

The method of mounting the single point cutting tool is also typically shown in Fig. 4.5.21.

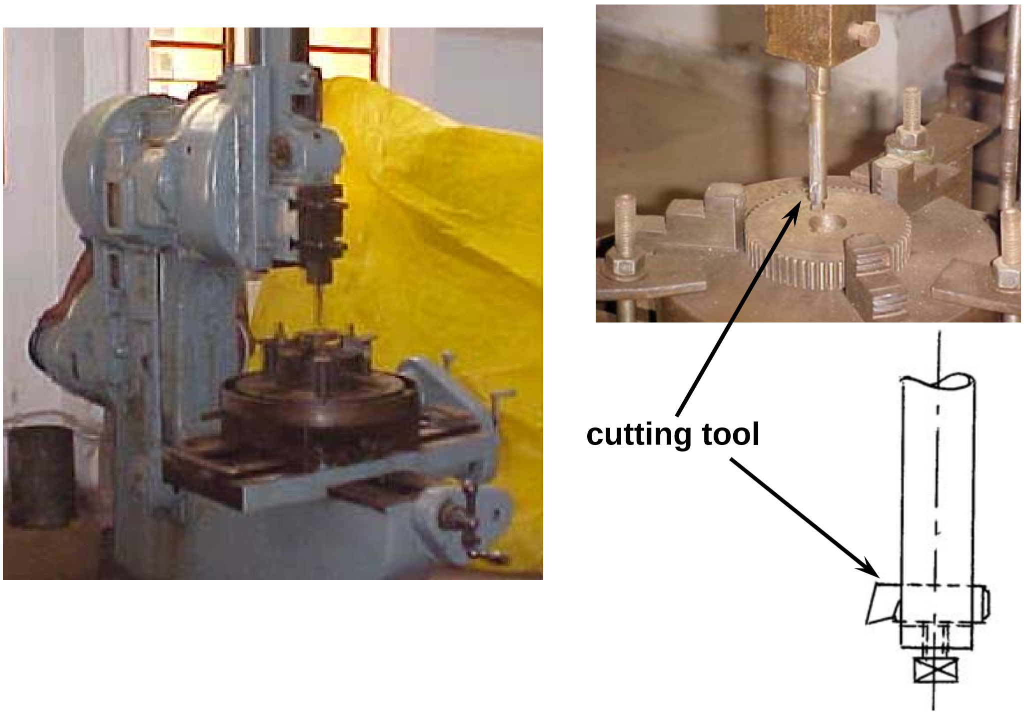


Fig. 4.5.21 *Mounting of job and tool in slotting machine*

(ii) (d) Mounting of Job and Tool in milling machines

- **Mounting of job or blank**

Job or blank is mounted in general purpose milling machines as follows :

- relatively large and irregular shaped jobs for piece or job order production are directly mounted and clamped on the table with the help of clamps, supports, Vee-blocks, T-bolts etc.
- small components of geometrical shape are gripped in the vice which is rigidly clamped on the table
- jobs requiring indexing motion, e.g., prisms, bolt-heads, gears, splines etc. are mounted directly or indirectly (using a mandril) in a dividing or indexing head as shown in Fig. 4.5.22
- small jobs, for its repetitive or batch production, are preferably mounted (located, supported and clamped) in the fixture (designed for the purpose) which is firmly clamped on the table.

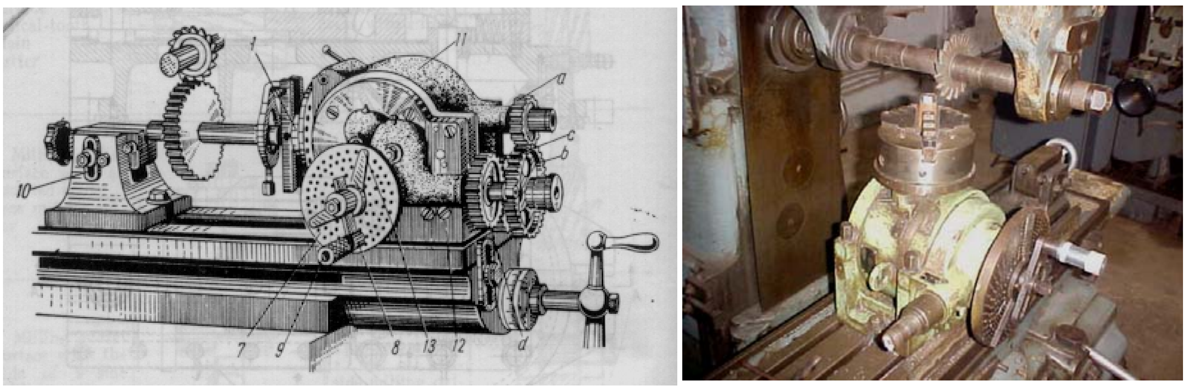


Fig. 4.5.22 *Mounting of job on the dividing head in milling machine.*

- **Mounting of cutting tools in milling machines**

Milling cutters are rotary tools of various sizes, configurations and materials. The general methods of mounting cutting tools in general purpose milling machines are :

- Plain or slab milling cutters and disc type profile sharpened or form relieved cutters (having central bore) are mounted on horizontal milling arbour as shown in Fig. 4.5.23.
- End milling cutters with straight shank are mounted coaxially in the spindle – bore with the help of collet - chuck as shown in Fig. 4.5.24
- Shell milling cutters and heavy face milling cutters are mounted in the hollow spindle with the help of a short but rugged arbour, a fastening screw and a draw bar as shown in Fig. 4.5.25
- In case of carbide tipped milling cutters, the uncoated or coated carbide inserts of desired size, shape and number are mechanically clamped at the periphery of the plain and disc type milling cutters, large end milling cutters and face milling cutters as typically shown in Fig. 4.5.26. End mills of very small diameter are provided with one or two carbide inserts clamped at the tool – end.

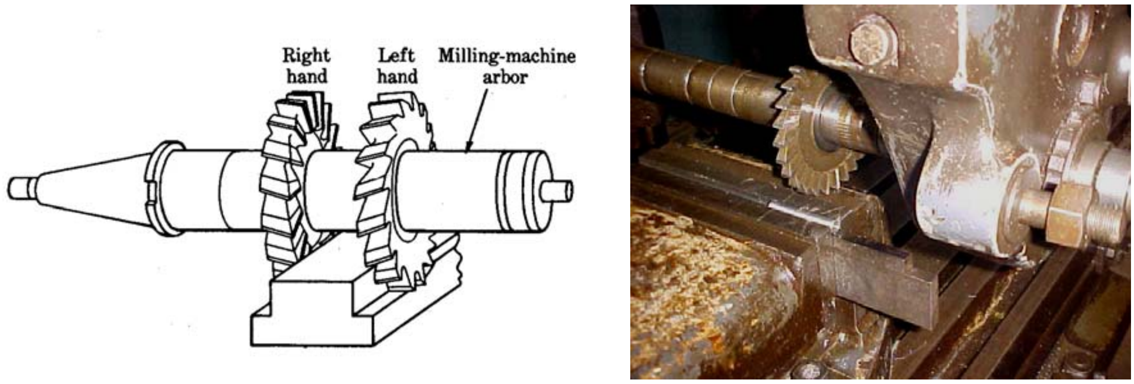


Fig. 4.5.23 *Mounting of cutting tools on milling arbours.*

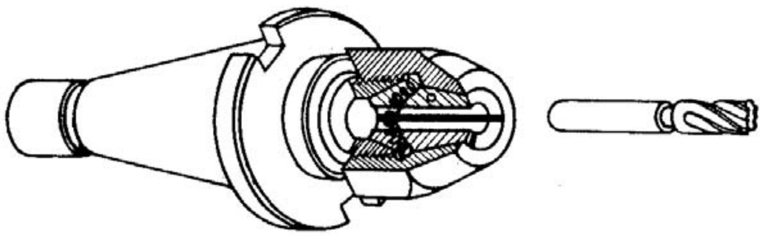


Fig. 4.5.24 *Mounting of straight shank end milling cutters in spindle by collet.*

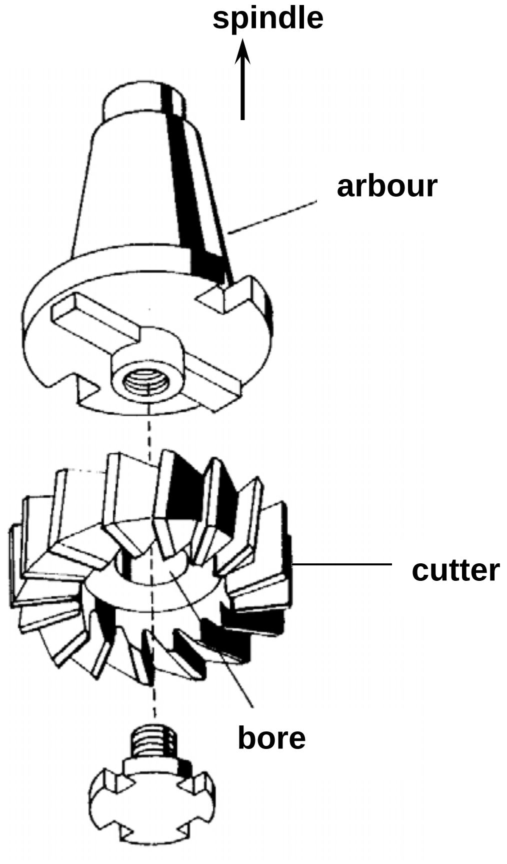
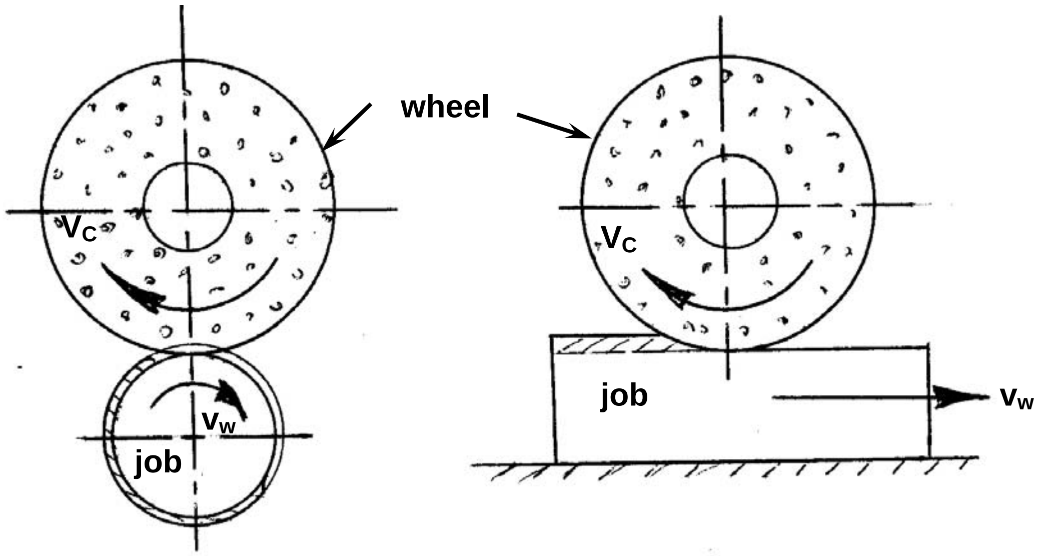


Fig. 4.5.25   Mounting shell and face milling cutters in milling machine spindle.

Fig. 4.5.26   Carbide tips clamped in milling cutters.

(ii) (e) Mounting of job and tool in grinding machines

Grinding is a finishing process in which material is removed by the large number of tiny tool like abrasive particles dispersed or embedded in a softer matrix or on a metallic substrate respectively. In grinding, the cutting tool, i.e., the wheel rotates about its axis at high speed imparting the cutting velocity and the job or workpiece moves slowly against the wheel imparting the desired feed motion as schematically shown in Fig. 4.5.27.



(a) cylindrical grinding (b) surface grinding

V_C : cutting velocity v_w : work feed **d** : infeed

Fig. 4.5.27 *Tool work interactions in grinding*

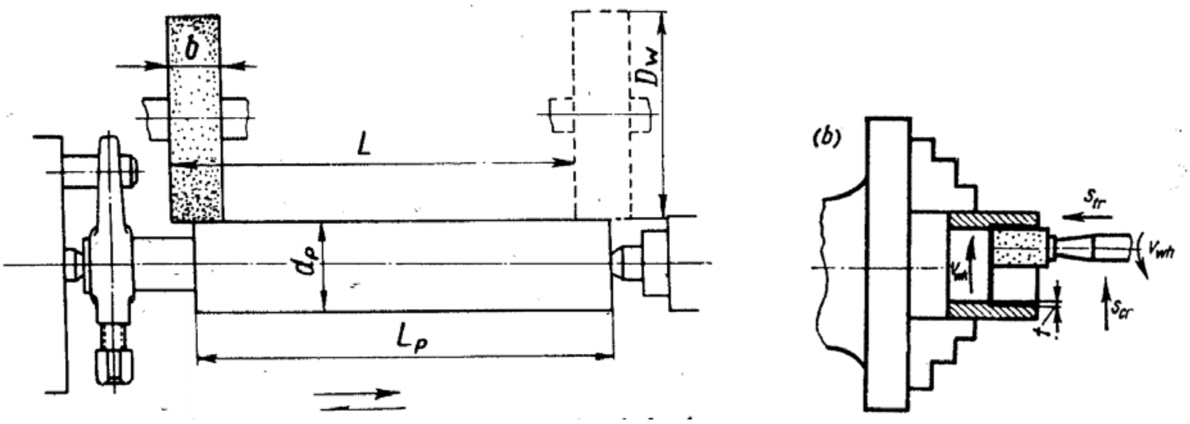
The method of mounting job and tool (wheel), specially job, depends upon the type of the grinding process under consideration.

Though grinding has several applications, the basic types of grinding processes are

- Cylindrical grinding : ∗ external
  - ∗ internal
- surface (flat) grinding : ∗ horizontal wheel axis
  - ∆ reciprocating work table
  - ∆ rotating table
  - ∗ vertical wheel axis
  - ∆ linearly moving table
  - ∆ rotating table
- form grinding : ∗ external
  - ∗ internal
- free form grinding : 3-D contouring
- centreless grinding : ∗ external
  - ∗ internal

Mounting of job (workpiece / blank) in grinding machines

Fig. 4.5.28 schematically shows the typical methods of mounting the jobs in cylindrical grinding machines. The cylindrical job is mounted in between centres for external grinding and in chuck in internal grinding.



(a) external (b) internal

Fig. 4.5.28 *Mounting of job in cylindrical grinding.*

In reciprocating type surface grinding, the workpiece is mounted on the work table in four possible ways :

- On a rectangular magnetic chuck which is clamped on the table as shown in Fig. 4.5.29
- Gripped in a vice which is held on the magnetic chuck or directly clamped on the table
- Directly clamping on the table by clamps, T-bolts etc
- In a fixture which will be clamped on the table or the magnetic chuck.

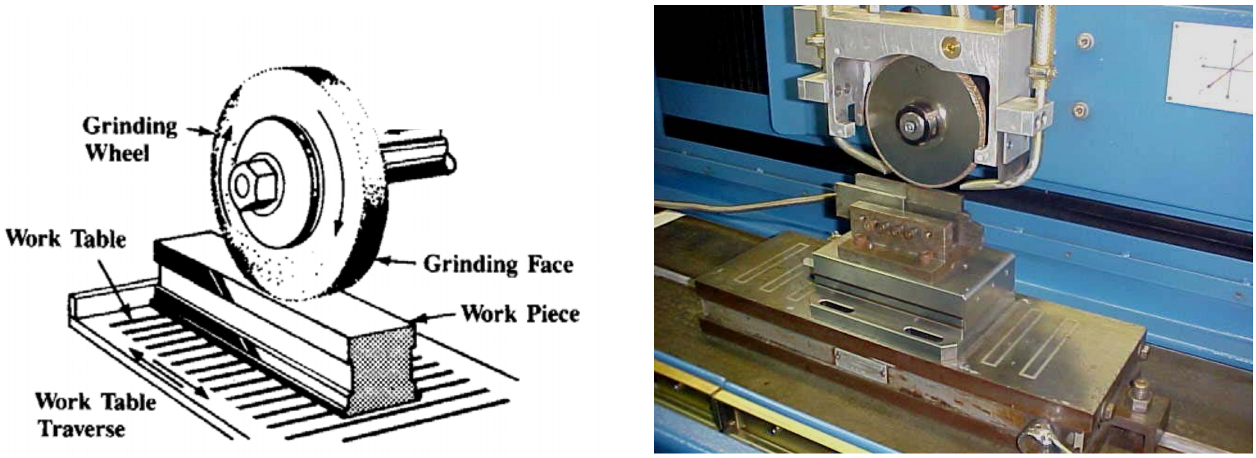
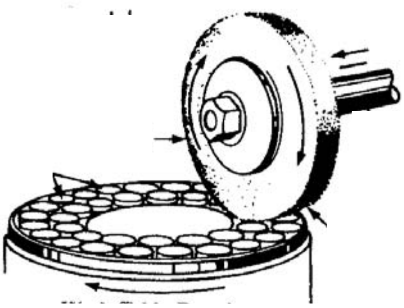
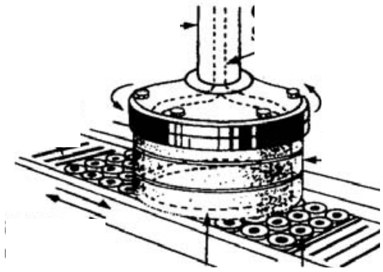


Fig. 4.5.29 *Mounting job on magnetic chuck in reciprocating type surface grinding.*

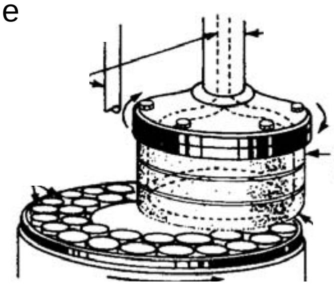
The methods of mounting small jobs in batches for surface grinding with horizontal and vertical wheel axis are shown in Fig. 4.5.30.



(a) horizontal wheel axis and rotating table



(b) vertical wheel axis and sliding table



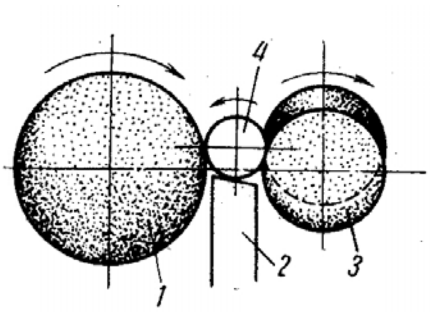
(c) vertical wheel axis and rotating table

Fig. 4.5.30 *Mounting of small jobs for surface grinding in batch production.*

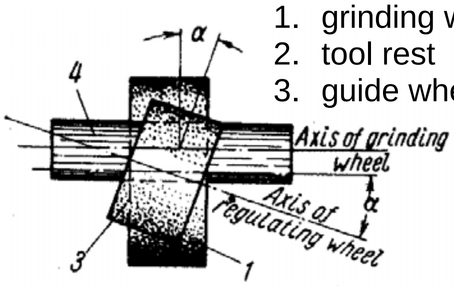
Form grinding like grinding of screw threads, gear teeth, cutter flutes etc. may be in both cylindrical grinding and surface grinding modes. Therefore, job mounting is done accordingly.

Fig. 4.5.31 schematically shows how the job is mounted and ground in centreless grinding. In external centreless grinding the rod shaped job is held in position, slowly rotated and also axially moved, if necessary, by a rest and the guide wheel which rotates slowly providing the desired work feed motions. In internal centreless grinding, the ring shaped blank is held in position by the guide wheel and the supporting wheels but attains its rotary feed motion from the rotating guide wheel only.

1. grinding wheel
2. tool rest
3. guide wheel

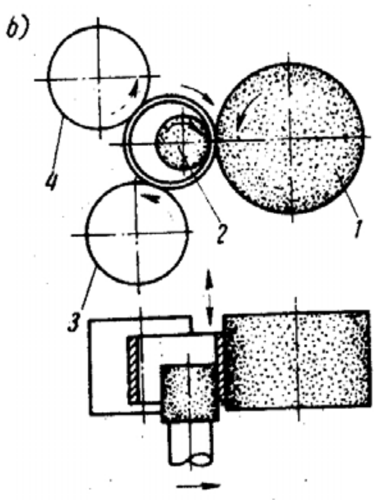


plunge feed grinding



through feed grinding

(a) external grinding

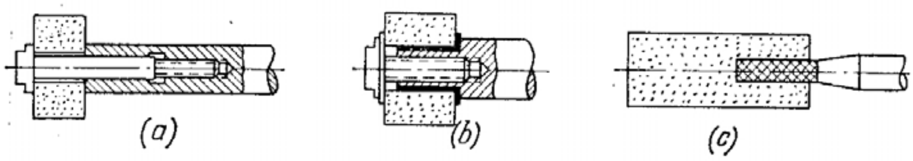


(b) internal grinding

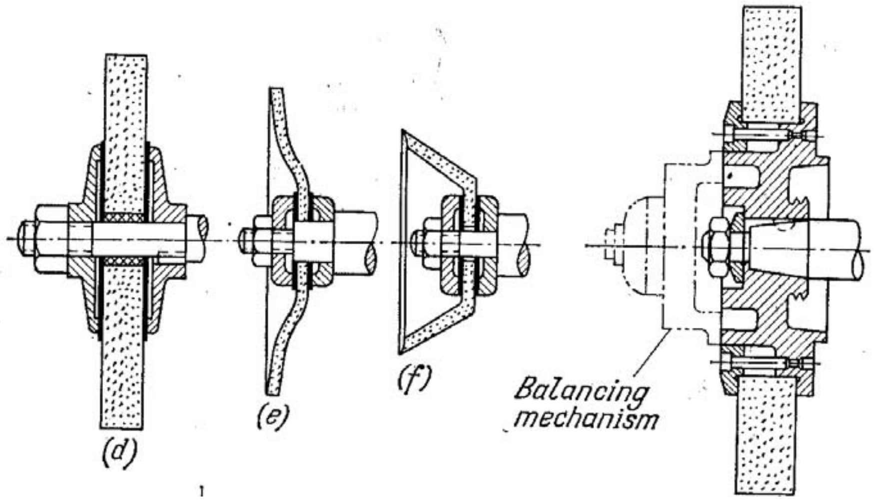
Fig. 4.5.31 *Mounting of job in centreless grinding.*

- **Mounting wheel in grinding machines**

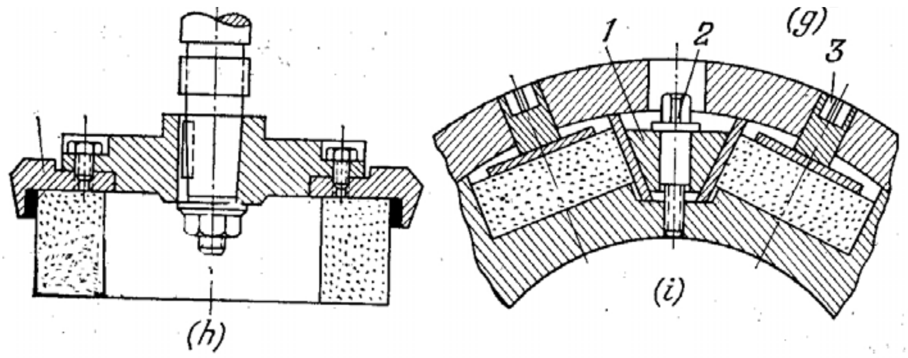
All the grinding wheels are circular shaped and rotate only about their own axis. A grinding wheel is always coaxially mounted on the spindle nose as shown in Fig. 4.5.32 which visualises the variation in the exact method of mounting of the wheel depending upon the type, size and shape of the wheels.



(i) for internal grinding



(ii) for external grinding with horizontal wheel axis



(iii) large and heavy ring shaped wheel on vertical spindle

Fig. 4.5.32 *Mounting of grinding wheels on spindle*

(iii) Mounting of job and tool in CNC machine tools

- **Mounting of jobs**

CNC machine tools are also general purpose machine tools but distinguished for;

- Flexibility through programmability enabling quick change over to new products
- Versatility
- Ability to machine complex geometry
- Dimensional accuracy

- Computer control

Successful accomplishment of the aforesaid features of CNC machines necessitates the job – tool and their mounting to have some essential characteristics :

- **Characteristics of job – mounting**

  - Easy, quick and very accurate locating, supporting and clamping
  - Quick and easy loading and unloading of the unfinished and finished job to and from the machine tool, preferably by robots
  - Avoidance of jigs and fixtures
  - Ability to cover wide range of size and shape of the blanks
  - Identification or fixation of datum surfaces

In CNC lathes and turning centres, jobs are mounted on the spindle by using quick acting collet chucks operated pneumatically or hydraulically. In CNC milling and drilling machines, the jobs are clamped directly or in a vice on the table as shown in Fig. 4.5.33. Jigs and fixtures are not used.

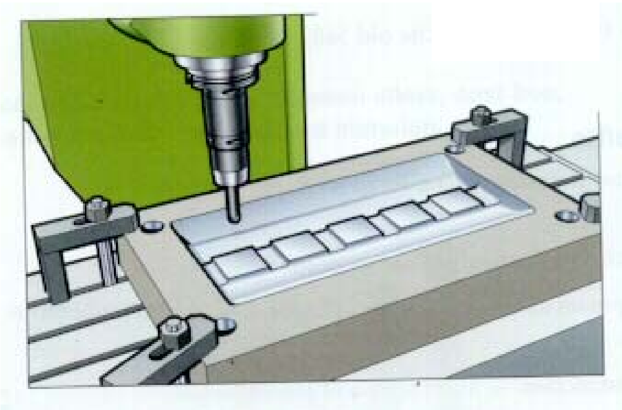


Fig. 4.5.33 *Mounting of job on the bed by clamping in CNC milling machine.*

- **Characteristics of tool mounting**

  - Easy, quick and accurate locating and clamping
  - Large tool bank
  - Quick tool change
  - All the tools to be used in a specific machine tool must have same shank of standard dimensions.

Fig. 4.5.34 schematically shows tool mounting in a turret type CNC drilling machine where the tools are used in sequence according to requirement and programmed.

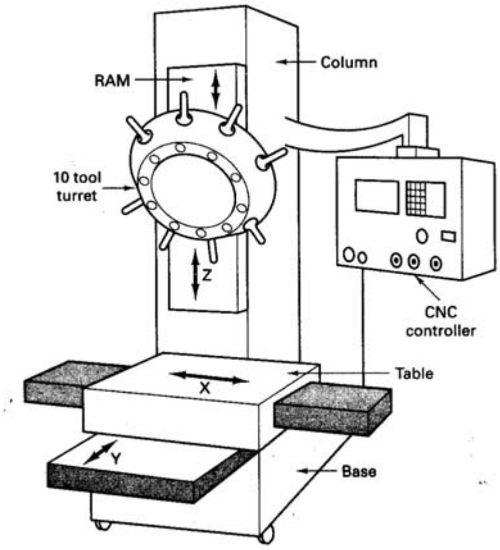
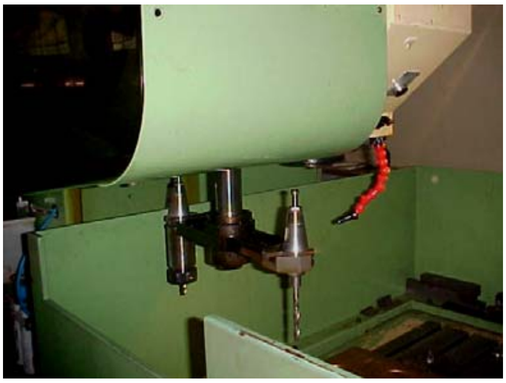


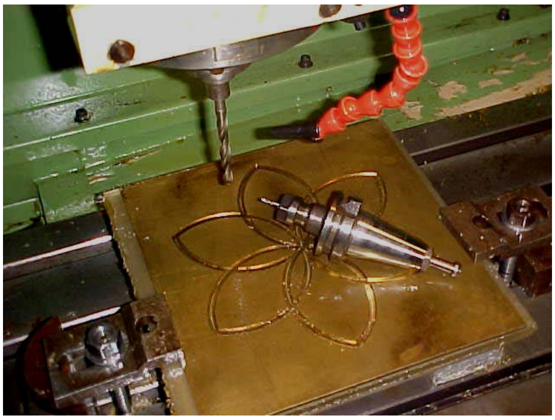
Fig. 4.5.34 *Tool mounting in turret type CNC drilling machine.*

Fig. 4.5.35 typically shows (a) tool bank, (b) auto-tool-changer (ATC) and the (c) configuration of tool holder being used in versatile CNC milling machine or Machining Centre.

(a) tool bank



(b) auto-tool-changer (ATC)



(c) configuration of tool holder

Fig. 4.5.35 *Tool bank, auto tool changer (ATC) and configuration of tool holder used in CNC milling machine.*

The sophisticated and precision CNC machine tools are essentially characterised by quick and accurate mounting and rigid clamping of the cutting tools and also proper and rigid mounting of the blanks in appropriate positions.

Module 4

General Purpose Machine Tools

Lesson
22
Use of various Attachments in Machine Tools.

Instructional objectives

At the end of this lesson, the students will be able to;

(i) Comprehend and state the use of accessories and attachments in machine tools
(ii) Realize and Identify why and when Attachments are necessarily used
(iii) Describe the basic construction and application principles of different attachments used in;
- Centre lathes
- Drilling machines
- Shaping machines
- Planing machines
- Milling machines

(i) Use Of Various Accessories And Attachments In General Purpose Machine Tools.

ACCESSORIES :

A general purpose machine tool is basically comprised of power drive and kinematic system for the essential formative and auxiliary tool – work motions and a rigid body or structure to accommodate all of the above. But several additional elements or devices called accessories are also essentially required for that machines' general functioning, mainly for properly holding and supporting the workpiece and the cutting tool depending upon the type and size of the tool – work and the machining requirements.

These accessories generally include for instance, in case of;

- Centre lathes : chucks, collets, face plate, steady and follower rests, centres, tool holders etc.
- Drilling machines : vices, clamps, drill chuck and sockets etc.
- Shaping and planning machines : vices, clamps, tool holders etc.
- Milling machines : vices, clamps, parallel blocks, collets, job – support like tailstock etc.

Such accessories, inevitable for general functioning of the machine tools, are usually enlisted in the supply list and covered within the total price of the machine tools. Occasionally, some accessories are ordered separately as and when required.

ATTACHMENTS

Each general purpose conventional machine tool is designed and used for a set of specific machining work on jobs of limited range of shape and size. But often some unusual work also need to be done in a specific machine tools, e.g. milling in a lathe, tapping in a drilling machine, gear teeth cutting in shaping machine and so on. Under such conditions, some special devices or systems are additionally used being mounted in the ordinary machine tools. Such additional special devices, which augment the processing capability of any ordinary machine tool, are known as Attachments, Unlike accessories, Attachments are not that inevitable and procured separately as and when required and obviously on extra payment. Some attachments being used in the general purpose conventional machine tools are :

- **In centre lathes :**
  - Taper turning attachment
  - Copy turning attachments
  - Milling and cylindrical grinding attachments
  - Spherical turning attachments
  - Relieving attachment
- **In drilling machines :**
  - Tapping attachment
- **In shaping machines :**
  - Double cut tool head
  - Thread rolling attachment
  - Matterson's attachment (gear teeth cutting)
- **In planing machines :**
  - Contour forming attachment
  - Helical grooving attachment
  - Oil grooving attachments
  - Milling and grinding attachments
- **In Milling machines :**
  - universal milling attachment
  - indexing / dividing head
  - rotary table
  - slotting attachment

(ii) Conditions And Places Suitable For Application Of Attachments In Machine Tools.

With the rapid and vast advancement of science and technology, the manufacturing systems including machine tools are becoming more and more versatile and productive on one hand for large lot or mass production and also having flexible automation and high precision on the other hand required for production of more critical components in pieces or small batches. With the increase of versatility and precision (e.g., CNC machines) and the advent of dedicated high productive special purpose machines, the need of use of special attachments is gradually decreasing rapidly.

However, some attachments are occasionally still being used on non automatic general purpose machine tools in some small and medium scale machining industries;

- when and where machining facilities are very limited
- when production requirement is very small, may be few pieces
- product changes frequently as per job order
- repair work under maintenance, specially when spare parts are not available
- when CNC machine tools and even reasonable number of conventional machine tools cannot be afforded.

Therefore, use of aforesaid attachments is restricted to manufacture of unusual jobs in small quantities under limited facilities and at low cost.

(iii)Working Principles And Application Of Various Attachments In Different Machine Tools.

(a) Attachments used in centre lathes

- **Taper turning attachment**

Taper cylindrical surface, which is a very common feature of several engineering components, is generally produced in lathes in a number of methods, depending upon length and angle of the tapered position of the job, such as offsetting tailstock, swivelling the compound slide using form tool and combined feed motions. But jobs with wide ranges of length and angle of taper, are easily machined by using a simple attachment, called taper turning attachment. Fig. 4.6.1 schematically shows a taper turning attachment where the cross slide is delinked from the saddle and is moved crosswise by the guide block which moves along the guide bar preset at the desired taper angle. Thus, the cutting tool, which is fitted on the cross slide through the tool post and the compound slide, also moves along with the guide black in the same direction resulting the desired taper turning.

- **Copy turning attachment**

There are two common types of copy turning;

- o mechanical type
- o hydraulic type

o **Mechanical copying**

A simple mechanical type copy turning attachment has been schematically shown in Fig. 4.6.2. The entire attachment is mounted on the saddle after removing the cross slide from that. The template replicating the job-profile desired is clamped at a suitable position on the bed. The stylus is fitted in the spring loaded tool slide and while travelling longitudinally along with saddle moves in transverse direction according to the template profile enabling the cutting tool produce the same profile on the job as indicated in the Fig. 4.6.2

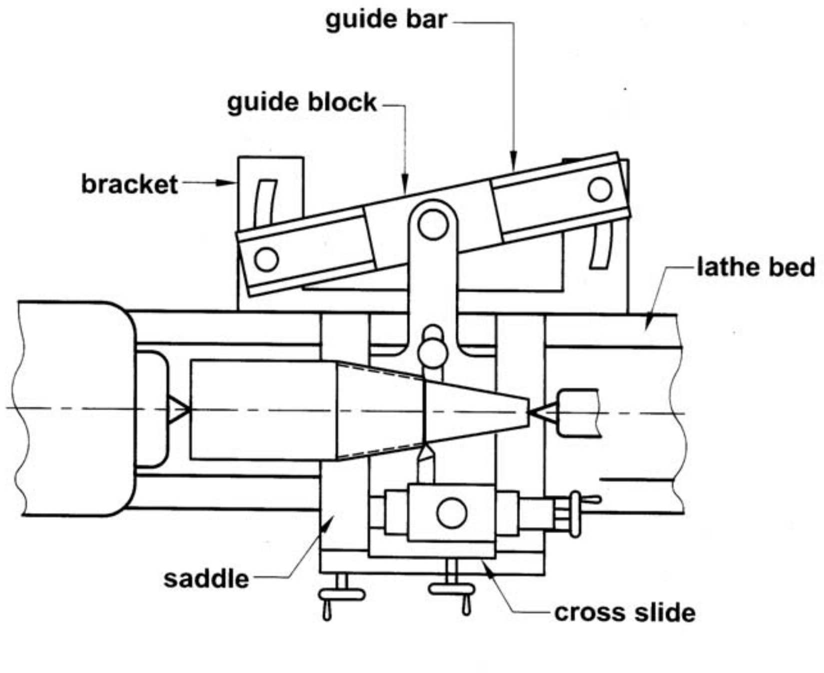


Fig. 4.6.1 *Taper turning attachment.*

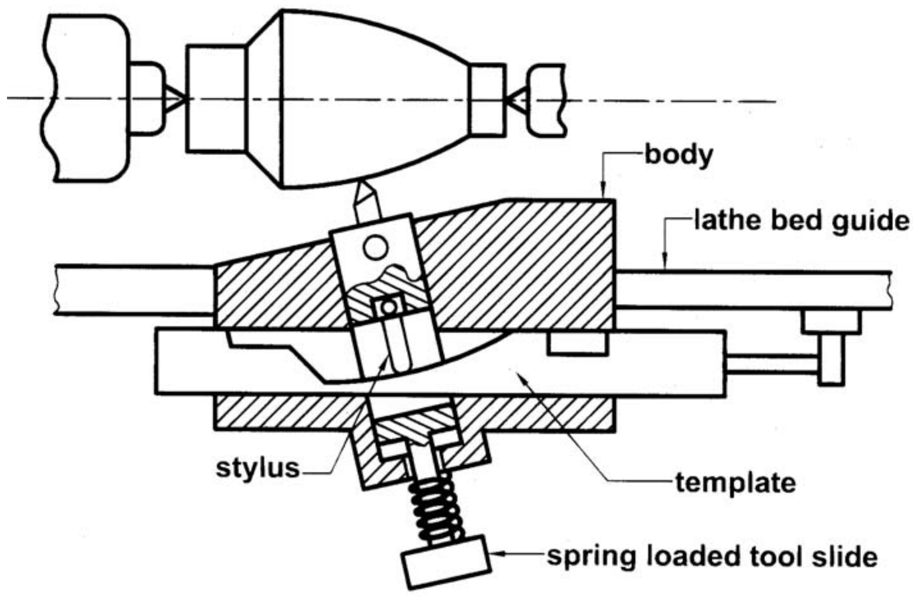


Fig. 4.6.2 *Mechanical type copying attachment.*

o **Hydraulic copying attachment**

The mounting and working principle of hydraulic copying attachment for profile turning in centre lathe are schematically shown in Fig. 4.6.3. Here also, the stylus moves along the template profile to replicate it on the job. In mechanical system (Fig. 4.6.2) the heavy cutting force is transmitted at the tip of the stylus, which causes vibration, large friction and faster wear and tear. Such problems are almost absent in hydraulic copying, where the stylus works simply as a valve – spool against a light spring and is not affected by the cutting force. Hydraulic copying attachment is costlier than the mechanical type but works much smoothly and accurately. The cutting tool is rigidly fixed on the cross slide which also acts as a valve – cum – cylinder as shown. So long the stylus remains on a straight edge parallel to the lathe bed, the cylinder does not move transversely and the tool causes straight turning. As soon as the stylus starts moving along a slope or profile, i.e., in cross feed direction the ports open and the cylinder starts moving accordingly against the piston fixed on the saddle. Again the movement of the cylinder i.e., the slide holding the tool, by same amount travelled by the stylus, and closes the ports. Repeating of such quick incremental movements of the tool, Δx and Δy result in the profile with little surface roughness.

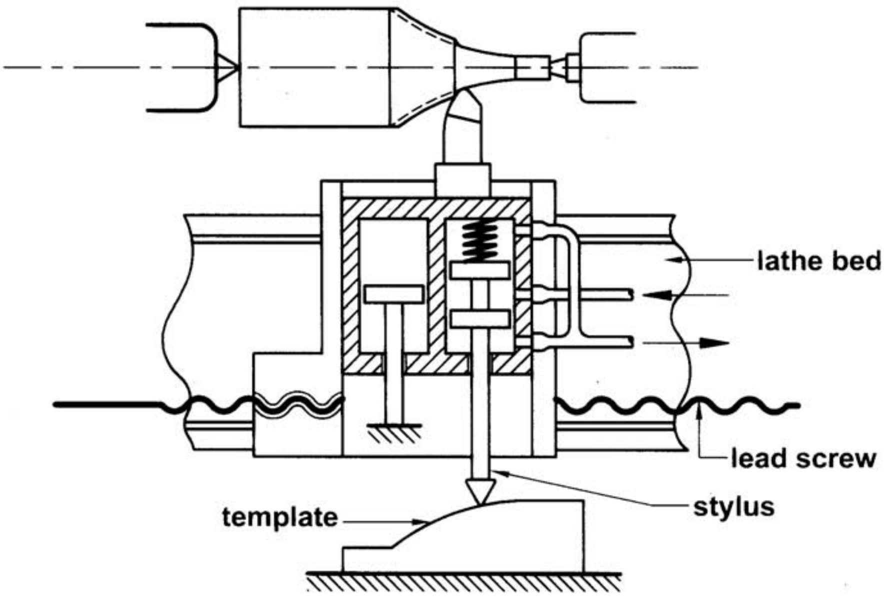


Fig. 4.6.3 Hydraulic copying attachment.

- **Milling attachment**

This is a milling head, comprising a motor, a small gear box and a spindle to hold the milling cutter, mounted on the saddle after removing the cross slide etc. as shown in Fig. 4.6.4. Milling attachments are generally used for making flat surfaces, straight and helical grooves, splines, long and deep screw threads, worms etc. in centre lathes by using suitable milling cutters.

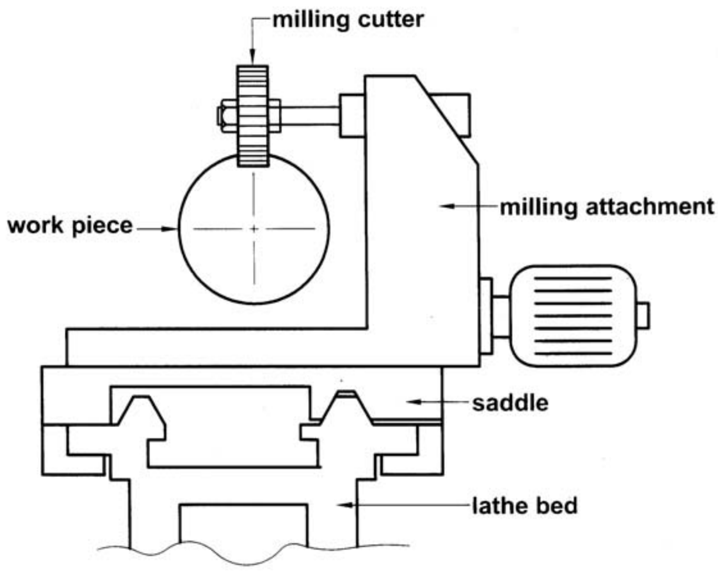


Fig. 4.6.4 *Milling attachment used in lathe.*

- **Grinding attachment**

Grinding attachment is very similar to milling attachment. But in the former, there is no gear box and the spindle speed is much higher as needed for grinding operation. Such attachments are employed for external and internal cylindrical grinding, finishing grooves, splines etc. and also for finish grinding of screw threads in centre lathe. But unlike dedicated machines, attachments cannot provide high accuracy and finish.

- **Spherical turning attachments**

These simple attachments are used in centre lathes for machining spherical; both convex and concave surfaces and similar surfaces. Fig. 4.6.5 schematically visualises the usual setting and working principle of such attachments. In Fig. 4.6.5 (b), the distance R_i can be set according to the radius of curvature desired. In the type shown in Fig. 4.6.5 (a) the desired path of the tool tip is controlled by the profile of the template which is pre-made as per the radius of curvature required. The saddle is disconnected from the feed rod and the leadscrew. So when the cross slide is moved manually in transverse direction, the tool moves axially freely being guided by the template only.

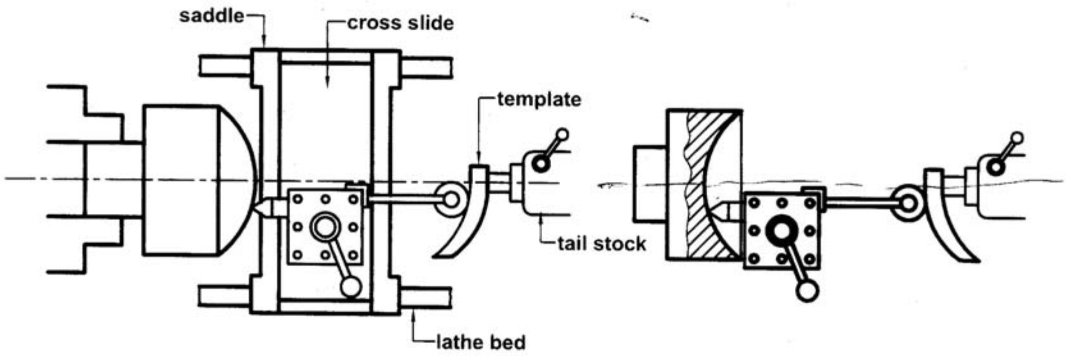


***Fig. 4.6.5** (a) Spherical turning using template.*

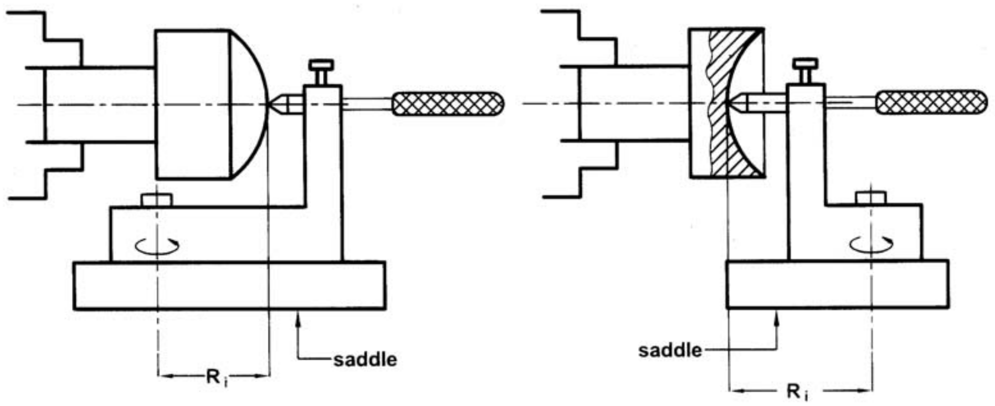
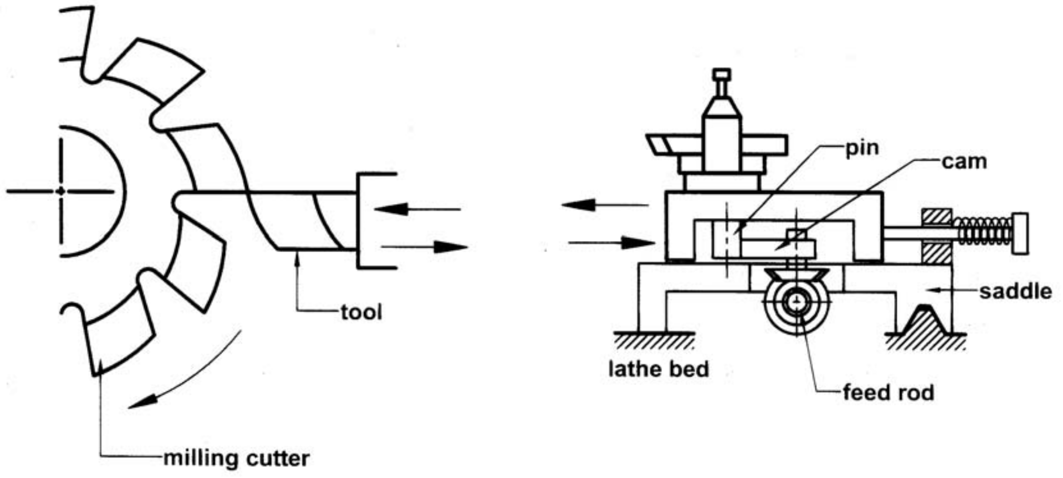


***Fig. 4.6.5** (b) Spherical turning without template.*

- **Relieving attachment**

The teeth of form relieved milling cutters like gear milling cutters, taps, hobs etc. are provided with flank having archemedian spiral curvature. Machining and grinding of such curved flanks of the teeth need relieving motion to the tool (or wheel) as indicated in Fig. 4.6.6 (a). The attachment schematically shown in Fig. 4.6.6 (b) is comprised of a spring loaded bracket which holds the cutting tool and is radially reciprocated on the saddle by a plate cam driven by the feed rod as indicated.



(a) (b)

Fig. 4.6.6 *Relieving attachment used in lathe.*

- **Thread pitch correcting attachment**

While cutting screw thread in centre lathes by single point chasing tool, often the actual pitch, p_a deviates from the desired (or stipulated) pitch, p_s by an error (say $\pm \Delta p$) due to some kinematic error in the lathe.
Mathematically,

$$p_s - p_a = \pm \Delta p \qquad (4.6.1)$$

Therefore for correct pitch, the error $\pm \Delta p$ need to be compensated and this may be done by a simple differential mechanism, namely correcting bar attachment as schematically indicated in Fig. 4.6.7.
In equation 4.6.1,

$$p_a = 1 \times U_C \times L$$

$$\pm \Delta p = p_s \tan(\pm\alpha).L/(\pi m Z) \qquad (4.6.2)$$

where, U_C = transmission ratio
L = lead of the leadscrew
m, Z = module and no. of teeth of the gear fixed with the nut and is additionally rotated slightly by the movement of the rack along the bar.

Such differential mechanism of this attachment can also be used for intentionally cutting thread whose pitch will be essentially slightly more or less than the standard pitch, as it may be required for making differential screws having threads of slightly different pitch at two different locations of the screw.

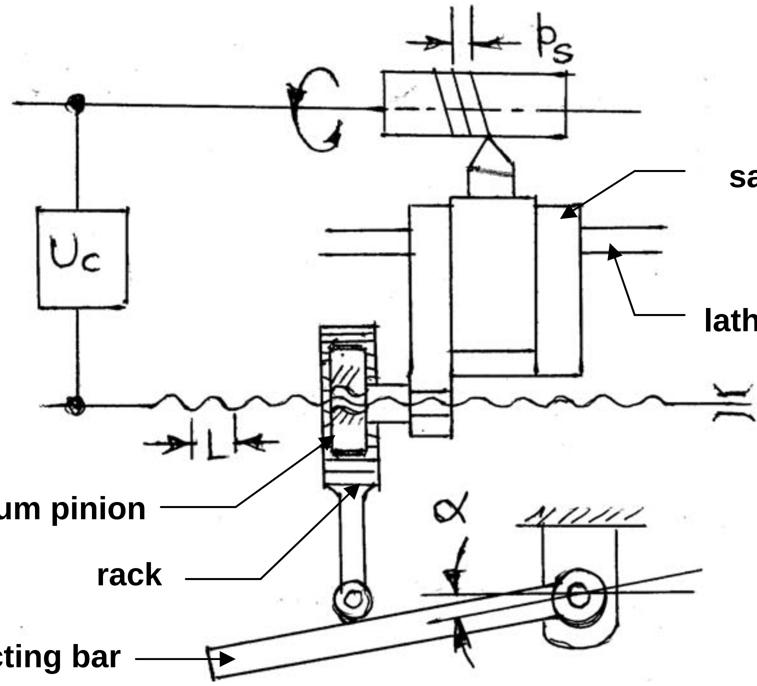


Fig. 4.6.7 *Thread pitch correcting attachment.*

(b) Attachments used in drilling machines

o **Tapping attachment**

It has been mentioned earlier in the previous lessons that several machining work other than drilling can be done in drilling machine using different types of cutting tools and job holding device. Tapping of nuts for their internal threads is also often done in a drilling machine by using tapping attachment as schematically shown in Fig. 4.6.8. Return of the tap by reverse rotation of the spindle without damage of the thread and the tap is the most critical design. Fig. 4.6.8 (a) visualises that the spring loaded sliding clutch engages with the free tapping clutch during threading. The clearance between the jaws of the two clutches and the spring action enable safe return of the tap following that of the spindle. Fig. 4.6.8 (b) shows another faster working tapping system where the hexagonal blanks are fed one by one and the tapping unit, rotating at a constant speed in the same direction moves only up and down for ejecting the threaded nuts by centrifugal force.

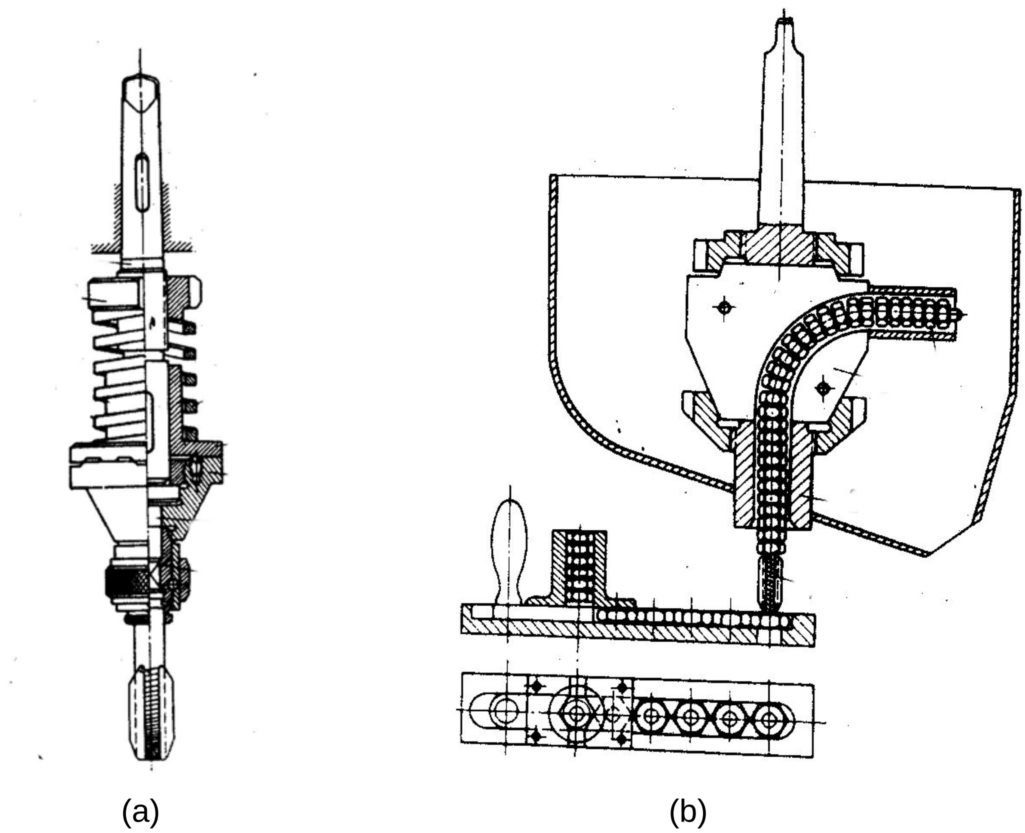


Fig. 4.6.8 *Tapping attachment used in drilling machine.*

(c) Attachments used in shaping machine

Some attachments are often used for extending the processing capabilities of shaping machines and also for getting some unusual work in ordinary shaping machine.

- **Attachment for double cut**

This simple attachment is rigidly mounted on the vertical face of the ram replacing the clapper box. It is comprised of a fixed body with two working flat surfaces and a swing type tool holder having two tools on either faces as can be seen in Fig. 4.6.9. The tool holder is tilted by a spring loaded lever which is moved by a trip dog at the end of its strokes.
Such attachment simply enhances the productivity by utilising both the strokes in shaping machines.

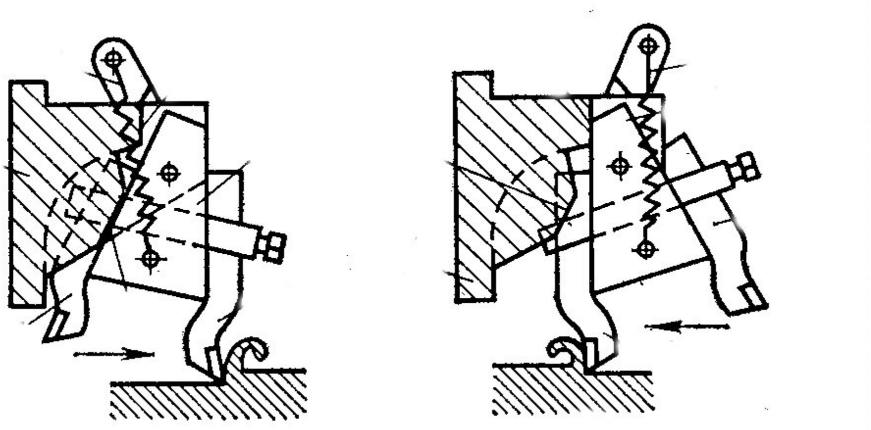


Fig. 4.6.9 *Double cut attachment used in shaping machine.*

- **Thread rolling attachment**

The thread of fasteners is done by mass production methods. Thread rolling is hardly done nowadays in shaping machines. However the configuration, mounting and the working principle of the thread rolling (in shaping machine) attachment are visualised in Fig. 4.6.10. In between the flat dies, one fixed and one reciprocating, the blanks are pushed and thread – rolled one by one.

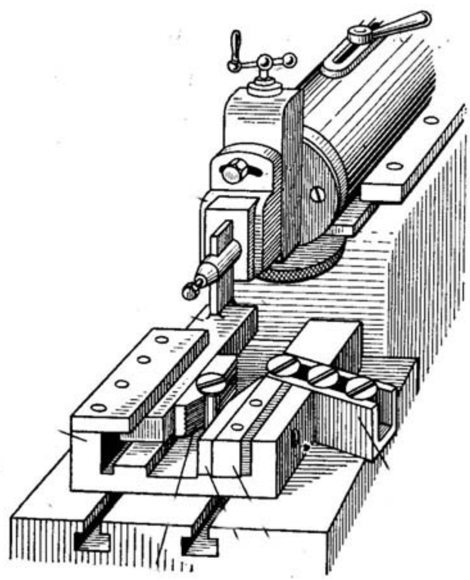


Fig. 4.6.10 *Thread rolling attachment used in shaping machine.*

- **Matterson's attachment**

Various machines and processes have been developed for producing gear teeth with high productivity and job quality. Gear teeth are hardly produced nowadays in shaping machines. But, if required, it may be occasionally done by shaping machine in some small tool room or small workshop specially for repair and maintenance work. One or two, even all the teeth of a gear may be cut by forming tool in shaper using an indexing head. But such forming, specially in shaper is not only very slow process but also not at all accurate. But the Matterson's attachment can produce gear (spur) teeth even in shaping machine by generation process. The working principle of the attachment is shown in Fig. 4.6.11. For generation of the tooth by rolling the blank is rotated and the bed is travelled simultaneously at same linear speed by the synchronised kinematics as indicated in the diagram. After completing one tooth gap both the tool and blank are returned to their initial positions and then after indexing the blank for one tooth, the tool – work motions are repeated.

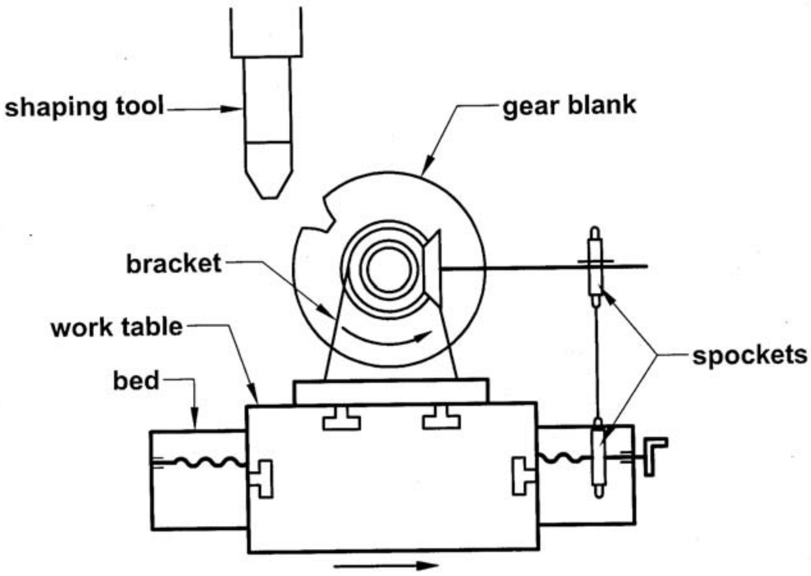
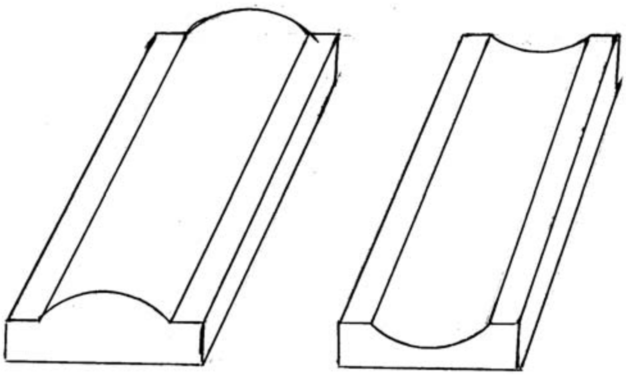


Fig. 4.6.11 *Matterson's Attachment for gear teeth generation in shaping machine.*

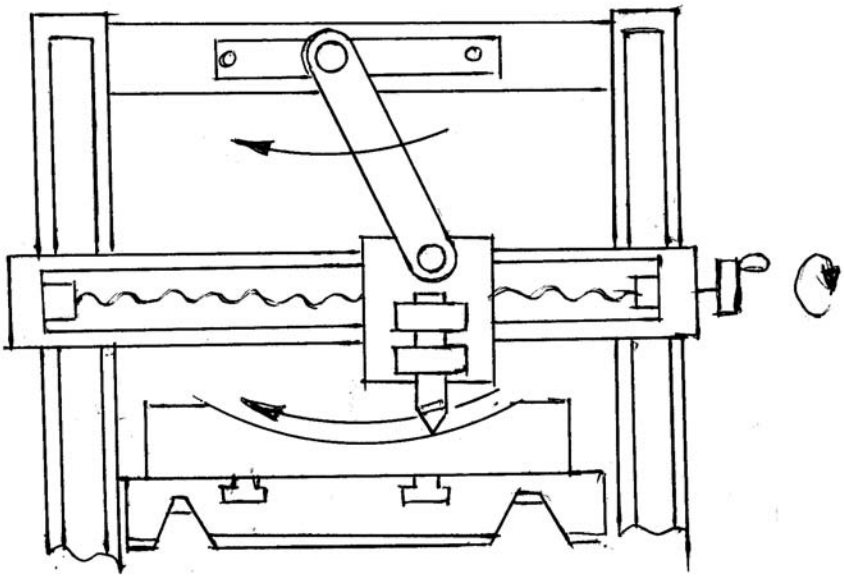
(d) Attachments used in planing machines

- **Contour forming attachment**

This simple and low cost attachment may be used in planing macvhine for producing 2 – D form of circular section in long heavy tables or beds as indicated in Fig. 4.6.12 (a). The basic working principle is schematically shown in Fig. 4.6.12 (b). The convex circular arc form is produced by a swinging bar hinged at the upper bracket and connected with one tool head which is manually or automatically moved axially by the horizontal leadscrew. The horizontal rail is kept delinked from the vertical leadscrews. The horizontal feed alone will move the tool – tip in circular path with the help of the swing – bar. Similarly, with slight modification the concave form can also be made.



(a)



(b)

***Fig. 4.6.12** Contour forming attachment used in planning machine.*

- **Helical grooving attachment**

Long lead helical grooves on large rod type jobs can be done easily and inexpensively in a planing machine, if available, by using simple attachment as shown in Fig. 4.6.13. Swinging of the bar clamping the linearly travelling rod (job) due to the prefixed inclined bar causes the required rotation of the rod. Such rotation along with linear axial travel produce the groove.

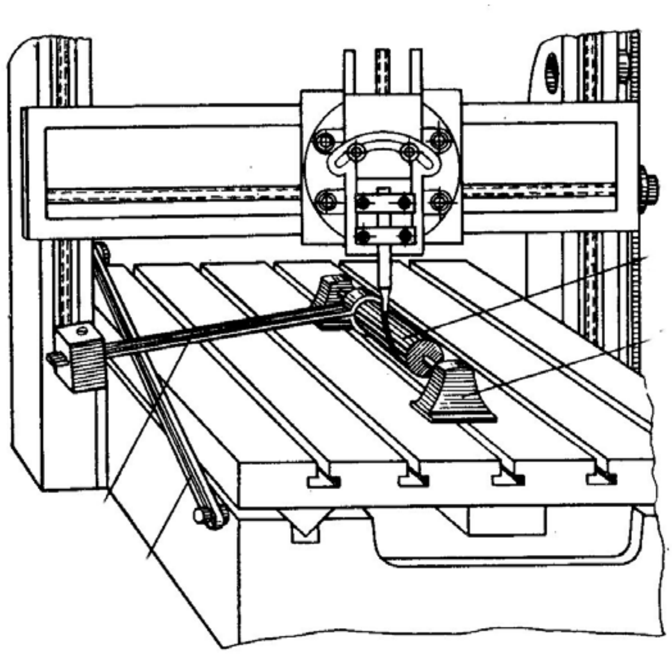


Fig. 4.6.13 *Attachment in planing machine for cutting long lead helical grooves.*

- **Other attachments used in planing machine**
  - Δ Shallow oil grooves of various patterns can be cut on the flat surfaces of large tables or beds of large machineries by replacing the stationary fixed single point tool (s) by a rotary tool driven by a separate motor.
  - Δ Hydraulic tracer control type attachments are often used for making complex shaped 2 – D contours on large components in planing machines. The form of the template is replicated on the product as described in case of hydraulic copying lathe.
  - Δ Milling and grinding attachments.

    Both productivity and process capability of conventional planing machines are low for use of single point tools. Both productivity and finish are substantially increased by replacing those single point tool heads by milling and grinding heads on the horizontal and / or vertical rails. Such powered heads with rotary tools led to development of high productive plano millers and plano grinders.

(e) Attachments used in Milling machines

- **Universal milling attachment**

Amongst the knee type conventional milling machines, horizontal arbour type is very widely used, where various types and sizes of milling cutters viz. plain or slab milling cutters and disc type cutters including single and double side(s) cutter, slot cutter, form cutters, gear milling cutters, slitting cutter etc. having axial bore are mounted on the horizontal arbour. For milling by solid end mill type and face milling cutters, separate vertical axis type milling machines are available. But horizontal arbour type milling machines can also be used for those operations to be done by end milling and smaller size face milling cutters by using proper attachments. The universal milling attachment is shown in Fig. 4.6.14. The rotation of the horizontal spindle is transmitted into rotation about vertical and also in any inclined direction by this attachment which thus extends the processing capabilities and application range of the milling machine.

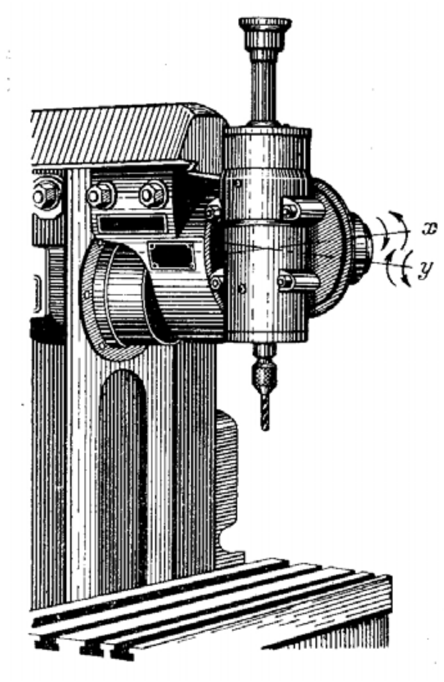


Fig. 4.6.14 *Universal milling attachment.*

- **Indexing or Dividing head**

This device is essentially so frequently and widely needed and used that it is also considered as an accessory. But it is taken as an attachment possibly for being procured separately. This attachment is basically used for equi-angular rotation by simple compound or differential indexing of the job while machining. Fig. 4.6.15 typically shows a universal type dividing head and its mounting and an application.

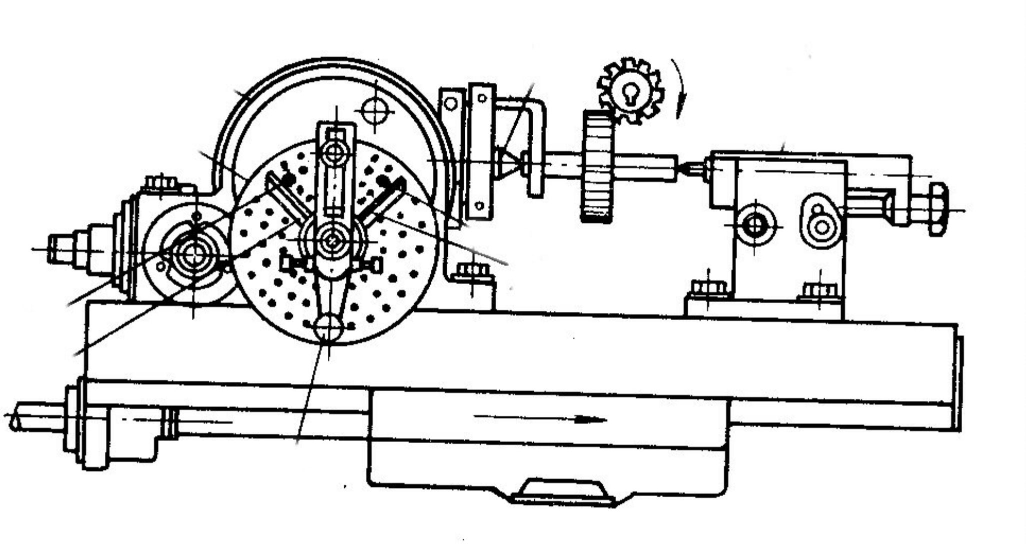


Fig. 4.6.15 A Universal type dividing head and its application.

- **Rotary table**

This device may also be considered both accessory or attachment and is generally used in milling machines for both offline and online indexing / rotation of the job, clamped on it, about vertical axis. Fig. 4.6.16 visualises such a rotary table which is clamped or mounted on the machine bed / table.

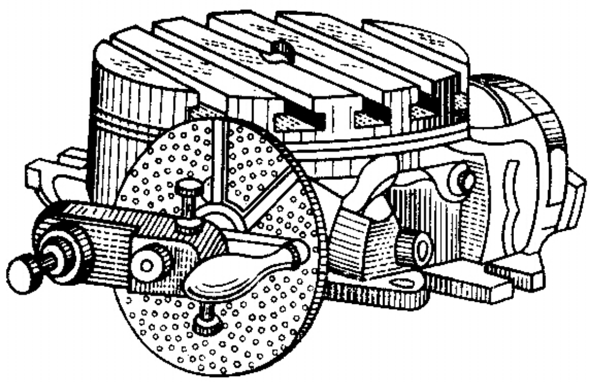


Fig. 4.6.16 *A rotary table which can be clamped or mounted on the machine bed.*

- **Slotting attachment**

Such simple and low cost attachment is mounted on the horizontal spindle for producing keyways and contoured surface requiring linear travel of single point tool in milling machine where slotting machine and broaching machine are not available. The configuration of such a slotting attachment and its mounting and operation can be seen in Fig. 4.6.17. The mechanism inside converts rotation of the spindle into reciprocation of the single point tool in vertical direction. The direction of the tool path can also be tilted by swivelling the circular base of the attachment body.

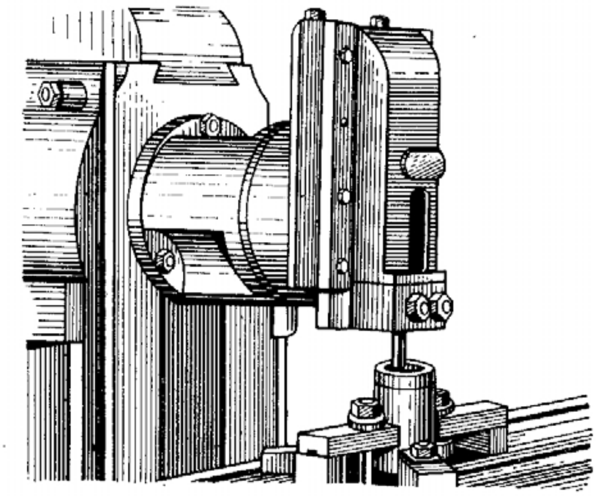


Fig. 4.6.17 *Slotting attachment*

There are several other possible attachments which can be used for some specific application not included in the basic range of a particular machine tool. New attachments can also be developed if so demanded. But need and use of attachments are gradually decreasing for rapid and vast developments in types of machine tools and more so after the advent of CNC machine tools with flexible automation.

Module
4
General Purpose Machine Tools

Lesson
23
Construction, Operation and Tool layout in Semiautomatic and Automatic lathes.

Instructional objectives

This lesson will enable the students ;

(i) Illustrate the constructional features and uses of semiautomatic and automatic lathes.
(ii) Show the kinematic system and explain the working principles of semiautomatic and automatic lathes of common use.
(iii) Plan and visualise tool layout for machining in semiautomatic and automatic lathes.

(i) Constructional Features And Uses Of General Purpose Semiautomatic And Automatic Lathes.

Automation is incorporated in a machine tool or machining system as a whole for higher productivity with consistent quality aiming meeting the large requirements and overall economy. Such automation enables quick and accurate auxiliary motions, i.e., handling operations like tool – work mounting, bar feeding, tool indexing etc. repeatably with minimum human intervention but with the help of special or additional mechanism and control systems. These systems may be of mechanical, electro-mechanical, hydraulic or electronic type or their combination.
It is already mentioned that according to degree of automation machine tools are classified as,

- Non automatic where most of the handling operations irrespective of processing operations, are done manually, like centre lathes etc.
- Semiautomatic
- Automatic where all the handling or auxilliary operations as well as the processing operations are carried out automatically.

General purpose machine tools may have both fixed automation or flexible automation where the latter one is characterised by computer Numerical Control (CNC).
Amongst the machine tools, lathes are most versatile and widely used. Here automation of lathes only have been discussed.
The conventional general purpose automated lathes can be classified as,

(a) Semiautomatic :
- capstan lathe (ram type turret lathe)
- turret lathe
- multiple spindle turret lathe
- copying (hydraulic) lathe

(b) Automatic :
- Automatic cutting off lathe
- Single spindle automatic lathe
- Swiss type automatic lathe
- multiple spindle automatic lathes

The other categories of semiautomatic and automatic lathes are :

- Vertical turret lathe
- Special purpose lathes
- Non conventional type, i.e., flexibly automatic CNC lathes, turning centre etc.

(a) Semiautomatic lathes

The characteristic features of such lathes are ;

- some major auxiliary motions and handling operations like bar feeding, speed change, tool change etc. are done quickly and consistently with lesser human involvement
- the operators need lesser skill and putting lesser effort and attention
- suitable for batch or small lot production
- costlier than centre lathes of same capacity.

Capstan and Turret lathes

The semiautomatic lathes, capstan lathe and turret lathe are very similar in construction, operation and application. Fig. 4.7.1 schematically shows the basic configuration of capstan lathe and Fig. 4.7.2 shows that of turret lathe.

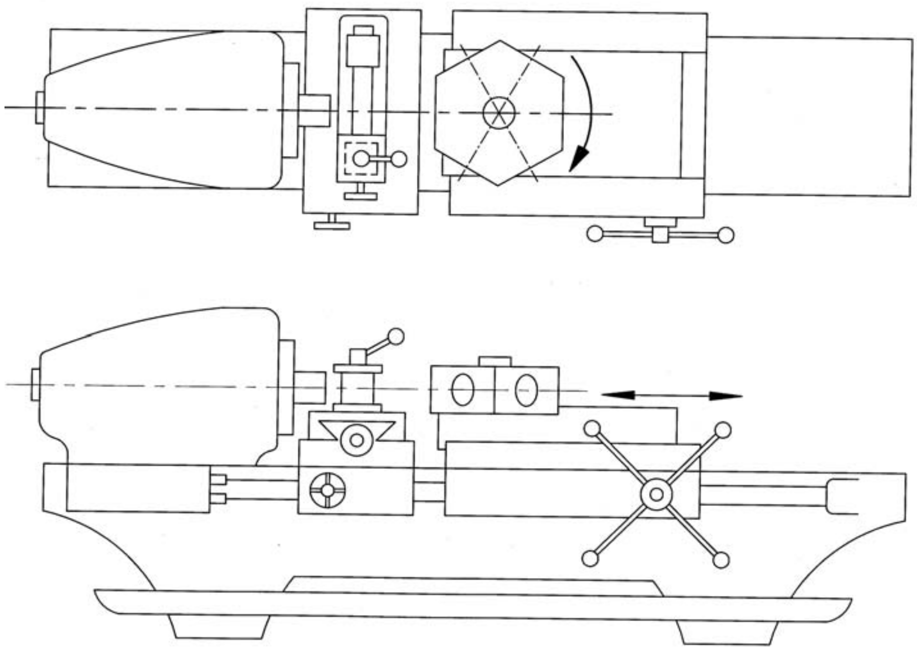


Fig. 4.7.1 *Schematic configuration of capstan lathe.*

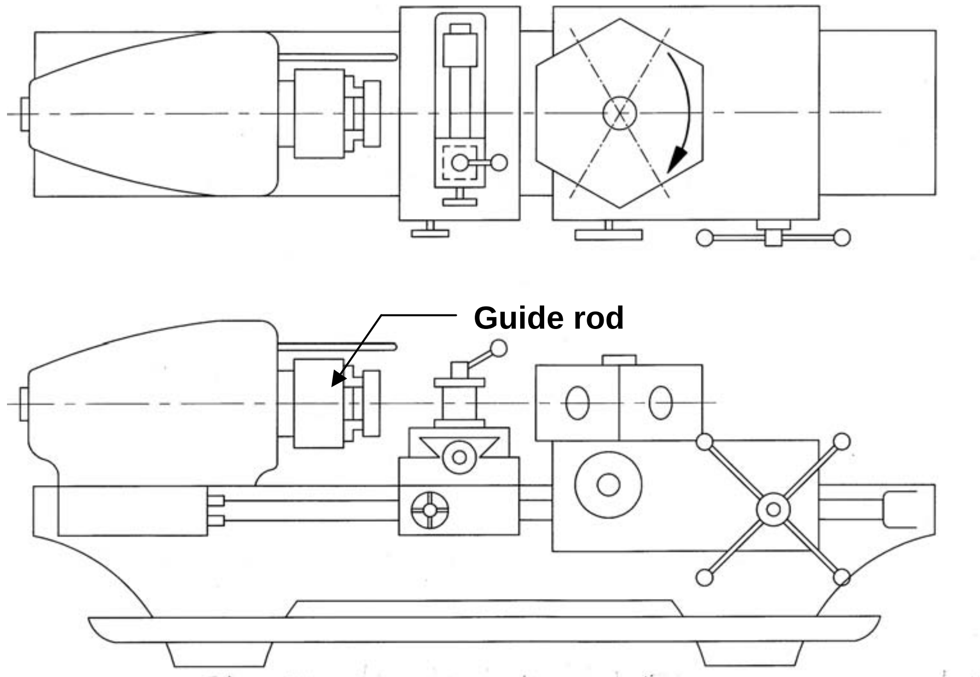


Fig. 4.7.2 *Schematic configuration of turret lathe.*

In contrast to centre lathes, capstan and turret lathes

- are semiautomatic
- possess an axially movable indexable turret (mostly hexagonal) in place of tailstock
- holds large number of cutting tools; upto four in indexable tool post on the front slide, one in the rear slide and upto 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 relatively costlier
- are suitable and economically viable for batch production or small lot production.

There are some differences in between capstan and turret lathes such as,

- Turret lathes are relatively more robust and heavy duty machines
- Capstan lathes generally deal with short or long rod type blanks held in collet, whereas turret lathes mostly work on chucking type jobs held in the quick acting chucks
- In capstan lathe, the turret travels with limited stroke length within a saddle type guide block, called auxiliary bed, which is clamped on the main bed as indicated in Fig. 4.7.1, whereas in turret lathe, the

heavy turret being mounted on the saddle which directly slides with larger stroke length on the main bed as indicated in Fig. 4.7.2

- One additional guide rod or pilot bar is provided on the headstock of the turret lathes as shown in Fig. 4.7.2, to ensure rigid axial travel of the turret head
- External screw threads are cut in capstan lathe, if required, using a self opening die being mounted in one face of the turret, whereas in turret lathes external threads are generally cut, if required, by a single point or multipoint chasing tool being mounted on the front slide and moved by a short leadscrew and a swing type half nut.

Fig. 4.7.3 and Fig. 4.7.4 are showing the pictorial views of a typical capstan lathe and a horizontal turret lathe respectively.

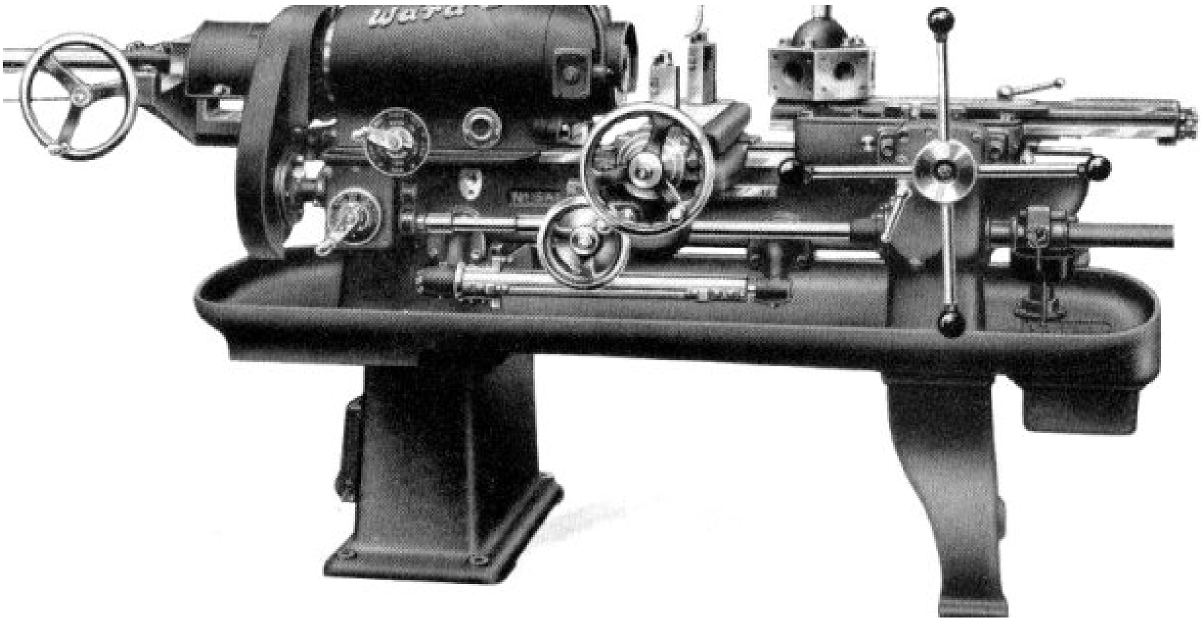


Fig. 4.7.3 *Pictorial view of a capstan lathe*

Ram type turret lathes, i.e., capstan lathes are usually single spindle and horizontal axis type. Turret lathes are also mostly single spindle and horizontal type but it may be also

- Vertical type and
- Multispindle type

Some more productive turret lathes are provided with preoptive drive which enables on-line presetting and engaging the next work-speed and thus help in reducing the cycle time.

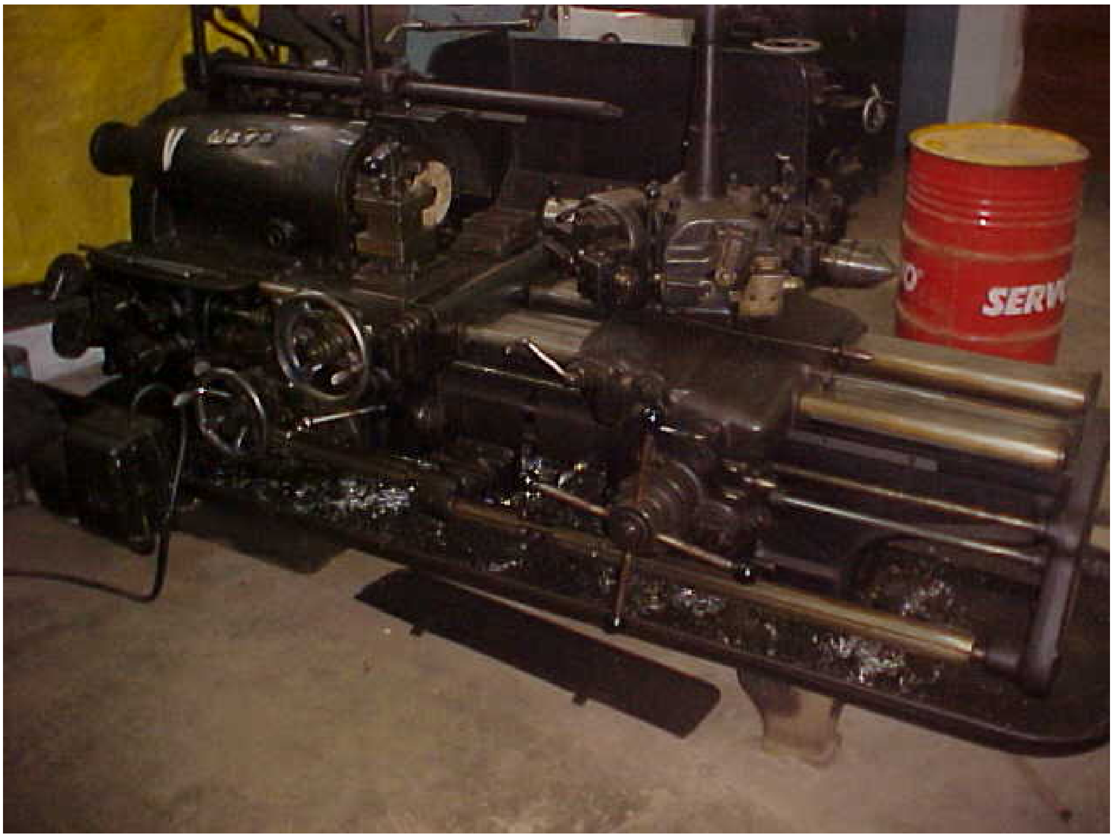


Fig. 4.7.4 *Pictorial view of a turret lathe.*

Multiple spindle Vertical Turret lathe

Turret lathes are mostly horizontal axis single spindle type. The multiple spindle vertical turret lathes are characterised by :

- Suitably used for large lot or mass production of jobs of generally ;
    - ∆ chucking type
    - ∆ relatively large size
    - ∆ requiring limited number of machining operations
- Machine axis – vertical for
    - ∆ lesser floor space occupied
    - ∆ easy loading and unloading of blanks and finished jobs
    - ∆ relieving the spindles of bending loads due to job – weight.
- Number of spindle – four to eight.

Fig. 4.7.5 visualise the basic configuration of multiple spindle vertical turret lathes which are comprised mainly of a large disc type spindle carrier and a tool holding vertical ram as shown.

Such vertical turret lathes are of three categories :

∗ **Parallel processing type :**

The spindle carrier remains stationary. Only the tool slides move with cutting tools radially and axially. Identical jobs (say six) are simultaneously mounted and machined in the chucks parallely at all stations each one having same set of axially and / or radially moving cutting tools.

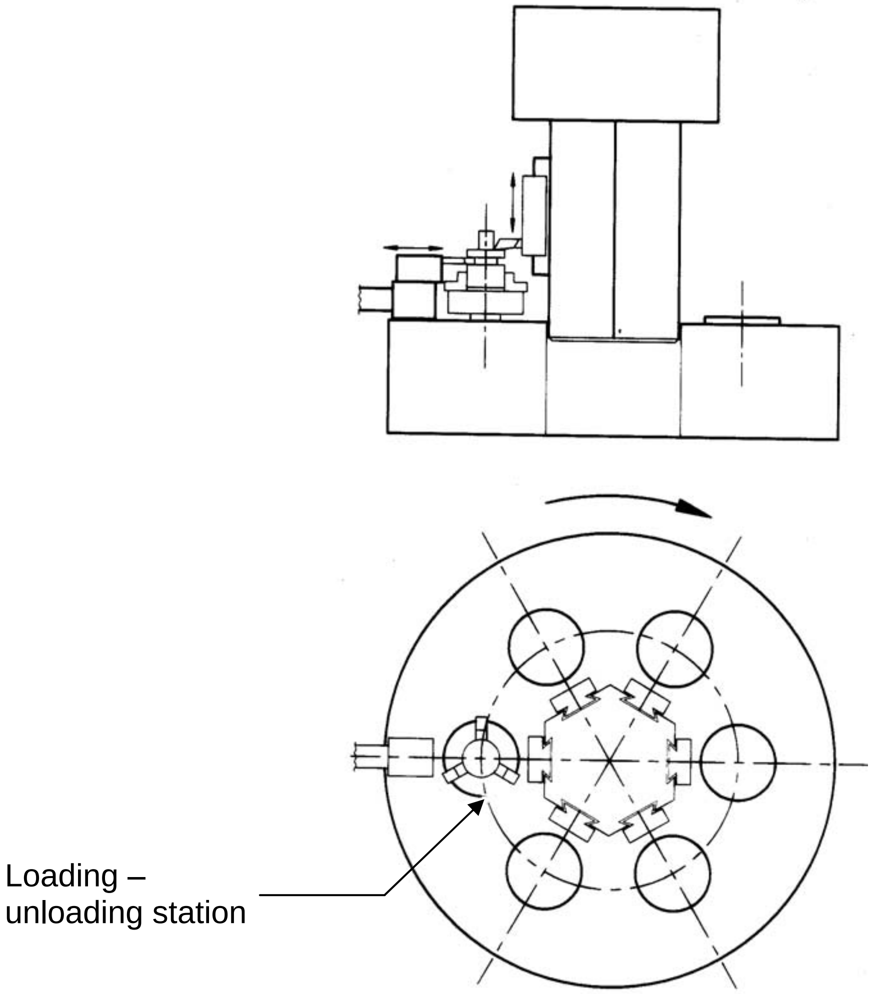


Fig. 4.7.5 *Basic configuration of multispindle automatic vertical lathe*

∗ **Progressively processing type :**

The spindle carrier with the blanks fitted in the chucks on the rotating spindle is indexed at regular interval by a Geneva mechanism. At each station the job undergoes a few preset machining work by the axially and / or radially fed cutting tools. The blank getting all the different machining operations progressively at the different work stations is unloaded at a particular station where the finished job is replaced by another fresh blank. This type of lathes are suitable for jobs requiring large number of operations.

∗ **Continuously working type :**

Like in parallel processing type, here also each job is finished in the respective station where it was loaded. The set of cutting tools, mostly fed only axially along a face of the ram continuously work on the same blank throughout its one cycle of rotation along with the spindle carrier. The tool ram having same tool sets on its faces also rotate simultaneously along with the spindle carrier which after each rotation halts for a while for unloading the finished job and loading a fresh blank at a particular location. Such system is also suitable for jobs requiring very few and simple machining operations.

- **Hydraulic copying (tracer controlled) lathes**

Jobs having steps, tapers and / or curved profiles, as typically shown in Fig. 4.7.6, are conveniently and economically produced in batch or lot in semiautomatically operated tracer controlled hydraulic copying lathe. The movement of the stylus along the template provided with the same desired job-profile) is hydraulically transmitted to the cutting tool tip which replicates the template profile.

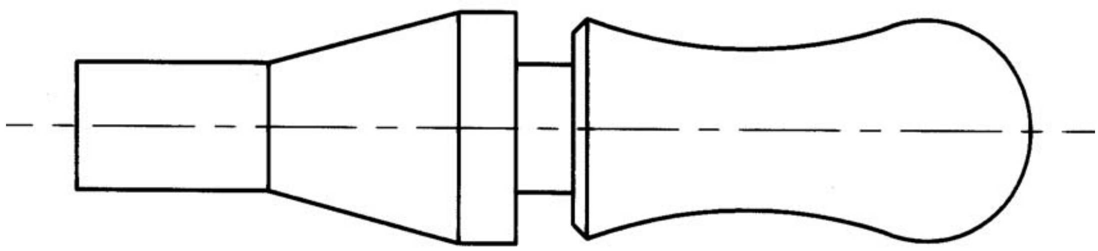


Fig. 4.7.6 A typical job suitable for copy turning.

(b) General Purpose Automatic lathes

Automatic lathes are essentially used for large lot or mass production of small rod type of jobs. Automatic lathes are also classified into some distinguished categories based on constructional features, operational characteristics, number of spindles and applications as follows

- Single spindle
    - Δ Automatic cutting off lathes
    - Δ Automatic (screw cutting) lathe
    - Δ Swiss type automatic lathe
- Multispindle automatic lathe

Automatic cutting off lathe

These simple but automatic lathes are used for producing short work pieces of simple form by using few cross feeding tools. In addition to parting some simple operations like short turning, facing, chamfering etc. are also done.

Single spindle automatic lathe

The general purpose single spindle automatic lathes are widely used for quantity or mass production (by machining) of high quality fasteners; bolts, screws, studs etc., bushings, pins, shafts, rollers, handles and similar small metallic parts from long bars or tubes of regular section and also often from separate small blanks.
Fig. 4.7.7 shows a typical single spindle automatic lathe.
Unlike the semiautomatic lathes, single spindle automats are :

- preferably and essentially used for larger volume of production i.e., large lot production and mass production
- used always for producing jobs of rod, tubular or ring type and of relatively smaller size.
- run fully automatically, including bar feeding and tool indexing, and continuously over a long duration repeating the same machining cycle for each product
- provided with upto five radial tool slides which are moved by cams mounted on a cam shaft
- of relatively smaller size and power but have higher spindle speeds

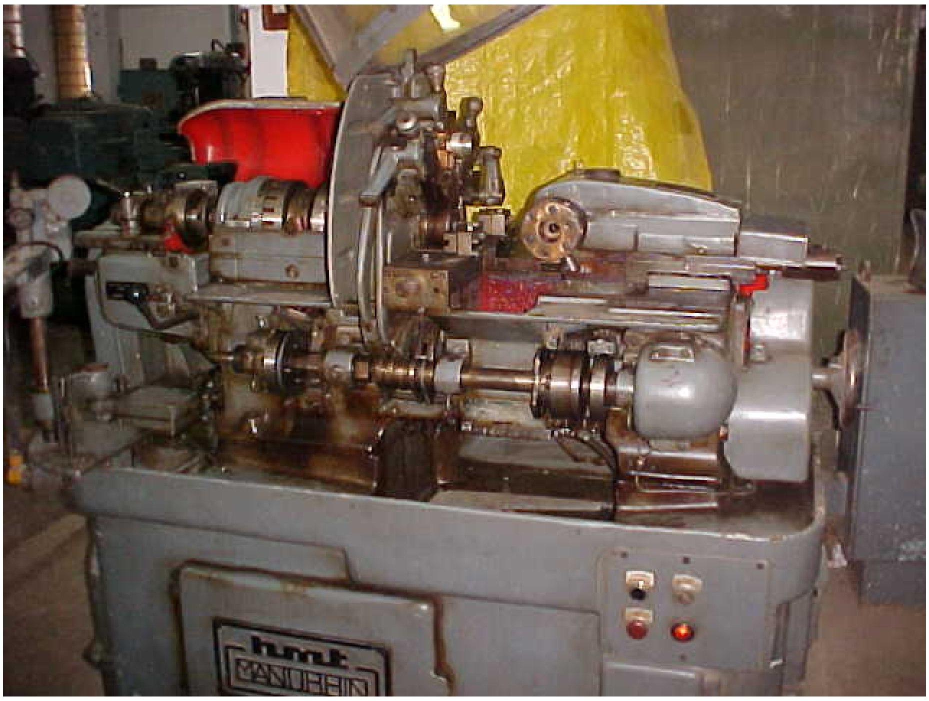


Fig. 4.7.7 *A typical single spindle automatic lathe.*

Swiss type automatic lathe

The characteristics and applications of these single spindle automatic lathes are :

- In respect of application :
  Used for lot or mass production of thin slender rod or tubular jobs, like components of small clocks and wrist watches, by precision machining;
  - Job size (approximately)
    - Diameter range – 2 to 12 mm
    - Length range – 3 to 30 mm

  Dimensional accuracy and surface finish – almost as good as provided by grinding
- In respect of configuration and operation
  - The headstock travels enabling axial feed of the bar stock against the cutting tools as indicated in Fig. 4.7.8
  - There is no tailstock or turret
  - High spindle speed (2000 – 10,000 rpm) for small job diameter
  - The cutting tools (upto five in number including two on the rocker arm) are fed radially
  - Drilling and threading tools, if required, are moved axially using swivelling device(s)
  - The cylindrical blanks are prefinished by grinding and are moved through a carbide guide bush as shown.

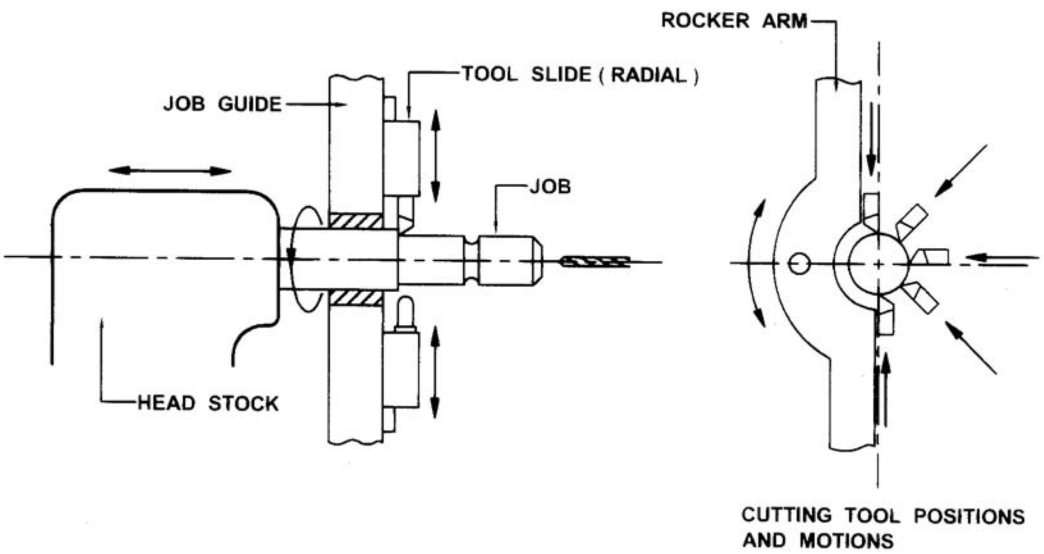


Fig. 4.7.8 *Basic principle of Swiss type automatic lathe.*

Multispindle automatic lathes

For further increase in rate of production of jobs usually of smaller size and simpler geometry. Multispindle automatic lathes having four to eight parallel spindles are preferably used. Unlike multispindle turret lathes, multispindle automatic lathes ;

- are horizontal (for working on long bar stocks)
- work mostly on long bar type or tubular blanks

Multiple spindle automats also may be parallel action or progressively working type. Machining of the inner and outer races in mass production of ball bearings are, for instance, machined in multispindle automatic lathes.

(ii) Kinematic Systems And Working Principles Of Semi Automatic And Automatic Lathes

The kinematic systems and basic principles of working of the following general purpose semi-automatic and automatic lathes of common use have been visualised and briefly discussed here :

(a) Semi-automatic lathes :
- Capstan and single spindle turret lathe
- Hydraulic copying lathe

(b) Automatic lathes
- Single spindle automatic (screw cutting) lathe
- Swiss type automatic lathe

Kinematic system and working principle of capstan lathe

Like general configurations and applications, the basic kinematic systems are also very similar in capstan lathes and turret lathes (particularly single spindle bar and horizontal types) in respect of their major functions, i.e.,

- bar feeding mechanism
- turret moving and indexing
- speed and feed drives

Bar feeding mechanism of capstan lathe

Fig. 4.7.9 typically shows the kinematic arrangement of feeding and clamping of bar stock in capstan lathes.

The bar stock is held and tightly clamped in the push type spring collet which is pushed by a push tube with the help of a pair of bell-crank levers actuated by a taper ring as shown in Fig. 4.7.9. Bar feeding is accomplished by four elementary operations;

- unclamping of the job – by opening the collet
- bar feed by pushing it forward
- clamping of the bar by closing the collet
- free return of the bar-pushing element

After a job is complete and part off, the collet is opened by moving the lever manually rightward to withdraw the push force on the collet. Further moving of the lever in the same direction causes forward push of the bar with the help of the ratchet – paul system shown. After the projection of the bar from the collet face to the desired length controlled by a pre-set stop – stock generally held in one face of the turret or in a separate swing stop, the lever is moved leftward resulting closing of the collet by clamping of the barstock. Just before clamping of the collet, the leftward movement of the lever pushes the bar feeder (ratchet) back freely against the paul.

Turret indexing mechanism in capstan and turret lathes
Turret indexing mechanism of capstan and single spindle turret lathe is typically shown schematically in Fig. 4.7.10.
The turret (generally hexagonal) holding the axially moving cutting tools have the following motions to be controlled mechanically and manually ;

- o forward axial traverse comprising;
    - ∆ quick approach – manually done by rotating the pinion as shown
    - ∆ slow working feed – automatically by engaging the clutch
    - ∆ stop at preset position depending upon the desired length of travel of the individual tools
- o quick return – manually done by disengaging the clutch and moving the turret back
- o indexing of the turret by 60^o (or multiple of it) – done manually by further moving the turret slide back.

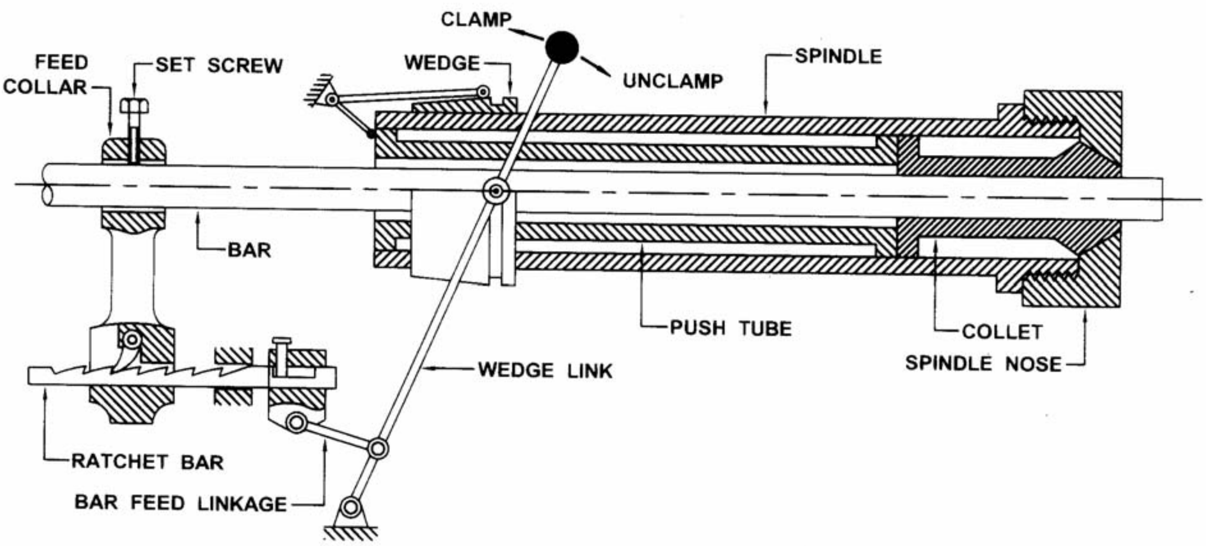
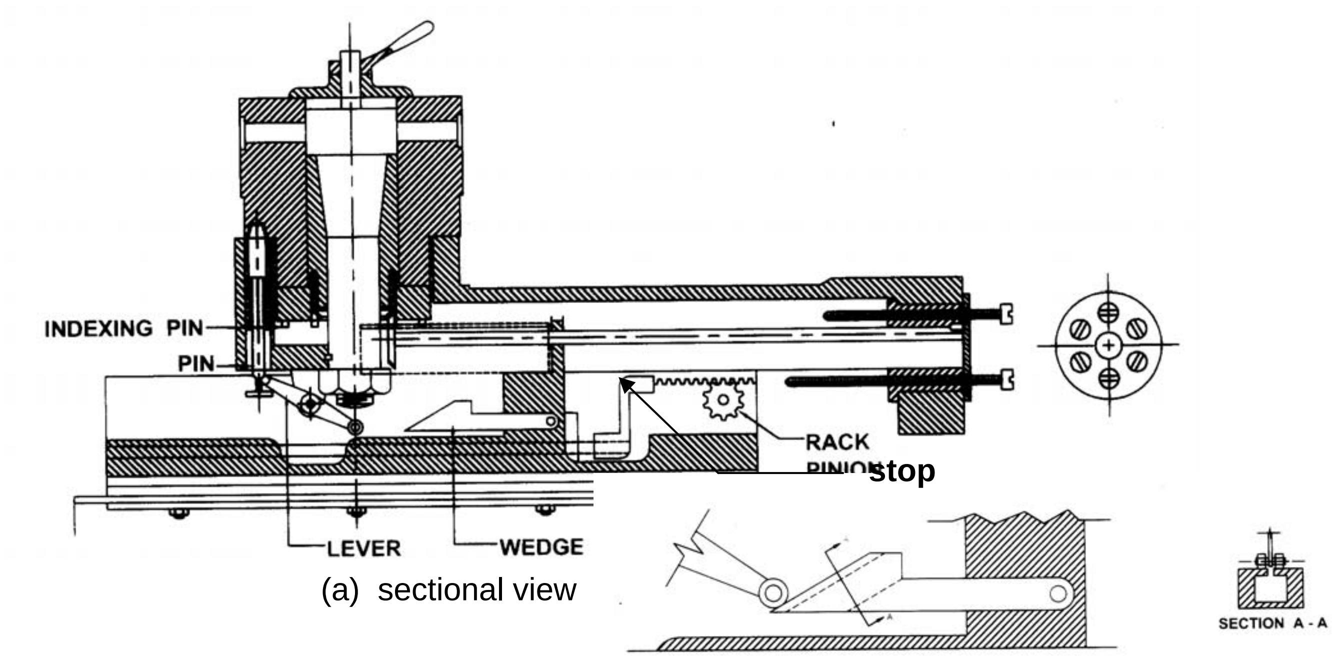
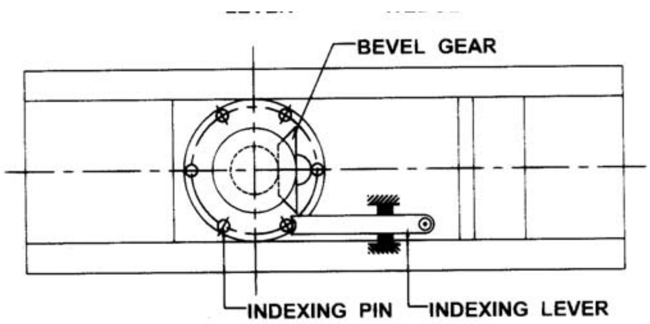


Fig. 4.7.9 *Typical bar feeding mechanism in capstan lathe.*

Just before indexing at the end of the return stroke, the locking pin is withdrawn by the lever which is lifted at its other end by gradually riding against the hinged wedge as indicated in Fig. 4.7.10 (a). Further backward travel of the turret slide causes rotation of the free head by the indexing pin and lever as indicated in Fig. 4.7.10 (b). Rotation of the turret head by exact angle is accomplished by insertion of the locking pin in the next hole of the six equispaced holes. After indexing and locking, the turret head is moved forward with the next cutting tool at its front face when the roller of the lever returns through the wider slot of the wedge without disturbing the locking pin as indicated in the figure. The forward motion of the turret head is automatically stopped when the set-screw corresponding to the working tool is arrested by the mechanical stop. The end position and hence length of travel of the tool is governed by presetting the screw. There are six such screws, each one corresponds with particular face or tool of the turret. The drum holding those equispaced six screw with different projection length is rotated along with the indexing (rotation) of the turret head by a pair of bevel gears (1:1) as indicated in Fig. 4.7.10 (a). The bottom most screw, which corresponds with the tool on the front face of the turret, when hits or touches the stop, the turret movement is stopped either manually by feeling or automatically by disengaging the clutch between the feed rod and the turret slide.



(a) sectional view



(b) top (inner) view

Fig.4.7.10 *Turret indexing in capstan and turret lathe.*

Kinematics and working principle of hydraulic copying lathe

Hydraulic drive is often preferably used in some machine tools for smooth motions without jerk and noise, self lubrication, flexible transmission system and stepless variation in speed and feed despite the limitations like larger space requirement, oil leakage, difficult maintenance etc.
Fig. 4.7.11 typically shows the circuitry of a hydraulically driven (tool travel) drilling machine. The direction and length of travel of the drilling head fitted on the moving piston are controlled by movement of the spool of the direction control valve which is actuated by the pilot valve and governed by the electromechanical stop as indicated in the figure. The rate of travel of the drill head i.e., the feed rate is governed by the throttle or metre controlling valve which is again controlled by a template like cam and a follower coupled with the spool of the throttle valve as shown in Fig. 4.7.11. To keep feed rate constant irrespective of the working force on the piston, a pressure reducing valve is provided prior to the throttle valve. The pressure reducing valve helps keep its exit pressure i.e., input pressure of the throttle valve fixed to a preset value irrespective of the input pressure of the pressure reducing valve which varies with the working load on the drill piston. Constant pressure difference keeps constant fluid flow rate through the throttle valve resulting constant feed rate irrespective of the cutting force.

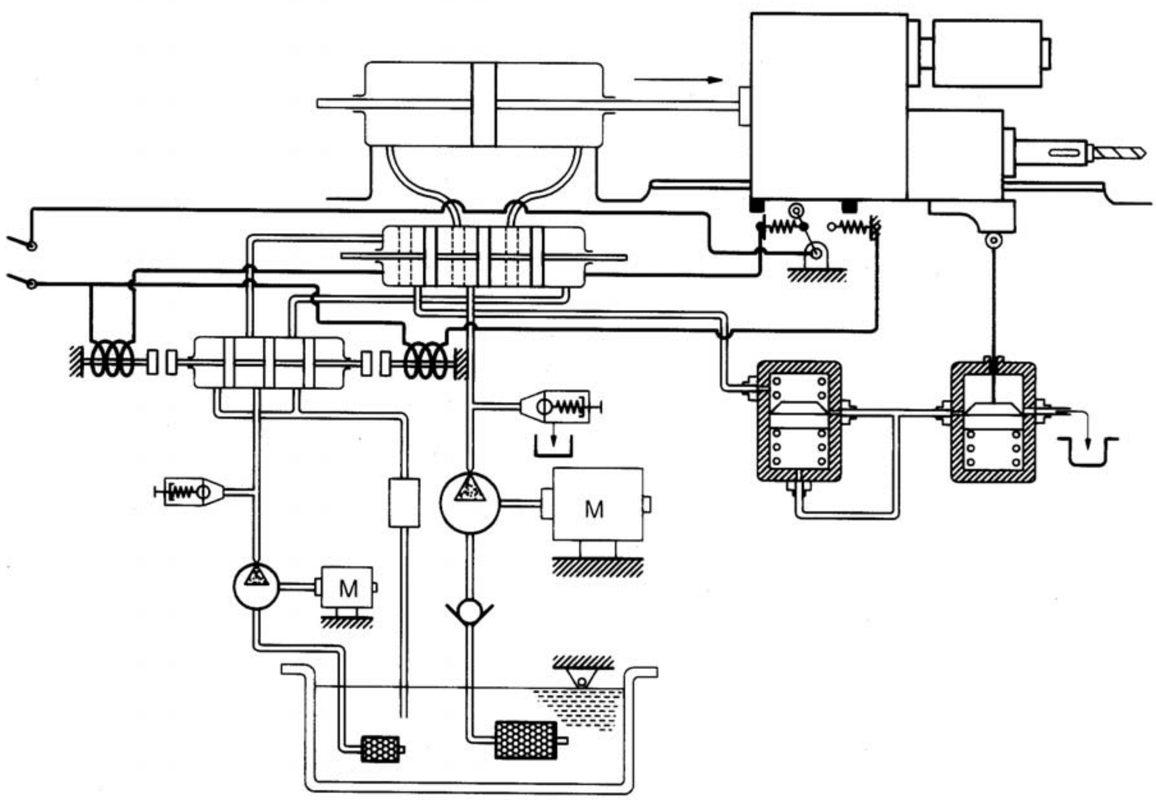


Fig. 4.7.11 *Circuitry and kinematic system of hydraulically driven machine tool*

Fig.4.7.12 schematically shows the principle of typical hydraulic copying lathe. The cross feed is controlled, under fixed longitudinal feed, hydraulically. When the stylus moves in the transverse direction slightly (by say ∆x) due to slope or profile in the fixed template, the ports open enabling the high pressure fluid enter in the lower chamber. Since the piston is fixed, the sliding cylinder holding the cutting tool will start moving down. When the tool also retracts by ∆x the ports get closed. This way the incremental or discrete motion of the stylus is replicated by the tool tip resulting true copying of the profile from the template to the job.

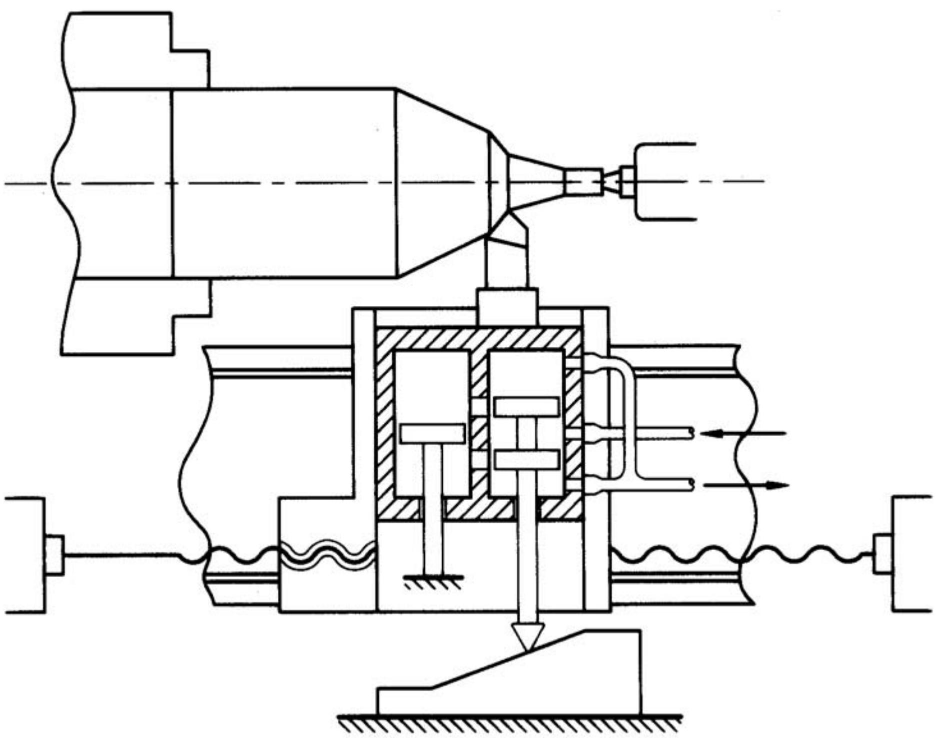


Fig.4.7.12 *Principle of hydraulic copy turning.*

- **Kinematic system and working principle of automatic lathes of common use.**

o **Single spindle automatic lathe**

This general purpose and widely used autmatic lathe is also known as single spindle automatic screw cutting lathe (ssASCL) because such lathes were introduced aiming mainly mass production of fasteners having screw threads.
Fig. 4.7.13 schematically shows the typical kinematic system of single spindle automat. The major characteristic functions that are automatically accomplished in sequence and proper synchrony in such lathes are :

- ∆ spindle speed change – magnitude and direction of rotation
- ∆ bar feeding
- ∆ transverse tools – feeding
- ∆ turret indexing and travelling

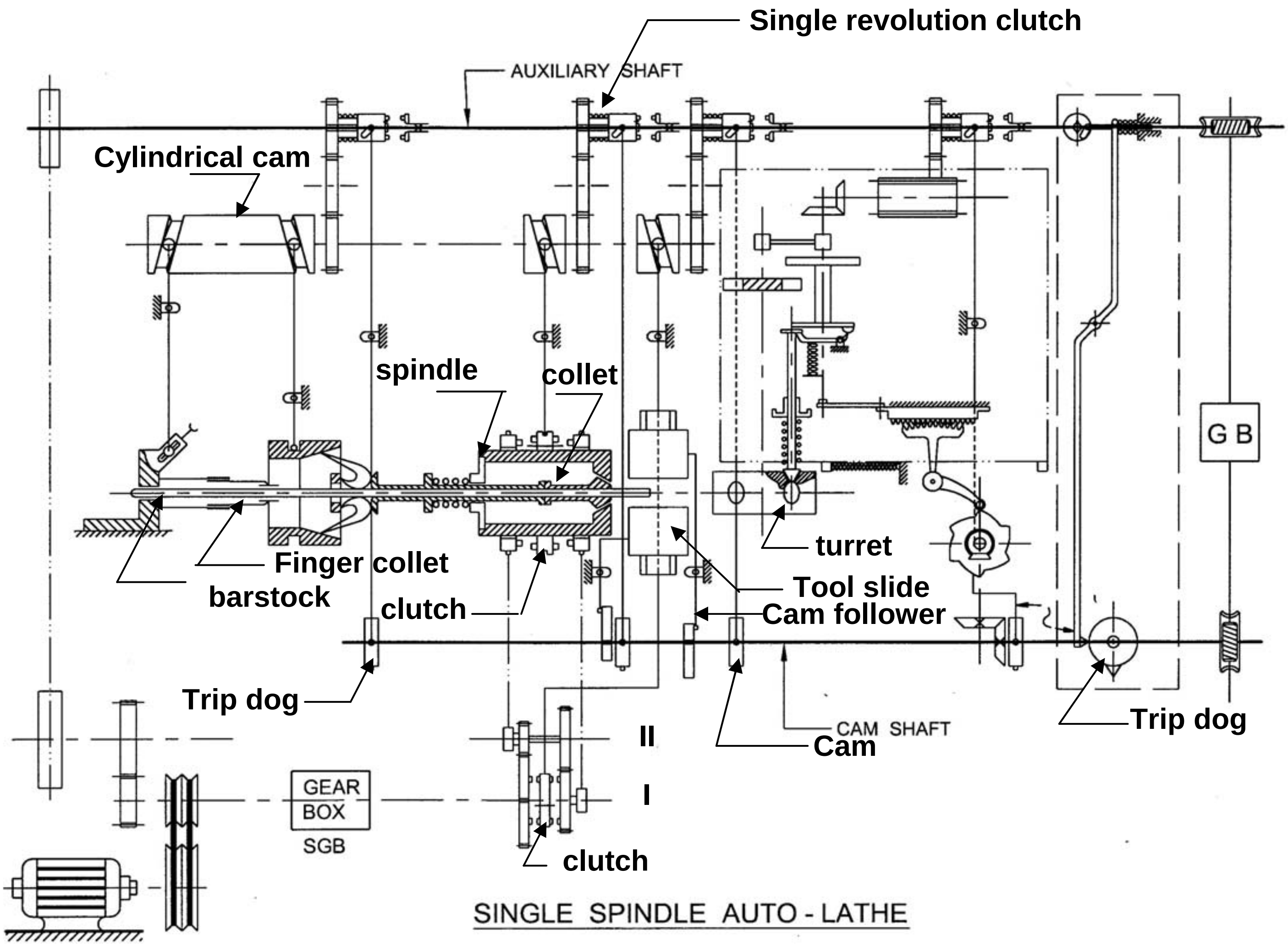


Fig. 4.7.13 *Typical kinematic system of single spindle automatic lathe.*

∆ **Change of spindle speed**

Repetitive production in large volume and limted ranges of job – tool materials and job – diameter necessitate a small number of spindle speeds in automatic lathes unlike centre lathes. However, at least two speeds, high and low (for threading etc.) and provision of reversal of those speeds need to be provided in automatic lathes. Power and speed are transmitted from the motor to shaft – I through belt-pulley and a speed gear box (SGB) if required as can be seen in Fig. 4.7.13. The two gear loosely mounted on shaft I are in mesh with two gears fixed on shaft II. Rotations are transmitted from shaft II to the spindle by two pairs of chain and sprockets as indicated in the kinematic diagram (Fig. 4.7.13). The two sprockets are loosely mounted on the spindle and simultaneously rotate at the same speed, low or high, but in opposite directions. The spindle is made to rotate at high or low speed and clockwise or anticlockwise by engaging the clutches on shaft I and the spindle respectively. The clutch is shifted by a lever and cylindrical cam which is rotated at the desired moment by one revolution only with the help of a single revolution clutch which is again triggered by a trip dog controlled by the camshaft as shown in the figure.

∆ **Bar feeding mechanism**

For feeding the barstock to a desired projection length after completing machining and parting a job, first the collet is opened by withdrawing the push force by moving the taper ring outward by a lever automatically with the help of the cylindrical cam. Then the cam at the other end of the cylinder pushes the rod forward using the lever, a slide and finger collet. Next half of the rotation of that cylindrical cam accomplishes clamping collet and return of the finger collet by moving the levers in opposite direction.

Here again, the cylindrical cam is rotated by only one revolution by actuating another single revolution clutch at the proper moment by a trip dog as indicated in the figure.

∆ **Transverse tool feeds**

The radially moving cutting tools (upto five) are fed sequentially at preset timings and desired length and rate of travel by individual cams mounted on the cam shaft which rotates slowly with one rotation for one machining cycle i.e., one product.

All the single revolution clutches are mounted on the auxiliary shaft which positively roates at a constant speed of 120 rpm. Rotation is transmitted from that to the cam shaft through speed reduction and a feed gear box (FGB) to vary the cam-shaft speed depending upon the cycle time for each job.

∆ **Feed motions of the axially fed cutting tools mounted on the turret**

The end points, length and rate of travel of the six tools on the turret are governed by a single plate cam having six lobes corresponding to the tools in the turret as shown in the figure. The rotational speed of that cam is kept same as that of the cam shaft.

∆ **Turret indexing mechanism**

The hexagonal turret is rotated (for indexing) by a Geneva mechanism where a Geneva disc having six radial slots is driven by a revolving pin. Before starting rotation, the locking pin is withdrawn by a cam lever mechanism shown in the diagram. The single rotation of the disc holding the indexing pin is derived from the auxiliary shaft with the help of another single revolution clutch as indicated

- **Kinematic system and operating principle of Swiss type automatic lathe**

The kinematic diagram of typical Swiss type automatic lathe is schematically shown in Fig. 4.7.14.

Both the high speed of the spindle and the low speed of the cam shaft are derived from the motor as indicated in the diagram. All the cutting tools mounted on the transverse slides are travelled to desired depth and at desired feed rate by a set of plate cams mounted on the cam shaft. The headstock with the spindle having the barstock clamped in it is moved forward and returned at desired feed rate by a set of plate cams mounted on the camshaft as shown.

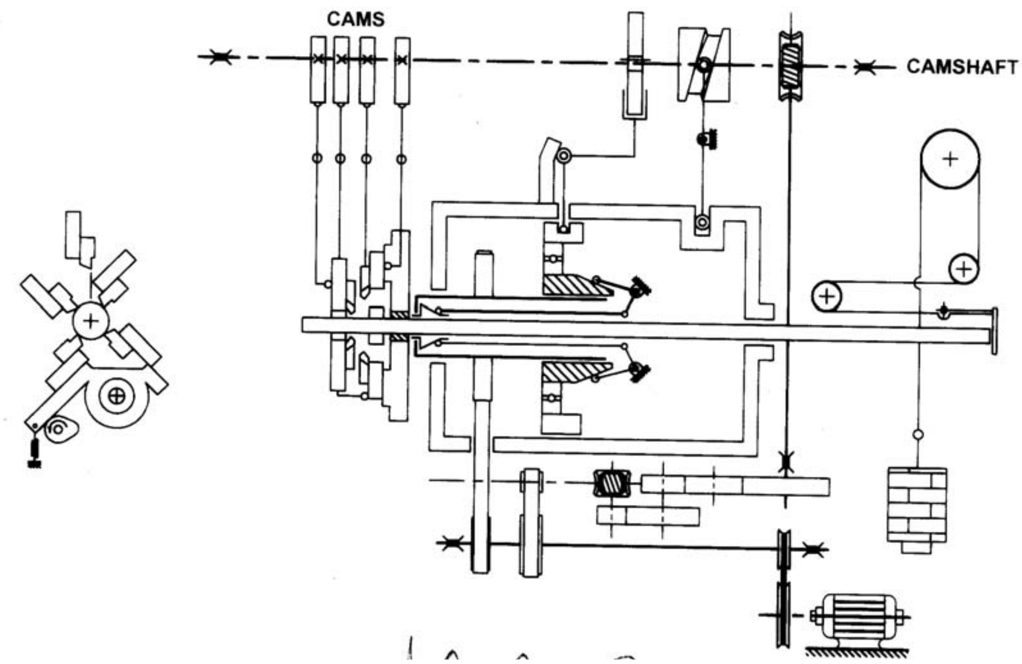


Fig. 4.7.14 *Kinematic system of Swiss type automatic lathe.*

Feeding of the bar, after completion and parting of a job is done sequentially by

- Opening the collet by shifting the taper ring by a cam as shown
- Pushing the bar, against the last working tool, by a gravitational force
- Collet clamping by return of the ring

(iii) Process Planning And Tool Layout For Machining A Product In Semi-Automatic And Automatic Lathes.

The procedural steps to be followed in sequence for batch or lot production of a job by machining in semi-automatic and automatic general purpose machine tools are :

(a) Thorough study of the job to be produced: in respect of :

- volume of production, i.e., number of pieces of the specific job to be produced
- material and its properties
- size and shape
- surfaces to be machined
- required dimensions with tolerances and surface finish
- end use of the product

(b) Selection of machine tool (after studying the job): in respect of ;
  - type
  - size
  - precision
  - kind and degree of automation

(c) Selection of blank (based on job and machine selected): in respect of;
  - bar chucking or housing type
  - preformed by; casting, forging, rolling etc.
  - if bar type; cross section (circular, tubular, square, hexagon etc.)
  - nominal size based on largest dimensions and availability
  - preformed by hot working or cold working

(d) Identification and listing of the elementary machining operations required, depending upon the product configuration

(e) Combine elementary machining operations as much as possible for saving time

(f) Sequence the operations (after combining)

(g) Select cutting tools: in respect of;
  - type
  - material
  - size
  - geometry
  - availability

  depending upon the machining operations (after combining) and work material

(h) work scheduling or preparation of the instruction sheet or operation chart giving column-wise :
  - description of the machining work to be done in sequence
  - cutting tools : type and location
  - speed and feed for each operation
  - length of travel of the tools
  - cutting fluid application;
    - o yes or not required
    - o type of cutting fluid

(i) Tool layout : schematically showing the type and configuration of the cutting tools and their location and mounting.

A typical tool layout for a particular job being machined in a single spindle automatic lathe is schematically shown in Fig. 4.7.15.

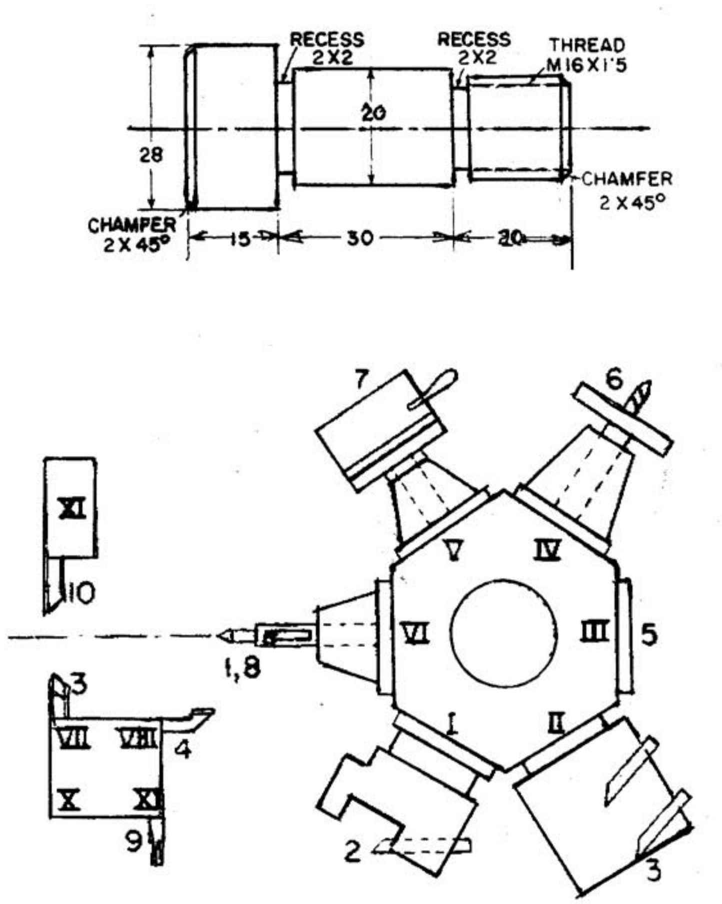


Fig. 4.7.15 *Tool layout for a typical job in single automatic lathe.*

(Iv) Case Study : As An Example

- **Task (say)** : 2500 pieces of hollow hexagonal headed mild steel bolts, as shown in Fig. 4.7.16, are to be produced by machining.

o **Machine tool selected** :
Single spindle automatic lathe for
  - Lot production (for smaller volume of production capstan lathe is better)
  - Circular bar type job
  - Common machinable material
  - Simple machining operations required

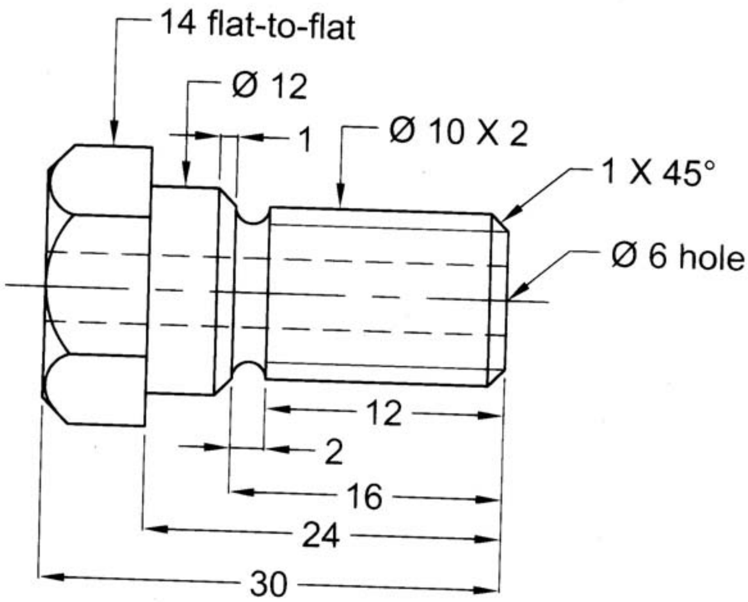


Fig. 4.7.16 *Shape and dimension of the specific job*

- **Blank selected** :
  Hot rolled hexagonal section mild steel bars for;
  - saving machining of the hexagonal head portion
  - the hexagonal head is of standard size which is available
  - job size – reasonable for single spindle automatic
  - not being precision job

- **Elementary machining operations** – identified and listed :
  - Facing
  - Centering
  - Chamfering (1) – front
  - Chamfering (2) – middle portion
  - Chamfering (3) – bolt head
  - Rough turning (1) – to make circular from hexagon
  - Rough turning (2) – to reduce diameter to 12 mm
  - Finish turning – to ϕ10
  - Drilling
  - Grooving (forming)
  - Thread cutting
  - Initial parting
  - Parting

o **Combining elementary operations**

  Δ combining operations to be done by a compound tool in a single travel from one tool position
  Δ paralleling or overlapping operations to be done by different tools moving in different directions.

The listed elementary operations can be combined and sequenced as follows :

1 Rough turning (1), initial parting and rear chamfering (3)
2 Rough turning (to ϕ12) and drilling and centering (for the next job)
3 Finish turning (ϕ10)
4 Spot facing and front chamfering (1)
5 Grooving and central chamfering (2)
6 Thread cutting
7 Parting

- **Scheduling – operation chart indicating tools and tool positions and machining conditions.**

N = spindle speed (rpm), s = feed (mm/rev), L = tool travel, CF = cutting fluid
HT (1) = hexagonal turret face 1, RS = Rear slide, FS = front slide, VS = vertical slide

Table – 1 : Scheduling; operation chart

Sl. No.	Operation	Tool	Tool position	N	S	L	CF
1	Stop stock & bar feed	Stop	HT (1)	-	-	-	N
2	Rough turning (1) Initial parting Chamfering (3) →	Turning tool Formed Parting tool	HT(2) RS	640	0.10 0.05	30 6	Y Y
3	Rough parting (2) Drilling (ϕ6) centering →	Turning tool Drill	HT(3)	640	0.10	50	Y
4	Finish turning	Turning tool	HT(4)	640	0.05	25	Y
5	Spot facing Chamfering (1) →	Compound tool	HT(5)	640	0.05	5	Y
6	Grooving Chamfering (2) →	Form tool	FS	640	0.05	10	Y
7	Threading	Solid die	HT(6)	56	2	20	Y
8	Parting	Parting tool	VS	640	0.05	12	Y

- **Tool layout –**
  The possible tool layout made based on the scheduling made for the product is schematically shown in Fig. 4.7.17.

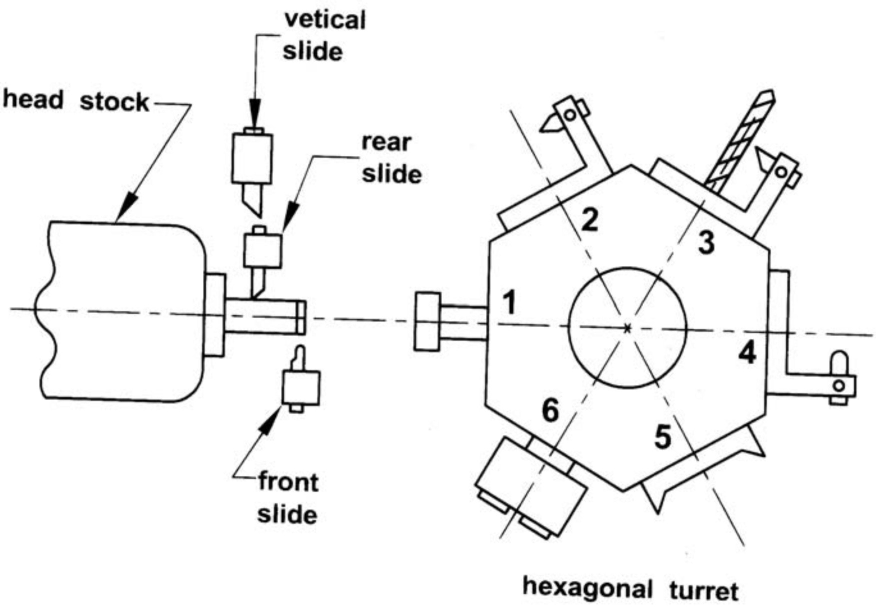


Fig. 4.7.17 *Tool layout for machining the given job in single spindle automatic lathe*

Module
4
General Purpose Machine Tools

Lesson
24
Forces developing and acting in machine tools

Instructional objectives

At the end of this lesson, the students will be able to;

(i) Identify the sources and pattern of the forces that develop in machine tools during machining.
(ii) State the effects of the forces in machine tools and its operations.
(iii) Comprehend the purposes of analysis of forces acting in machine tools
(iv) Visualise and evaluate the forces originated and distributed in machine tools.

(i) Sources And The Types Of The Forces That Develop In Machine Tools During Machining.

- **Cutting forces originating at the cutting point(s)**
  - In continuous type machining;
    - — Main cutting force, P_Z along the velocity vector, V_C
    - — Feed or thrust force, P_X along the feed direction
    - — Transverse force, P_Y normal to $P_Z – P_X$ plane
      in turning, boring and similar single point cutting process
    - — Torque and thrust force
      in drilling, counterboring, counter sinking etc.
  - In impact initiated type;
    - — Shaping, planing, slotting, gear shaping etc.
  - In intermittent type;
    - — Fluctuating forces due to intermittent cutting in milling, hobbing etc.

- **Gravitational forces**
  - Dead weight of the major and heavy components of the Machine – Fixture – Tool – Work (M – F – T – W) system, e.g., workpiece, headstock, tailstock, saddle, bed and moving tables etc.

- **Frictional forces**
    - Due to rubbing at the sliding surfaces.
- **Inertia forces**
    - Due to acceleration and deceleration at the end points of sliding and reciprocating motions of heavy parts like carriage or saddle, turret slide, tool slides, moving beds, reciprocating tables, rams, jobs etc.
- **Centrifugal forces**
    - Due to high speed rotation of eccentric masses
    - Due to wide run out or eccentric rotation of jobs, machine tool parts, spindle, shafts, tools etc.

(ii) Effects Of The Various Forces On Machining And Machine Tools

- Energy or power consumption
- Increased cutting zone temperature and its detrimental effects
- Dynamic forces resulting vibration and chatter cause poor surface quality and reduction of life of cutting tools as well as damage of the machine tools
- Elastic deflection and thermo-elastic deformation of several bodies leading to dimensional inaccuracy
- Rapid wear and tear at the sliding surfaces
- Noise and inconvenience
- Chances of premature mechanical failure of cutting tools and other components due to excessive stresses, thermal fracture, wear, fatigue, resonance etc.

(iii) Purposes Of Analysis And Evaluation Of The Forces Acting In Machine Tools.

It is essentially needed to know or determine the magnitude, location and direction of action and also the nature of the forces that develop and act during machining to enable :

- Estimate the cutting power and total power requirement for selection of type and capacity of the main power sources (motors)
- Design of the machine tool and cutting tool systems and the tool – workholding devices
- Design of the machine tool foundations
- Evaluate process capability of the machine tools

- Assess the machinability characteristics of various tool – work combinations under different operating conditions of the machine tools
- Determination of the role of the different process, geometrical and environmental parameters on the magnitude and pattern of the forces, which will help their optimal selection for good performance of the M – F – T – W system and overall economy.
- Comprehend the need and way of improvement in design, construction, performance, safety and service life of the machine tools.

(iv)Analysis Of Forces Acting During Machining In :

(a) Centre lathes
(b) Drilling machines
(c) Shaping machines
(d) Planing machines
(e) Milling machines

It has already been mentioned that forces of varying magnitude, location and direction develop in a machine tool mainly due to the machining action. Besides that forces also develop in various parts and locations due to dead weights, inertia, friction, impacts and eccentricity of rotating masses.

Here the forces that develop in different parts of the machine tool due to the cutting forces only have been discussed.

(a) Forces develop and act in centre lathes

Centre lathes are used for various machining work but mostly for straight turning.
Fig. 4.8.1 shows the location and direction of action of the different forces that develop in the headstock and tailstock being originated by the machining forces (components) :

- Tangential component, P_Z – main force
- Axial component, P_X – feed force
- Transverse component, P_Y – thrust force

- **Forces acting on the Headstock side :** [see Fig. 4.8.1]
    - **On the headstock (HT) centre** : -

$$P_{ZH} = P_Z\left(\frac{x}{L_w}\right) - \frac{W}{2}$$
$$P_{YH} = P_Y\left(\frac{x}{L_w}\right) + P_X\left(\frac{D_w}{2L_w}\right) \qquad (4.8.1)$$
$$P_{XH} = P_X + K$$

where, W = weight of the workpiece (rod)
L_W = length of the workpiece

D_w= maximum diameter of the workpiece
K = axial tightening force
X = distance of the cutting tool from the tailstock centre

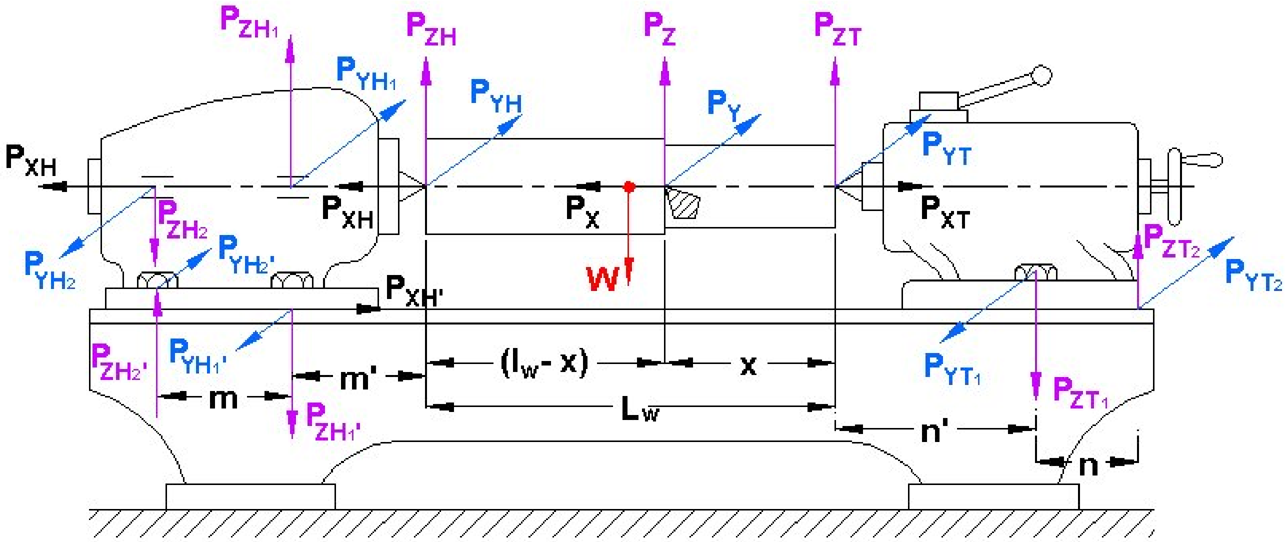


Fig. 4.8.1 *Forces acting on the lathe*

- **At the bearing housings**

$$P_{ZH_1} = P_{ZH}\left(\frac{m+m'}{m}\right)$$
$$P_{ZH_2} = P_{ZH}\left(\frac{m'}{m}\right) \quad (4.8.2)$$
$$P_{YH_1} = P_{YH}\left(\frac{m+m'}{m}\right)$$
$$P_{YH_2} = P_{YH}\left(\frac{m'}{m}\right)$$

- **At the supports (bolting)**

$$P_{ZH_1'} = -P_{ZH_1}$$
$$P_{ZH_2'} = -P_{ZH_2} \quad (4.8.3)$$
$$P_{YH_1'} = -P_{YH_1}$$
$$P_{YH_2'} = -P_{YH_2}$$

- **Forces acting on the Tailstock side**

  - **On the Tailstock centre**

$$
\begin{aligned}
P_{ZT} &= P_Z\left(\frac{L_W - x}{L_W}\right) - \left(\frac{W}{2}\right)\\
P_{YT} &= P_Y\left(\frac{L_W - x}{L_W}\right) - P_X\left(\frac{D_w}{2L_w}\right)\\
P_{XT} &= K - P_X
\end{aligned}
\qquad (4.8.4)
$$

  - **At the bolting and rear bottom end (heel)**

$$
\begin{aligned}
P_{ZT_1} &= P_{ZT}\left(\frac{n+n'}{n}\right) + P_{XT}\left(\frac{H}{n}\right)\\
P_{ZT_2} &= P_{ZT}\left(\frac{n'}{n}\right) + P_{XT}\left(\frac{H}{n}\right)\\
P_{YT_1} &= P_{YT}\left(\frac{n+n'}{n}\right)\\
P_{YT_2} &= P_{YT}\left(\frac{n'}{n}\right)
\end{aligned}
\qquad (4.8.5)
$$

- **Forces acting on lathe bed**

The lathe bed receives forces through;

- The headstock and tailstock
- The saddle on which the cutting tool is mounted

  - **Forces through headstock and tailstock**

The headstock is kept fixed by two pairs of bolts or studs on the lathe bed and the tailstock is clamped on the bed by one bolt. The forces acting on the bed through the front and the rear pair of bolts are :

$$
\begin{aligned}
P_{V_1} &= P_{ZH_1}\\
P_{V_2} &= P_{ZH_2}\\
P_{H_1} &= P_{YH_1}\\
P_{H_2} &= P_{YH_2}
\end{aligned}
\qquad (4.8.6)
$$

where, PV_1 and PV_2 are vertical forces and PH_1 and PH_2 are horizontal.

Similarly the forces acting on the lathe bed through the tailstock are :

$$P'_{V_1} = -P_{ZT_1}$$
$$P'_{V_2} = -P_{ZT_2} \qquad (4.8.7)$$
$$P'_{H_1} = -P_{YT_1}$$
$$P'_{H_2} = -P_{YT_2}$$

- **Forces acting on the lathe bed through the saddle.**

The cutting tool receives all the forces P_Z, P_X and P_Y but in opposite direction as reaction forces. And those forces are transmitted on the lathe bed through the saddle as indicated in Fig. 4.8.2.
The saddle rests on and travels along the lathe bed. All the forces acting on the bed through the saddle are assumed to be concentrated at four salient locations, A, B, C and D within the saddle – bed overlapped area as shown. Then from the force diagram in Fig. 4.8.2 the vertical forces (V) and horizontal forces (H) can be roughly determined;

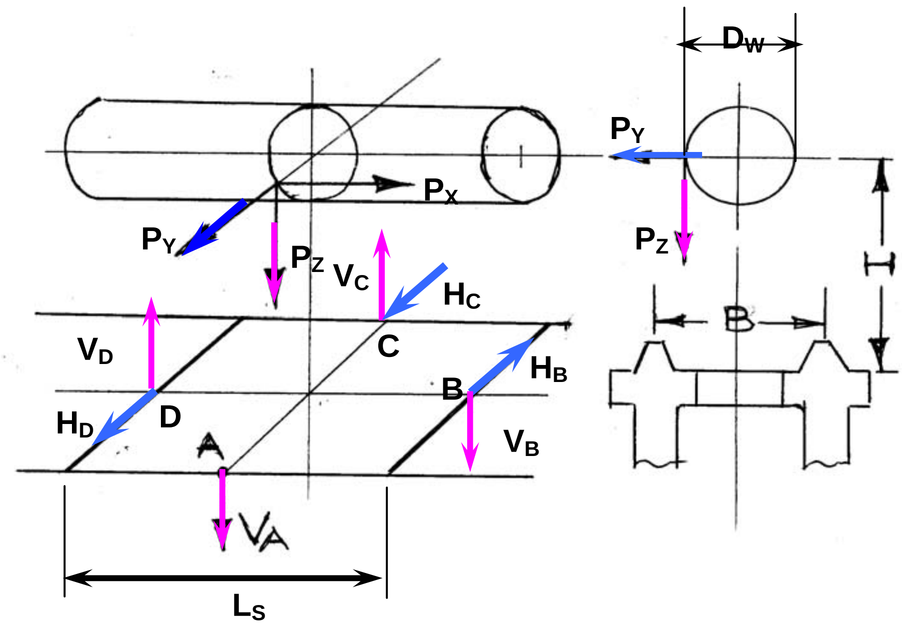


Fig. 4.8.2 *Forces acting on the lathe bed through the saddle due to cutting forces.*

$$V_A = P_Z\left(\frac{B+D_W}{2B}\right) + P_Y\left(\frac{H}{B}\right)$$
$$V_C = P_Z\left(\frac{B-D_W}{2B}\right) - P_Y\left(\frac{H}{B}\right) \qquad (4.8.8)$$
$$V_B = V_D = P_X\left(\frac{H}{L_S}\right)$$

$$H_B = H_D = P_X \left(\frac{D_W}{2L_S} \right)$$

where, B, L_s = width and length of the saddle
H = centre height

(b) Forces acting in Drilling machines

The main source and location of the originating forces in drilling machine are the cutting forces, i.e., torque, T and the thrust or axial force, P_X as shown in Fig. 4.8.3

The other sources of forces that develop and act in drilling machine are :

- Dead weight of the heavy unit;
  - Δ Drilling head
  - Δ Radial arm (if it is a radial drilling machine)
  - Δ Column
  - Δ Bed or table
  - Δ Workpiece, if it is large and heavy
- Balancing weight, if provided
- Sliding friction
- Inertia forces due to moving parts

Both the drill and the job are subjected to equal amount of torque, T and thrust P_X but in opposite direction as action and reaction as indicated in Fig. 4.8.3.

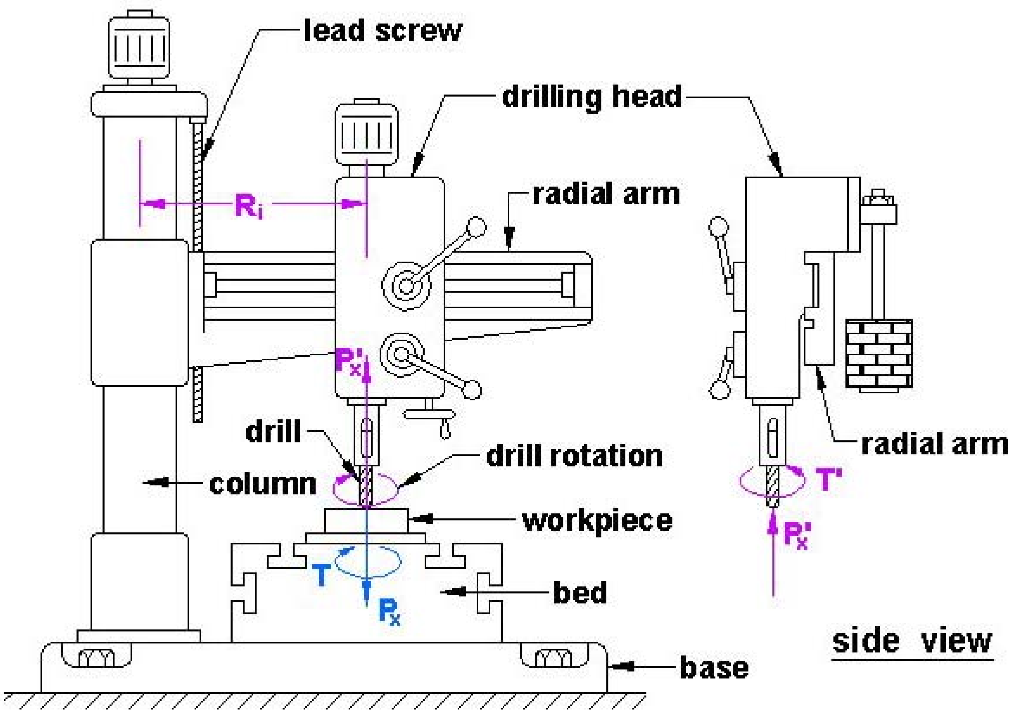


Fig. 4.8.8 *Forces acting in a drilling machine.*

Due to the torque and thrust, forces will develop and act on the several components of the drilling machine as follows :

- **Bed, base and foundation** –
  Both T and P_X will be transmitted to the base and the foundation from the job and through the bed, clamps and the foundation bolts
- **Spindle** –
  This salient component will be subjected to both the torque and thrust and is designed accordingly
- **The motor is selected** based on the maximum torque and spindle speed
- **Radial arm** –
  This cantelever beam is subjected to large bending moment, $P_X x R_i$ depending upon the magnitude of P_X and the distance R_i of the drilling head from the column axis. This arm will also be subjected to another twist in the other vertical plane due to P_X depending upon its distance from the mid-plane of the radial arm.
  Beside that the arm will bear the weight of the drilling head and its balancing weight, which will also induce bending moment.
- **Column –**
  This main structural part will have two axial forces, weight and P_X' acting vertically downward and upward respectively. The force P_X' will also induce a large bending moment, equal to P_X' x R_i in the column.

(c) Forces acting in shaping machine

The forces that develop at the cutting point and due to that act on the major components during machining in a shaping machine are schematically shown in Fig. 4.8.4.

- **The forces that develop at the cutting point** and
  — act on the job : P_Z, P_X and P_Y
  — act on the tool : P_Z', P_X' and P_Y' as reaction
  The magnitude of those force components depend upon the work material, tool geometry, feed and depth of cut and cutting fluid application
  Those cutting forces then are transmitted in the various parts as indicated;
  - The ram is subjected to R_{X1}, R_{X2}, R_{Y1} and R_{Y2} in addition P_X', P_Y' and P_Z' as shown and the friction forces.
  - The bed receives directly the forces P_X, P_Y and P_Z and is also subjected to the forces B_1 and B_2 as indicated.
  - The column of the shaping machine is subjected to the various forces coming from the cutting tool side and the bed side as shown.

The magnitude of those forces will depend upon the dimensions of the shaping machine, magnitude, location and direction of the cutting force components and other sources of forces. All those forces can therefore be easily evaluated.

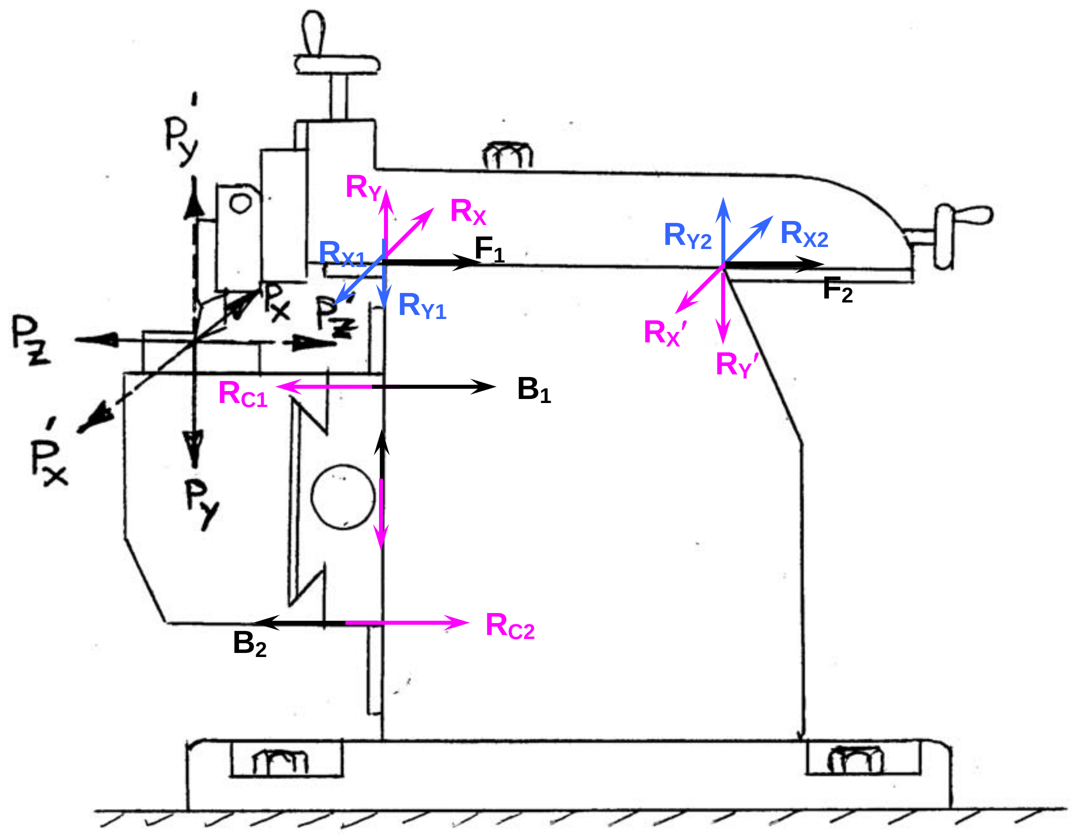


Fig. 4.8.4 *Forces that develop and act on major parts during shaping.*

(d) Forces that develop and act in planing machine

Since the basic principle of machining is same in shaping machine and planing machine, the characteristics of the forces; magnitude and directions are also same at the cutting pint. The forces that will act due to those machining forces on the major parts of planning machine will depend on the configuration and dimensions of the machine and its parts.

(e) Forces that develop and act in milling machine

Fig. 4.8.5 schematically shows the forces that originate at the cutting point and get transmitted to the major parts of the milling machine.

- The forces that develop at the cutting point are resolved into three orthogonal directions. Those forces, acting on the job as actions and on the cutting tool as reactions, have been indicated (in Fig. 4.8.5) by P_V, P_H, and P_A which are again transmitted to the different parts.

- Due to the cutting forces the different parts of the milling machine receive number of forces, such as;
  - The milling arbour holding the cutting tool is subjected to (in addition to P_V, P_H and P_A) P_{V1}, P_{H1} and P_{V2}, P_{H2} and also P_A (axially)
  - The overarm or ram is subjected to P_{V1}, P_{H1}, P_{V2}, P_{H2}, P_{V3} and P_{H3}. It also receives an axial force, P_A'.
  - The bed is subjected directly to the cutting forces, P_V, P_H and P_A, and also other forces, $(-P_{A1})$, $(-P_{H1})$, P_V etc. as shown in the figure.
  - Due to the cutting forces, the column is subjected to various forces (at its different locations) coming through the arbour and ram on the one hand and bed on the other side as indicted in Fig. 4.8.5.

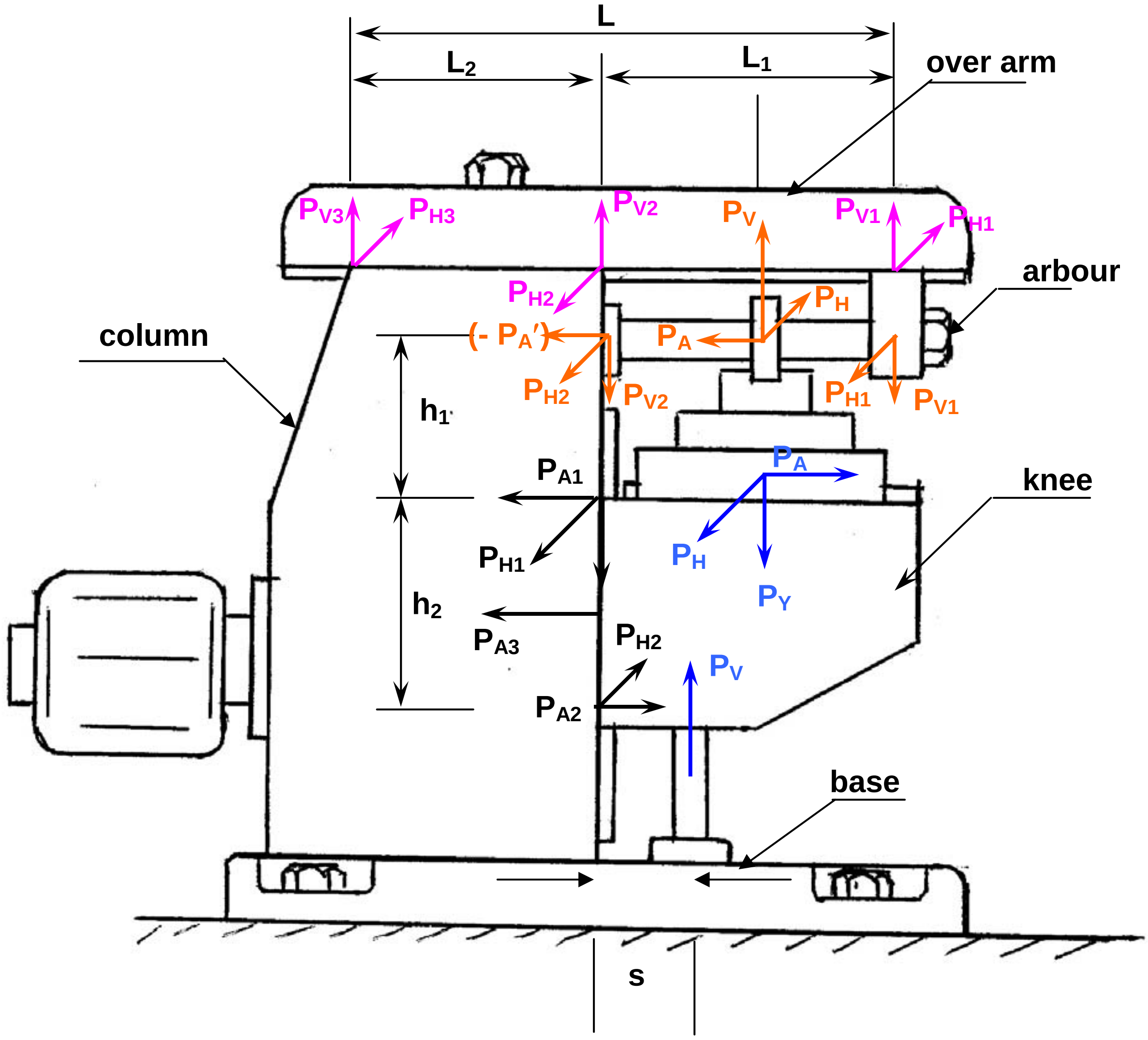


Fig. 4.8.5 *Development of forces in milling machine.*

Again, all those forces acting on the different components depend upon and can be evaluated from the values of the cutting forces, configuration and dimension of the machine and its major components.

Similarly, the forces acting on any machine tool can be determined for the different purposes.

Module
4
General Purpose Machine Tools

Lesson
25
Estimation of machining time

Instructional objectives

At the end of this lesson, the students will be able to

(i) Realize the necessity of evaluating the machining time requirement
(ii) Identify the factors that govern the machining time.
(iii) Estimate or evaluate the time required for specific;
  (a) turning operation
  (b) drilling and boring operations
  (c) shaping and planing operations
  (d) milling operation.

(i) Necessity Of Estimation Or Determination Of Machining Time Requirement For Particular Operations.

The major aim and objectives in machining industries generally are;

- reduction of total manufacturing time, T
- increase in MRR, i.e., productivity
- reduction in machining cost without sacrificing product quality
- increase in profit or profit rate, i.e., profitability.

All those objectives are commonly and substantially governed by the total machining time per piece, T_p, where again,

$$T_p = T_i + T_C + \frac{T_C}{T_L} TCT \qquad (4.9.1)$$

where, T_i = idle time per piece, min
T_C= actual cutting time per piece
TL= Tool life
TCT= average tool change time per piece.

T_i and TCT could have been spectacularly reduced by development and application of modern mechanisation or automation.

The tool life, TL has been substantially enhanced by remarkable developments in the cutting tool materials.

Therefore, the actual cutting or machining time T_C remains to be controlled as far as possible for achieving the objectives and meeting the growing demands.

Hence, it becomes extremely necessary to determine the actual machining time, T_C required to produce a job mainly for,

- assessment of productivity
- evaluation of machining cost
- measurement of labour cost component
- assessment of relative performance or capability of any machine tool, cutting tool, cutting fluid or any special or new techniques in terms of saving in machining time.

The machining time, T_C required for a particular operation can be determined

- roughly by calculation i.e., estimation
- precisely, if required, by measurement.

Measurement definitely gives more accurate result and in detail but is tedious and expensive. Whereas, estimation by simple calculations, though may not be that accurate, is simple, quick and inexpensive.
Hence, determination of machining time, specially by simple calculations using suitable equations is essentially done regularly for various purposes.

(ii) Major Factors That Govern Machining Time

The factors that govern machining time will be understood from a simple case of machining. A steel rod has to be reduced in diameter from D_1 to D_2 over a length L by straight turning in a centre lathe as indicated in Fig. 4.9.1.

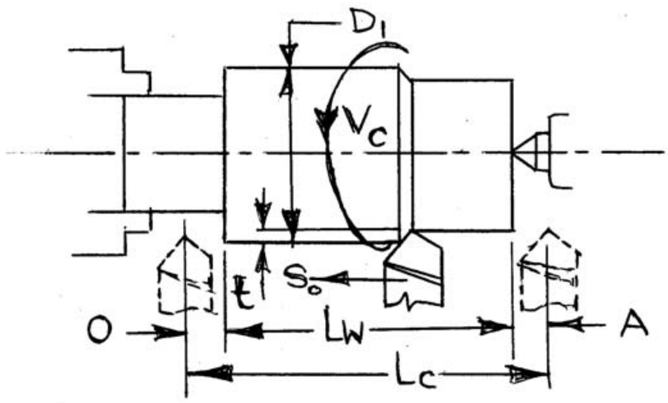


Fig. 4.9.1 *Estimation of machining time in turning.*

Here, $$T_C = \frac{L_C}{Ns_o} x n_p \qquad (4.9.2)$$

where, L_C = actual length of cut
= L + A + O
A, O = approach and over run as shown
N = spindle speed, rpm
s_o = feed (tool), mm/rev
n_p = number of passes required

Speed, N, is determined from cutting velocity, V_C

$$V_C = \frac{\pi DN}{1000} m/\min \qquad (4.9.3)$$

where, D = diameter of the job before cut

Therefore, $$N = \frac{1000V_C}{\pi D} \qquad (4.9.4)$$

The number of passes, n_p is mathematically determined from,

$$n_p = \frac{D_1 - D_2}{2t} \qquad (4.9.5)$$

where, t = depth of cut in one pass, mm.

But practically the value of t and hence n_p is decided by the machining allowance kept or left in the preformed blanks. Usually, for saving time and material, very less machining allowance is left, if not almost eliminated by near – net – shape principle.

Hence, number of passes used is generally one or maximum two : one for roughing and one for finishing.

However, combining equations 4.9.2, 4.9.4 and 4.9.5, one gets,

$$T_C = \frac{\pi D L_C (D_1 - D_2)}{2000 V_C s_o t} \quad (4.9.6)$$

or

$$T_C = \frac{\pi D L_C}{1000 V_C s_o} \text{ for single pass turning} \quad (4.9.7)$$

Equation 4.9.7 clearly indicates that in turning to a given diameter and length, the cutting time, T_C is governed mainly by the selection of the values of cutting velocity, V_C and feed, s_o. This is true more or less in all machining operations being done in different machine tools.

A number of factors are essentially considered while selecting or deciding the values of V_C and s_o for any machining work.

The major factors considered for selecting V_C are :

- **Nature of the cut;**
    - Continuous cut like turning, boring, drilling etc. are done at higher V_C
    - Shock initiated cuts in shaping machine, planing machine, slotting machine etc. are conducted at lower V_C
    - Intermittent cuts, as in milling, hobbing etc. are done at quite lower speed for dynamic loading
- **Work material** (type, strength, hardness, heat resistance, toughness, chemical reactivity etc.) For instance;
    - Harder, stronger, heat resistant and work hardenable materials are machined at lower V_C
    - Soft, non-sticky and thermally conductive materials can be machined at relatively higher cutting velocity
- **Cutting tool material** (type, strength, hardness, heat and wear resistance, toughness, chemical stability, thermal conductivity etc.); For instance;
    - HSS tools are used at within 40 m/min only in turning mild steel whereas for the same work cemented carbide tools can be used at V_C, 80 to 300 m/min
    - High performance ceramic tools and cBN tools are used at very high speed in machining steels of different strength and hardness.
    - Diamond tools can be used in machining various materials (excepting Fe-base) at V_C beyond 500 m/min
- **Cutting fluid application**; for instance,
    - Proper selection and application of cutting fluid may allow increase in V_C by 20 to 50%
- **Purpose of machining;** for instance,

- Rough machining with large MRR is usually done at relatively low or moderate velocity
    - Finish machining with small feed and depth of cut is usually done at high V_C
- **Kind of machining operation;**
    - Unlike turning, boring etc. the operation like threading, reaming etc. are carried out at much lower (20 to 50%) cutting velocity for achieving quality finish
- **Capacity of the machine tool**
    - powerful, strong, rigid and stable machine tools allow much higher V_C, if required and permissible
- **Condition of the machine tool**
    - Cutting velocity is kept lower than its normal value stipulated for a given tool – work material pair , if the machine tool is pretty old and / or having limitations due to wear and tear, backlash, misalignment, unstability etc.

The factors that are considered during selecting the value of feed, s_o are,

- Work material (type, strength, hardness etc.)
- Capacity of the machine tool (power, rigidity etc.)
- Cutting tool; material, geometry and configuration
- Cutting fluid application
- Surface finish desired
- Type of operation, for instance threading operation needs large feed according to the lead of the thread.
- Nature of cut; continuous, shock initiated type, and intermittent
  Feed, which raises cutting forces proportionally, is kept low in shock and intermittent type cuts

Apart from the total volume of material to be removed, permissible values of cutting velocity, feed and depth of cut and cutting fluid application, there are few more factors which also play role on machining time.
Those additional factors include :

- Quick return ratio in operations like shaping, planing, slotting, gear shaping etc.
- Jobs of odd size and shape and irregular and harder surfaces like large castings are essentially machined much slowly with lower cutting velocity
- Some special techniques like hot machining and cryomachining enables faster machining of some exotic materials and even some common metals like steels at higher V_C and s_o.

(iii) Estimation Of Machining Time By Calculations

(a) In case of turning in lathes

Fig. 4.9.1 and equations like Equation 4.9.7 enable determination of the amount of time required for straight turning in lathes following the given procedural steps :

- Determine the length of cut by proper selection of amount of approach, A (2 ~ 5 mm) and over run, O (1 to 3 mm), if required
- Select the approximate values of V_C and s_o based on the tool – work materials and other factors previously mentioned [depth of cut is decided based on the machining allowance available and the final diameter desired]
- Determine the spindle speed, N using equation 4.9.4 and then fix N as well as s_o from the chart giving the lists of N and s_o available in that lathe
- Finally determine T_C using equation 4.9.7.

$$T_C = \frac{\pi D\left(L_w + A + O\right)}{1000 V_C s_o}$$

Example

For, D = 100 mm, L_w = 200 mm, A = O = 5 mm, V_C = 120 m/min and s_o=0.2 mm/rev,

$$T_C = \frac{\pi x 100 x \left(200 + 5 + 5)\right)}{1000 x 120 x 0.2} \text{ min}$$

$$= 2.75 \text{ min}$$

The machining time for facing, grooving, taper turning, threading, parting etc. in lathes can also be determined or estimated following the same principle and method.

(b) In case of drilling and boring

The basic principle and procedure of estimation of machining time in drilling and boring are almost same as that of turning operations. Fig. 4.9.2 shows making through hole by drilling and boring.

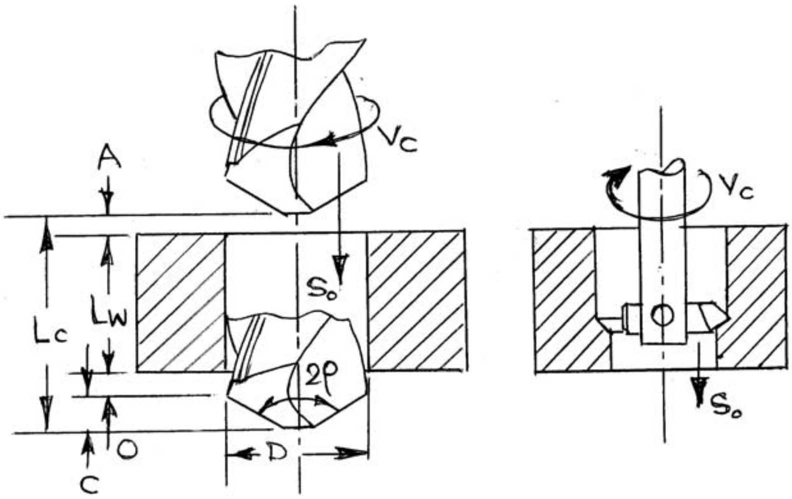


Fig. 4.9.2 *Drilling and boring operations.*

For drilling a through hole (Fig. 4.9.2),

The machining time, T_C is estimated from,

$$T_C = \frac{L_C'}{Ns_o} \quad (4.9.8)$$

where, $L_C' = L_h + A + O + C$

A, O = approach and over run

and $C = \frac{D}{2}\cot\rho$

D = diameter of the hole, i.e., drill

ρ = half of the drill point angle.

Speed, N and feed s_o are selected in the same way as it is done in case of turning.

Therefore, the drilling time can be determined from,

$$T_C = \frac{\pi D\left(L_h + A + O + C\right)}{1000 V_C s_o} \quad (4.9.9)$$

In the same way T_C is determined or estimated in boring also. Only the portion 'C' is not included.

For blind hole, only over run, 'O' is excluded.

Example

For $D = 25$ mm, $\rho = 60^o$, $V_C = 44$ m/min

$L = 60$ mm, $s_o = 0.25$ mm/rev

$A = O = 2$ mm

$T_C = \pi x25\{60 + 2 + 2 + (25/2)\cot 60^0\} / (1000x44x0.25)$

$= 0.5$ min.

(c) Machining time in shaping and planing

Machining time in shaping can be estimated using the scheme given in Fig. 4.9.3 which shows the length of tool – work travels required to remove a layer of material from the top flat surface of a block in a shaping machine.

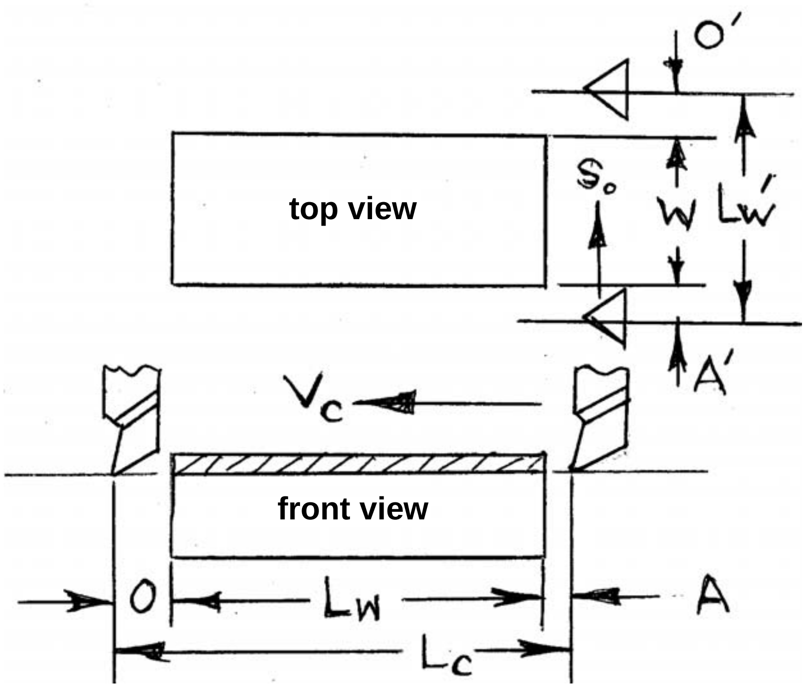


Fig. 4.9.3 *Surfacing in shaping machine.*

Using Fig. 4.9.3, the total machining time, T_C can be determined form the expression,

$$T_C = \frac{L_w}{N_s s_0} \text{ min} \tag{4.9.10}$$

where, L_w = total length of travel of the job
= W + A' + O'
w = width of the job
A', O' = approach and over run
N_s = number of strokes per min
s_o = feed of the job, mm/stroke

N_s has to be determined from,

$$V_C = \frac{N_s}{1000}\left[L_C\left(1+Q\right)\right] \text{ m/min} \tag{4.9.11}$$

where, V_C = cutting velocity, m/min
L_C = stroke length, mm
= L_w + A' + O'
L_w = length of the workpiece
A', O'= approach and over run
and Q = quick return ratio
= time of return stroke ÷ time of cutting stroke

Therefore, $N_s = (1000V_C)/\left[L_C(1+Q)\right]$ (4.9.12)

Practically the speed that is available nearest to this calculated value is to be taken taken up.

The values of V_C and s_o are to be selected or decided considering the relevant factors already mentioned in case of turning.

Example

For L_w = 100 mm, A = 5, O = 5, W = 60, A' = O' = 2
Q = 2/3 , V_C = 40 m/min and s_o = 0.2 mm/stroke
N_s= (1000x40)/[(100+5+5)(1+2/3)] = 200
Then, T_C = (60+2+2)/(0.2x200) = 1.6 min

Machining times of planing operations in planing machine are also determined in the same way, because the only difference is that in planing machine, cutting strokes and feed travels are imparted to the job and the tool respectively, just opposite to that of shaping machine. Besides that, though both shaping and planing are reciprocating type, planing machine may allow higher V_C.

(d) Machining time in Milling operations

There are different types of milling operations done by different types of milling cutters;

- Plain milling by slab milling cutter mounted on arbour
- End milling by solid but small end mill cutters being mounted in the spindle through collet
- Face milling by large face milling cutters being directly fitted in the spindle.

Fig. 4.9.4 shows the scheme of plain milling by a plain or slab milling cutter and indicates how the machining time is to be calculated.

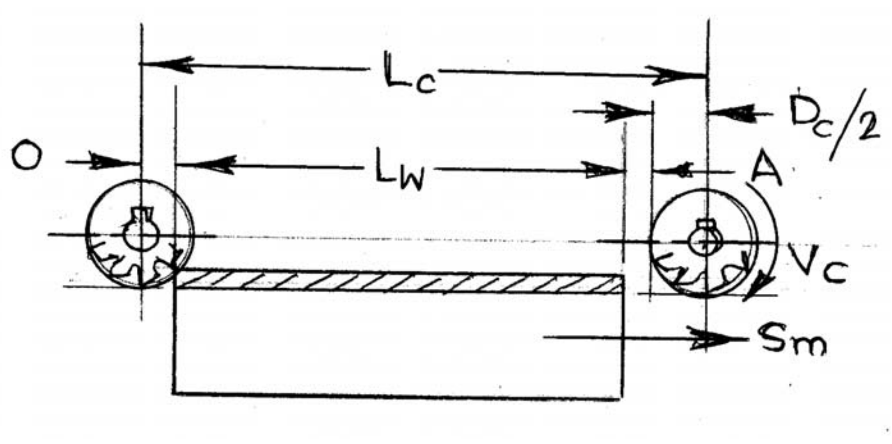


Fig. 4.9.4 *Plain milling operation.*

Following the Fig. 4.9.4, the machining time, T_C for plain milling a flat surface can be determined as,

$T_C = L_C / s_m$ (for job width < cutter length) (4.9.13)

Where, L_C = total length of travel of the job

$= L_w + A + O + D_c/2$

L_w = length of the workpiece

A, O = approach and over run (5 to 10 mm)

D_C= diameter of the cutter, mm

S_m= table feed, mm/min

$= s_o Z_C N$

where, s_o = feed per tooth, mm/tooth

Z_C= number of teeth of the cutter

N = cutter speed, rpm.

Again, N has to be determined from V_C as

$$V_C = \frac{\pi D_C N}{1000} \text{ m/min}$$

V_C and s_o have to be selected in the usual way considering the factors stated previously. Since milling is an intermittent cutting process, V_C should be taken lower (20 ~ 40%) of that recommended for continuous machining like turning. S_o should be taken reasonably low (within 0.10 to 0.5 mm) depending upon the tooth – size, work material and surface finish desired.

Example :

Determine T_C for plain milling a rectangular surface of length 100 mm and width 50 mm by a helical fluted plain HSS milling cutter of diameter 60 mm, length 75 mm and 6 teeth. Assume A = O = 5 mm, V_C = 40 m/min and s_o = 0.1 mm/tooth

Solution:

$$T_C = \frac{L_C}{s_m} \min$$

$$L_C = L_w + A + O + \frac{D_C}{2} = 100 + 5 + 5 + 30 = 140\, mm$$

$$s_m = s_o Z_C N = 0.1x6xN$$

where, $$N = \frac{1000V_C}{\pi D_C} = \frac{1000x40}{\pi x60} \cong 200\, rpm$$

$$s_m = 0.2x6x200 = 120\, mm/\min$$

So, $$T_C = \frac{L_C}{s_m}$$

$$= \frac{140}{120} = 1.17 \min.$$

In the same method, T_C can be determined for end milling and face milling by proper selection of speed and feed depending upon the tool – work materials and other relevant factors.

Exercise – 4.9

1. How much machining time will be required to reduce the diameter of a cast iron rod from 120 mm to 116 mm over a length of 100 mm by turning using a carbide insert. Reasonably select values of V_C and s_o.

2. Determine the time that will be required to drill a blind hole of diameter 25 mm and depth 40 mm in a mild steel solid block by a HSS drill of 118^0 cone angle. Assume suitable values of V_C and s_o.

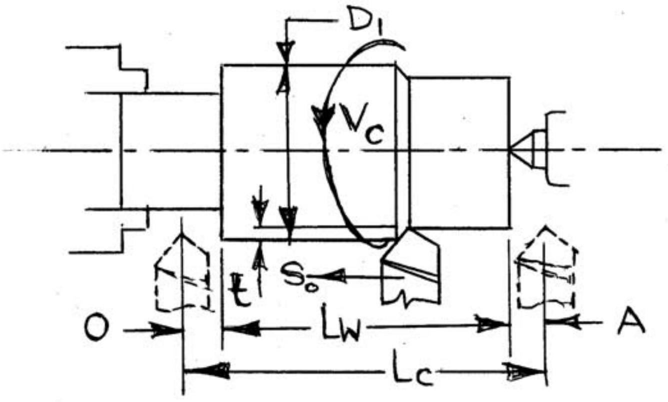
3. In a mild steel block, a flat surface of length 100 mm and width 60 mm has to be finished in a shaping machine in a single pass. How much machining time will be required if N_s = 80, s_o = 0.2 mm/stroke, A = O = 5 mm, QRR = 0.5.

4. Estimate the machining time that will be required to finish a vertical flat surface of length 100 mm and depth 20 mm by an 8 teeth HSS end mill cutter of 32 mm diameter and 60 mm length in a milling machine. Assume, V_C = 30 m/min, s_o = 0.12 mm/tooth.

Solution of the Problems in Exercise – 4.9

Problem – 1

Solution :



$$T_C = \frac{L_C}{Ns_o} \text{ for single pass}$$

L_C = 100 + 5 + 5 = 110 mm

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

For turning C.I. by carbide insert, V_C is taken as 100 m/min and s_o = 0.2 mm/rev

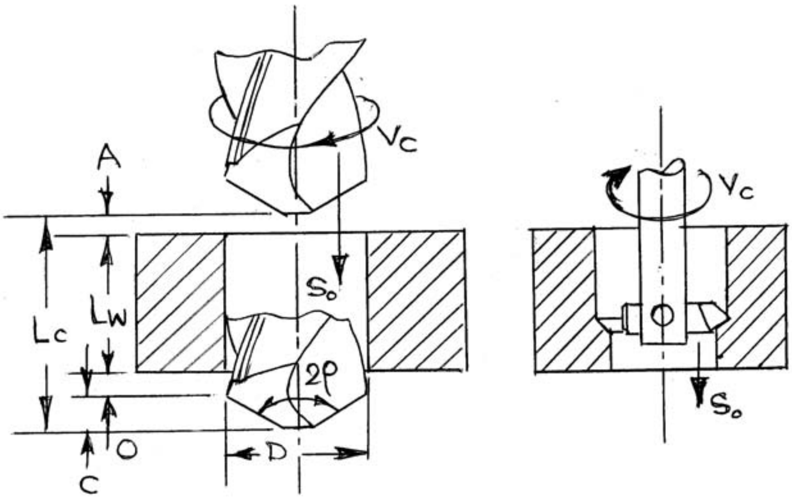
$$\therefore \quad N = \frac{1000x100}{\pi.120} \cong 250 \; rpm$$

Nearest standard speed, N = 225

$$\therefore \quad T_C = \frac{110}{225x0.2} = 2.5 \min \quad \textbf{Ans.}$$

Problem – 2

Solution :



Assumed for the given condition, V_C = 25 m/min and s_o = 0.16 mm/rev

$$T_C = \frac{L_C^{'}}{Ns_o} \qquad L_C' = L_h + A + O + C$$

$$= 40 + 5 + 0.0 + 25/2\cot 59^o = 50 \text{ mm}$$

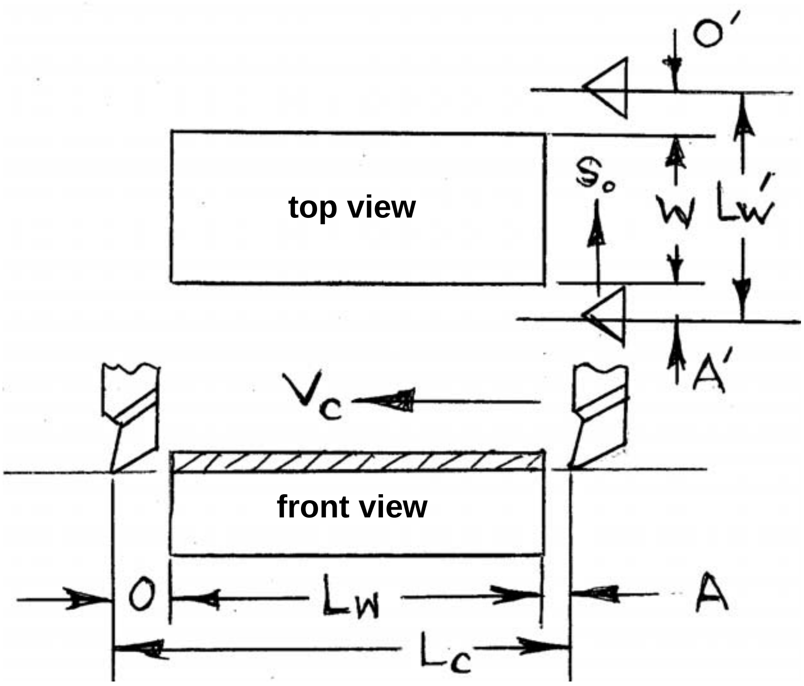
$$\boldsymbol{N} = \frac{1000\boldsymbol{V_C}}{\pi \boldsymbol{D}} = \frac{1000\boldsymbol{x}25}{\pi\boldsymbol{x}25} \cong 320\ \boldsymbol{rpm}$$

Nearest standard speed, N = 315 rpm

$$\therefore \quad \boldsymbol{T_C} = \frac{50}{315\boldsymbol{x}0.16} = 1.0 \text{ min} \quad \textbf{Ans.}$$

Problem – 3

Solution :



$$T_C = \frac{L_w}{N_s s_0}; \quad L_w = W + A' + O' = 60 + 5 + 2.5 = 67.5 \text{ mm}$$

$V_C = N_s L_C(1+Q)$ mm/min

For the given condition, let V_C = 20 m/min, s_o = 0.12 mm/stroke

Also assume Q = 0.6

Then 20x1000 = N_s x(100+10+10)(1 + 0.6)

$\therefore$ $N_s \cong 100$

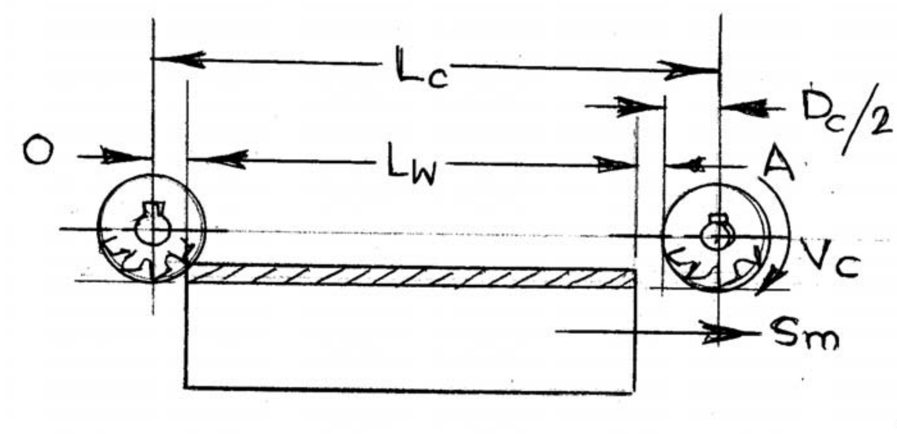
Nearest (lower side) standard speed, N_s = 90

Then, $\boldsymbol{T_C} = \frac{67.5}{90\boldsymbol{x}0.12} = 6.25 \text{ min}$ **Ans**

Or $\boldsymbol{T_C} = \frac{\boldsymbol{L_w}}{\boldsymbol{Ns_o}} = \frac{60+5+5}{80\boldsymbol{x}0.2} = \frac{70}{16} = 4.4 \text{ min}$ **Ans**

Problem – 4

Solution :



$T_C = L_C / s_m$; $L_C = 100 + 2 + 2 + 16 = 120$ mm

$s_m = s_o Z_C N = 0.12x8xN$

$$N = \frac{1000V_C}{\pi D_C} = \frac{1000x30}{\pi x32} \cong 300\, rpm$$

Then $s_m = 0.12x8x320 = 320$ mm/min

$$\therefore \quad T_C = \frac{120}{300} \cong 0.40 \text{ min}$$ **Ans.**

Module
4
General Purpose Machine Tools

Lesson
26
Broaching – Principles, Systems and Applications

Instructional objectives

This lesson will enable the students,

(i) State and visualise the basic principle of broaching
(ii) Describe constructional features and functioning of broaching tools
(iii) Illustrate different broaching tools and their applications
(iv) Classify broaching machines w.r.t. configuration and use
(v) Identify the advantages and limitations of broaching.

(i) BASIC PRINCIPLES OF BROACHINING

Broaching is a machining process for removal of a layer of material of desired width and depth usually in one stroke by a slender rod or bar type cutter having a series of cutting edges with gradually increased protrusion as indicated in Fig. 4.10.1. In shaping, attaining full depth requires a number of strokes to remove the material in thin layers step – by – step by gradually infeeding the single point tool (Fig. 4.10.1).. Whereas, broaching enables remove the whole material in one stroke only by the gradually rising teeth of the cutter called broach. The amount of tooth rise between the successive teeth of the broach is equivalent to the infeed given in shaping.

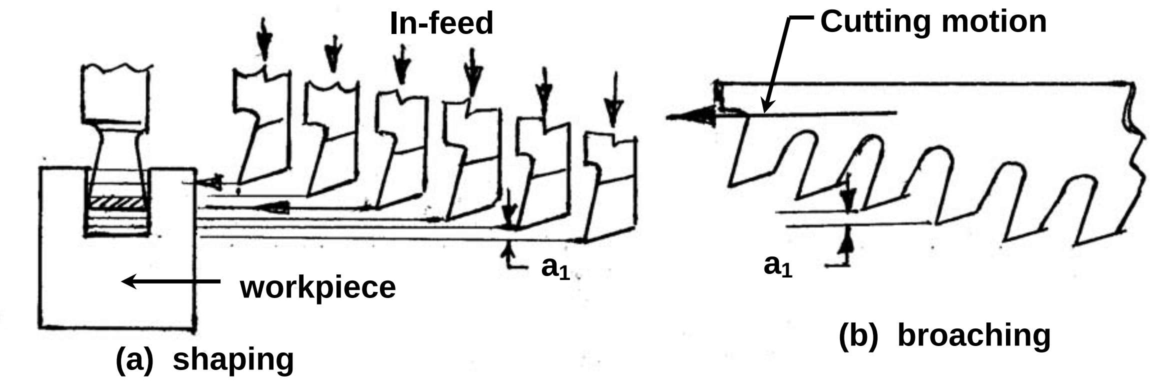
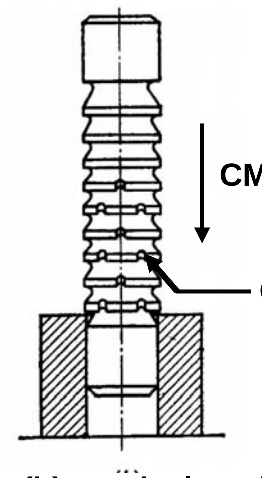


Fig. 4.10.1 *Basic principle of broaching.*

Machining by broaching is preferably used for making straight through holes of various forms and sizes of section, internal and external through straight or helical slots or grooves, external surfaces of different shapes, teeth of external and internal splines and small spur gears etc. Fig. 4.10.2 schematically shows how a through hole is enlarged and finished by broaching.



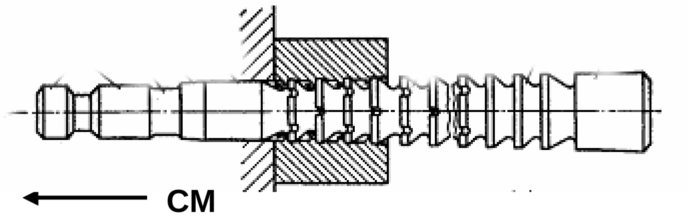


Fig. 4.10.2 *Schematic views of finishing hole by broaching.*

(ii) Construction And Operation Of Broaching

- **Construction of broaching tools**

Construction of any cutting tool is characterised mainly by

- Configuration
- Material and
- Cutting edge geometry

- **Configuration of broaching tool**

Both pull and push type broaches are made in the form of slender rods or bars of varying section having along its length one or more rows of cutting teeth with increasing height (and width occasionally). Push type broaches are subjected to compressive load and hence are made shorter in length to avoid buckling.
The general configuration of pull type broaches, which are widely used for enlarging and finishing preformed holes, is schematically shown in Fig. 4.10.3.

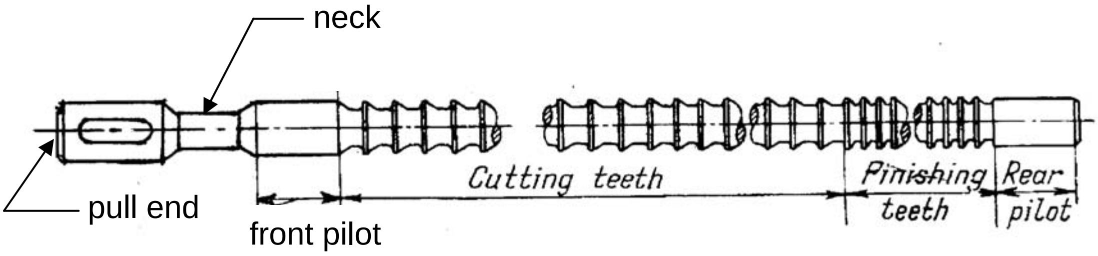


Fig. 4.10.3 *Configuration of a pull type broach used for finishing holes.*

The essential elements of the broach (Fig. 4.10.3) are :

- Pull end for engaging the broach in the machine

- Neck of shorter diameter and length, where the broach is allowed to fail, if at all, under overloading
- Front pilot for initial locating the broach in the hole
- Roughing and finishing teeth for metal removal
- Finishing and burnishing teeth
- Rear pilot and follower rest or retriever

Broaches are designed mostly pull type to facilitate alignment and avoid buckling. The length of the broach is governed by;

- Type of the broach; pull or push type
- Number of cutting edges and their pitch depending upon the work material and maximum thickness of the material layer to be removed
- Nature and extent of finish required.

Keeping in view that around 4 to 8 teeth remain engaged in machining at any instant, the pitch (or gap), p, of teeth is simply decided from

$$\boldsymbol{p} = 1.25\sqrt{\boldsymbol{L}} \text{ to } 1.5\sqrt{\boldsymbol{L}}$$

where, L = length of the hole or job.
The total number of cutting teeth for a broach is estimated from,

$T_n \geq$ (total depth of material) / tooth rise, a_1 (which is decided based on the tool – work materials and geometry).

Broaches are generally made from solid rod or bar. Broaches of large section and complex shape are often made by assembling replaceable separate sections or inserting separate teeth for ease of manufacture and maintenance.

- **Material of broach**

Being a cutting tool, broaches are also made of materials having the usual cutting tool material properties, i.e., high strength, hardness, toughness and good heat and wear resistance.
For ease of manufacture and resharpening the complex shape and cutting edges, broaches are mostly made of HSS (high speed steel). To enhance cutting speed, productivity and product quality, now-a-days cemented carbide segments (assembled) or replaceable inserts are also used specially for stronger and harder work materials like cast irons and steels. TiN coated carbides provide much longer tool life in broaching. Since broaching speed (velocity) is usually quite low, ceramic tools are not used.

- **Geometry of broaching teeth and their cutting edges**

Fig. 4.10.4 shows the general configuration of the broaching teeth and their geometry. The cutting teeth of HSS broaches are provided with positive radial or orthogonal rake (5^o to 15^o) and sufficient primary and secondary clearance angles (2^o to 5^o and 5^o to 20^o respectively) as indicated in Fig. 4.10.4.
Small in-built chip breakers are alternately provided on the roughing teeth of the broach as can be seen in Fig. 4.10.2 to break up the wide curling chips

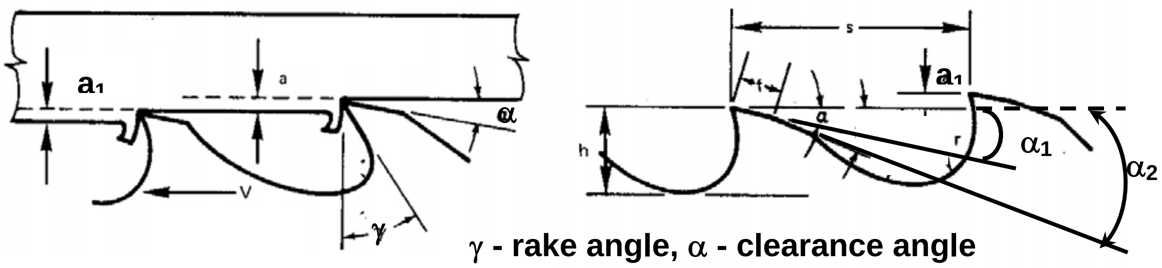


Fig. 4.10.4 *Geometry of teeth of broaching tools.*

and thus preventing them from clogging the chip spaces and increasing forces and tool wear. More ductile materials need wider and frequent chip breakers.

- **Broaching operation**

Like any other machining, broaching is also accomplished through a series of following sequential steps :

- Selection of broach and broaching machine
- Mounting and clamping the broach in the broaching machine
- Fixing workpiece in the machine
- Planning tool - work motions
- Selection of the levels of the process parameters and their setting
- Conducting machining by the broach.

- **Selection of broach and broaching machine**

There are various types of broaches available. The appropriate one has to be selected based on

- type of the job; size, shape and material
- geometry and volume of work material to be removed from the job
- desired length of stroke and the broach
- type of the broaching machines available or to be used

Broaching machine has to be selected based on

- The type, size and method of clamping of the broach to be used
- Size, shape and material of the workpiece
- Strength, power and rigidity required for the broaching machine to provide the desired productivity and process capability.

- **Mounting and clamping broach in the machine**

The broach needs to be mounted, clamped and moved very carefully and perfectly in the tool holding device of the broaching machine which are used for huge lot or mass production with high accuracy and surface finish.
Pull type and push type broaches are mounted in different ways.

Fig. 4.10.5 typically shows a broach pull head commonly used for holding, clamping and pulling pull type broach. Just before fitting in or removing the broach from the broach pull head (Fig. 4.10.5 (a)), the sliding outer socket is

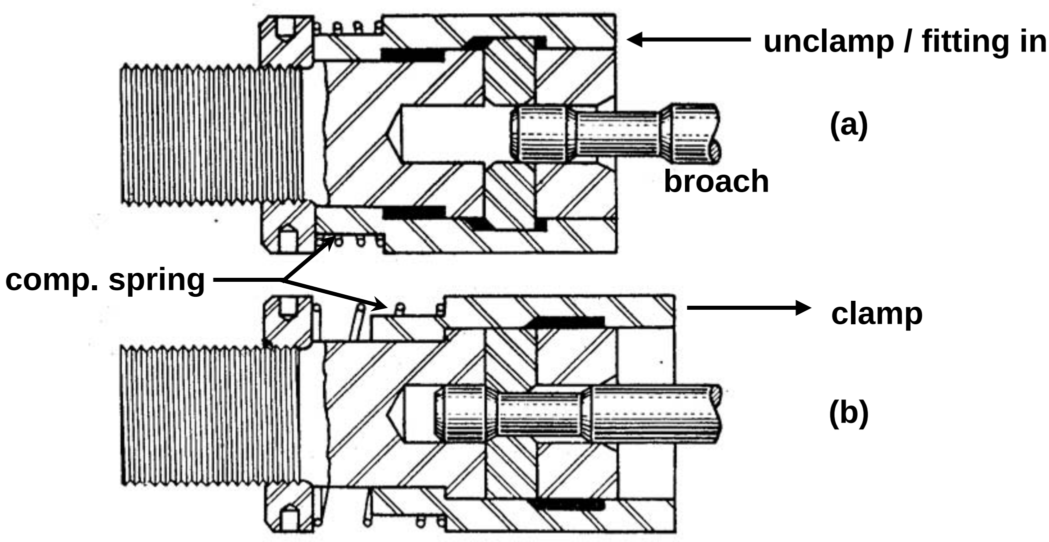


Fig. 4.10.5 *Mounting and clamping pull type broach.*

pushed back against the compression spring. After full entry of the pull end of the broach in the head the socket is brought forward which causes locking of the broach by the radially moving strips as shown in Fig. 4.10.5 (b).
Pull type broaches are also often simply and slight flexibly fitted by a suitable adapter and pin as can be seen in Fig. 4.10.6.

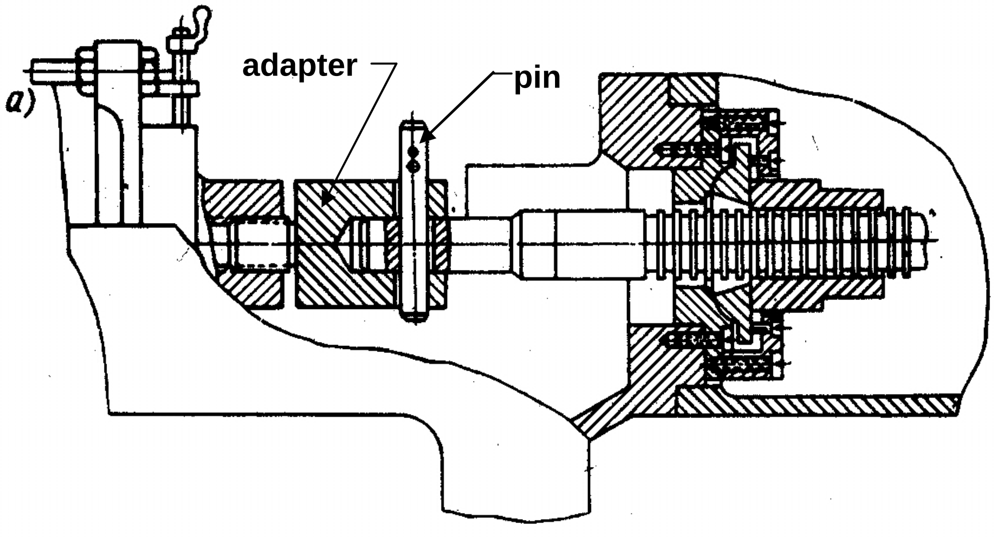


Fig. 4.10.6 *Fitting pull type broach by an adapter and a pin.*

- **Mounting of workpiece or blank in broaching machine**

Broaching is used for mass production and at fast rate. The blanks are repeatedly mounted one after another in an appropriate fixture where the blanks can be easily, quickly and accurately located, supported and clamped.

In broaching, generally the job remains fixed and the broach travels providing cutting velocity.

Fig. 4.10.7 schematically shows a typical method of mounting push or pull type external broach for through surfacing, slotting or contouring.

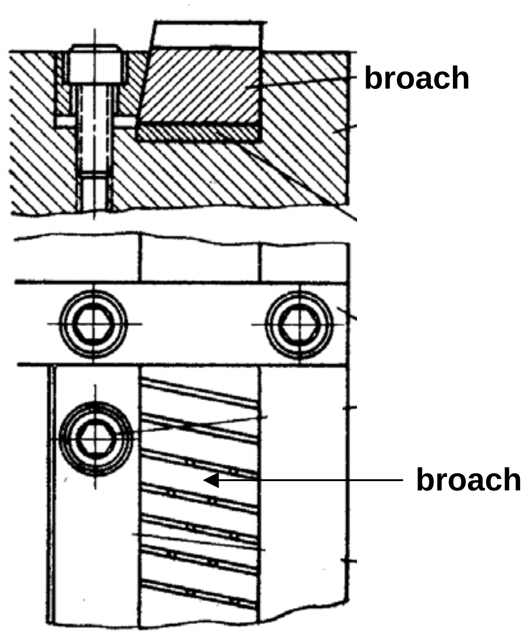


Fig. 4.10.7 *Mounting external broach for surfacing and slotting.*

- **Tool – work motions and process variables**

Any machining is associated with 2 to 5 tool – work motions as well as cutting velocity, feed and depth of cut as process variables. But broaching operation / machine needs only one motion which is cutting motion and is mostly imparted to the tool. In broaching feed is provided as tooth rise. The magnitude of cutting velocity, V_C is decided based on the tool – work materials and the capability of the broaching machine. In broaching metals and alloys, HSS broaches are used at cutting velocity of 10 to 20 m/min and carbide broaches at 20 to 40 m/min. The value of tooth rise varies within 0.05 mm to 0.2 mm for roughing and 0.01 to 0.04 mm for finishing teeth. Some cutting fluids are preferably used mainly for lubrication and cooling at the chip – tool interfaces.

Fig. 4.10.8 typically shows mounting of blank in fixture. But occasionally the job is travelled against the stationary broach as in continuous working type broaching machine.

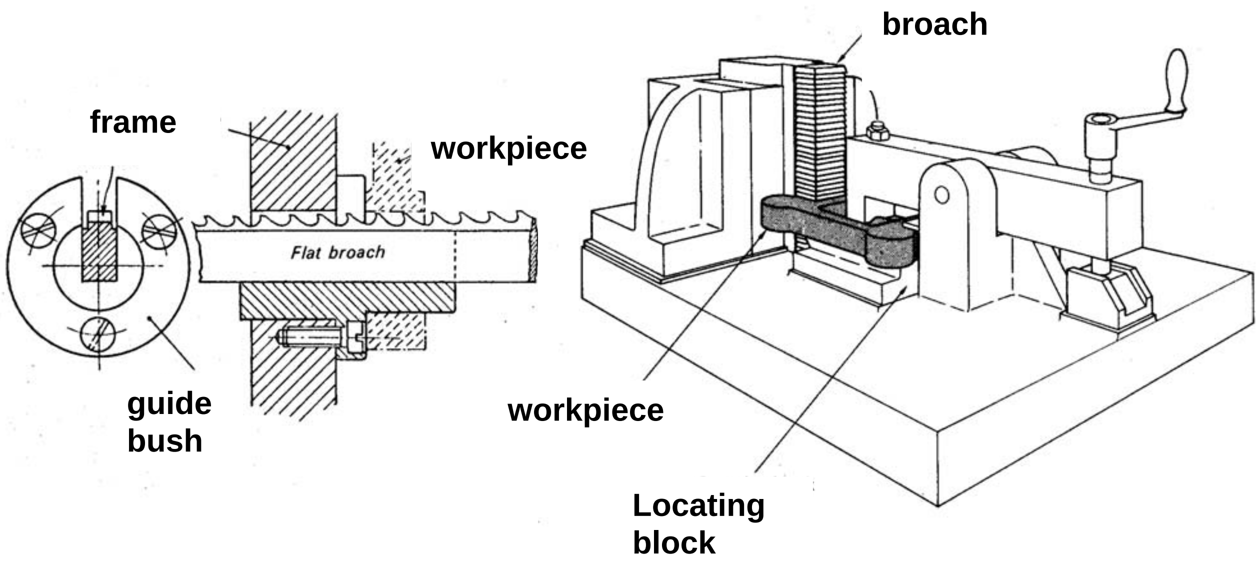


Fig. 4.10.8 *Mounting blank in broaching machine.*

(iv) Different Types Of Broaches And Their Applications

Broaching is getting more and more widely used, wherever feasible, for high productivity as well as product quality. Various types of broaches have been developed and are used for wide range of applications.
Broaches can be broadly classified in several aspects such as,

- Internal broaching or External broaching
- Pull type or Push type
- Ordinary cut or Progressive type
- Solid, Sectional or Modular type
- Profile sharpened or form relieved type

- **Internal and external broaching (tool)**

  - **Internal broaching and broaches**

Internal broaching tools are used to enlarge and finish various contours in through holes preformed by casting, forging, rolling, drilling, punching etc. Internal broaching tools are mostly pull type but may be push type also for lighter work. Pull type internal broaching tools are generally provided with a set of roughing teeth followed by few semi-finishing teeth and then some finishing teeth which may also include a few burnishing teeth at the end. The wide range of internal broaching tools and their applications include;

- through holes of different form and dimensions as indicated in fig. 4.10.9
- non-circular holes and internal slots (fig. 4.10.9)
- internal keyway and splines
- teeth of straight and helical fluted internal spur gears as indicated in fig. 4.10.9

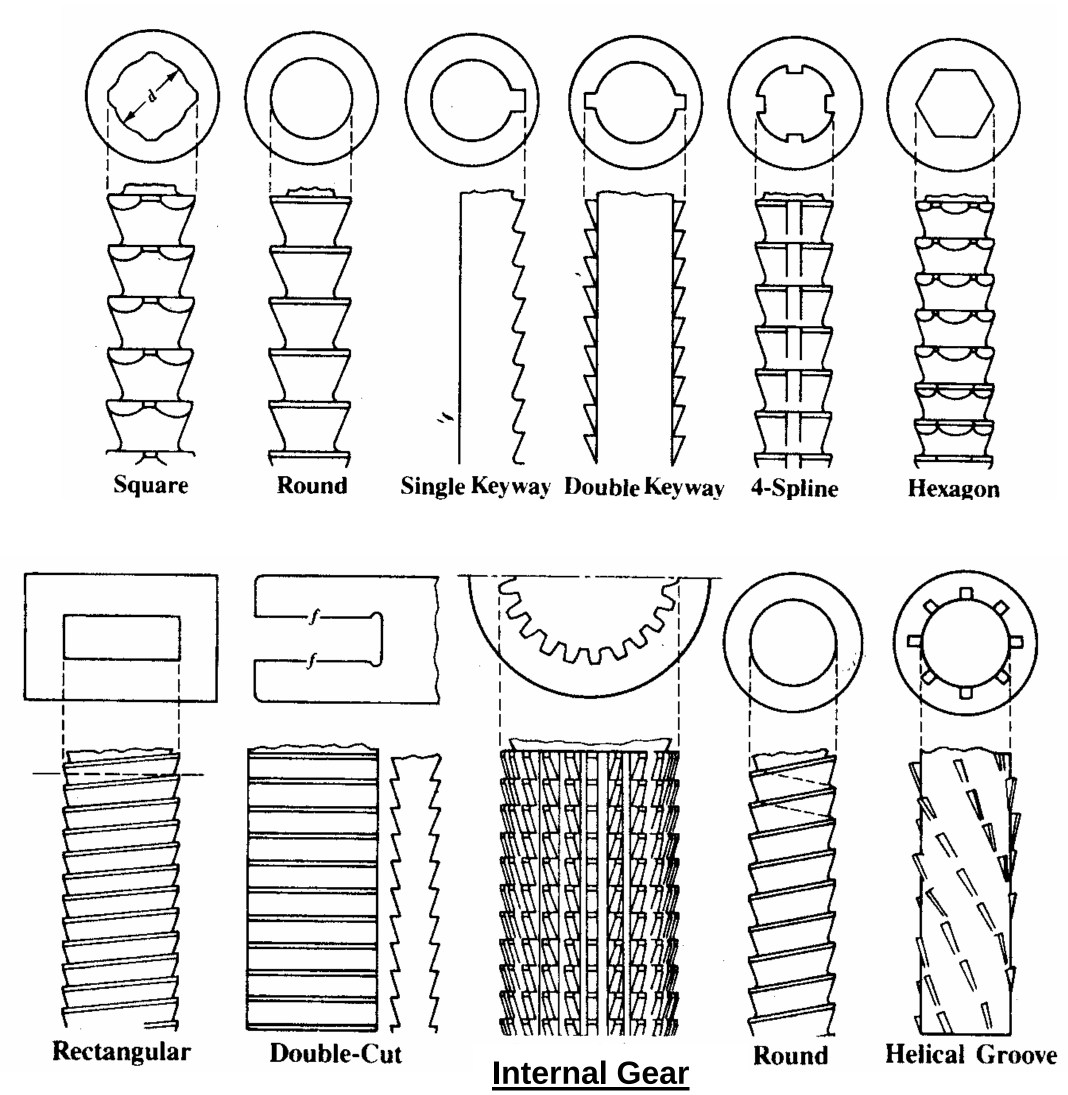


Fig. 4.10.9 *Internal broaching – tools and applications.*

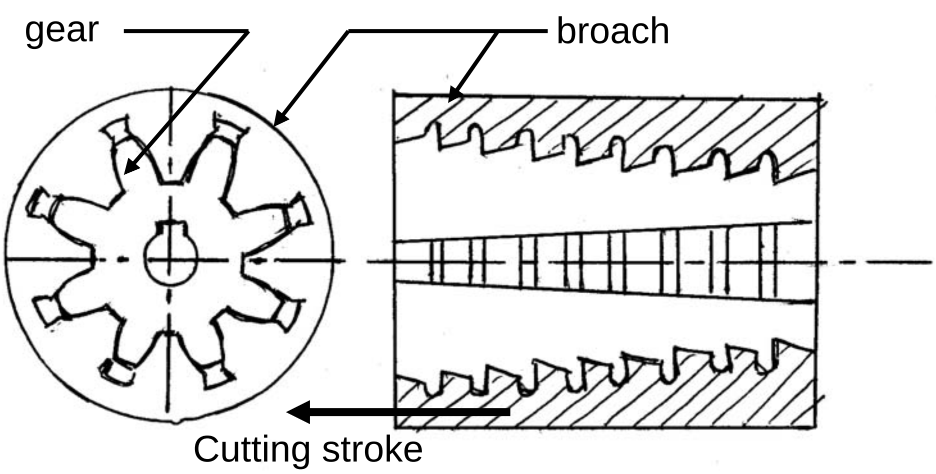


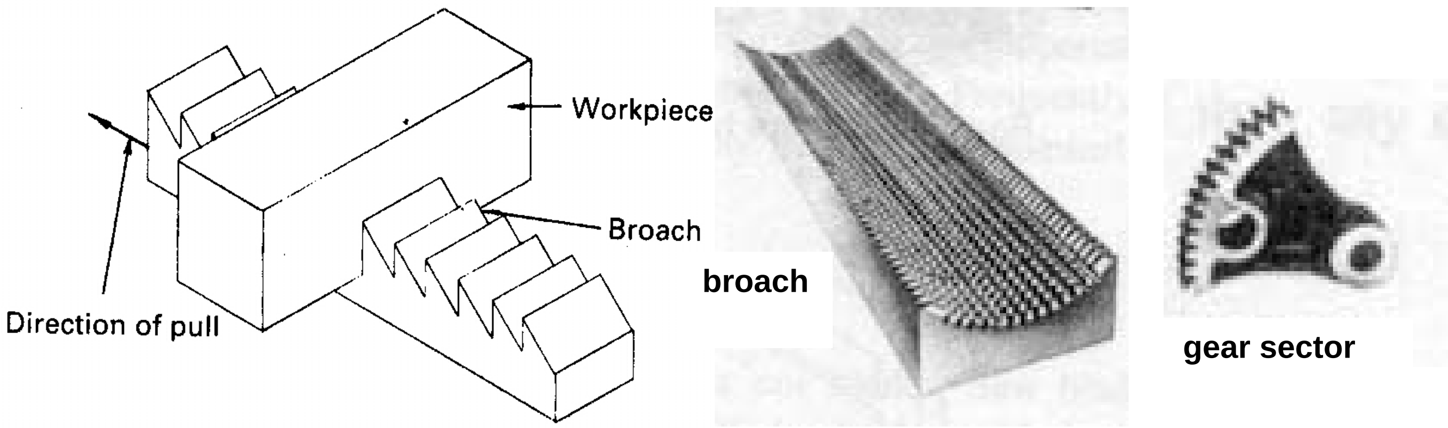
Fig. 4.10.10 *Machining external gear teeth by broaching.*

- **External broaching**

External surface broaching competes with milling, shaping and planing and, wherever feasible, outperforms those processes in respect of productivity and product quality. External broaching tools may be both pull and push type.
Major applications of external broaching are :

- un-obstructed outside surfacing; flat, peripheral and contour surfaces (fig. 4.10.11 (a))
- grooves, slots, keyways etc. on through outer surfaces of objects (Fig. 4.10.8)
- external splines of different forms
- teeth of external spur gears or gear sectors as shown in Fig. 4.10.10 and Fig. 4.10.11 (b)

External broaching tools are often made in segments which are clamped in fixtures for operation.



(a) (b)

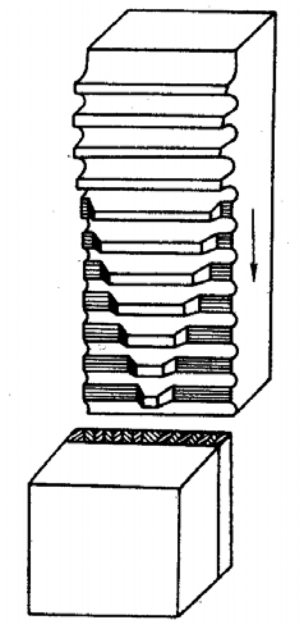
Fig. 4.10.11 *Typical external broaching (a) making slot (b) teeth of gear sector*

- **Pull type and push type broaches**

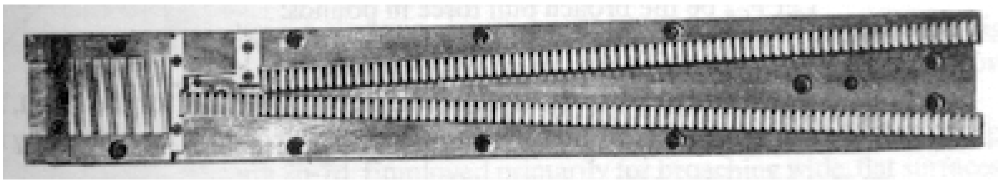
During operation a pull type broach is subjected to tensile force, which helps in maintaining alignment and prevents buckling.
Pull type broaches are generally made as a long single piece and are more widely used, for internal broaching in particular. Push type broaches are essentially shorter in length (to avoid buckling) and may be made in segments. Push type broaches are generally used for external broaching, preferably, requiring light cuts and small depth of material removal.

- **Ordinary – cut and Progressive type broach**

Most of the broaches fall under the category of Ordinary – cut type where the teeth increase in height or protrusion gradually from tooth to tooth along the length of the broach. By such broaches, work material is removed in thin layers over the complete form. Whereas, Progressive – cut type broaches have their teeth increasing in width instead of height. Fig. 4.10.12 shows the working principle and configuration of such broach.



(a) single strip

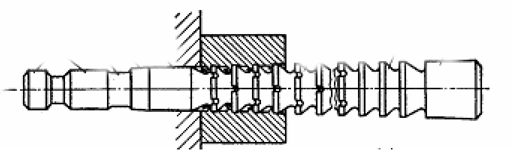


(b) double strip type

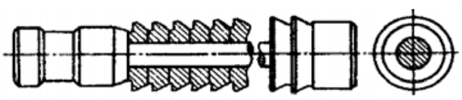
Fig. 4.10.12 *Progressive – cut type broaches; (a) single bar and (b) double bar type*

- **Solid, Sectional and module type broaches**

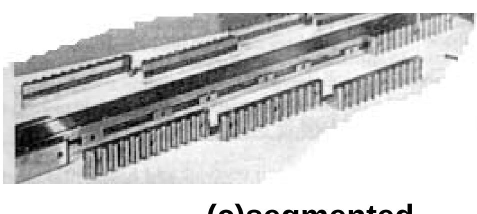
Broaches are mostly made in single pieces specially those used for pull type internal broaching. But some broaches called sectional broaches, are made by assemblying several sections or cutter-pieces in series for convenience in manufacturing and resharpening and also for having little flexibility required by production in batches having interbatch slight job variation. External broaches are often made by combining a number of modules or segments for ease of manufacturing and handling. Fig. 4.10.13 typically shows solid, sectional and segmented (module) type broaches.



(a) solid



(b) sectional



(c)segmented

Fig. 4.10.13 *(a) Solid, (b) Sectional and (c) Segmented broaches.*

- **Profile sharpened and form relieved type broaches**

Like milling cutters, broaches can also be classified as

- **Profile sharpened type broaches;**

  Such cutters have teeth of simple geometry with same rake and clearance angles all over the cutting edge. These broaches are generally designed and used for machining flat surface(s) or circular holes.

- **Form relieved type broaches**

  These broaches, being used for non-uniform profiles like gear teeth etc., have teeth where the cutting edge geometry is more complex and varies point – to – point along the cutting edges. Here the job profile becomes the replica of the tool form. Such broaches are sharpened and resharpened by grinding at their rake faces unlike the profile sharpened broaches which are ground at the flank surfaces.

(iv) Broaching Machines

The unique characteristics of broaching operation are

- For producing any surface, the form of the tool (broach) always provides the Generatrix and the cutting motion (of the broach relative to the job surface) provides the Directrix.
- So far as tool – work motions, broaching needs only one motion and that is the cutting motion (velocity) preferably being imparted to the broach.

Hence design, construction and operation of broaching machines, requiring only one such linear motion, are very simple. Only alignments, rigidity and reduction of friction and wear of slides and guides are to be additionally considered for higher productivity, accuracy and surface finish.
Broaching machines are generally specified by

- Type; horizontal, vertical etc.
- Maximum stroke length
- Maximum working force (pull or push)
- Maximum cutting velocity possible
- Power
- Foot print

Most of the broaching machines have hydraulic drive for the cutting motion. Electro-mechanical drives are also used preferably for high speed of work but light cuts.

There are different types of broaching machines which are broadly classified

- According to purpose of use
  - ∆ general purpose
  - ∆ single purpose
  - ∆ special purpose

- According to nature of work
  - ∆ internal broaching
  - ∆ external (surface) broaching

- According to configuration
  - ∆ horizontal
  - ∆ vertical

- According to number of slides or stations
  - ∆ single station type
  - ∆ multiple station type
  - ∆ indexing type

- According to tool / work motion
  - ∆ intermittent (one job at a time) type
  - ∆ continuous type

Some of the broaching machines of common use have been discussed here.

- **Horizontal broaching machine**

Horizontal broaching machines, typically shown in Fig. 4.10.14, are the most versatile in application and performance and hence are most widely employed for various types of production. These are used for internal broaching but external broaching work are also possible. The horizontal broaching machines are usually hydraulically driven and occupies large floor space.

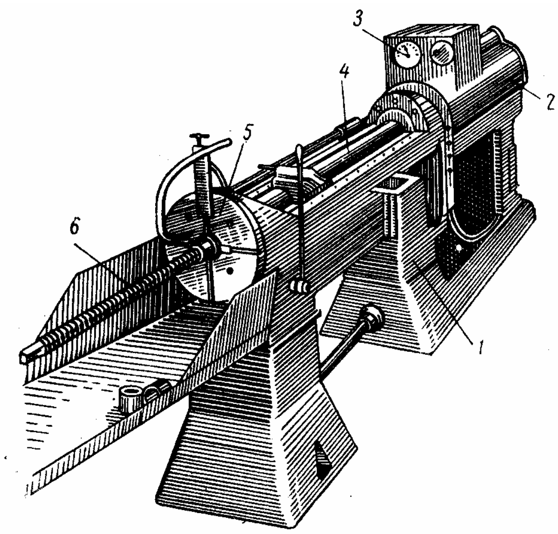


Fig. 4.10.14 *Horizontal broaching machine.*

- **Vertical broaching machine**

Vertical broaching machines, typically shown in Fig. 4.10.15,

- occupies less floor space
- are more rigid as the ram is supported by base
- mostly used for external or surface broaching though internal broaching is also possible and occasionally done.

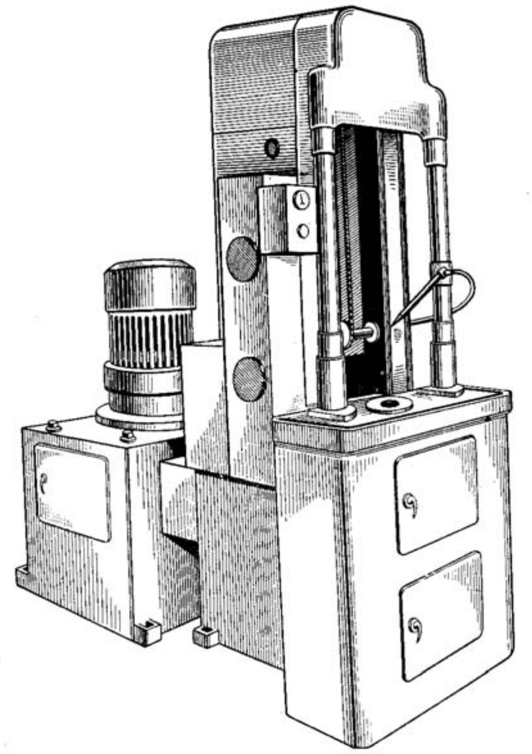


Fig. 4.10.15 *Vertical broaching machine.*

- **High production broaching machines**

Broaching operation and broaching machines are as such high productive but its speed of production is further enhanced by;

- incorporating automation in tool – job mounting and releasing
- increasing number of workstations or slides for simultaneous multiple production
- quick changing the broach by turret indexing
- continuity of working

Fig. 4.10.16 schematically shows the principle and methods of continuous broaching, which is used for fast production of large number of pieces by surface broaching.

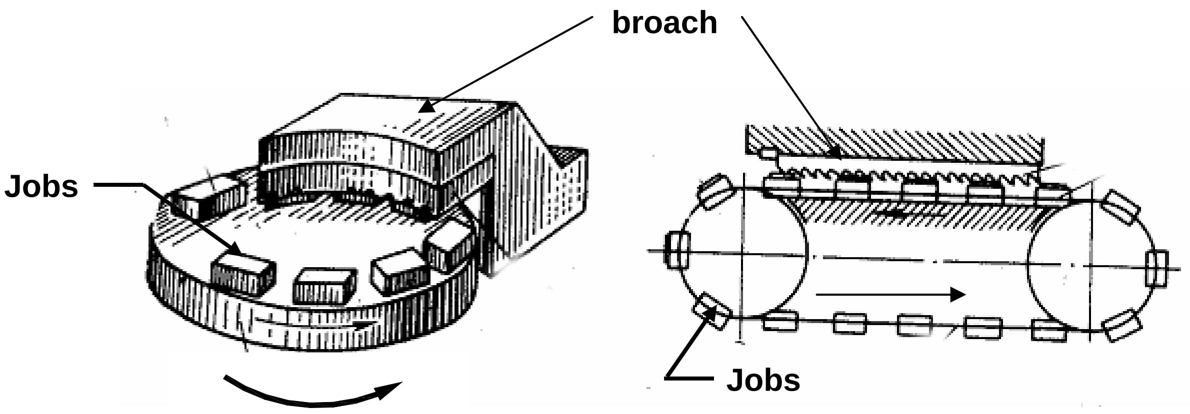


Fig. 4.10.16 *Continuous broaching.*

(v) ADVANTAGES AND LIMITATIONS OF BROACHING

Major advantages

- Very high production rate (much higher than milling, planing, boring etc.)
- High dimensional and form accuracy and surface finish of the product
- Roughing and finishing in single stroke of the same cutter
- Needs only one motion (cutting), so design, construction, operation and control are simpler
- Extremely suitable and economic for mass production

Limitations

- Only through holes and surfaces can be machined
- Usable only for light cuts, i.e. low chip load and unhard materials
- Cutting speed cannot be high
- Defects or damages in the broach (cutting edges) severely affect product quality
- Design, manufacture and restoration of the broaches are difficult and expensive
- Separate broach has to be procured and used whenever size, shape and geometry of the job changes
- Economic only when the production volume is large.

Module
5
Abrasive Processes (Grinding)

Lesson
27
Basic principle, purpose and application of grinding

Instructional Objectives

At the end of this lesson the students would be able to

(i) understand basic principle of grinding.
(ii) recognize purpose and application of grinding.
(iii) understand cause of development of force during grinding.
(iv) understand variation of grinding characteristics with grinding conditions.
(v) illustrate various methods of wheel conditioning.

27. Grinding

Grinding is the most common form of abrasive machining. It is a material cutting process which engages an abrasive tool whose cutting elements are grains of abrasive material known as grit. These grits are characterized by sharp cutting points, high hot hardness, chemical stability and wear resistance. The grits are held together by a suitable bonding material to give shape of an abrasive tool.

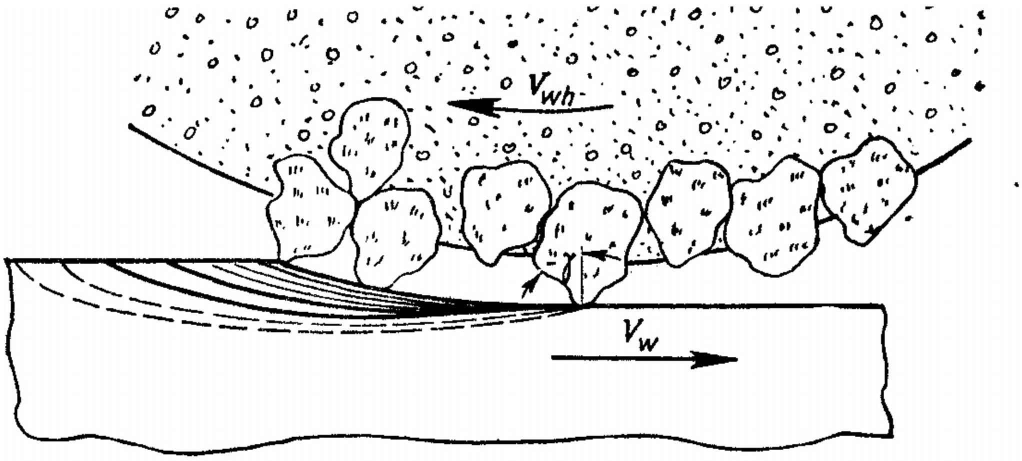


Fig. 27.1 *Cutting action of abrasive grains*

Fig. 27.1 illustrates the cutting action of abrasive grits of disc type grinding wheel similar to cutting action of teeth of the cutter in slab milling.

27.1 Major advantages and applications of grinding

Advantages
A grinding wheel requires two types of specification

- dimensional accuracy
- good surface finish
- good form and locational accuracy
- applicable to both hardened and unhardened material

Applications

- surface finishing
- slitting and parting
- descaling, deburring
- stock removal (abrasive milling)
- finishing of flat as well as cylindrical surface
- grinding of tools and cutters and resharpening of the same.

Conventionally grinding is characterized as low material removal process capable of providing both high accuracy and high finish. However, advent of advanced grinding machines and grinding wheels has elevated the status of grinding to abrasive machining where high accuracy and surface finish as well as high material removal rate can be achieved even on an unhardened material. This is illustrated in Fig. 27.2.

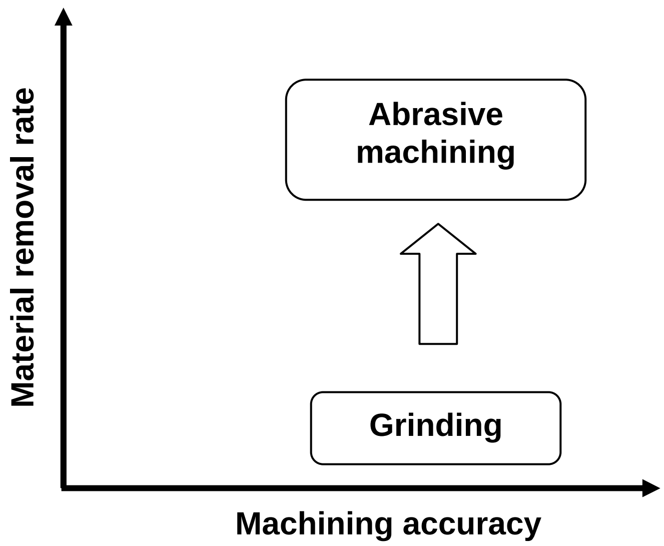


Fig. 27.2 *Elevation of the status of grinding to abrasive machining*

27.2 Grinding wheel and workpiece interaction

The bulk grinding wheel-workpiece interaction as illustrated in Fig. 27.3 can be divided into the following:

1. grit-workpiece (forming chip)
2. chip-bond
3. chip-work piece
4. bond-work piece

Except the grit workpiece interaction which is expected to produce chip, the remaining three undesirably increase the total grinding force and power requirement.

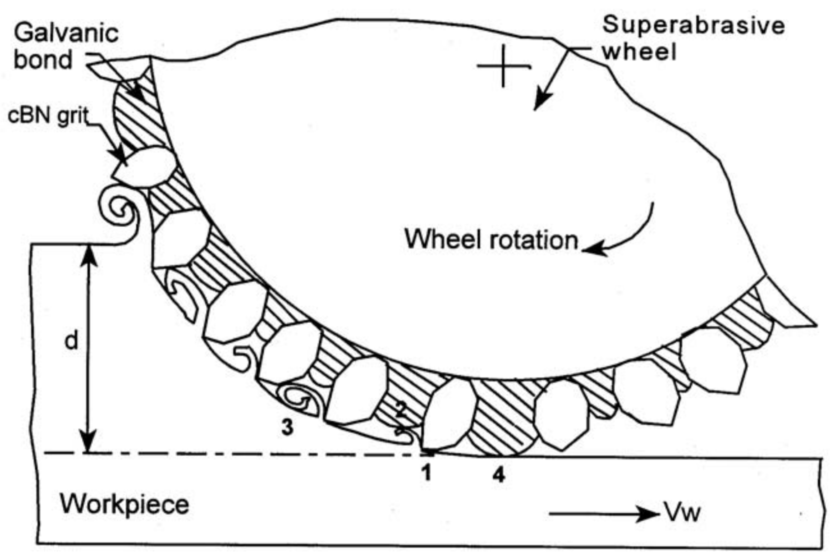


Fig. 27.3 *Grinding wheel and workpiece interaction*

Therefore, efforts should always be made to maximize grit-workpiece interaction leading to chip formation and to minimize the rest for best utilization of the available power.

27.3 Interaction of the grit with the workpiece

The importance of the grit shape can be easily realized because it determines the grit geometry e.g. rake and clearance angle as illustrated in Fig. 27.4. It appears that the grits do not have definite geometry unlike a cutting tool and the grit rake angle may vary from $+45^0$ to -60^0 or more.

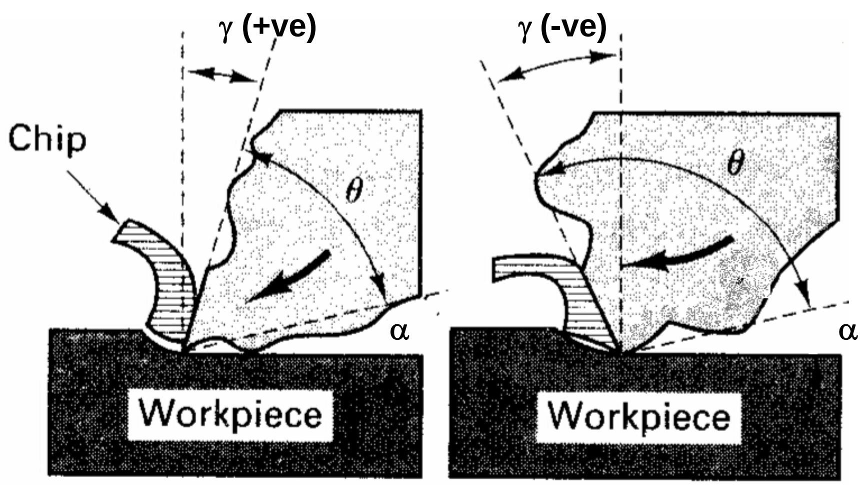


Fig. 27.4 *Variation in rake angle with grits of different shape*

Grit with favourable geometry can produce chip in shear mode. However, grits having large negative rake angle or rounded cutting edge do not form chips but may rub or make a groove by ploughing leading to lateral flow of the workpiece material as illustrated in Fig. 27.5.

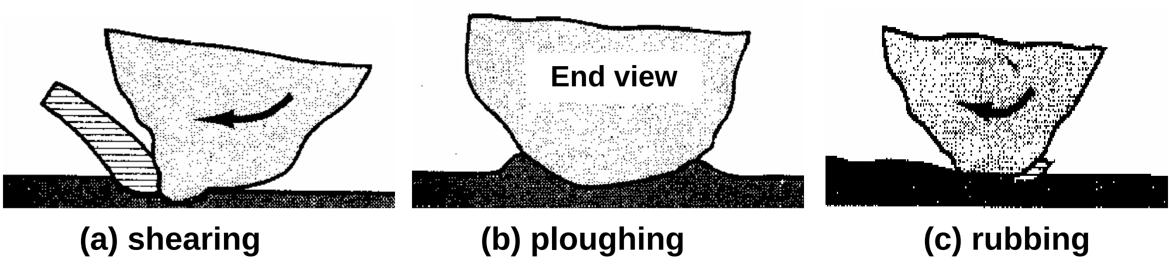


Fig. 27.5 *Grits engage shearing, ploughing and rubbing*

27.4 Effect of grinding velocity and rake angle of grit on grinding force

Figure 27.6 shows the role of rake angle on cutting force. A negative rake angle always leads to higher cutting force than what is produced with a cutting point having positive rake angle. The figure further illustrates that at low grinding velocity this difference in grinding force is more pronounced. It is interesting to note that the difference is narrowed at a high grinding velocity and the grinding force became virtually independent of the rake angle. This is one of the reasons of conducting grinding at a very high velocity in order to minimize the influence of negative rake angle.

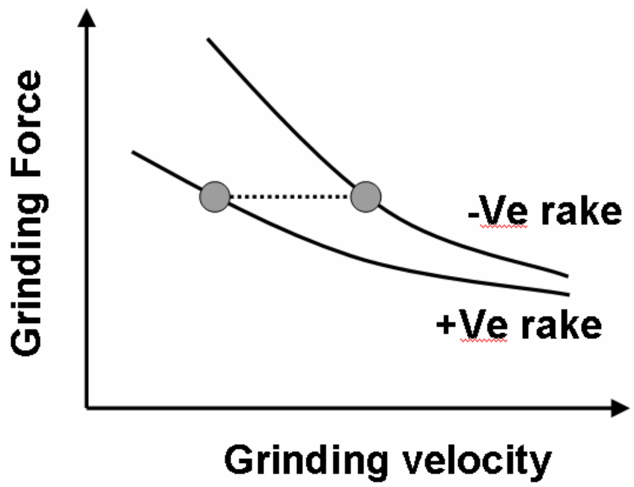


Fig. 27.6 *Variation of grinding force with grinding velocity and rake angle of grit*

27.5 Variation of critical grit depth of cut with grinding velocity

Grinding is a combination of rubbing, ploughing and cutting (actual chip formation) with contribution of each being highly governed by grit geometry, work material characteristics, grinding loop stiffness and the grinding velocity.

It is evident that specific energy in sliding or ploughing is more than that required in cutting or chip formation. It is the common experience in grinding that a certain level

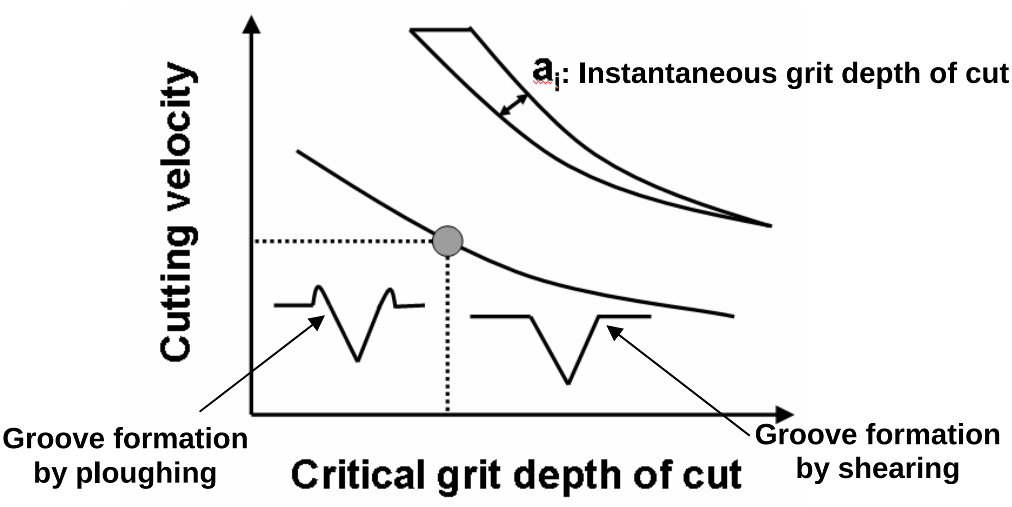


Fig. 27.7 *Variation of critical grit depth of cut With grinding velocity*

of grit penetration into workpiece is required before chip formation can start. Figure 27.7 illustrates variation of critical grit depth of cut with cutting velocity to initiate chip formation in grinding. It can be seen from this figure that magnitude of critical grit depth of cut required to initiate cutting becomes less with the increase of grinding velocity.

27.6 Various stages of grinding with grit depth of cut

Figure 27.8 illustrates the various stages of grinding and grinding force with grit depth of cut. At a small grit penetration only sliding of the grit occurs against the workpiece. In this zone rise of force with increase of grit penetration is quite high. With further increase of grit penetration, grit starts ploughing causing plastic flow of the material also associated with high grinding force.

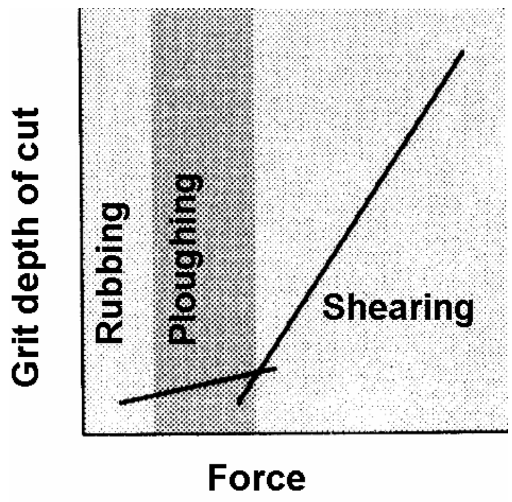


Fig. 27.8 *Various stages of grinding with grit depth of cut*

It can be seen that with further increase of penetration, the grits start cutting and the rate of rise of force with increase of grit depth of cut is much less than what can be seen in the sliding or ploughing zone.

27.7 Change in effective grit geometry due to material loading at the grit tip

Grit geometry may undergo substantial change due to mechanical or chemical attrition leading to rounding or flattening of the sharp cutting points. This happens when the work material has hard or abrasive constituent or where the workmaterial or environment chemically attacks the grit material. However, Fig. 27.9 shows that a

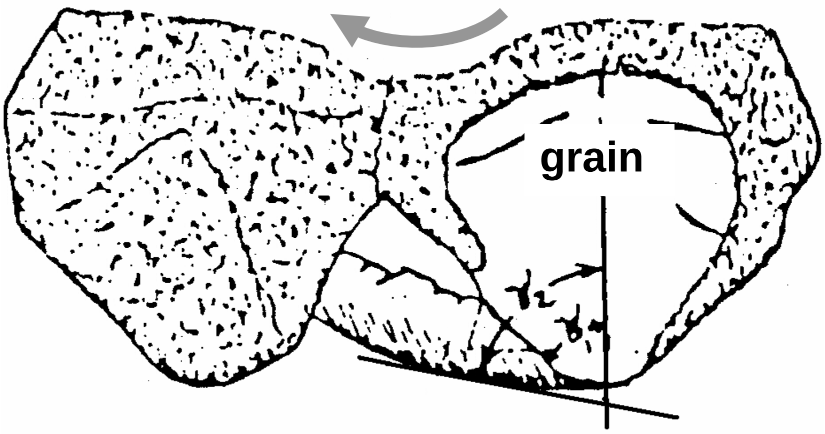


Fig. 27.9 *Change in effective grit geometry due to material loading at the grit tip*

chip material adhered to the tip of grit because of some chemical affinity can also change the effective rake angle of the grit leading to high grinding force, temperature and poor performance of the grinding wheel.

27.8 Chip accommodation problem in grinding

During grinding the volume of chip produced by each grit must be accommodated in the space available ahead of it. Absence of adequate chip storage space can lead to wheel loading, thus terminating the use of the wheel much before its expectedly long service life.

The requirement of chip accommodation space in a grinding wheel is analogous to the chip space required ahead of each tooth of a broaching tool as illustrated in Fig. 27.10. Uncut layer of length ‘L’ after deformation has to be accommodated freely in the chip gullet to avoid breakage of the tooth.

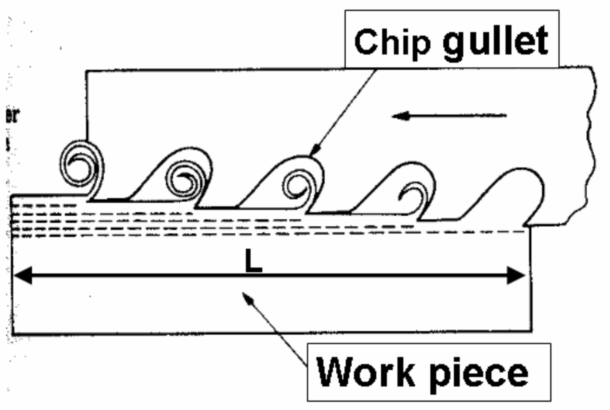
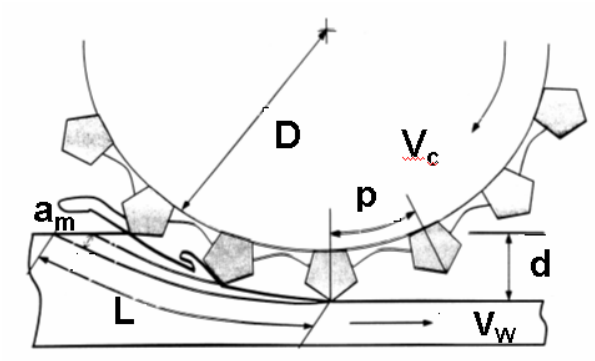


Fig. 27.10 *chip formation an accommodation during broaching*

27.8.1 Grit depth of cut and wheel-workpiece contact length

Volume of chip produced by individual grit depends upon the maximum grit depth of cut, wheel workpiece contact length and grit width of cut. Figure 27.11 shows a grinding wheel with a single layer configuration having tip of all the grits in the same level, engaged in up grinding mode.



Maximum uncut chip thickness , a_m

$$a_m = 2\frac{V_W}{V_C}.p.\sqrt{(d/D)}$$

Length of undeformed chip , L $L = \sqrt{(d.D)}$

Fig. 27.11 *Maximum grit depth of cut and length of undeformed chip*

The figure further shows the maximum grit depth of cut or thickness of the undeformed chip which depends on grinding velocity, workpiece speed, wheel depth of cut, wheel diameter and circular pitch of the grits. The length of the undeformed chip, however, depends only on the wheel depth of cut and its diameter. The volume of the chip produced by each grit depend on both 'a_m' and 'l_c ' as shown in Fig. 27.12.

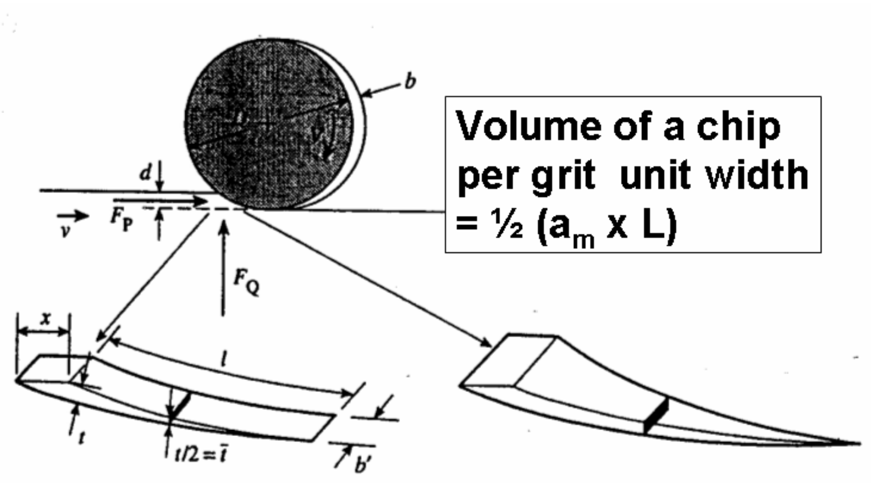


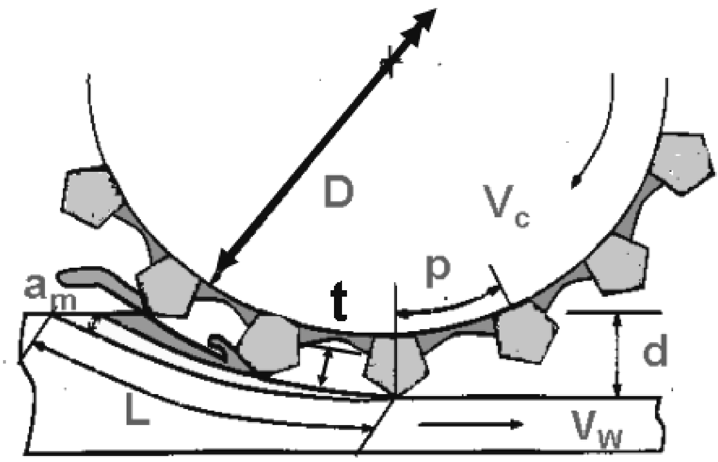
Fig. 27.12 *Volume of chip produced by a grit*

27.8.2 Determination of grit spacing and grit protrusion

Following three constraints are to be considered while determining spacing of grit and its protrusion:

- Chip volume
- Chip thickness
- Chip length

Various parameters involved in determination of grit space and its protrusion are shown in Fig. 27.13.



D : wheel diameter
V_c : grinding velocity
V_W : table speed
d : wheel depth of cut
p : circular pitch of the grits
t : protrusion of grit from bond level
a_m ; max[m] undeformed chip thickness
L : length undeformed of chip

Fig. 27.13 *Different parameters involved in determination of chip spacing and grit protrusion.*

Chip volume Constraint

Chip storage space available per unit time = V_c b t

V_c b t > V_w d b

Or, t > (V_w/V_c) d

Chip thickness constraint

Chip produced by each grit = ½ a_m x L x b

No. of grit participating per unit time = V_c/p

(½) a_m L b $(V_c/p) = V_w db$

rr, am = 2. (V_W/V_C) . d. (p/L)

Therefore, t > 2. (V_W/V_C) . d. (p/L)

Chip length constraint

undeformed length of the chip L = √(d.D)

Ld = ς L   where, ς = chip reduction coefficient

p > Ld, where ς = grit spacing

27.9 Specific energy consumption in grinding

Fig. 27.14 illustrates that specific grinding energy starts to decrease with increase of

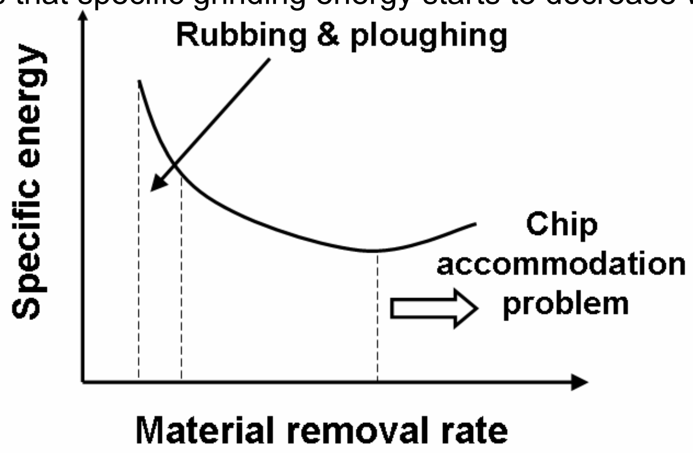


Fig. 27.14 *Variation of specific energy with material removal rate*

material removal rate because rake angle of the grit becomes favourable (less negative). However, after attaining a certain material removal rate, the specific energy may start increasing as shown in the same figure. This may happen because of the chip accommodation problem with large volume of chip, which promotes large chip-bond and chip-workpiece sliding leading to increase in grinding force.

27.10 Grinding wheel performance against materials with different hardness

In machining, under identical conditions, the cutting force increases with the shear strength of the material. However, in case of grinding a different observation can be made as shown in fig. 27.15. A hardened material exhibited higher value of normal force than an unhardened material while the latter showed higher tangential grinding force than the former.

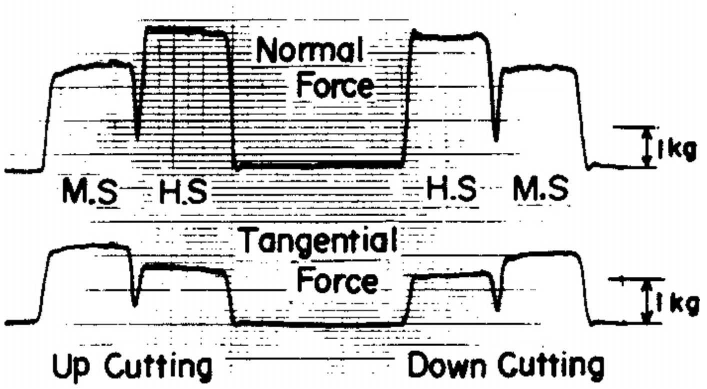


Fig. 27.15 *Force during grinding mild steel and hardened steel*

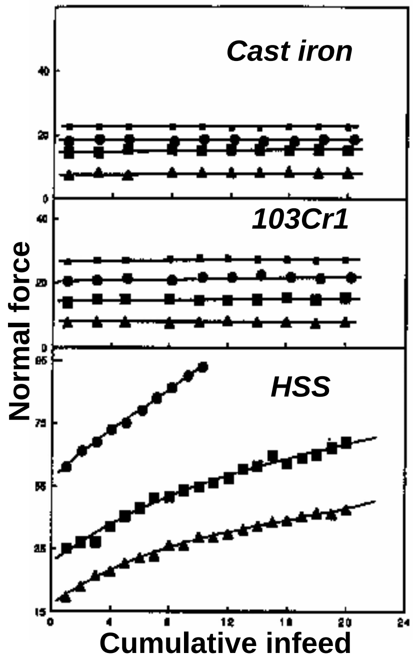


Fig. 27.16 *Grinding behaviour of cBN wheel against diff. materials*

Resistance to penetration could be translated into high normal force in case of hardened material, In case of grinding unhardened material force due to rubbing and ploughing may be more and can account for large tangential force. In addition, enhanced bond-chip and chip-workpiece rubbing with relatively long chip of unhardened material may also contribute towards escalation of the tangential force.

Grinding behaviour of a wheel is best understood with a wheel having just a single layer of abrasive grains bonded to a metallic core. Figure 27.16 shows steady grinding force with such a wheel during grinding of grey cast iron and unhardened bearing steel with gradual increase of cumulative infeed. This observation simply suggests that the grit geometry did not change significantly and wheel loading was also absent. This is true for all the infeeds.

However, situation was different when HSS (High speed steel) was ground. The grinding force showed clearly an increase with passage of grinding. The rate of increase of force also enhanced with increase of infeed. HSS being harder than unhardened bearing steel is expected to create less chip accommodation problem and can not be the cause of increase of grinding force. Hard constituents like carbides of W, Cr and V caused attrition wear on the grit tip leading to grit rounding and flattening. The irreversible change on the grit geometry was the main cause of gradual increase in grinding force with HSS.

27.11 Effect of grinding parameters on grinding force and surface roughness of the workpiece

Figure 27.17(a) indicates progressive decrease in grinding force with increase of grinding velocity. The opposite trend is observed when workpiece traverse speed on wheel depth of cut is increased.

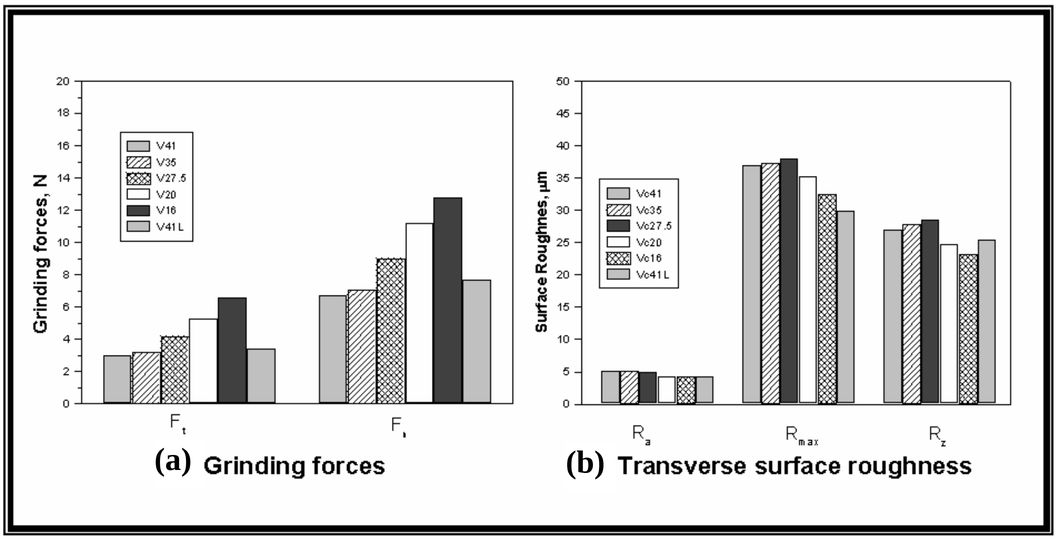
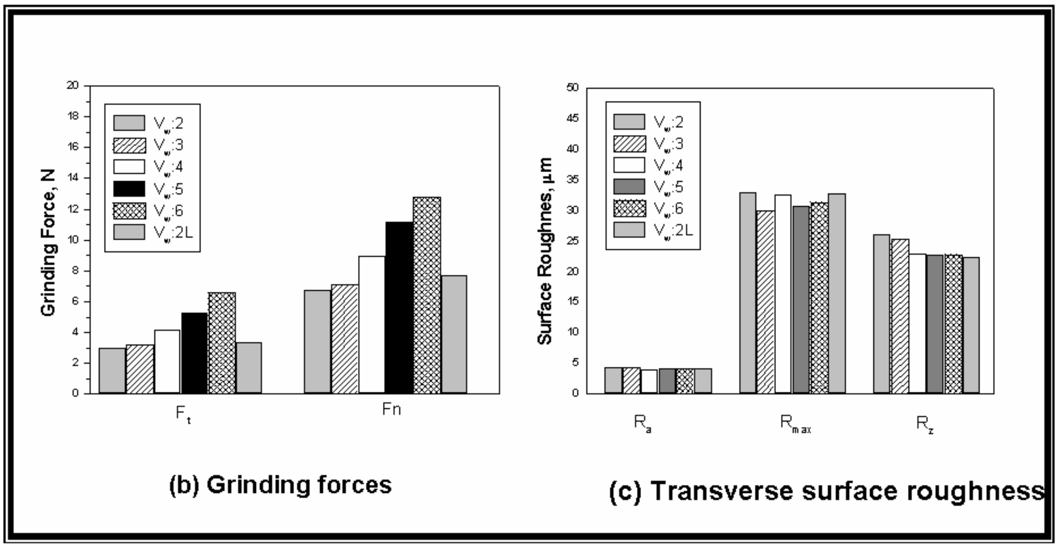


__Fig. 27.17__ Effect of grinding velocity (m/s)

This is indicated in Fig. 27.18(a) and Fig. 27.19(a). The variation of uncut layer thickness with grinding parameters causes the variation in force per grit as well as in total grinding force.



(a) (b)

__Fig. 27.18__ Effect of table feed (m/min)

Surface roughness of the workpiece in the transverse direction is a subject of major concern. Surface roughness in longitudinal direction is mostly found to be significantly low. The transverse surface roughness of a workpiece depends mainly on the grit geometry, over lap cuts made by the grits and lateral plastic flow of the work material.

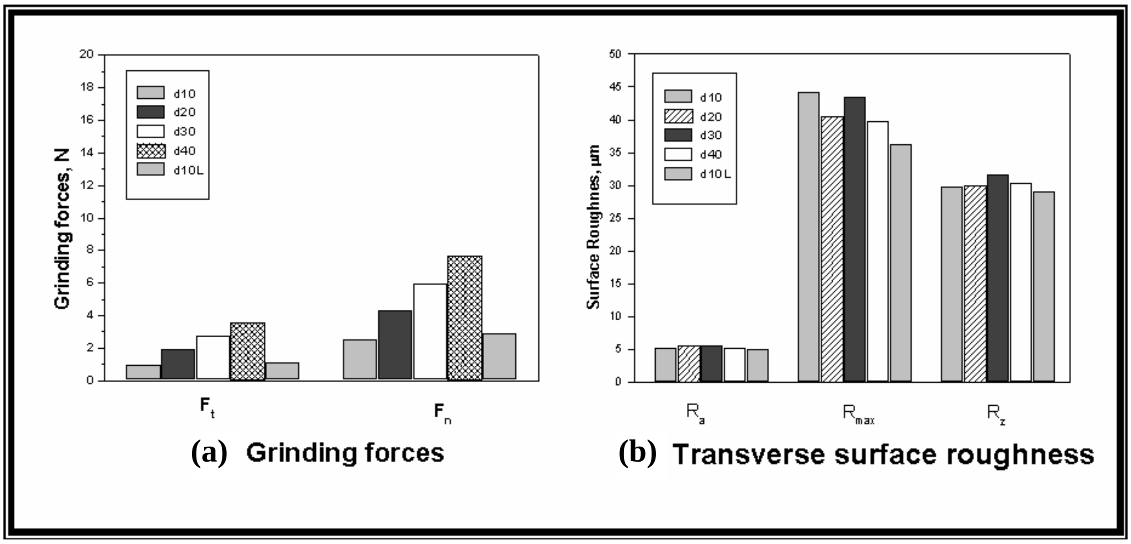


Fig. 27.19 *Effect of depth of cut (µm)*

Grinding parameters like grinding velocity, traverse speed or wheel depth of cut affects the grinding force which in turn can cause fracture, rounding or flattening on few overlying grits thus, bringing more number of underlying grits into action. This change in topographical feature of single layer wheel, in various levels, affects the surface roughness of the workpiece as illustrated in Fig. 27.17(b), 27.18(b) and 27.19(b). Grinding force increases with decrease in grinding velocity while the same increases with increase in table speed and depth of cut. Accordingly a trend is observed on decrease of surface roughness with decrease in grinding velocity and increase of both traverse speed and wheel depth of cut.

Exercise 27

Questions

Q1: Why is high velocity desired in grinding?

Q2: How may the specific grinding energy vary with material removal rate in grinding?

Q3: How is chip accommodation volume is related to material removal rate?

Q4: On which factors does the transverse roughness of workpiece depend during grinding?

Q5: Why does single layer grinding wheel show progressive rise of force during grinding of high speed steel?

Answers:

Ans 1:
It is desired to off set the adverse effect of very high negative rake angle of the working grit, to reduce the force per grit as well as the overall grinding force.

Ans 2:
Specific grinding energy will start decreasing with material removal rate because rake angle of the grit becomes more favourable with increase of grit depth of cut. However, if increase of material removal rate causes chip accommodation problem in the available inter-grit space then specific energy may increase.

Ans 3:
Volume of chip accommodation space ahead of each grit must be greater than the chip volume produced by each grit to facilitate easy evacuation of the chip from the grinding wheel.

Ans 4.
It mainly depends on the shape of the grits and overlap cuts made by the grits in the transverse direction. Lateral plastic flow of the material as a result of ploughing also influences the surface roughness.

Ans 5
The geometry of grit undergoes irreversible change in the form of rounding or flattening due to wear caused by rubbing action of hard carbides present in high speed steel.

Module
5
Abrasive Processes (Grinding)

Lesson
28
Selection of wheels and their conditioning

Instructional Objectives

At the end of this lesson the students would be able to

(i) identify need and purpose of grinding wheel specification
(ii) state the role of various compositional parameters of the grinding wheel
(iii) state the logical steps in selecting a grinding wheel
(iv) recognize need and purpose of grinding wheel conditioning
(v) illustrate various methods of wheel conditioning

28. Grinding wheels

Grinding wheel consists of hard abrasive grains called grits, which perform the cutting or material removal, held in the weak bonding matrix. A grinding wheel commonly identified by the type of the abrasive material used. The conventional wheels include aluminium oxide and silicon carbide wheels while diamond and cBN (cubic boron nitride) wheels fall in the category of superabrasive wheel.

28.1 Specification of grinding wheel

A grinding wheel requires two types of specification
(a) Geometrical specification
(b) Compositional specification

28.1.1 Geometrical specification

This is decided by the type of grinding machine and the grinding operation to be performed in the workpiece. This specification mainly includes wheel diameter, width and depth of rim and the bore diameter. The wheel diameter, for example can be as high as 400mm in high efficiency grinding or as small as less than 1mm in internal grinding. Similarly, width of the wheel may be less than an mm in dicing and slicing applications. Standard wheel configurations for conventional and superabrasive grinding wheels are shown in Fig.28.1 and 28.2.

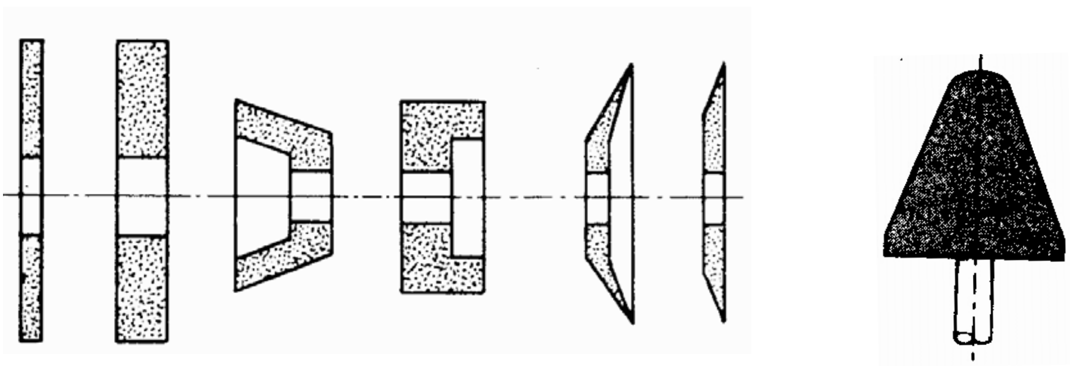


Fig.28.1*: Standard wheel configuration for conventional grinding wheels*

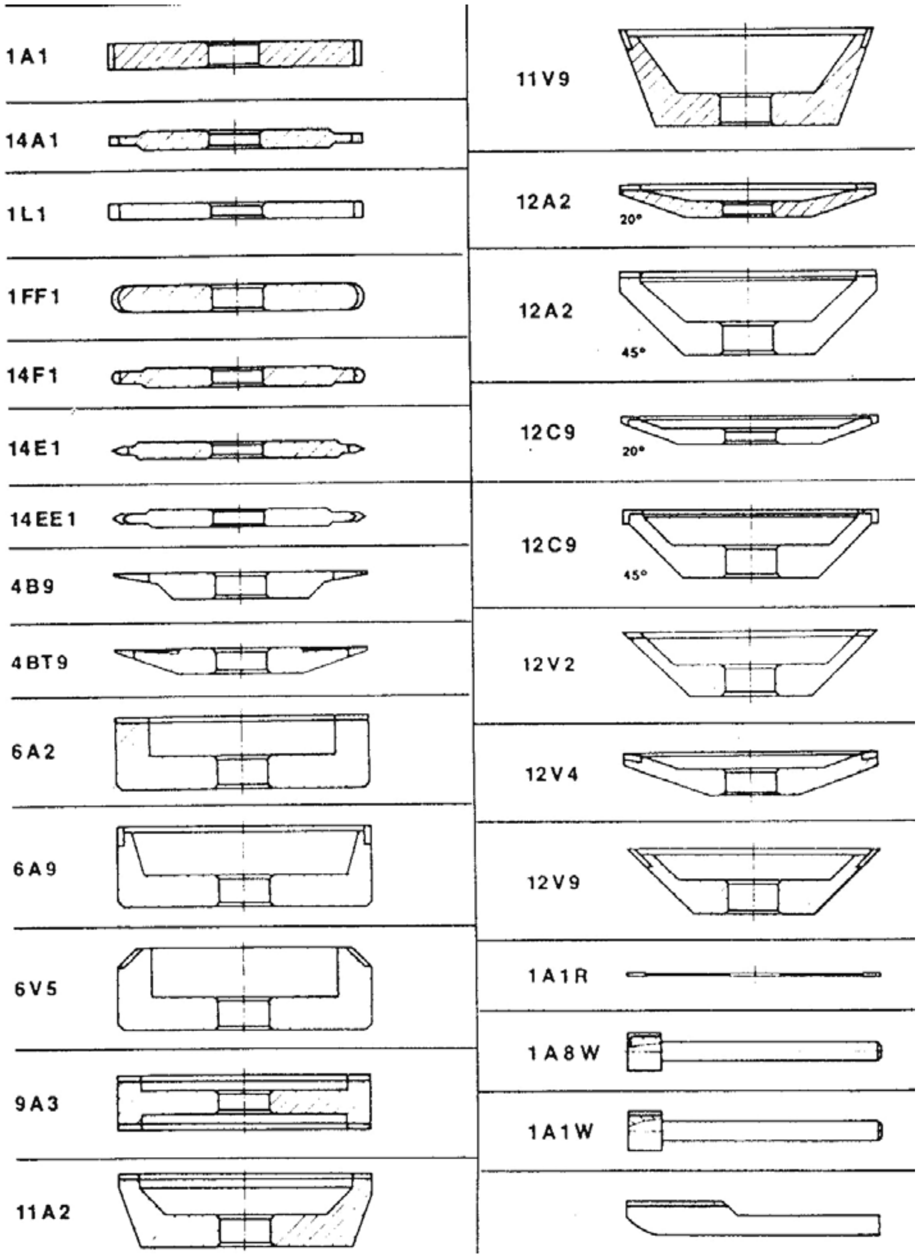


Fig.28.2: *Standard wheel configuration for superabrasive wheel*

<u>28.1.2 Compositional specifications</u>

Specification of a grinding wheel ordinarily means compositional specification. Conventional abrasive grinding wheels are specified encompassing the following parameters.

1) the type of grit material
2) the grit size
3) the bond strength of the wheel, commonly known as wheel hardness
4) the structure of the wheel denoting the porosity i.e. the amount of inter grit spacing
5) the type of bond material
6) other than these parameters, the wheel manufacturer may add their own identification code prefixing or suffixing (or both) the standard code.

Marking system for conventional grinding wheel

The standard marking system for conventional abrasive wheel can be as follows:

51 A 60 K 5 V 05, where

- The number ‘51’ is manufacturer’s identification number indicating exact kind of abrasive used.
- The letter ‘A’ denotes that the type of abrasive is aluminium oxide. In case of silicon carbide the letter ‘C’ is used.
- The number ‘60’ specifies the average grit size in inch mesh. For a very large size grit this number may be as small as 6 where as for a very fine grit the designated number may be as high as 600.
- The letter ‘K’ denotes the hardness of the wheel, which means the amount of force required to pull out a single bonded abrasive grit by bond fracture. The letter symbol can range between ‘A’ and ‘Z’, ‘A’ denoting the softest grade and ‘Z’ denoting the hardest one.
- The number ‘5’ denotes the structure or porosity of the wheel. This number can assume any value between 1 to 20, ‘1’ indicating high porosity and ‘20’ indicating low porosity.
- The letter code ‘V’ means that the bond material used is vitrified. The codes for other bond materials used in conventional abrasive wheels are B (resinoid), BF (resinoid reinforced), E(shellac), O(oxychloride), R(rubber), RF (rubber reinforced), S(silicate)
- The number ‘05’ is a wheel manufacturer’s identifier.

Marking system for superabrasive grinding wheel

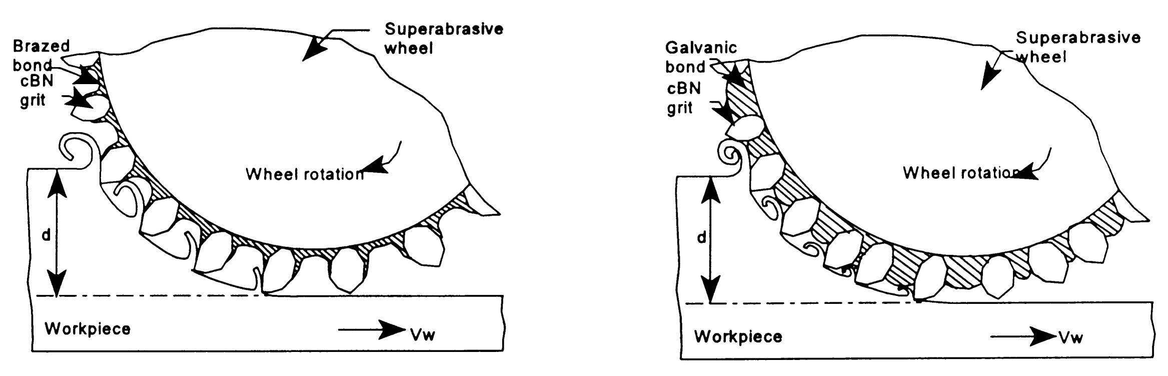
Marking system for superabrasive grinding wheel is somewhat different as illustrated below

R D 120 N 100 M 4, where

- The letter ‘R’ is manufacture’s code indicating the exact type of superabrasive used.
- The letter ‘D’ denotes that the type of abrasive is diamond. In case of cBN the letter ‘B’ is used.
- The number ‘120’ specifies the average grain size in inch mesh. However, a two number designation (e.g. 120/140) is utilized for controlling the size of superabrasive grit. The two number designation of grit size along with corresponding designation in micron is given in table 28.1.
- Like conventional abrasive wheel, the letter ‘N’ denotes the hardness of the wheel. However, resin and metal bonded wheels are produced with almost no porosity and effective grade of the wheel is obtained by modifying the bond formulation.
- The number ‘100’ is known as concentration number indicating the amount of abrasive contained in the wheel. The number ‘100’ corresponds to an

abrasive content of 4.4 carats/cm^3. For diamond grit, ‘100’ concentration is 25% by volume. For cBN the corresponding volumetric concentration is 24%.

- The letter ‘M’ denotes that the type of bond is metallic. The other types of bonds used in superabrasive wheels are resin, vitrified or metal bond, which make a composite structure with the grit material. However, another type of superabrasive wheel with both diamond and cBN is also manufactured where a single layer of superabrasive grits are bonded on a metal perform by a galvanic metal layer or a brazed metal layer as illustrated in Fig.28.3.



Brazed type wheel **Galvanic type wheel**

Fig.28.3 *Schematic diagrams for the relative comparison of brazed type and galvanically bonded single layer cBN grinding wheel*

28.2 Selection of grinding wheels

Selection of grinding wheel means selection of composition of the grinding wheel and this depends upon the following factors:

1) Physical and chemical characteristics of the work material
2) Grinding conditions
3) Type of grinding (stock removal grinding or form finish grinding)

28.2.1 Type of abrasives

Aluminium oxide

Aluminium oxide may have variation in properties arising out of differences in chemical composition and structure associated with the manufacturing process.

Pure Al_2O_3 grit with defect structure like voids leads to unusually sharp free cutting action with low strength and is advantageous in fine tool grinding operation, and heat sensitive operations on hard, ferrous materials.

Regular or brown aluminium oxide (doped with TiO_2) possesses lower hardness and higher toughness than the white Al_2O_3 and is recommended heavy duty grinding to semi finishing.

Al_2O_3 alloyed with chromium oxide (<3%) is pink in colour.

Monocrystalline Al_2O_3 grits make a balance between hardness and toughness and are efficient in medium pressure heat sensitive operation on ferrous materials.

Microcrystalline Al_2O_3 grits of enhanced toughness are practically suitable for stock removal grinding. Al_2O_3 alloyed with zirconia also makes extremely tough grit mostly suitably for high pressure, high material removal grinding on ferrous material and are not recommended for precision grinding. Microcrystalline sintered Al_2O_3 grit is the latest development particularly known for its toughness and self sharpening characteristics.

Silicon carbide

Silicon carbide is harder than alumina but less tough. Silicon carbide is also inferior to Al_2O_3 because of its chemical reactivity with iron and steel.

Black carbide containing at least 95% SiC is less hard but tougher than green SiC and is efficient for grinding soft nonferrous materials.

Green silicon carbide contains at least 97% SiC. It is harder than black variety and is used for grinding cemented carbide.

Diamond

Diamond grit is best suited for grinding cemented carbides, glass, sapphire, stone, granite, marble, concrete, oxide, non-oxide ceramic, fiber reinforced plastics, ferrite, graphite.

Natural diamond grit is characterized by its random shape, very sharp cutting edge and free cutting action and is exclusively used in metallic, electroplated and brazed bond.

Monocrystalline diamond grits are known for their strength and designed for particularly demanding application. These are also used in metallic, galvanic and brazed bond.

Polycrystalline diamond grits are more friable than monocrystalline one and found to be most suitable for grinding of cemented carbide with low pressure. These grits are used in resin bond.

cBN (cubic boron nitride)

Diamond though hardest is not suitable for grinding ferrous materials because of its reactivity. In contrast, cBN the second hardest material, because of its chemical stability is the abrasive material of choice for efficient grinding of HSS, alloy steels, HSTR alloys.

Presently cBN grits are available as monocrystalline type with medium strength and blocky monocrystals with much higher strength. Medium strength crystals are more friable and used in resin bond for those applications where grinding force is not so high. High strength crystals are used with vitrified, electroplated or brazed bond where large grinding force is expected.

Microcrystalline cBN is known for its highest toughness and auto sharpening character and found to be best candidate for HEDG and abrasive milling. It can be used in all types of bond.

28.2.2 Grit size

The grain size affects material removal rate and the surface quality of workpiece in grinding.
Large grit- big grinding capacity, rough workpiece surface
Fine grit- small grinding capacity, smooth workpiece surface

28.2.3 Grade

The worn out grit must pull out from the bond and make room for fresh sharp grit in order to avoid excessive rise of grinding force and temperature. Therefore, a soft grade should be chosen for grinding hard material. On the other hand, during grinding of low strength soft material grit does not wear out so quickly. Therefore, the grit can be held with strong bond so that premature grit dislodgement can be avoided.

28.2.4 Structure / concentration

The structure should be open for grinding wheels engaged in high material removal to provide chip accommodation space. The space between the grits also serves as pocket for holding grinding fluid. On the other hand dense structured wheels are used for longer wheel life, for holding precision forms and profiles.

28.2.5 Bond

vitrified bond

Vitrified bond is suitable for high stock removal even at dry condition. It can also be safely used in wet grinding. It can not be used where mechanical impact or thermal variations are like to occur. This bond is also not recommended for very high speed grinding because of possible breakage of the bond under centrifugal force.

Resin bond

Conventional abrasive resin bonded wheels are widely used for heavy duty grinding because of their ability to withstand shock load. This bond is also known for its vibration absorbing characteristics and finds its use with diamond and cBN in grinding of cemented carbide and steel respectively. Resin bond is not recommended with alkaline grinding fluid for a possible chemical attack leading to bond weakening. Fiberglass reinforced resin bond is used with cut off wheels which requires added strength under high speed operation.

Shellac bond

At one time this bond was used for flexible cut off wheels. At present use of shellac bond is limited to grinding wheels engaged in fine finish of rolls.

Oxychloride bond

It is less common type bond, but still can be used in disc grinding operation. It is used under dry condition.

Rubber bond

Its principal use is in thin wheels for wet cut-off operation. Rubber bond was once popular for finish grinding on bearings and cutting tools.

Metal bond

Metal bond is extensively used with superabrasive wheels. Extremely high toughness of metal bonded wheels makes these very effective in those applications where form accuracy as well as large stock removal is desired.

Electroplated bond

This bond allows large (30-40%) crystal exposure above the bond without need of any truing or dressing. This bond is specially used for making small diameter wheel, form wheel and thin superabrasive wheels. Presently it is the only bond for making wheels for abrasive milling and ultra high speed grinding.

Brazed bond

This is relatively a recent development, allows crystal exposure as high 60-80%. In addition grit spacing can be precisely controlled. This bond is particularly suitable for very high material removal either with diamond or cBN wheel. The bond strength is much greater than provided by electroplated bond. This bond is expected to replace electroplated bond in many applications.

28.3 Truing and dressing of grinding wheel

28.3.1 Truing

Truing is the act of regenerating the required geometry on the grinding wheel, whether the geometry is a special form or flat profile. Therefore, truing produces the macro-geometry of the grinding wheel.

Truing is also required on a new conventional wheel to ensure concentricity with specific mounting system. In practice the effective macro-geometry of a grinding wheel is of vital importance and accuracy of the finished workpiece is directly related to effective wheel geometry.

28.3.2 Truing tools

There are four major types of truing tools:

Steel cutter:

These are used to roughly true coarse grit conventional abrasive wheel to ensure freeness of cut.

Vitrified abrasive stick and wheel:

It is used for off hand truing of conventional abrasive wheel. These are used for truing resin bonded superabrasive wheel.

Steel or carbide crash roll

It is used to crush-true the profile on vitrified bond grinding wheel.

Diamond truing tool:

Single point diamond truing tools

The single point diamond truing tools for straight face truing are made by setting a high quality single crystal into a usually cylindrical shank of a specific diameter and length by brazing or casting around the diamond. During solidification contraction of the bonding metal is more than diamond and latter is held mechanically as result of contraction of metal around it. Some application of single point diamond truing tool is illustrated in Fig.28.4

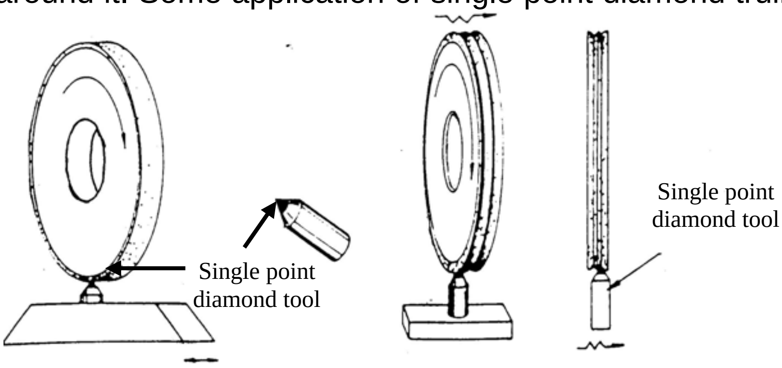
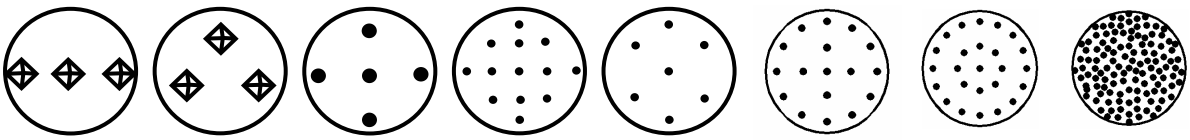


Fig 28.4 *Application of single point diamond truing tool*

Multi stone diamond truing tool

In this case the truing tool consists of a number of small but whole diamonds, some or all of which contact the abrasive wheel at the same time. The diamond particles are surface set with a metal binder and it is possible to make such tool with one layer or multilayer configuration. Normal range of diamond used in this tool is from as small as about 0.02 carat to as large as of 0.5 carat. These tools are suitable for heavy and rough truing operation. Distribution pattern of diamond in this tool shown in Fig.28.5



Distribution of diamond	Diamond weight	Distribution of diamond`	Diamond weight
(i) 1 layer-3stone	10	(v) 5 layer-17 stone	50
(ii) 2 layer-3 stone	10	(vi) 5 layer-7 stone	10
(iii) 3 layer-5 stone	10	(vii) 5 layer-25 stone	250
(iv) 5 layer-13 stone	25	(viii) throughout	50

Fig 28.5 *Diamond distribution pattern of diamond particles in multi-stone diamond*

Impregnated diamond truing tools

This wheel truing tool consists of crushed and graded diamond powder mixed with metal powder and sintered. The diamond particles are not individually set in a pattern but are distributed evenly throughout the matrix in the same way that an abrasive wheel consists of abrasive grains and bonding agent. The size of diamond particles may vary from 80-600 microns. By using considerably smaller diamond grit and smaller diamond section it is possible to true sharp edge and fine grit grinding wheel. The use of crushed diamond product ensures that there are always many sharp points in use at the same time and these tools are mainly used in fine grinding, profile grinding, thread grinding, cylindrical grinding and tool grinding. Truing action of an impregnated diamond tool is shown schematically in Fig28.6.

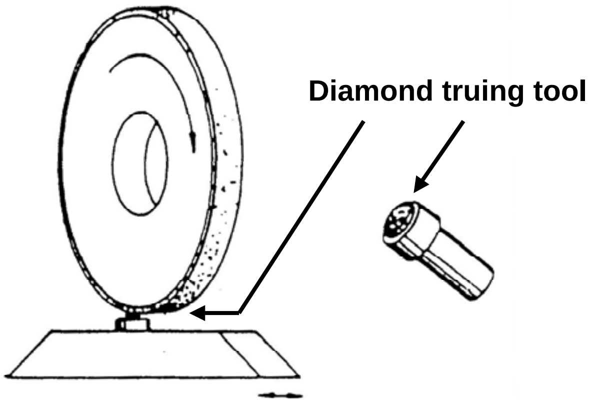


Fig. 28.6 *Impregnated diamond truing tools*

<u>Rotary powered diamond truing wheels</u>
Rotary powered truing devices (Fig.28.7) are the most widely recommended truing tool in long run mass production and are not ideally suited for those wheels with large diameters (greater than 200 mm). They can be pneumatic, hydraulic or electrically powered. Rotary powered truing device can be used in cross axis and parallel axis mode. Basically there are three types of truing wheels.

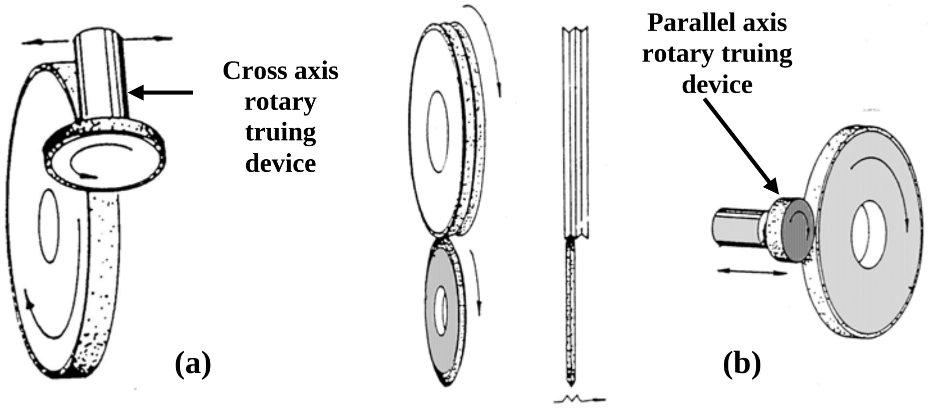


Fig. 28.7 *Rotary power truing wheel being used in (a) cross-axis (b) parallel-axis*

<u>Surface set truing wheels</u>
Here the diamond particles are set by hand in predetermined pattern. A sintered metal bond is used in this case. These truing wheels are designed for high production automated operations.

<u>Impregnated truing wheels</u>
In this case impregnated diamond particles are distributed in a random pattern to various depths in a metal matrix. This type of roll finds its best applications (i.e. groove grinding) where excess wheel surfaces must be dressed of.

Electroplated truing tool

In this truing wheel diamond particles are bonded to the wheel surface with galvanically deposited metal layer. Main advantage of this technique is that no mould is necessary to fabricate the diamond truing wheel unlike that of surface set or impregnated truing wheels.

Diamond form truing blocks

`Diamond form truing block can be either diamond impregnated metal bond or electroplated, as shown in Fig.28.8. Brazed type diamond truing block has also come as an alternative to electroplated one. They can be as simple as flat piece of metal plated with diamond to true a straight faced wheel or contain an intricate form to shape the grinding wheel to design profile. Truing block can eliminate the use of self propelled truing wheels and are used almost exclusively for horizontal spindle surface grinder to generate specific form.

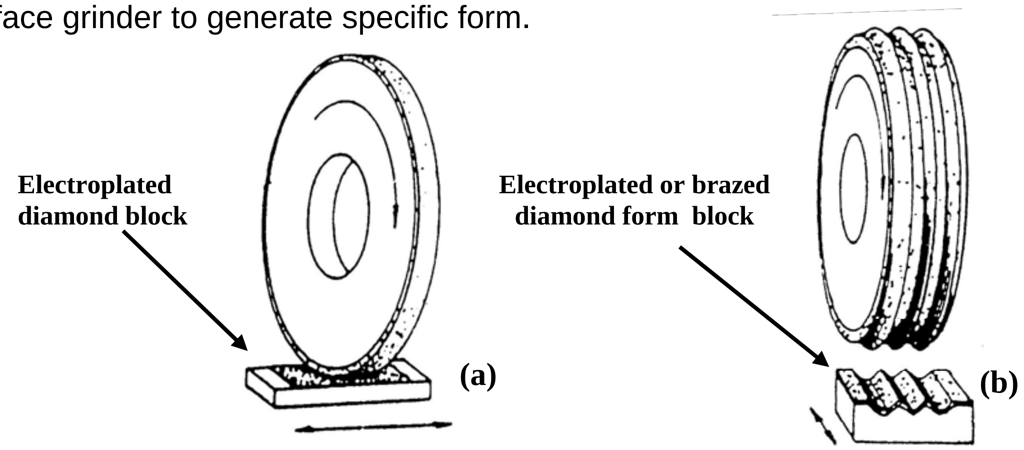


***Fig. 28.8** Diamond form truing block to true*

(a) a straight faced wheel (b) a form wheel

28.3.3 Dressing

Dressing is the conditioning of the wheel surface which ensures that grit cutting edges are exposed from the bond and thus able to penetrate into the workpiece material. Also, in dressing attempts are made to splinter the abrasive grains to make them sharp and free cutting and also to remove any residue left by material being ground. Dressing therefore produces micro-geometry. The structure of micro-geometry of grinding wheel determine its cutting ability with a wheel of given composition. Dressing can substantially influence the condition of the grinding tool.

Truing and dressing are commonly combined into one operation for conventional abrasive grinding wheels, but are usually two distinctly separate operation for superabrasive wheel.

Dressing of superabrasive wheel

Dressing of the superabrasive wheel is commonly done with soft conventional abrasive vitrified stick, which relieves the bond without affecting the superabrasive grits.

However, modern technique like electrochemical dressing has been successfully used in metal bonded superabrasive wheel. The wheel acts like an anode while a cathode plate is placed in front of the wheel working surface to allow electrochemical dissolution.

Electro discharge dressing is another alternative route for dressing metal bonded superabrasive wheel. In this case a dielectric medium is used in place of an electrolyte.

Touch-dressing, a new concept differs from conventional dressing in that bond material is not relieved. In contrast the dressing depth is precisely controlled in micron level to obtain better uniformity of grit height resulting in improvement of workpiece surface finish.

Exercise 28

Q1. Why is aluminium oxide preferred to silicon carbide in grinding steel?

Q2. Why is coarse grain and open structured wheel is preferred for stock removal grinding?

Q3. What is the main short coming of vitrified bond?

Q4. Is dressing necessary for single layer wheel?

Q5. Can a resin bonded cBN wheel be electrochemically dressed?

Answer to Exercise 28

Answer to Q1:
Al_2O_3 is tougher than SiC. Therefore it is preferred to grind material having high tensile strength like steel. Moreover, Al_2O_3 shows higher chemical inertness than SiC towards steel leading to much improved wear resistance during grinding.

Answer to Q2:
Coarse grit allows large grit protrusion and open structure provides large inter grit chip space. Thus in combination those two provide large space for chip accommodation during stock removal grinding and risk of wheel loading is minimized.

Answer to Q3:
Vitrified bond is brittle and can not with stand high impact loads. This bond can not be used for high wheel speed due to risk of wheel breakage under centrifugal force.

Answer to Q4:
Conventional macro level dressing is not required because the wheel inherently has an open structure. However, touch dressing is carried out to obtain better uniformity in grit height in order to improve surface finish of the workpiece.

Answer to Q5:
Electrochemical dressing is not possible with resin bonded wheel because it is not electrically conducting.

Module 5

Abrasive Processes (Grinding)

Lesson
29
Classification of grinding machines and their uses

Instructional Objectives

At the end of this lesson the students would be able to:

(i) recognise various types of basic grinding machines
(ii) illustrate techniques of grinding in these machines
(iii) state various applications of grinding machines

29. Grinding Machines

Grinding Machines are also regarded as machine tools. A distinguishing feature of grinding machines is the rotating abrasive tool. Grinding machine is employed to obtain high accuracy along with very high class of surface finish on the workpiece. However, advent of new generation of grinding wheels and grinding machines, characterised by their rigidity, power and speed enables one to go for high efficiency deep grinding (often called as abrasive milling) of not only hardened material but also ductile materials.

Conventional grinding machines can be broadly classified as:

(a) Surface grinding machine
(b) Cylindrical grinding machine
(c) Internal grinding machine
(d) Tool and cutter grinding machine

29.1 Surface grinding machine:

This machine may be similar to a milling machine used mainly to grind flat surface. However, some types of surface grinders are also capable of producing contour surface with formed grinding wheel.

Basically there are four different types of surface grinding machines characterised by the movement of their tables and the orientation of grinding wheel spindles as follows:

- Horizontal spindle and reciprocating table
- Vertical spindle and reciprocating table
- Horizontal spindle and rotary table
- Vertical spindle and rotary table

29.1.1 Horizontal spindle reciprocating table grinder

Figure 29.1 illustrates this machine with various motions required for grinding action. A disc type grinding wheel performs the grinding action with its peripheral surface. Both traverse and plunge grinding can be carried out in this machine as shown in Fig. 29.2

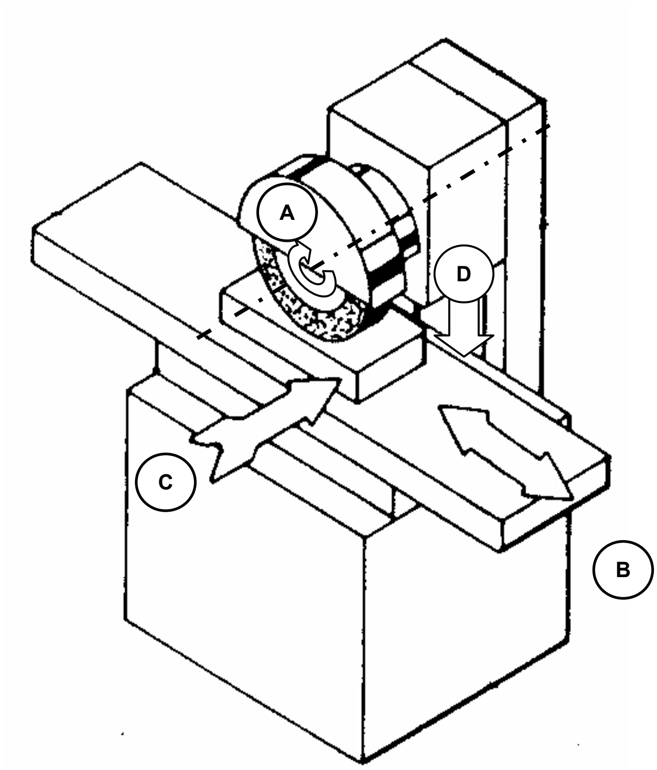


Fig.29.1*: Horizontal spindle reciprocating table surface grinder*

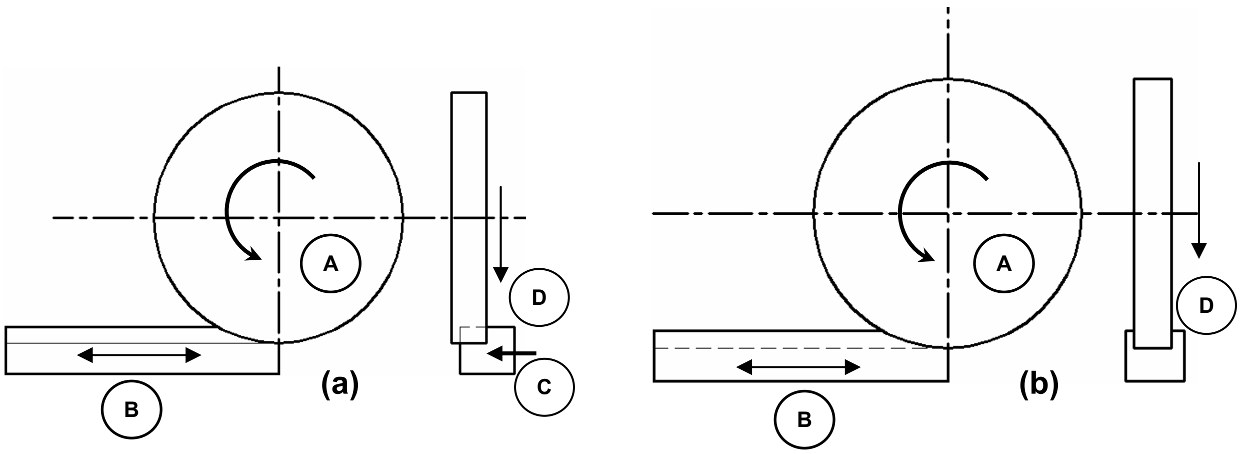


Fig. 29.2 *Surface grinding (a) traverse grinding (b) plunge grinding*

29.1.2 Vertical spindle reciprocating table grinder

This grinding machine with all working motions is shown in Fig. 29.3. The grinding operation is similar to that of face milling on a vertical milling machine. In this machine a cup shaped wheel grinds the workpiece over its full width using end face of the wheel as shown in Fig. 29.4. This brings more grits in action at the same time and consequently a higher material removal rate may be attained than for grinding with a peripheral wheel.

A: rotation of grinding wheel B: reciprocation of worktable
C: down feed of grinding wheel

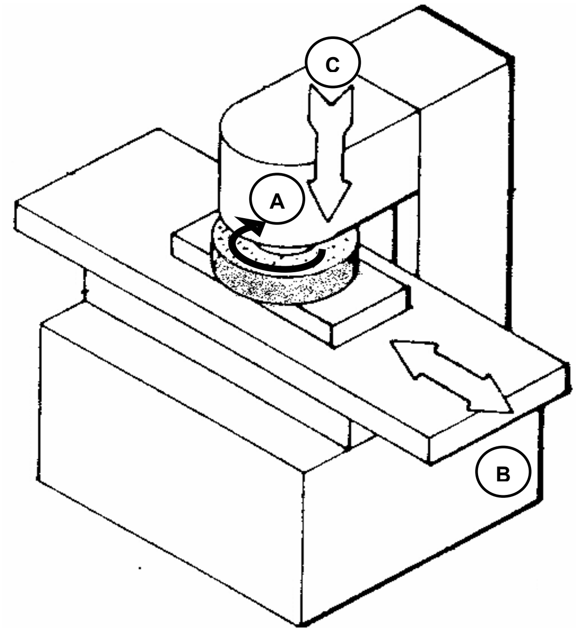


Fig. 29.3 *Vertical spindle reciprocating table surface grinder*

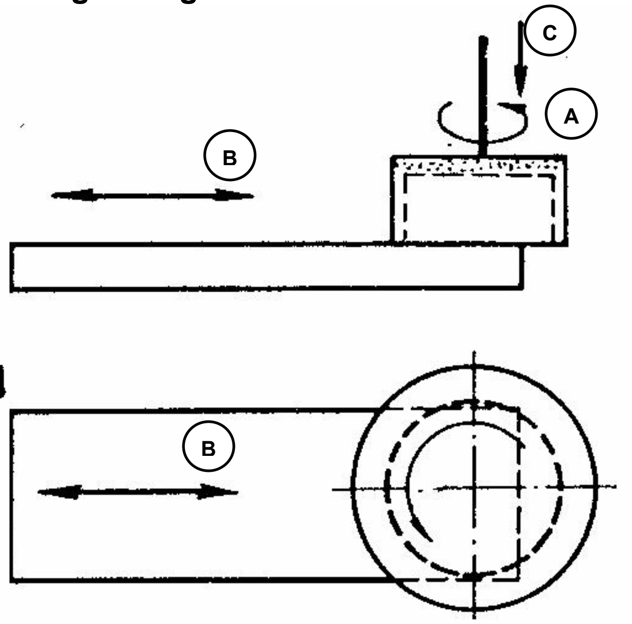
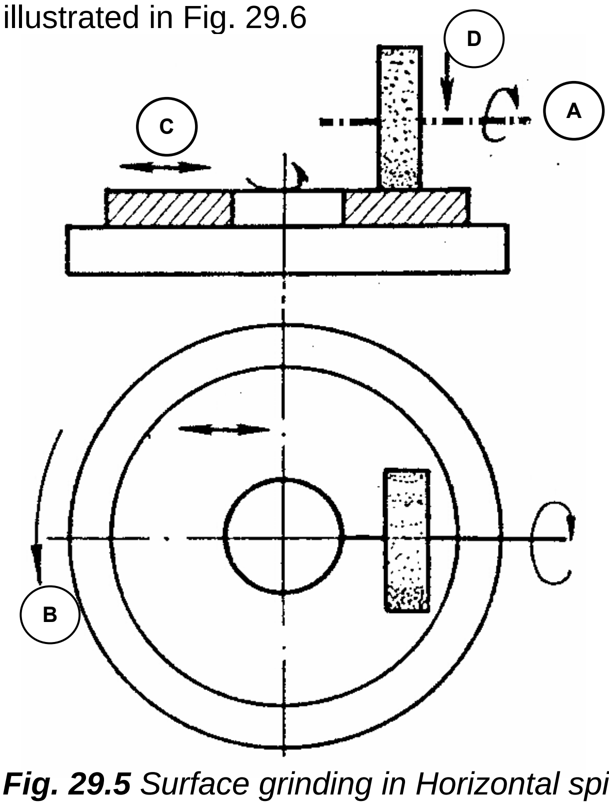


Fig. 29.4 *Surface grinding in Vertical spindle reciprocating table surface grinder*

29.1.3 Horizontal spindle rotary table grinder

Surface grinding in this machine is shown in Fig.29.5. In principle the operation is same as that for facing on the lathe. This machine has a limitation in accommodation of workpiece and therefore does not have wide spread use. However, by swivelling the worktable, concave or convex or tapered surface can be produced on individual part as illustrated in Fig. 29.6



A: rotation of grinding wheel
B: table rotation
C: table reciprocation
D: down feed of grinding wheel

Fig. 29.5 *Surface grinding in Horizontal spindle rotary table surface grinder*

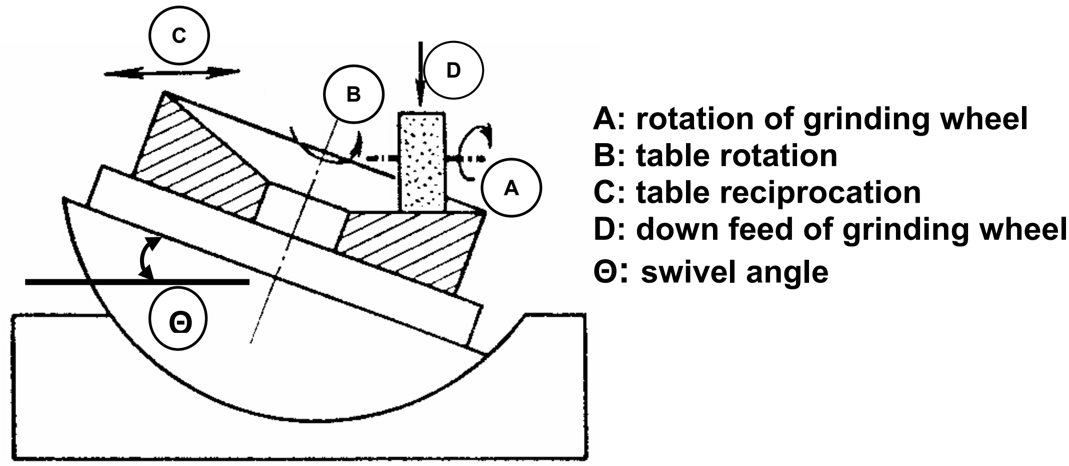


Fig. 29.6 *Grinding of a tapered surface in horizontal spindle rotary table surface grinder*

29.1.4 Vertical spindle rotary table grinder

The principle of grinding in this machine is shown in Fig. 29.7. The machine is mostly suitable for small workpieces in large quantities. This primarily production type machine often uses two or more grinding heads thus enabling both roughing and finishing in one rotation of the work table.

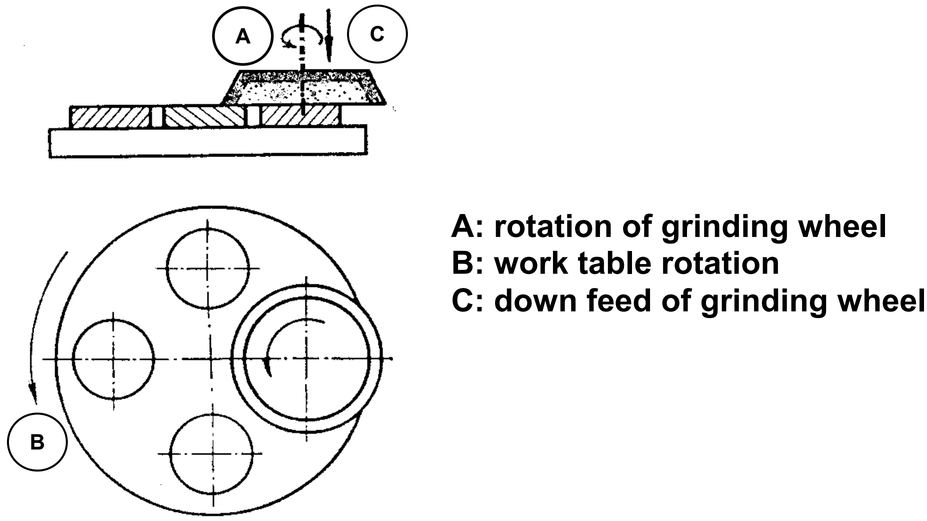


Fig. 29.7 *Surface grinding in vertical spindle rotary table surface grinder*

29.1.5 Creep feed grinding machine:

This machine enables single pass grinding of a surface with a larger downfeed but slower table speed than that adopted for multi-pass conventional surface grinding. This machine is characterised by high stiffness, high spindle power, recirculating ball screw drive for table movement and adequate supply of grinding fluid. A further development in this field is the creep feed grinding centre which carries more than one wheel with provision of automatic wheel changing. A number of operations can be performed on the workpiece. It is implied that such machines, in the view of their size and complexity, are automated through CNC.

29.1.6 High efficiency deep grinding machine:

The concept of single pass deep grinding at a table speed much higher than what is possible in a creep feed grinder has been technically realized in this machine. This has been made possible mainly through significant increase of wheel speed in this new generation grinding machine.

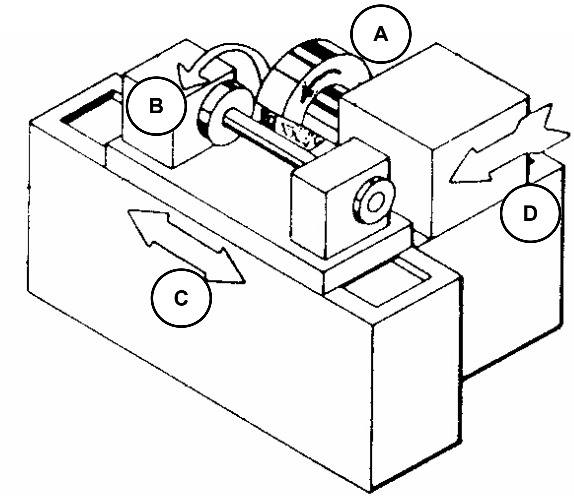
29.2 Cylindrical grinding machine

This machine is used to produce external cylindrical surface. The surfaces may be straight, tapered, steps or profiled. Broadly there are three different types of cylindrical grinding machine as follows:

1. Plain centre type cylindrical grinder
2. Universal cylindrical surface grinder
3. Centreless cylindrical surface grinder

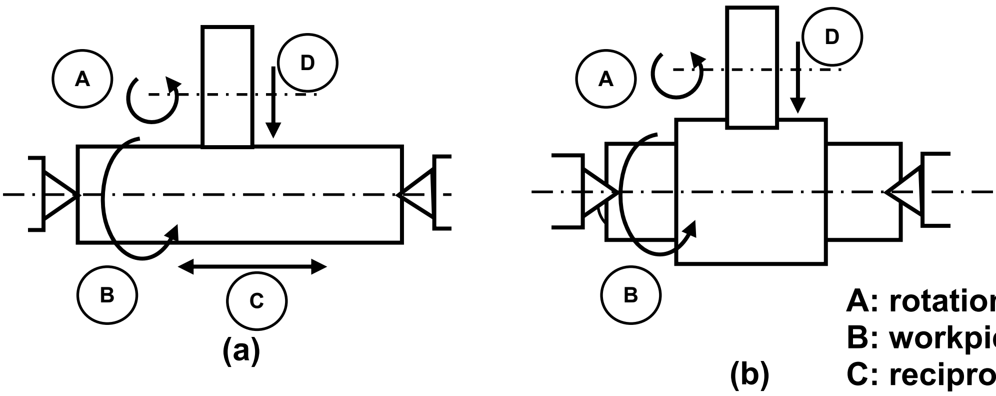
29.2.1 Plain centre type cylindrical grinder

Figure 29.8 illustrates schematically this machine and various motions required for grinding action. The machine is similar to a centre lathe in many respects. The workpiece is held between head stock and tailstock centres. A disc type grinding wheel performs the grinding action with its peripheral surface. Both traverse and plunge grinding can be carried out in this machine as shown in Fig.29.9.



A: rotation of grinding wheel
B: work table rotation
C: reciprocation of worktable
D: infeed

Fig. 29.8 *Plain centre type cylindrical grinder*

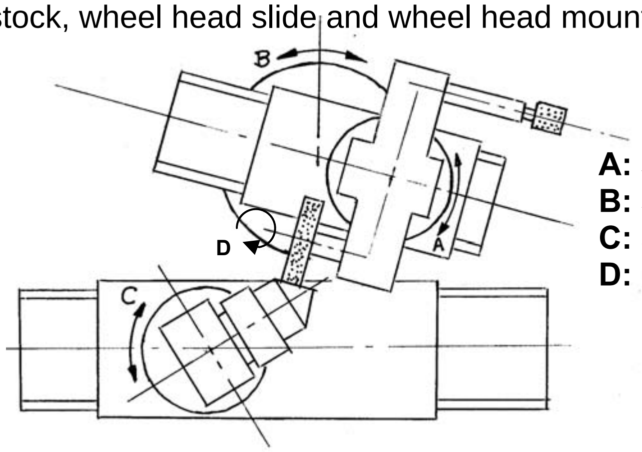


A: rotation of grinding wheel
B: workpiece rotation
C: reciprocation of worktable
D: infeed

Fig. 29.9 *cylindrical (a) traverse grinding and (b) plunge grinding*

29.2.2 Universal cylindrical surface grinder

Universal cylindrical grinder is similar to a plain cylindrical one except that it is more versatile. In addition to small worktable swivel, this machine provides large swivel of head stock, wheel head slide and wheel head mount on the wheel head slide.



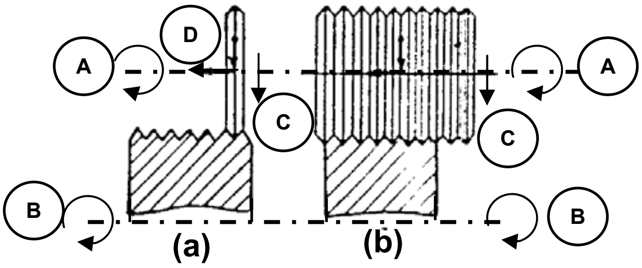
A: swivelling wheel head
B: swivelling wheel head slide
C: swivelling head stock
D: rotation of grinding wheel

Fig. 29.10 *important features of universal cylindrical grinding machine*

This allows grinding of any taper on the workpiece. Universal grinder is also equipped with an additional head for internal grinding. Schematic illustration of important features of this machine is shown in Fig.29.10.

29.2.3 Special application of cylindrical grinder

Principle of cylindrical grinding is being used for thread grinding with specially formed wheel that matches the thread profile. A single ribbed wheel or a multi ribbed wheel can be used as shown in Fig. 29.11.

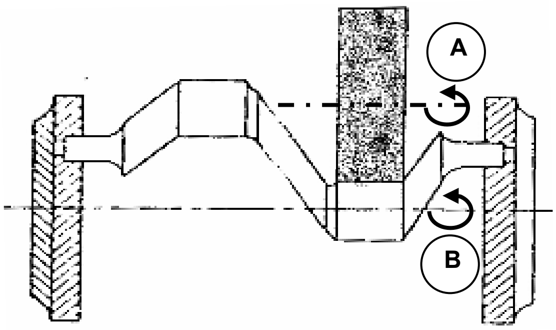


A: rotation of grinding wheel
B: rotation of workpiece
C: Downfeed
D: Longitudinal feed of wheel

Fig. 29.11 *Thread grinding with (a) single rib (b) multi-ribbed wheel*

Roll grinding is a specific case of cylindrical grinding wherein large workpieces such as shafts, spindles and rolls are ground.

Crankshaft or crank pin grinders also resemble cylindrical grinder but are engaged to grind crank pins which are eccentric from the centre line of the shaft as shown in Fig. 29.12. The eccentricity is obtained by the use of special chuck.



A: rotation of wheel
B: rotation of crank pin

Fig. 29.12 *Grinding of crank pin*

Cam and camshaft grinders are essentially subsets of cylindrical grinding machine dedicated to finish various profiles on disc cams and cam shafts. The desired contour on the workpiece is generated by varying the distance between wheel and workpiece axes. The cradle carrying the head stock and tail stock is provided with rocking motion derived from the rotation of a master cam that rotates in synchronisation with the workpiece. Newer machines however, use CNC in place of master cam to generate cam on the workpiece.

<u>29.2.4 External centreless grinder</u>

This grinding machine is a production machine in which out side diameter of the workpiece is ground. The workpiece is not held between centres but by a work support blade. It is rotated by means of a regulating wheel and ground by the grinding wheel.

In through-feed centreless grinding, the regulating wheel revolving at a much lower surface speed than grinding wheel controls the rotation and longitudinal motion of the workpiece. The regulating wheel is kept slightly inclined to the axis of the grinding wheel and the workpiece is fed longitudinally as shown in Fig. 29.14.

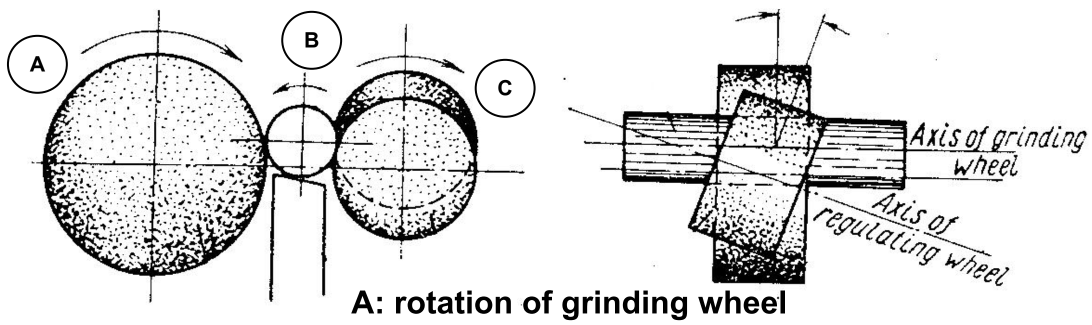
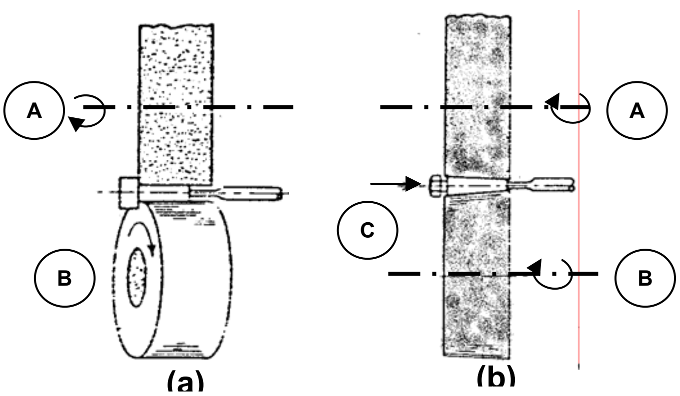


Fig.29.14: *Centreless through feed grinding*

Parts with variable diameter can be ground by Centreless infeed grinding as shown in Fig. 29.15(a). The operation is similar to plunge grinding with cylindrical grinder.
End feed grinding shown in Fig. 29.15 (b) is used for workpiece with tapered surface.



A: rotation of grinding wheel
B: rotation of regulating wheel
C: feed on workpiece

Fig. 29.15 *Centreless (a) infeed and (b) end feed grinding*

The grinding wheel or the regulating wheel or both require to be correctly profiled to get the required taper on the workpiece.

29.2.5 Tool post grinder

A self powered grinding wheel is mounted on the tool post or compound rest to provide the grinding action in a lathe. Rotation to the workpiece is provided by the lathe spindle. The lathe carriage is used to reciprocate the wheel head.

29.3 Internal grinding machine

This machine is used to produce internal cylindrical surface. The surface may be straight, tapered, grooved or profiled.
Broadly there are three different types of internal grinding machine as follows:

1. Chucking type internal grinder
2. Planetary internal grinder
3. Centreless internal grinder

29.3.1 Chucking type internal grinder

Figure 29.16 illustrates schematically this machine and various motions required for grinding action. The workpiece is usually mounted in a chuck. A magnetic face plate can also be used. A small grinding wheel performs the necessary grinding with its peripheral surface. Both transverse and plunge grinding can be carried out in this machine as shown in Fig. 29.17.

A: rotation of grinding wheel **B: workpiece rotation**
C: reciprocation of worktable **D: infeed**

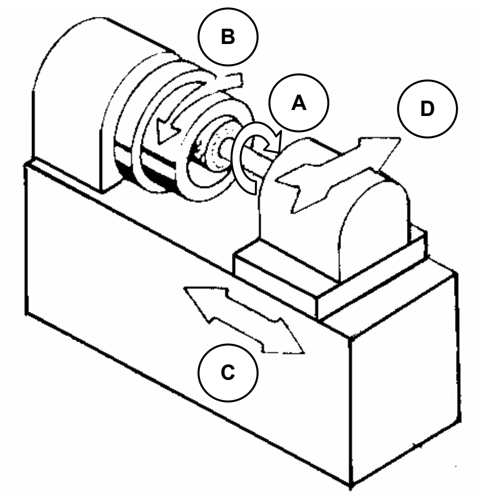


Fig. 29.16 Internal centreless grinder

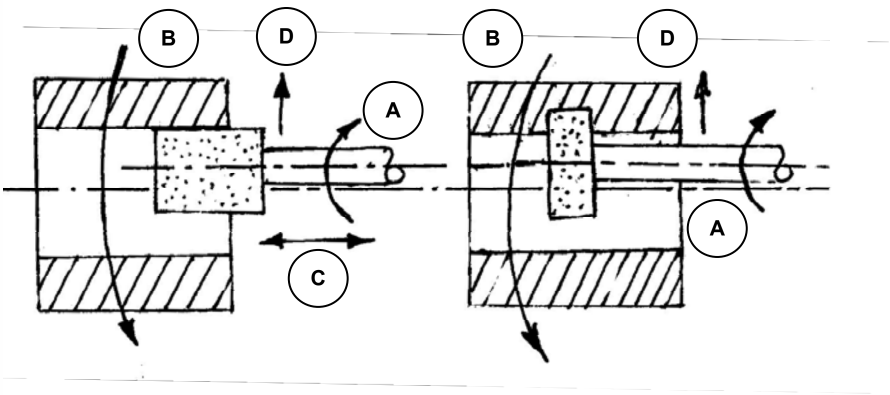
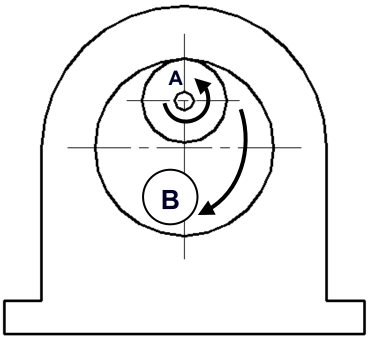


***Fig. 29.17** Internal (a) traverse grinding and (b) plunge grinding*

29.3.2 Planetary internal grinder

Planetary internal grinder is used where the workpiece is of irregular shape and can not be rotated conveniently as shown in Fig. 29.18. In this machine the workpiece does not rotate. Instead, the grinding wheel orbits the axis of the hole in the workpiece.

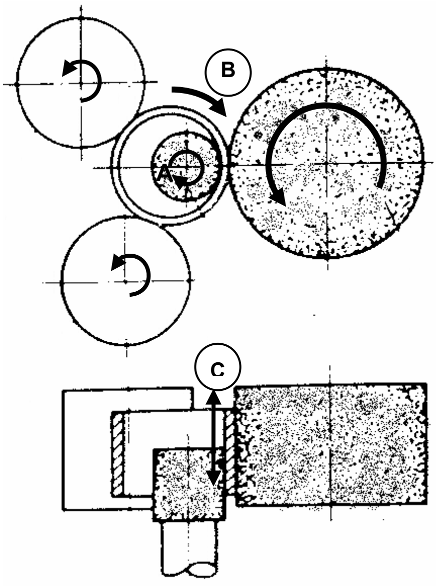


A: rotation of grinding wheel
B: orbiting motion of grinding

Fig. 29.18 *Internal grinding in planetary grinder*

29.3.3 Centreless internal grinder

This machine is used for grinding cylindrical and tapered holes in cylindrical parts (e.g. cylindrical liners, various bushings etc). The workpiece is rotated between supporting roll, pressure roll and regulating wheel and is ground by the grinding wheel as illustrated in Fig. 29.19



A: grinding wheel rotation
B: workpiece rotation
C: wheel reciprocation

Fig. 29.19 *Internal centreless grinding*

29.4 Tool and cutter grinder machine

Tool grinding may be divided into two subgroups: tool manufacturing and tool resharpening. There are many types of tool and cutter grinding machine to meet these requirements. Simple single point tools are occasionally sharpened by hand on bench or pedestal grinder. However, tools and cutters with complex geometry like milling cutter, drills, reamers and hobs require sophisticated grinding machine commonly known as universal tool and cutter grinder. Present trend is to use tool and cutter grinder equipped with CNC to grind tool angles, concentricity, cutting edges and dimensional size with high precision.

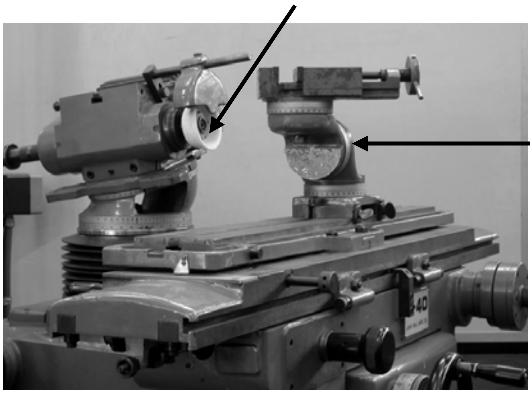


Fig. 29.20 *Pictorial view of a tool and cutter grinder*

Exercise 29

Q1. State the basic advantage of a creep feed grinder over a conventional surface grinder.
Q2. State the specific application of a planetary internal grinder.
Q3. What are the characteristic features of a universal cylindrical grinder?
Q4. State the disadvantages of centreless cylindrical grinding machine?
Q5. Is transverse feed provided in vertical spindle reciprocating table surface grinder?

Answer of the questions given in Exercise 29

Ans. to Q1.
Productivity is enhanced and life of the grinding wheel is extended.

Ans. to Q2.
Planetary internal grinders find application for grinding holes in workpieces of irregular shape or large heavy workpieces.

Ans. to Q3.
Characteristic features of a universal cylindrical grinder not possessed by plain cylindrical grinder are:

- Swivelling wheel head
- Swivelling wheel head slide
- Swivelling head stock

Ans. to Q4.
Disadvantages of a centreless cylindrical grinder are:

- It does not grind concentrically with centres.
- Large diameter short workpiece are difficult to control in the process
- It may not improve workpiece perpendicularity.

Ans to Q5.
Usually no transverse feed is provided in such machine. The wheel diameter is kept larger than the width of the workpiece surface to be ground.

Module
6
Superfinishing processes

Lesson 30

Superfinishing processes, Honing, Lapping and Superfinishing

Instructional Objectives

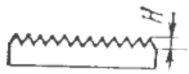
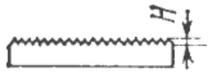
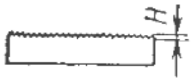
At the end of this lesson the students would be able to

(i) understand the significance of superfinishing process
(ii) state various applications of the superfinishing process
(iii) illustrate various techniques of superfinishing process

To ensure reliable performance and prolonged service life of modern machinery, its components require to be manufactured not only with high dimensional and geometrical accuracy but also with high surface finish. The surface finish has a vital role in influencing functional characteristics like wear resistance, fatigue strength, corrosion resistance and power loss due to friction. Unfortunately, normal machining methods like turning, milling or even classical grinding can not meet this stringent requirement.

Table 30.1 illustrates gradual improvement of surface roughness produced by various processes ranging from precision turning to superfinishing including lapping and honing.

Table 30.1

Process	Diagram of resulting surface	Height of micro irregularity (μm)
Precision Turning		1.25-12.50
Grinding		0.90-5.00
Honing		0.13-1.25
Lapping		0.08-0.25
Super Finishing		0.01-0.25

Therefore, superfinishing processes like lapping, honing, polishing, burnishing are being employed to achieve and improve the above-mentioned functional properties in the machine component.

30.1 Lapping

Lapping is regarded as the oldest method of obtaining a fine finish. Lapping is basically an abrasive process in which loose abrasives function as cutting points finding momentary support from the laps. Figure 30.1 schematically represents the lapping process. Material removal in lapping usually ranges from .003 to .03 mm but many reach 0.08 to 0.1mm in certain cases.

Characteristics of lapping process:

- Use of loose abrasive between lap and the workpiece
- Usually lap and workpiece are not positively driven but are guided in contact with each other
- Relative motion between the lap and the work should change continuously so that path of the abrasive grains of the lap is not repeated on the workpiece.

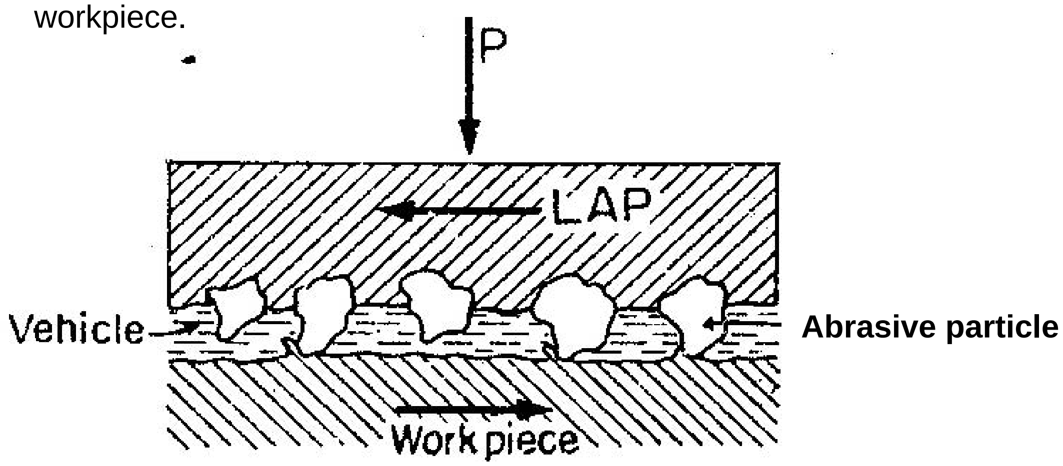


Fig. 30.1 *Scheme of lapping process*

Cast iron is the mostly used lap material. However, soft steel, copper, brass, hardwood as well as hardened steel and glass are also used.

Abrasives of lapping:

- Al_2O_3 and SiC, grain size 5~100μm
- Cr_2O_3, grain size 1~2 μm
- B_4C_3, grain size 5-60 μm
- Diamond, grain size 0.5~5 V

Vehicle materials for lapping

- Machine oil
- Rape oil
- grease

Technical parameters affecting lapping processes are:

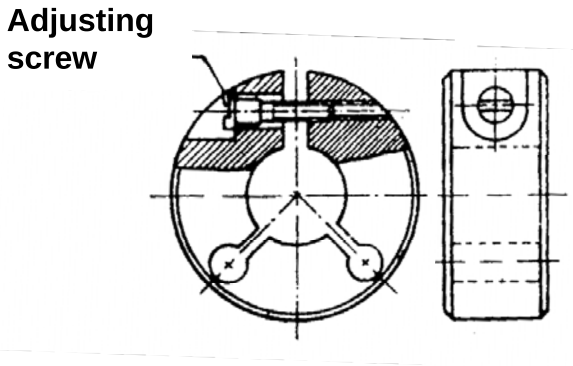
- unit pressure
- the grain size of abrasive
- concentration of abrasive in the vehicle
- lapping speed

Lapping is performed either manually or by machine. Hand lapping is done with abrasive powder as lapping medium, whereas machine lapping is done either with abrasive powder or with bonded abrasive wheel.

30.1.1 Hand lapping

Hand lapping of flat surface is carried out by rubbing the component over accurately finished flat surface of master lap usually made of a thick soft close-grained cast iron block. Abrading action is accomplished by very fine abrasive powder held in a vehicle. Manual lapping requires high personal skill because the lapping pressure and speed have to be controlled manually.

Laps in the form of ring made of closed grain cast iron are used for manual lapping of external cylindrical surface. The bore of the ring is very close to size of the workpiece however, precision adjustment in size is possible with the use of a set screw as illustrated in Fig.30.2(a). To increase range of working, a single holder with interchangeable ring laps can also be used. Ring lapping is recommended for finishing plug gauges and machine spindles requiring high precision. External threads can be also lapped following this technique. In this case the lap is in the form of a bush having internal thread.



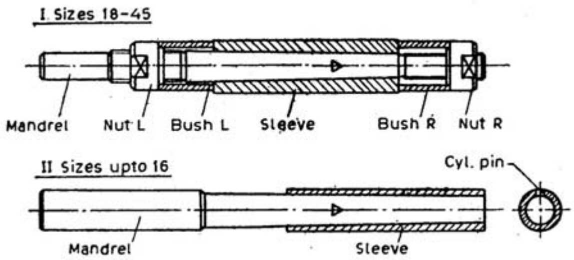


Fig. 30.2 *Manual Ring lapping of external cylindrical surface*

Fig. 30.2 *(b) Manual Lapping of internal cylindrical surfaces*

Solid or adjustable laps, which are ground straight and round, are used for lapping holes. For manual lapping, the lap is made to rotate either in a lathe or honing machine, while the workpiece is reciprocated over it by hand. Large size laps are made of cast iron, while those of small size are made of steel or brass. This process finds extensive use in finishing ring gauges.

30.1.2 Lapping Machine

Machine lapping is meant for economic lapping of batch qualities. In machine lapping, where high accuracy is demanded, metal laps and abrasive powder held in suitable vehicles are used. Bonded abrasives in the form wheel are chosen for commercial lapping. Machine lapping can also employ abrasive paper or abrasive cloth as the lapping medium. Production lapping of both flat and cylindrical surfaces are illustrated in Fig. 30.3 (a) and (b). In this case cast iron plate with loose abrasive carried in a vehicle can be used. Alternatively, bonded abrasive plates may also be used. Centreless roll lapping uses two cast iron rolls, one of which serves as the lapping roller twice in diameter than the other one known as the regulating roller. During lapping the abrasive compound is applied to the rolls rotating in the same direction while the workpiece is fed across the rolls. This process is suitable for lapping a single piece at a time and mostly used for lapping plug gauges, measuring wires and similar straight or tapered cylindrical parts.

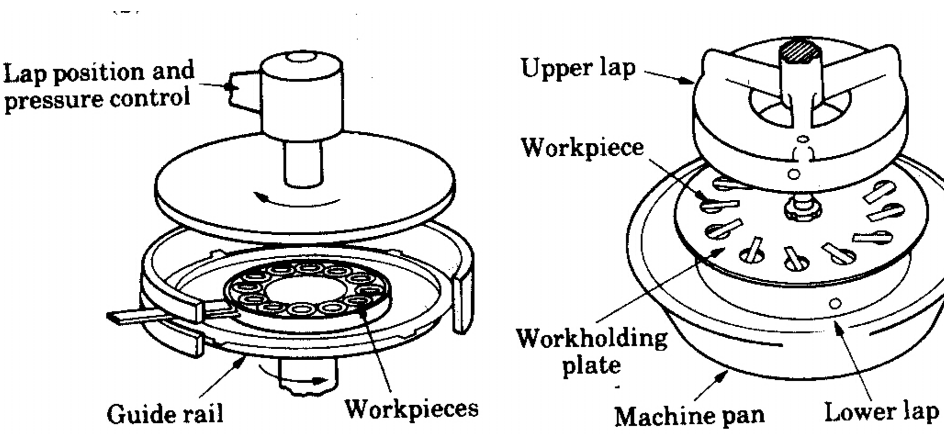


Fig.30.3 *Production lapping on (a) flat surface (b) cylindrical surface*

Centreless lapping is carried out in the same principle as that of centreless grinding. The bonded abrasive lapping wheel as well as the regulating wheel are much wider than those used in centreless grinding. This technique is used to produce high roundness accuracy and fine finish, the workpiece requires multi-pass lapping each with progressively finer lapping wheel. This is a high production operation and suitable for small amount of rectification on shape of workpiece. Therefore, parts are to be pre-ground to obtain substantial straightness and roundness. The process finds use in lapping piston rings, shafts and bearing races.

Machines used for lapping internal cylindrical surfaces resembles honing machines used with power stroke. These machines in addition to the rotation of the lap also provide reciprocation to the workpiece or to the lap. The lap made usually of cast iron either solid or adjustable type can be conveniently used.

Figure 30.4 shows that to maximize the MRR (material removal rate) an optimum lapping pressure and abrasive concentration in the vehicle have to be chosen.

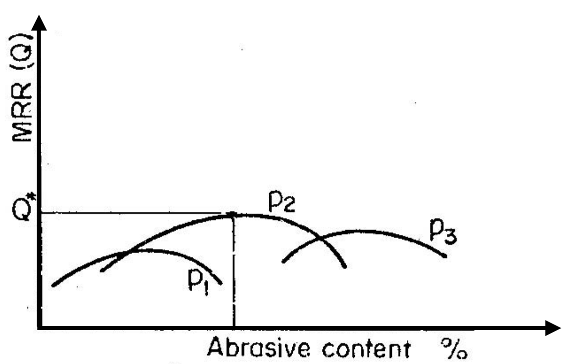


Fig. 30.4 *Effect of abrasive content on MRR*

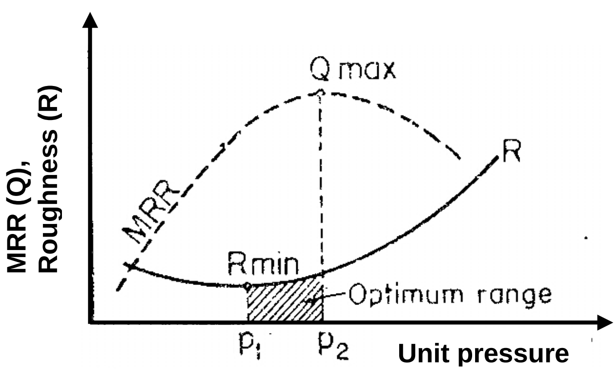


Fig. 30.5 *Effect of lapping pressure on surface roughness and MRR*

The effect of unit pressure on MRR and surface roughness is shown in Fig. 30.5. It is shown in the same figure that unit pressure in the range of p_1-p_2 gives the best values for MRR and roughness of the lapped surface.

The variation in MRR and surface roughness with grain size of abrasive are shown in Fig.30.6. It appears that grain size corresponding to permissible surface roughness and maximum MRR may be different. Primary consideration is made on the permissible surface roughness in selecting abrasive grain size.

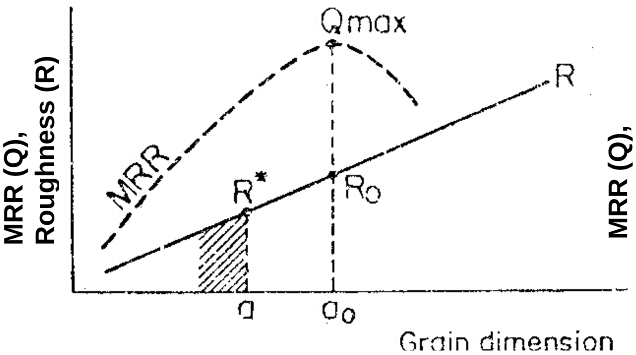


Fig. 30.6 *Effect of abrasive grain size on surface roughness and MRR*

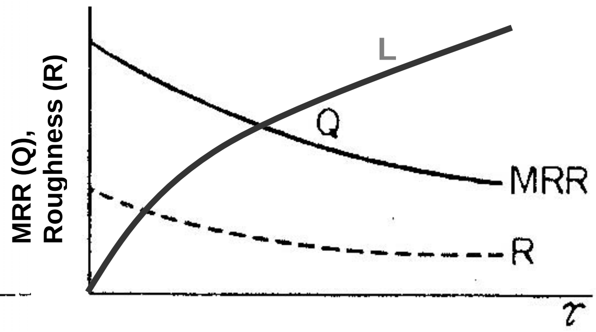


Fig. 30.7 *Effect of lapping time on surface roughness and MRR*

The dependence of MRR, surface roughness and linear loss (L) of workpiece dimension is shown in fig. 30.7. Lapping conditions are so chosen that designed surface finish is obtained with the permissible limit of linear loss of workpiece dimension as shown in Fig. 30.8.

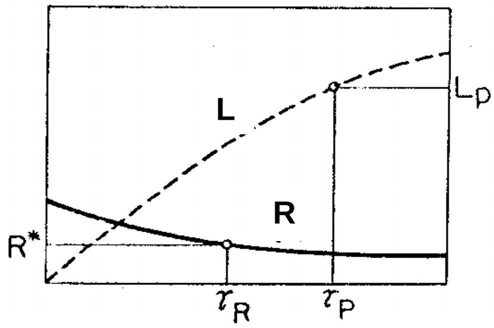


Fig. 30.8 *Criteria for choosing lapping time*

30.2 Honing

Honing is a finishing process, in which a tool called hone carries out a combined rotary and reciprocating motion while the workpiece does not perform any working motion. Most honing is done on internal cylindrical surface, such as automobile cylindrical walls. The honing stones are held against the workpiece with controlled light pressure. The honing head is not guided externally but, instead, floats in the hole, being guided by the work surface (Fig. 30.9). It is desired that

1. honing stones should not leave the work surface
2. stroke length must cover the entire work length.

In honing rotary and oscillatory motions are combined to produce a cross hatched lay pattern as illustrated in Fig. 30.10

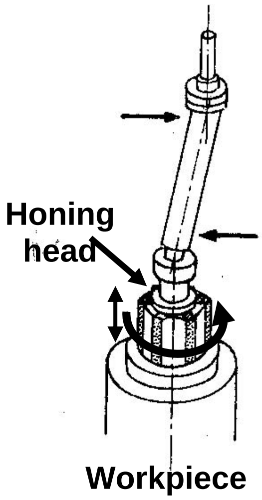


Fig. 30.9 *Honing tool*

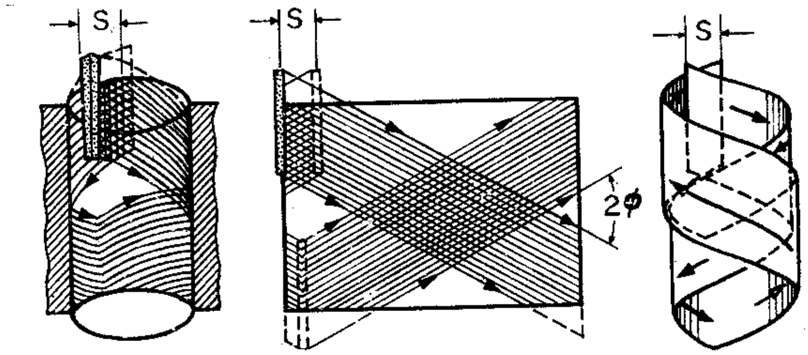


Fig. 30.10 *Lay pattern produced by combination of rotary and oscillatory motion*

The honing stones are given a complex motion so as to prevent every single grit from repeating its path over the work surface. The critical process parameters are:

1. rotation speed
2. oscillation speed
3. length and position of the stroke
4. honing stick pressure

With conventional abrasive honing stick, several strokes are necessary to obtain the desired finish on the work piece. However, with introduction of high performance diamond and cBN grits it is now possible to perform the honing operation in just one complete stroke. Advent of precisely engineered microcrystalline cBN grit has enhanced the capability further. Honing stick with microcrystalline cBN grit can maintain sharp cutting condition with consistent results over long duration.

Superabrasive honing stick with monolayer configuration (Fig. 30.11), where a layer of cBN grits are attached to stick by a galvanically deposited metal layer, is typically found in single stroke honing application.

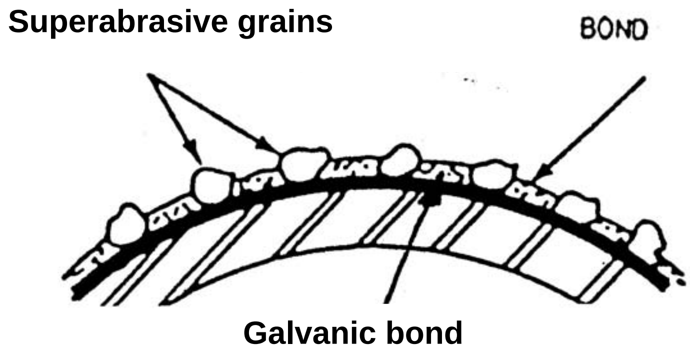


Fig.30.11 *Superabrasive honing stick with single layer configuration*

With the advent of precision brazing technique, efforts can be made to manufacture honing stick with single layer configuration with a brazed metal bond. Like brazed grinding wheel such single layer brazed honing stick are expected to provide controlled grit density, larger grit protrusion leading to higher material removal rate and longer life compared to what can be obtained with a galvanically bonded counterpart.

The important parameters that affect material removal rate (MRR) and surface roughness (R) are:

(i) unit pressure, p
(ii) peripheral honing speed, Vc
(iii) honing time, T

The variation of MRR (Q) and R with unit pressure is shown in Fig. 30.12. It is evident from the graph that the unit pressure should be selected so as to get minimum surface roughness with highest possible MRR.

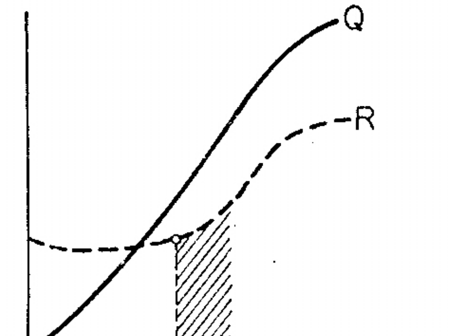


Fig. 30.12*: Effect of honing pressure on MRR and surface finish*

Figure 30.13 shows that an increase of peripheral honing speed leads to enhancement of material removal rate and decrease in surface roughness.

Figure 30.14 shows that with honing time T, MRR decreases. On the other hand, surface roughness decreases and after attaining a minimum value again rises. The selection of honing time depends very much on the permissible surface roughness.

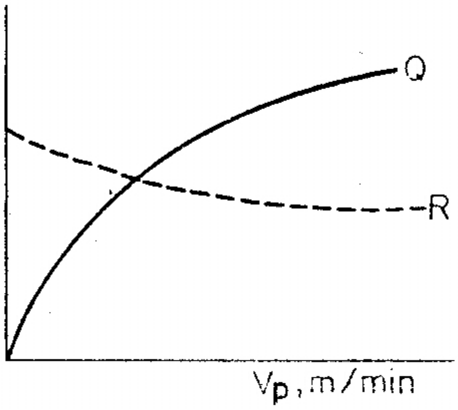


Fig. 30.13 *Effect of peripheral honing speed*

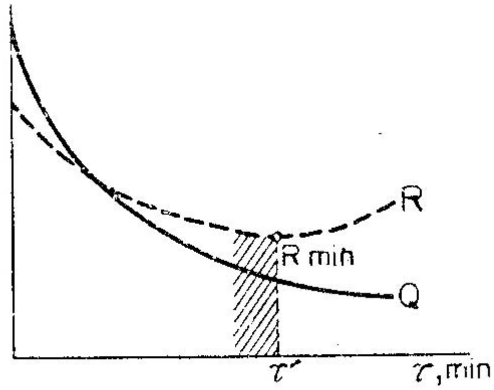


Fig. 30.14 *Effect of honing time on material removal rate and surface roughness*

30.3 Superfinishing

Figure 30.15 illustrates superfinishing end-face of a cylindrical workpiece. In this both feeding and oscillation of the superfinishing stone is given in the radial direction.

Figure 30.16 shows the superfinishing operation in plunge mode. In this case the abrasive stone covers the section of the workpiece requiring superfinish. The abrasive stone is slowly fed in radial direction while its oscillation is imparted in the axial direction.

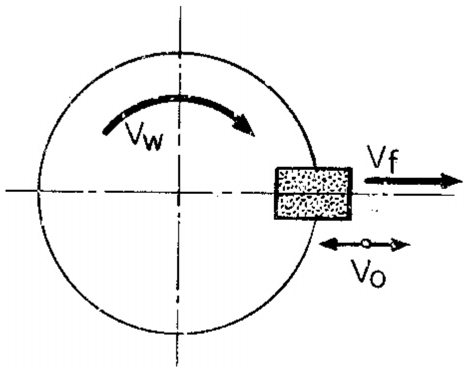


Fig. 30.15 *superfinishing of end face of a cylindrical work piece in radial mode*

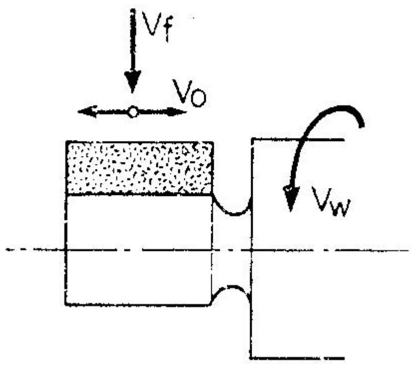


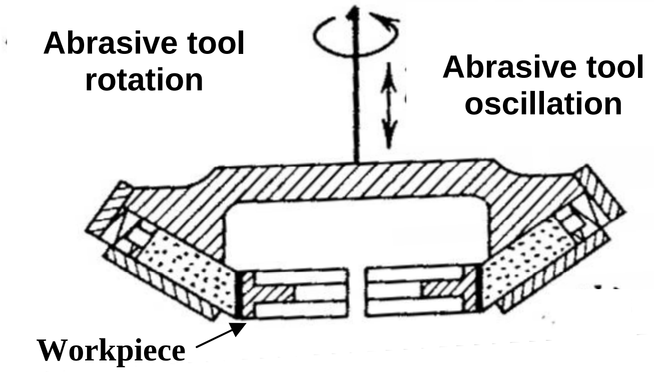
Fig. 30.16 *superfinishing operation in plunge mode*

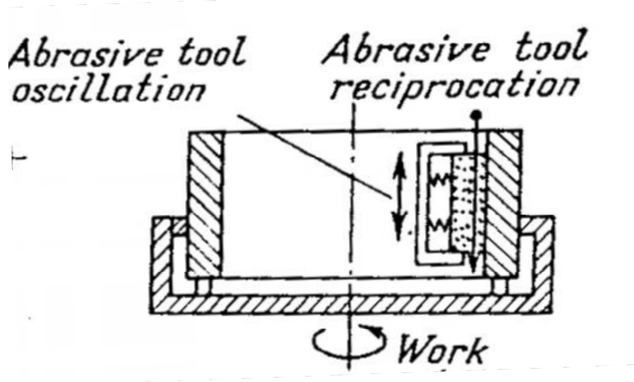
Superfinishing can be effectively done on a stationary workpiece as shown in Fig. 30.17. In this the abrasive stones are held in a disc which oscillates and rotates about the axis of the workpiece.

Fig. 30.18 shows that internal cylindrical surfaces can also be superfinished by axially oscillating and reciprocating the stones on a rotating workpiece.

Abrasive tool oscillation

Abrasive tool reciprocation





Abrasive tool oscillation

Workpiece

Fig. 30.17 *Abrasive tool rotating and oscillating about a stationary workpiece*

Fig. 30.18 *Superfinishing of internal surface*

30.3.1 Burnishing

The burnishing process consists of pressing hardened steel rolls or balls into the surface of the workpiece and imparting a feed motion to the same. Ball burnishing of a cylindrical surface is illustrated in Fig. 30.19.

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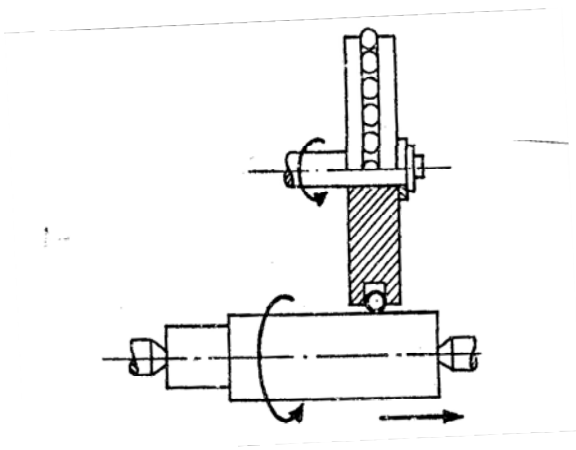


Fig. 30.19 *Scheme of ball burnishing*

During burnishing considerable residual compressive stress is induced in the surface of the workpiece and thereby fatigue strength and wear resistance of the surface layer increase.

30.3.2 Magnetic float polishing

Magnetic float polishing (Fig.30.20) finds use in precision polishing of ceramic balls. A magnetic fluid is used for this purpose. The fluid is composed of water or kerosene carrying fine ferro-magnetic particles along with the abrasive grains. Ceramic balls are confined between a rotating shaft and a floating platform. Abrasive grains ceramic ball and the floating platform can remain in suspension under the action of magnetic force. The balls are pressed against the rotating shaft by the float and are polished by their abrasive action. Fine polishing action can be made possible through precise control of the force exerted by the abrasive particles on the ceramic ball.

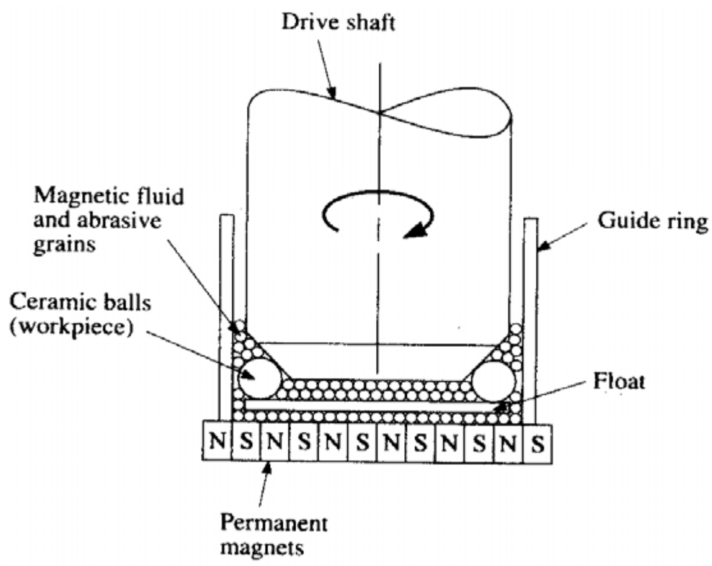


Fig. 30.20 *Scheme of magnetic float polishing*

30.3.3 Magnetic field assisted polishing

Magnetic field assisted polishing is particularly suitable for polishing of steel or ceramic roller. The process is illustrated schematically in Fig. 30.21. A ceramic or a steel roller is mounted on a rotating spindle. Magnetic poles are subjected to oscillation, thereby, introducing a vibratory motion to the magnetic fluid containing this magnetic and abrasive particles. This action causes polishing of the cylindrical roller surface. In this technique, the material removal rate increases with the field strength, rotational speed of the shaft and mesh number of the abrasive. But the surface finish decreases with the increase of material removal rate.

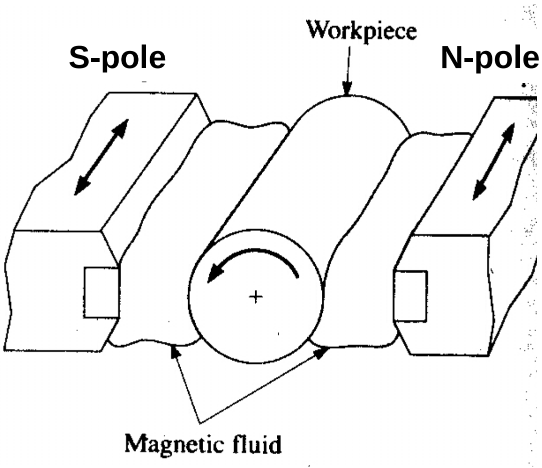


Fig. 30.21 *scheme of magnetic field assisted polishing*

30.3.4 Electropolishing

Electropolishing is the reverse of electroplating. Here, the workpiece acts as anode and the material is removed from the workpiece by electrochemical dissolution. The process is particularly suitable for polishing irregular surface since there is no mechanical contact between workpiece and polishing medium. The electrolyte electrochemically etches projections on the workpiece surface at a faster rate than the rest, thus producing a smooth surface. This process is also suitable for deburring operation.

Exercise 30

Q1: How is the size of the abrasive grain chosen?

Q2: Can cBN be used in honing stick in single layer configuration?

Q3: How does superfinishing differ from honing?

Q4: State the advantage of electro polishing over mechanical polishing.

Q5: How is the surface quality improved in ball burnishing?

Ans1:
Size of the abrasive grain is chosen keeping in view, the permissible roughness of the workpiece and maximum material removal rate attainable.

Ans2:
cBN grits in single layer configuration embedded in galvanic bond can be effectively used as honing stick. Such honing stick is preferred in production honing with just a single stroke operation.

Ans3:
Superfinishing, in a way, is similar to honing but with very low cutting pressure and different kinematic tool-work interactions like

- oscillatory motion of the abrasive stick with short stroke but with high frequency.
- rotation of workpiece is usually kept low.
- feed motion of the tool or the work piece.

Ans4:
Electropolishing has clear advantage in polishing irregular surfaces. The electrolyte attacks high points at a faster rate than rest of the surface resulting in production of a smooth surface.

Ans5:
In this process, a hardened steel ball presses the workpiece surface. The surface finish is markedly improved. In addition, a residual compressive stress is developed on the surface, which in turn improves the fatigue resistance. The work hardening effect, as a result of burnishing, also enhances wear resistance of the surface. Therefore, by ball burnishing the overall quality of the workpiece surface is significantly improved.

Module 7

Screw threads and gear manufacturing methods

Lesson
32
Manufacturing of Gears.

Instructional objectives

At the end of this lesson, the students will be able to

(i) State the basic purposes of use of gears
(ii) Cite the general applications of gears
(iii) Classify the types of gears of common use
(iv) Specify gears
(v) Describe the different methods of manufacturing various types of gears
    (a) Preforming
    (b) Producing gear teeth by machining
    (c) Finishing gear teeth

(i) Basic Purpose Of Use Of Gears

Gears are widely used in various mechanisms and devices to transmit power and motion positively (without slip) between parallel, intersecting (axis) or non-intersecting non parallel shafts,

- without change in the direction of rotation
- with change in the direction of rotation
- without change of speed (of rotation)
- with change in speed at any desired ratio

Often some gearing system (rack – and – pinion) is also used to transform rotary motion into linear motion and vice-versa.

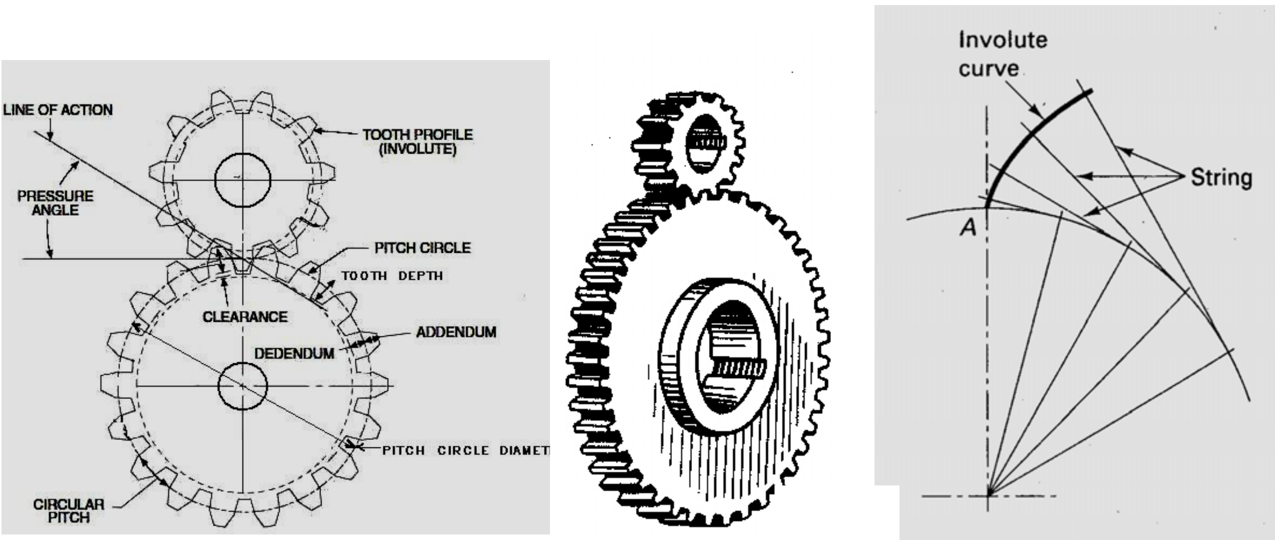


***Fig. 7.2.1** Features of spur gears and involute tooth profile*

Gears are basically wheels having, on its periphery, equispaced teeth which are so designed that those wheels transmit, without slip, rotary motion smoothly and uniformly with minimum friction and wear at the mating tooth – profiles. To achieve those favourable conditions, most of the gears have their tooth form based on involute curve, which can simply be defined as Locus of a point on a straight line which is rolled on the periphery of a circle or Locus of the end point of a stretched string while its unwinding over a cylinder as indicated in Fig. 7.2.1

(ii) General Applications Of Gears

Gears of various type, size and material are widely used in several machines and systems requiring positive and stepped drive. The major applications are :

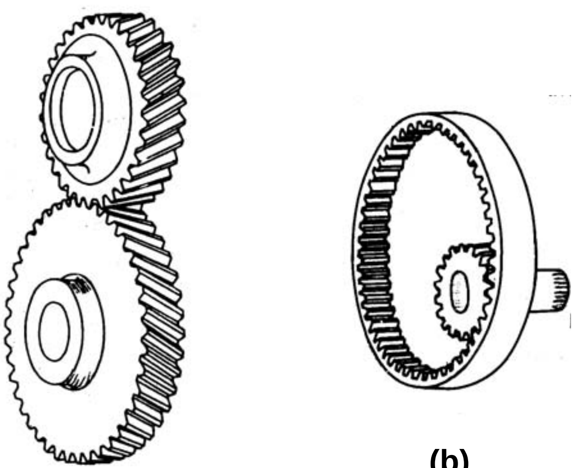
- Speed gear box, feed gear box and some other kinematic units of machine tools
- Speed drives in textile, jute and similar machineries
- Gear boxes of automobiles
- Speed and / or feed drives of several metal forming machines
- Machineries for mining, tea processing etc.
- Large and heavy duty gear boxes used in cement industries, sugar industries, cranes, conveyors etc.
- Precision equipments, clocks and watches
- Industrial robots and toys.

(iii) Types Of Gears And Their Characteristics

Gears are broadly classified

(a) According to configuration (Fig. 7.2.2)

- External gear
- Internal gear



(a) (b)

__Fig. 7.2.2__ Configuration of (a) external and (b) internal gears

(b) According to axes of transmission

- **Spur gears** – transmitting rotation between parallel shafts as shown in Fig. 7.2.3
    - o Straight toothed
    - o Helical toothed
        - — Single helical
        - — double helical (herringbone)

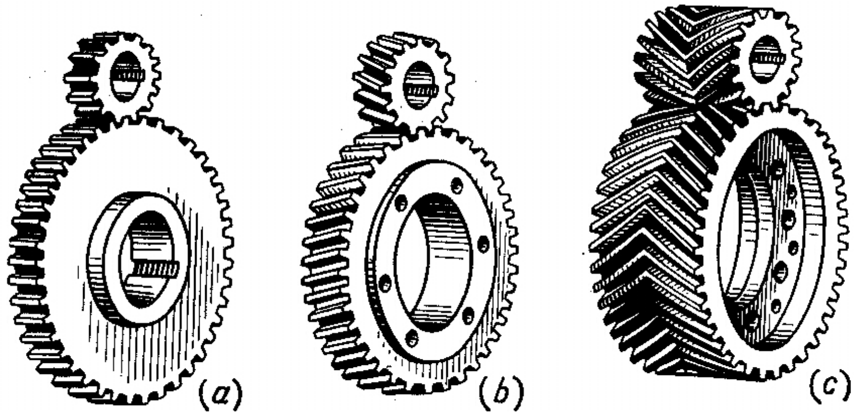


Fig. 7.2.3 *(a) Straight toothed (b)Helical and (c) Double helical gears*

Compared to straight toothed gears, helical toothed gears run more smoothly and can transmit larger torque. Double helical gears are of large size and used for heavy torque transmission.

- Bevel gears – transmitting motion between intersecting shafts (axes) (Fig. 7.2.4)
    - o Straight toothed
    - o Helical toothed
        - — Spiral bevel gear
        - — Hypoid gear

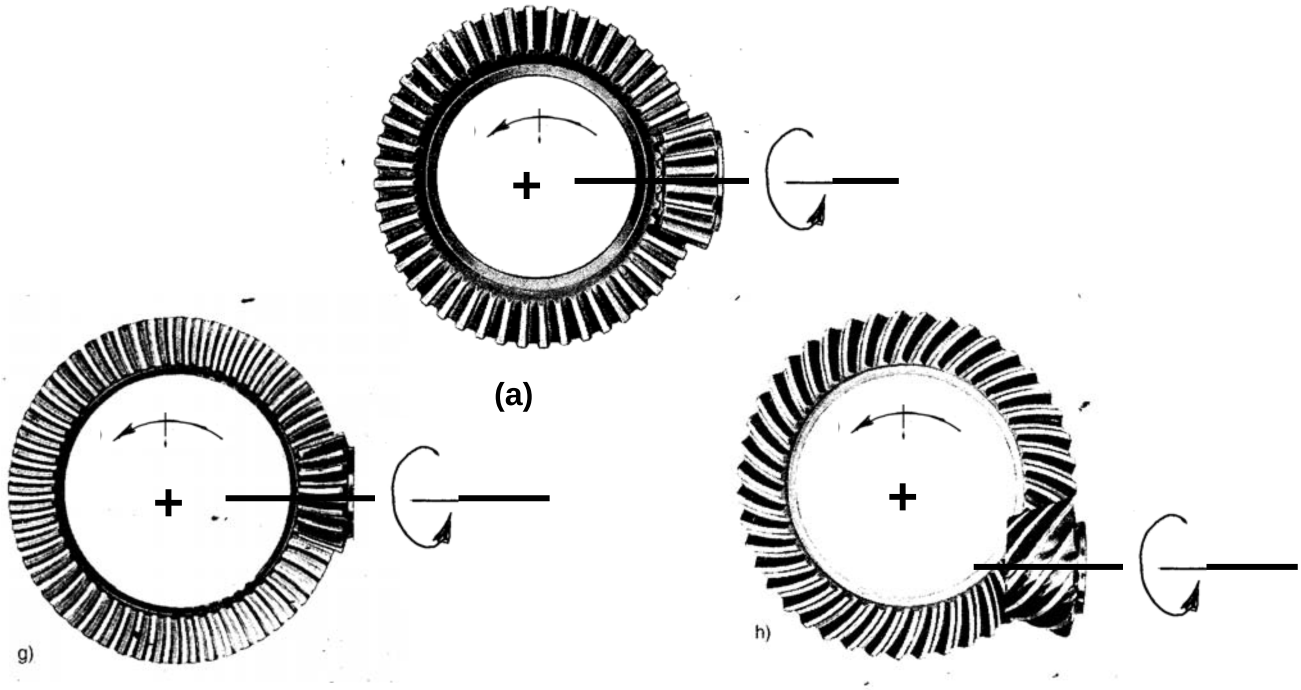
  Helical toothed bevel gears are used for smoother and larger torque transmission.

- Gears transmitting motion and power between non-parallel non-intersecting shafts (Fig. 7.2.5)
    - o Worm and worm wheel
    - o Spiral gears
    - o Skewed or hypoid bevel gears

Worm and worm wheel are generally used for speed reduction but are irreversible i.e., rotation can be transmitted only from the worm to the worm wheel unless the helix angle is tool large.
Spiral gears are used when torque or power to be transmitted is insignificant.

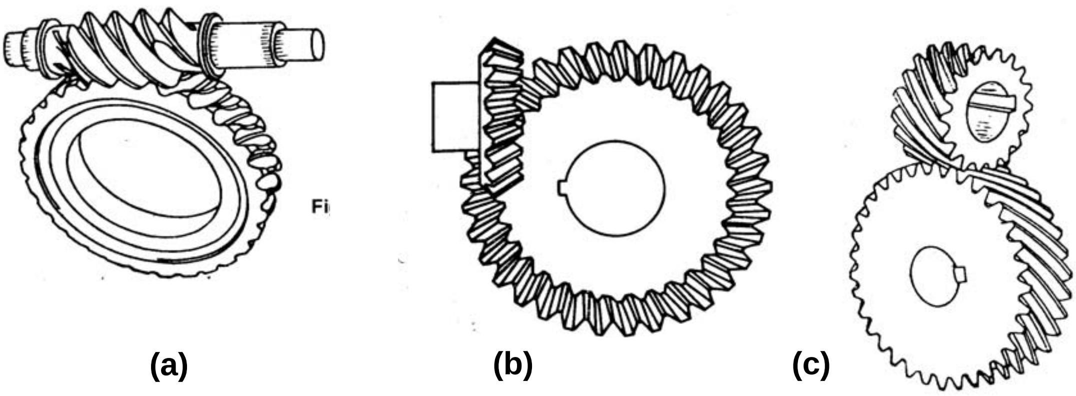
(c) According to pattern of motion

- Rotation to rotation : - (Fig. 7.2.6) wheel type gears
- Rotation to translation or vice versa – e.g. rack and pinion
    - Straight toothed
    - Helical toothed



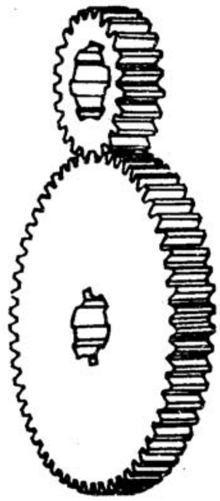
(a) (b) (c)

Fig. 7.2.4 *Bevel gears; (a) straight toothed, (b) spiral and hypoid gears*



(a) (b) (c)

Fig. 7.2.5 *Gears transmitting power between non-parallel non intersecting shafts. (a) worm and worm wheel, (b) hypoid gear and (c) spiral gears.*



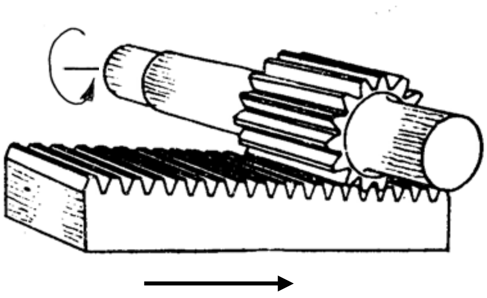


Fig. 7.2.6 *Gearing systems transforming (a) rotation to rotation and (b) rotation to translation*

(iv) Specification Of Gears

Gears are generally specified by their

- Type; e.g. spur, bevel, spiral etc.
- Material
- Size or dimensions
- Geometry
- Special features, if any

- **Type of gears** – has already been discussed in the previous section (iii)

- **Gear materials**

The materials of most of the gears used for transmitting reasonable torque and speed mainly need to be mechanically strong in shear and bending, sufficiently tough and resistant to wear, fatigue and chemical degradation.
However, the material for any gear is selected based on,

- o The working condition ie, power, speed and torque to be transmitted
- o Working environment, i.e., temperature, vibration, chemical etc.
- o Ease of manufacture
- o Overall cost of material and manufacture

The materials generally used for making gears are :

Δ Ferrous metals – for high loads

- Grey cast iron – preferred for reasonable strength and wear resistance, ease of casting and machining and low cost
- Forged or rolled high carbon steels and alloy steels (Ni-Cr, Mo etc.) which are either fully hardened or surface hardened for use under high stresses and speed.

- ∆ Non ferrous metals – for light load
  - Aluminium, bronze and brass are used for making gears having fine teeth and working at very light load – e.g., in equipments, toys etc. or against hard steel mating gears
  - Aluminium alloys like aluminium bronze, Zinc – Al. alloy etc.

- ∆ Non-metals – widely used for light load, non-precision and noiseless operation. Polymers (plastics) : both themoplastic and thermosetting type and various composites (metals, graphite, wood dust or ceramic powders dispersed in thermosetting plastics)

- **Size or major dimensions**

The dimensional features that are used to express or specify the gears are ;

- ∆ For spur gears and worm wheels
  - — number of teeth, z
  - — module, m
  - — helix angle, if any (θ)
  - — width (b)

For example, pitch circle diameter (PCD) = $mZ/\cos\theta$

- ∆ For worm (single or double toothed gears)
  - — number of start
  - — module helix angle length

- **Gear geometry**

Some geometrical features also need to be mentioned while specifying gears, such as,

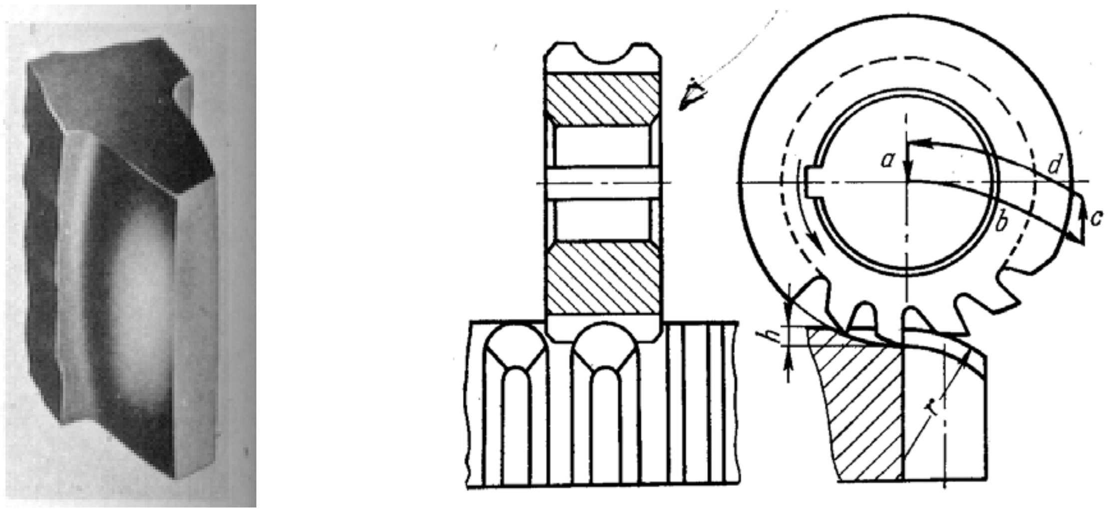
- ∆ Pressure angle
- ∆ Addendum and dedendum

- **Special features**

If there be any special feature, that also has to be included with gear specification, such as

- — Tooth bevelling for safe handling
- — Tooth crowning for uniform wear and long service life
- — Tooth rounding for easy engagement

as indicated in Fig. 7.2.7



(a) **(b)**

Fig. 7.2.7 *Modification of spur gear tooth; (a) crowning and (b) tooth rounding*

(V) Manufacture Of Gears

Manufacture of gears needs several processing operations in sequential stages depending upon the material and type of the gears and quality desired. Those stages generally are :

— Preforming the blank without or with teeth
— Annealing of the blank, if required, as in case of forged or cast steels
— Preparation of the gear blank to the required dimensions by machining
— Producing teeth or finishing the preformed teeth by machining
— Full or surface hardening of the machined gear (teeth), if required
— Finishing teeth, if required, by shaving, grinding etc.
— Inspection of the finished gears.

In this section, performing, producing teeth by machining and gear teeth finishing have been discussed in detail.

Preforming Gear Blanks

- **Casting**

Gear blanks and even gears along with teeth requiring substantial to little machining or finishing are produced by various casting processes.

- o **Sand casting**
  The blanks of large cast iron gears, if required to be made one or few pieces, are produced by sand casting. Then the blank is prepared to appropriate dimensions and the teeth are produced by machining that cast preform. Complete gears with teeth can also be directly produced by such casting and used at low speed in machineries like farm

machinery and hand operated devices where gear accuracy and finish are not that much required.

- **Metal mould casting**
  Medium size steel gears with limited accuracy and finish are often made in single or few pieces by metal mould casting. Such unfinished gears are used in several agro-industries. For general and precision use the cast preforms are properly machined.

- **Die casting**
  Large lot or mass production of small gears of low melting point alloys of Al, Zn, Cu, Mg etc. are done mainly by die casting. Such reasonably accurate gears are directly or after little further finishing are used under light load and moderate speeds, for example in instruments, camera, toys.

- **Investment casting**
  This near-net-shape method is used for producing small to medium size gears of exotic materials with high accuracy and surface finish hardly requiring further finishing. These relatively costly gears are generally used under heavy loads and stresses.

- **Shell mould casting**
  Small gears in batches are also often produced by this process. The quality provided by this process lies in between that of sand casting and investment casting.

- **Centrifugal casting**
  The solid blanks or the outer rims (without teeth) of worm wheels made of cast iron, phosphor bronze or even steel are preferably preformed by centrifugal casting. The performs are machined to form the gear blank of proper size. Then the teeth are developed by machining.

- **Manufacture of gears by rolling**

The straight and helical teeth of disc or rod type external steel gears of small to medium diameter and module are generated by cold rolling by either flat dies or circular dies as shown in Fig. 7.2.8. Such rolling imparts high accuracy and surface integrity of the teeth which are formed by material flow unlike cutting. Gear rolling is reasonably employed for high productivity and high quality though initial machinery costs are relatively high. Larger size gears are formed by hot rolling and then finished by machining

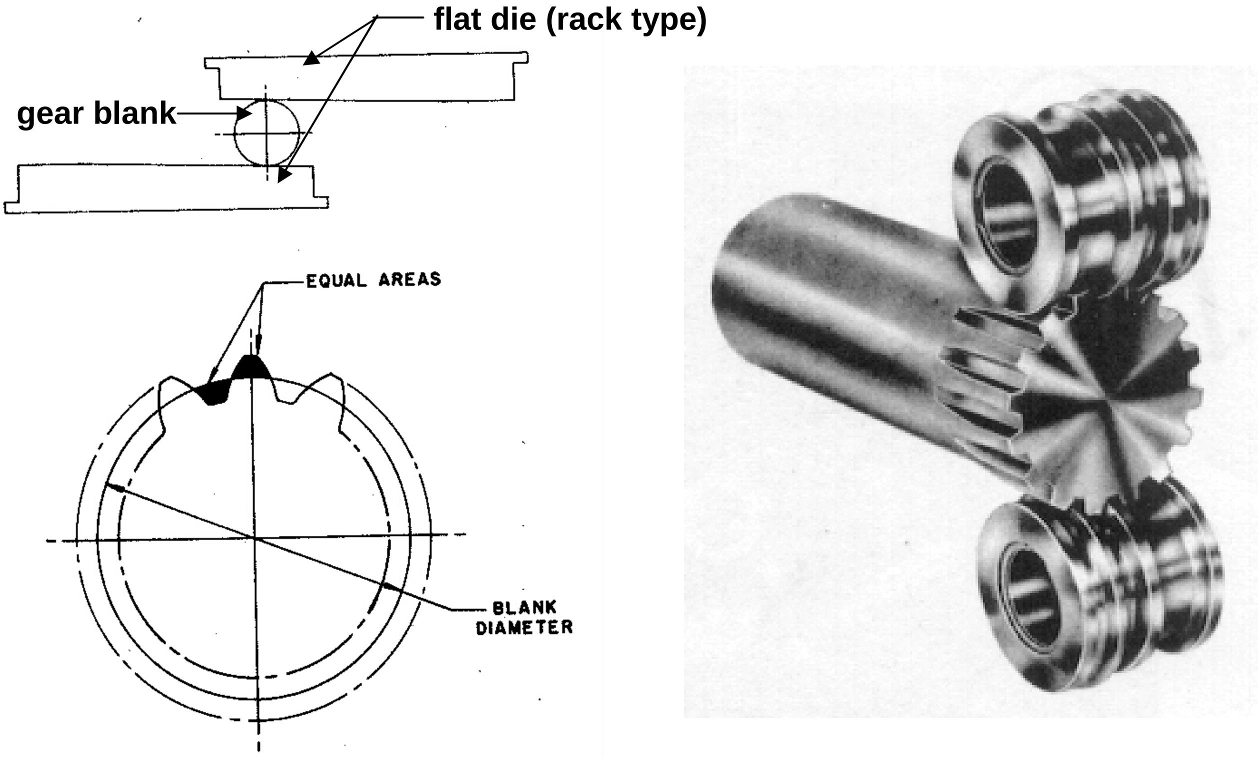


Fig. 7.2.8   Production of teeth of spur gears by rolling.

- **Powder metallurgy**

Small size high quality external or internal spur, bevel or spiral gears are also produced by powder metallurgy process. Large size gears are rolled after briquetting and sintering for more strength and life. Powder metallurgically produced gears hardly require any further finishing work.

- **Blanking in Press tool**

Mass production of small and thin metallic gears requiring less accuracy and finish are often done by blanking from sheets by suitably designed die and punch. Such gears are used for clocks, watches, meters, toys etc. However, quality gears can also be produced by slight finishing (shaving) after blanking.

- **Plastic moulding**

Small to medium size plastic gears with or without metal core are manufactured in large quantity by injection moulding. Such moderately accurate and less noisy gears, both external and internal types, are used under light loads such as equipments, toys, meters etc.

- **Extrusion process**

High quality small metallic or non metallic external gears are often produced in large quantity by extrusion. Number of gears of desired width are obtained by parting from the extruded rod of gear – section.

- **Wire EDM**

Geometrically accurate but moderately finished straight toothed metallic spur gears, both external and internal type, can be produced by wire type Electro-discharge Machining (EDM) as shown in Fig. 7.2.9

Fig. 7.2.9 *Production of teeth of external and internal spur gears by Wire-Electrodischarge machining (EDM)*

Production of Gear Teeth by Machining

It appears from the previous section that gears are manufactured in several routes ;

- ∆ The preformed blanks of approximate shape and irregular surface are machined to desired dimensions and finish and then the teeth are produced generally by machining and occasionally by rolling.
- ∆ Full gears with teeth are made by different processes and then finished by further machining and / or grinding
- ∆ Accurate gears in finished form are directly produced by near – net – shape process like rolling, plastic moulding, powder metallurgy etc. requiring slight or no further finishing.

The most commonly practiced method is preforming the blank by casting, forging etc. followed by pre-machining to prepare the gear blank to desired dimensions and then production of the teeth by machining and further finishing by grinding if necessary.
Gear teeth are produced by machining based on

- o **Forming** – where the profile of the teeth are obtained as the replica of the form of the cutting tool (edge); e.g., milling, broaching etc.
- o **Generation** – where the complicated tooth profile are provided by much simpler form cutting tool (edges) through rolling type, tool – work motions, e.g., hobbing, gear shaping etc.

- **Methods of production of gear teeth by machining on Forming principle**

    - **Shaping, planing and slotting**

Fig. 7.2.10 schematically shows how teeth of straight toothed spur gear can be produced in shaping machine, if necessary. Both productivity and product quality are very low in this process which therefore, is used, if at all, for making one or few teeth on one or two pieces of gears as and when required for repair and maintenance purpose. In principle planning and slotting machines work on the same principle. Planing machine is used, if required at all, for making teeth of large gears whereas slotting, generally, for internal gears.

- **Milling**

Gear teeth can be produced by both disc and end mill type form milling cutter as shown in Fig. 7.2.11

Production of gear teeth by form milling are characterised by :

- use of HSS form milling cutters
- use of ordinary milling machines
- low production rate for
    - — need of indexing after machining each tooth gap
    - — slow speed and feed
- low accuracy and surface finish
- inventory problem – due to need of a set of eight cutters for each module – pressure angle combination.
- End mill type cutters are used for teeth of large gears and / or module.

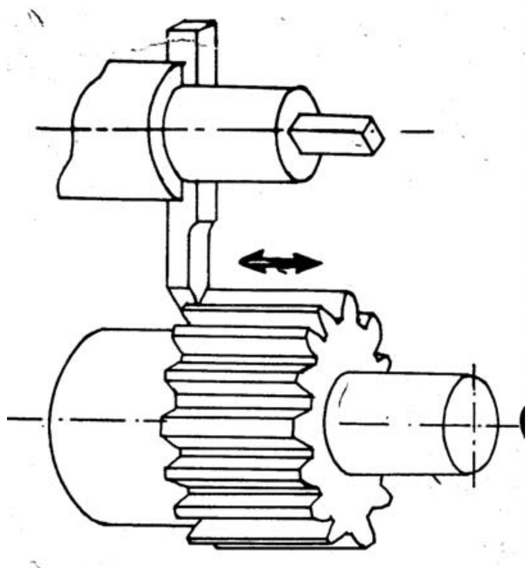


Fig. 7.2.10 *Gear teeth cutting in ordinary shaping machine.*

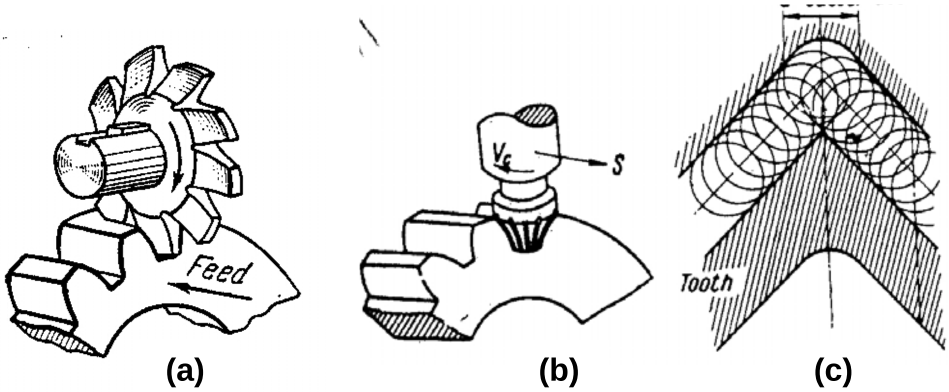


Fig. 7.2.11 Producing external teeth by form milling cutters (a) disc type and end mill type for (b) single helical and (c) double helical teeth

- **Fast production of teeth of spur gears**
  - **Parallel multiple teeth shaping**

In principle, it is similar to ordinary shaping but all the tooth gaps are made simultaneously, without requiring indexing, by a set of radially infeeding single point form tools as indicated in Fig. 7.2.12(a). This old process was highly productive but became almost obsolete for very high initial and running costs.

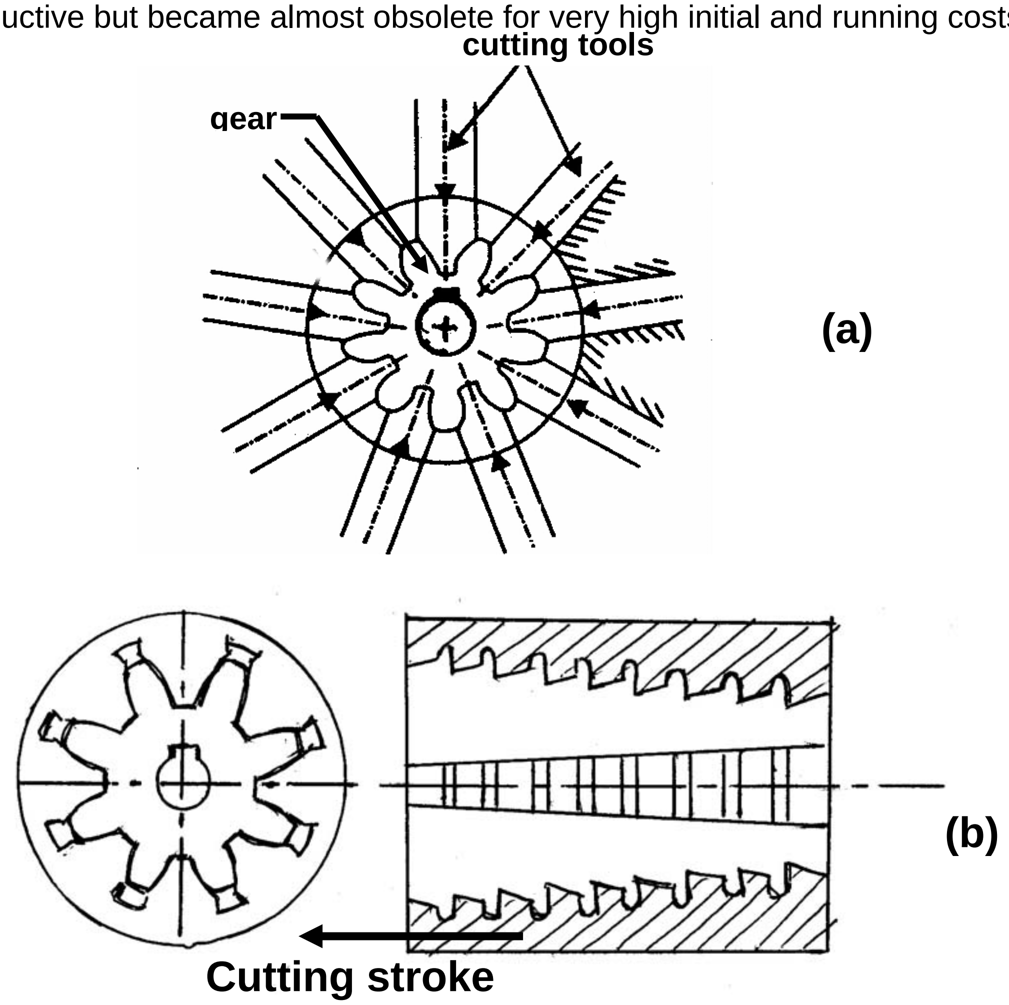


Fig. 7.2.12 High production of straight teeth of external spur gears by (a) parallel shaping (forming) and (b) broaching

- **Broaching**

Teeth of small internal and external spur gears; straight or single helical, of relatively softer materials are produced in large quantity by this process. Fig. 7.2.12 (b) schematically shows how external teeth are produced by a broaching in one pass. This method leads to very high productivity and quality but cost of machine and broach are very high.

- **Production of gear teeth by machining on Generation principle**

Generation method is characterised by automatic indexing and ability of a single cutter to cover the entire range of number of teeth for a given combination of module and pressure angle and hence provides high productivity and economy.

- **Sunderland method using rack type cutter**

Fig. 7.2.13 schematically shows the principle of this generation process where the rack type HSS cutter (having rake and clearance angles) reciprocates to accomplish the machining (cutting) action while rolling type interaction with the gear blank like a pair of rack and pinion. The favourable and essential applications of this method (and machine) include :

- moderate size straight and helical toothed external spur gears with high accuracy and finish
- cutting the teeth of double helical or herringbone gears with a central recess (groove)
- cutting teeth of straight or helical fluted cluster gears

However this method needs, though automatic, few indexing operations.

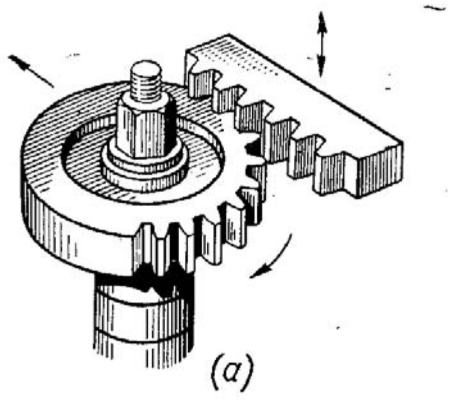


Fig. 7.2.13 *External gear teeth generation by rack type cutter (Sunderland method)*

- **Gear shaping**

In principle, gear shaping is similar to the rack type cutting process, excepting that, the linear type rack cutter is replaced by a circular cutter as indicated in Fig. 7.2.14, where both the cutter and the blank rotate as a pair of spur gears in addition to the reciprocation of the cutter.

Generation method is characterised by automatic indexing and ability of a single cutter to cover the entire range of number of teeth for a given combination of module and pressure angle and hence provides high productivity and economy.
The gear type cutter is made of HSS and possesses proper rake and clearance angles.
The additional advantages of gear shaping over rack type cutting are :

- separate indexing is not required at all
- straight or helical teeth of both external and internal spur gears can be produced with high accuracy and finish
- productivity is also higher.

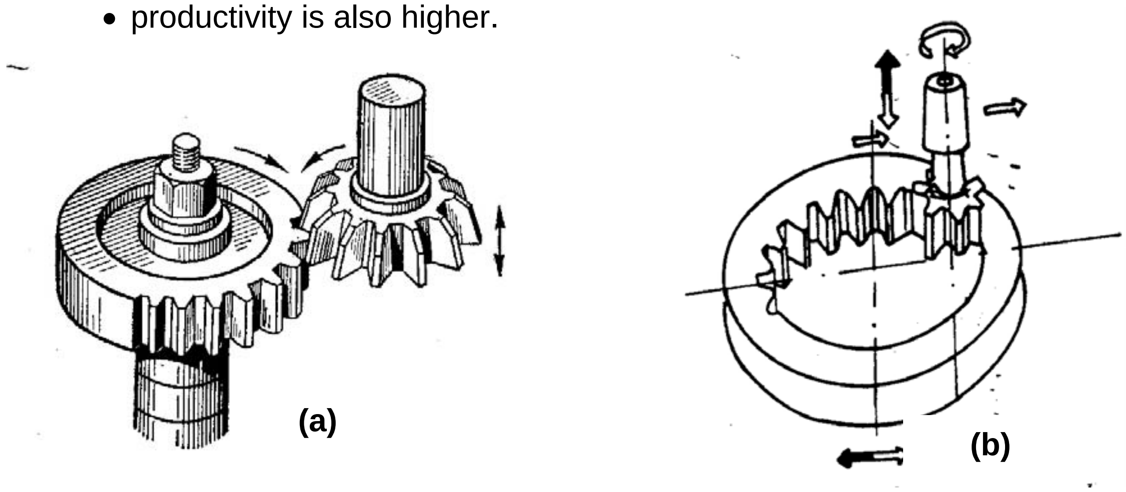


Fig. 7.2.14 *Gear teeth generation by gear shaping (a) external and (b) internal spur gear*

- **Hobbing**

The tool-work configuration and motions in hobbing are shown in Fig. 7.2.15, where the HSS or carbide cutter having teeth like gear milling cutter and the gear blank apparently interact like a pair of worm and worm wheel. The hob (cutter) looks and behaves like a single or multiple start worm. Having lesser number (only three) of tool – work motions, hobbing machines are much more rigid, strong and productive than gear shaping machine. But hobbing provides lesser accuracy and finish and is used only for cutting straight or helical teeth (single) of external spur gears and worm wheels.

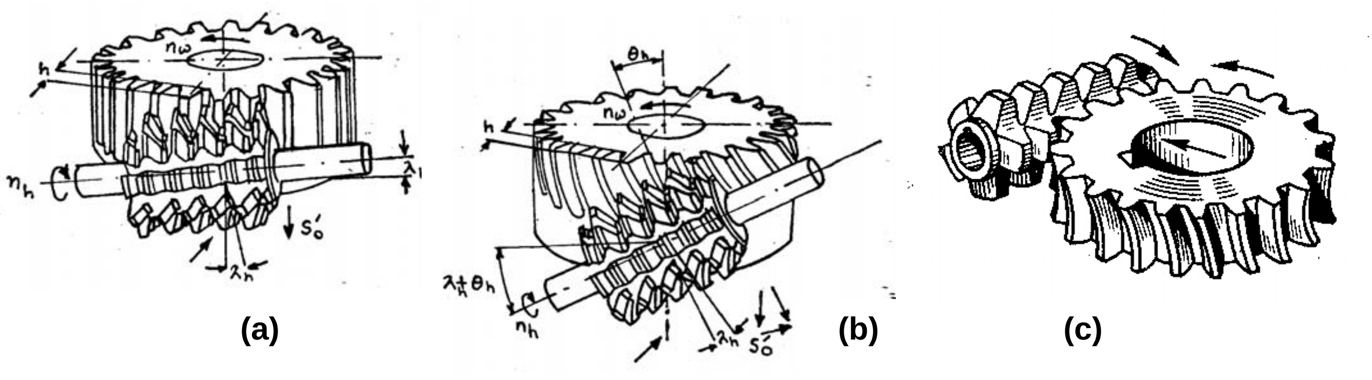


Fig. 7.2.15 *Generation of external gear teeth by Hobbing :*
(a) straight tooth (b) helical tooth and (c) worm wheel

∗ Manufacture of worm

The screw like single or multi-start worms (gears) made of steel are generally made by machining like long thread milling or by cold rolling like thread rolling followed by heat treatment for surface hardening and finishing by grinding.

∗ Manufacture of bevel gears

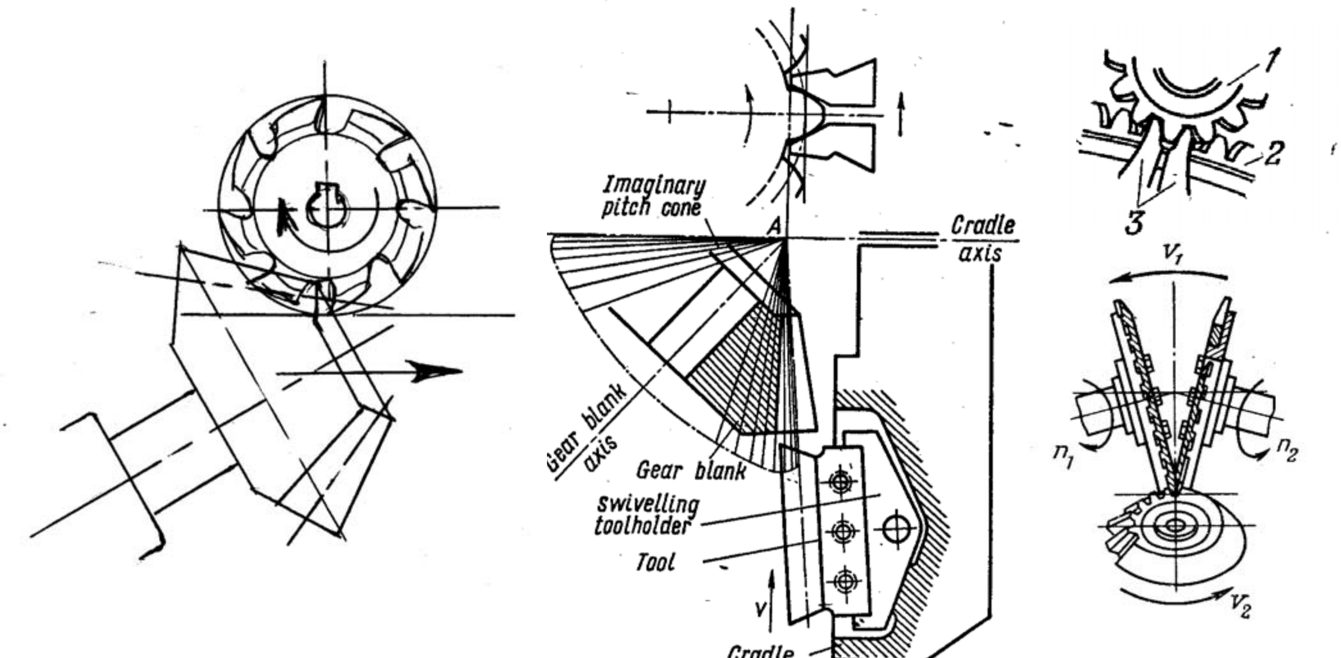
In manufacture of bevel gears, first the blanks are preformed by casting or forging followed by machining to desired dimensions in lathes or special purpose machine.

Then the teeth are produced in the blank by machining. The way of machining and machine tool are chosen based on the form of teeth and volume of production as follows :

- Δ Straight toothed bevel gear
    - o Forming by milling cutter – low productivity and quality hence employed for production requiring less volume and precision
    - o Generation – high accuracy and finish, hence applied for batch to mass production.

Fig. 7.2.16 schematically shows the principle of forming and generation of teeth of straight toothed bevel gear. In generation process, the inner flanks of two adjacent teeth are developed with involute profile by the straight teeth of the cutters under rolling action.

- Δ Teeth of spiral and hypoid bevel gears are produced by almost the same generation principle but the cutter resembles face milling cutter as shown in Fig. 7.2.17.



(a) (b)

Fig. 7.2.16 *Production of teeth of straight toothed spur gear by (a) forming and (b) generation*

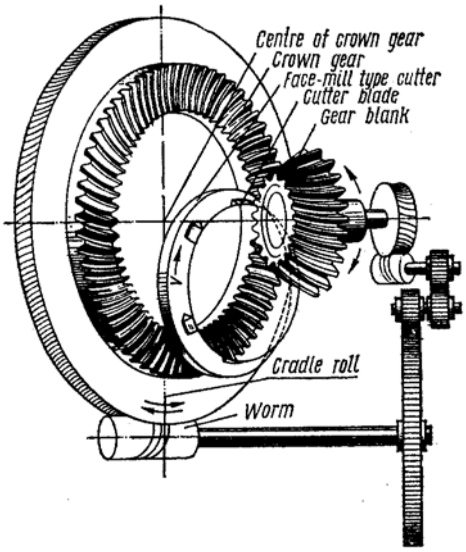


Fig. 7.2.17 *Generation of teeth of spiral and hypoid bevel gear.*

Finishing of Gear Teeth

For smooth running, good performance and long service life, the gears need

- to be accurate in dimensions and forms
- to have high surface finish and
- to be hard and wear resistive at their tooth flanks

which are achieved by some gear teeth finishing work after near accurate preforming and machining. Small gears made by cold rolling generally do not require further finishing. If a rolled gear needs further surface hardening only then little finishing by grinding and / or lapping is done after hardening.
Gears produced to near-net-shape by die casting, powder metallurgy, extrusion, blanking etc. need little finishing.
But machined and hardened gear teeth are essentially finished for accuracy and surface finish.

Common methods of gear teeth finishing

Gear teeth, after preforming and machining, are finished generally by;

- for soft and unhardened gears
    - gear shaving
    - gear rolling or burnishing
- for hard and hardened gears
    - grinding
    - lapping
- for soft but precision gears
    - shaving followed by surface hardening and then lapping

- **Gear shaving**

The teeth of straight or helical toothed external spur gears and worm wheels of moderate size and made of soft materials like aluminium alloy, brass, bronze, cast iron etc. and unhardened steels are mostly finished by shaving process. Fig. 7.2.18 shows the different types of shaving cutters which while their finishing action work apparently as a spur gear, rack or worm in mesh with the conjugate gears to be finished. All those gear, rack or worm type shaving cutters are of hard steel or HSS and their teeth are uniformly serrated as shown in Fig. 7.2.19(a) to generate sharp cutting edges.
While interacting with the gears, the cutting teeth of the shaving cutter keep on smoothening the mating gear flanks by fine machining to high accuracy and surface finish. For such minute cutting action, the shaving teeth need an actual or apparent movement relative to the mating teeth along their length as indicated in Fig. 7.2.19 (b).

- **Gear rolling or burnishing**

In this method the machined gear is rolled under pressure with three hardened master gears of high accuracy and finish. The minute irregularities of the machined gear teeth are smeared off by cold plastic flow, which also helps in improving the surface integrity of the desired teeth.

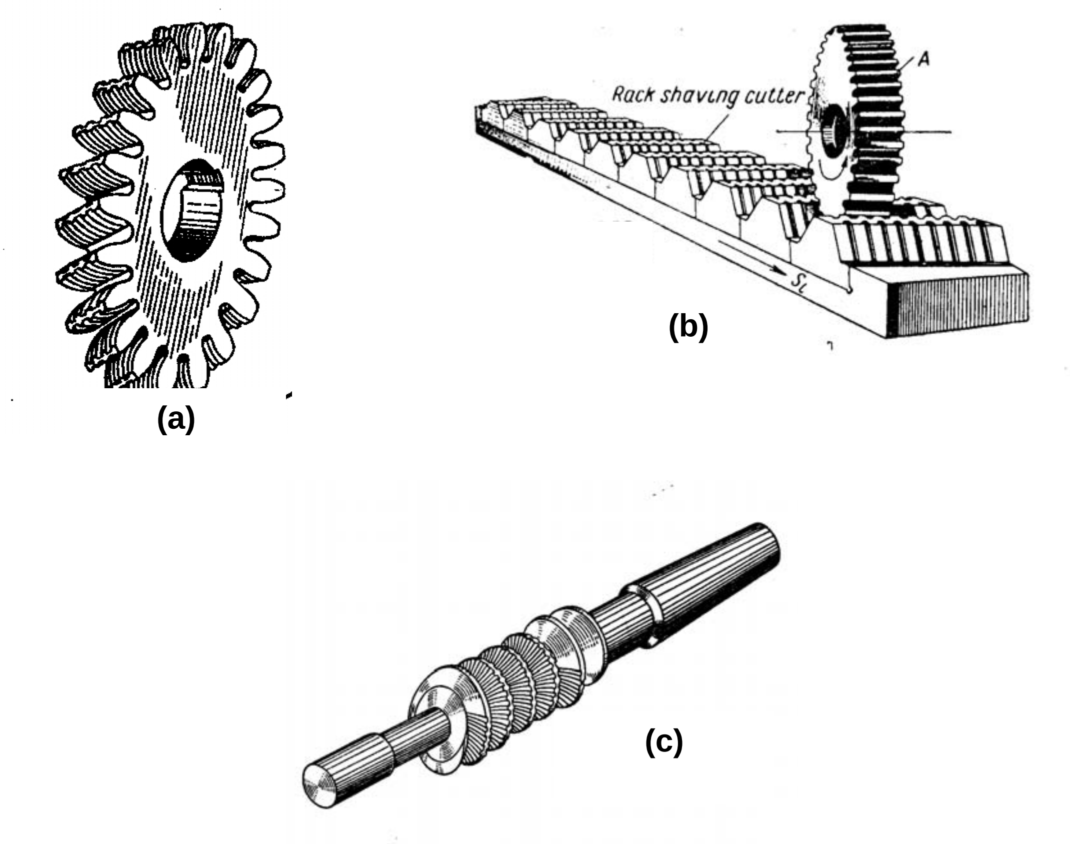
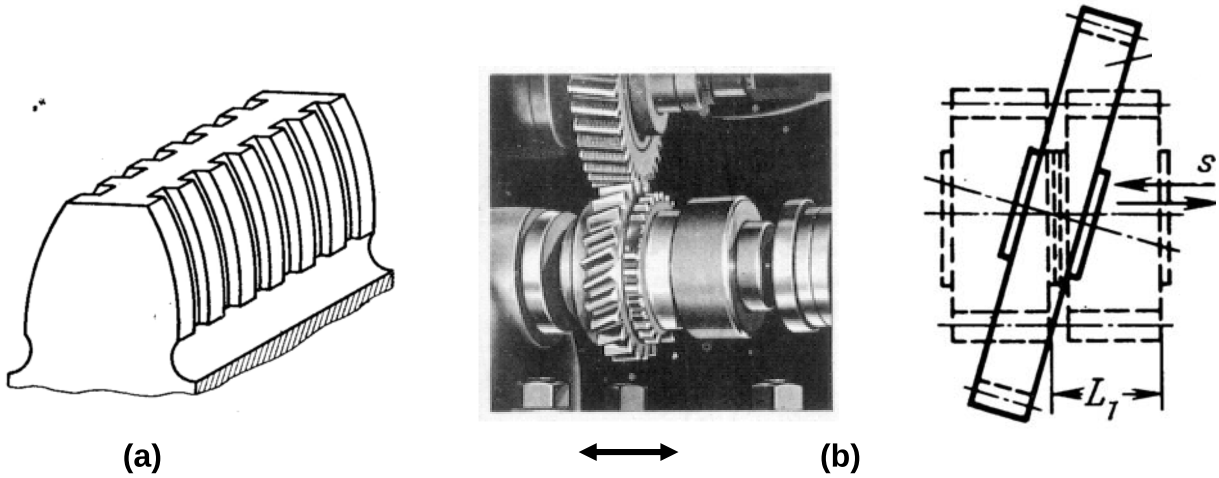


Fig. 7.2.18 *Gear shaving cutters of (a) spur gear type (b) rack and (c) worm type*



(a) **(b)**

Fig. 7.2.19 *Cutting teeth of gear shaving (a) cutter and its (b) action*

- **Gear teeth grinding**

Grinding is a very accurate method and is, though relatively expensive, more widely used for finishing teeth of different type and size of gears of hard material or hardened surfaces. The properly formed and dressed wheel finishes the gear teeth flanks by fine machining or abrading action of the fine abrasives.

Like gear milling, gear grinding is also done on two principles

- Δ Forming
- Δ Generation, which is more productive and accurate

Δ Gear teeth grinding on forming principle

This is very similar to machining gear teeth by a single disc type form milling cutter as indicated in Fig. 7.2.20 where the grinding wheel is dressed to the form that is exactly required on the gear. Need of indexing makes the process slow and less accurate. The wheel or dressing has to be changed with change in module, pressure angle and even number of teeth. Form grinding may be used for finishing straight or single helical spur gears, straight toothed bevel gears as well as worm and worm wheels.

Δ Gear teeth grinding on generation principle

Fig. 7.2.21 schematically shows the methods of finishing spur gear teeth by grinding on generation principle.

The simplest and most widely used method is very similar to spur gear teeth generation by one or multi-toothed rack cutter. The single or multi-ribbed rotating grinding wheel is reciprocated along the gear teeth as shown. Other tool – work motions remain same as in gear teeth generation by rack type cutter as indicated in Fig. 7.2.13. For finishing large gear teeth a pair of thin dish type grinding wheels are used as shown in Fig. 7.2.21 (c). Whatsoever, the contacting surfaces of the wheels are made to behave as the two flanks of the virtual rack tooth.

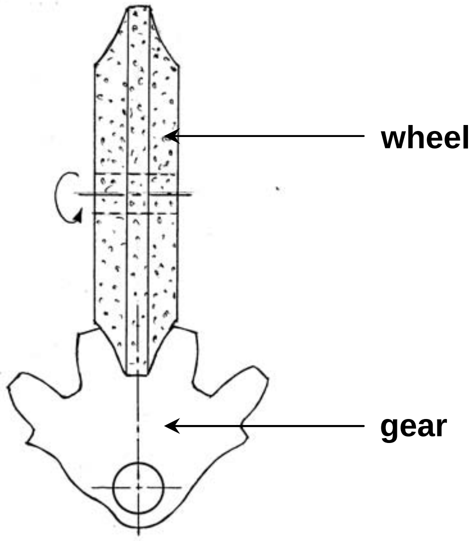


Fig. 7.2.20 *Gear teeth finishing by form grinding*

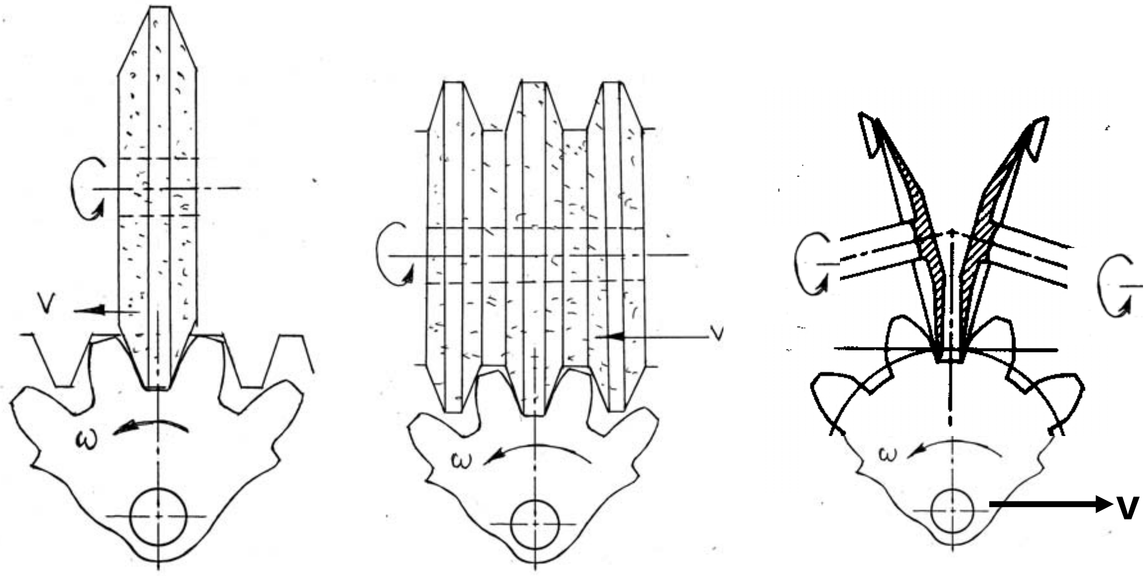


Fig. 7.2.21 *Gear teeth grinding on generation principle.*

Δ Gear teeth finishing by lapping

The lapping process only corrects minute deviations from the desired gear tooth profiles. The gear to be finished after machining and heat treatment and even after grinding is run in mesh with a gear shaped lapping tool or another mating gear of cast iron. An abrasive lapping compound is used in between them. The gear tooth contact substantially improves by such lapping.

Module
7
Screw threads and gear manufacturing methods

Lesson
32
Manufacturing of Gears.

Instructional objectives

At the end of this lesson, the students will be able to

(i) State the basic purposes of use of gears
(ii) Cite the general applications of gears
(iii) Classify the types of gears of common use
(iv) Specify gears
(v) Describe the different methods of manufacturing various types of gears
 (a) Preforming
 (b) Producing gear teeth by machining
 (c) Finishing gear teeth

(i) Basic Purpose Of Use Of Gears

Gears are widely used in various mechanisms and devices to transmit power and motion positively (without slip) between parallel, intersecting (axis) or non-intersecting non parallel shafts,

- without change in the direction of rotation
- with change in the direction of rotation
- without change of speed (of rotation)
- with change in speed at any desired ratio

Often some gearing system (rack – and – pinion) is also used to transform rotary motion into linear motion and vice-versa.

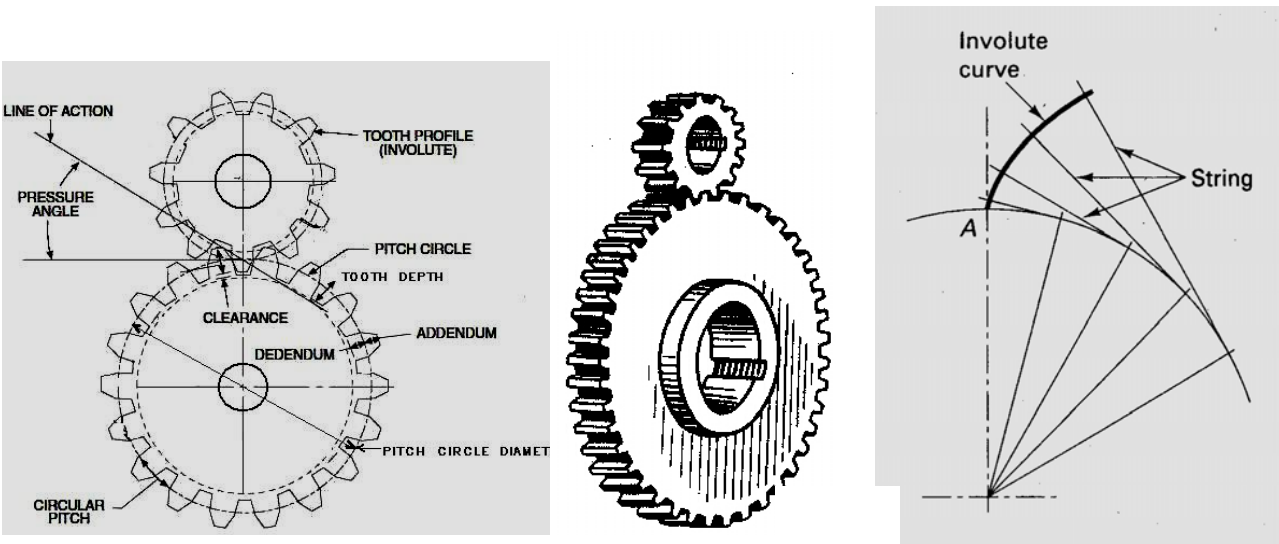


Fig. 7.2.1 *Features of spur gears and involute tooth profile*

Gears are basically wheels having, on its periphery, equispaced teeth which are so designed that those wheels transmit, without slip, rotary motion smoothly and uniformly with minimum friction and wear at the mating tooth – profiles. To achieve those favourable conditions, most of the gears have their tooth form based on involute curve, which can simply be defined as Locus of a point on a straight line which is rolled on the periphery of a circle or Locus of the end point of a stretched string while its unwinding over a cylinder as indicated in Fig. 7.2.1

(ii) General Applications Of Gears

Gears of various type, size and material are widely used in several machines and systems requiring positive and stepped drive. The major applications are :

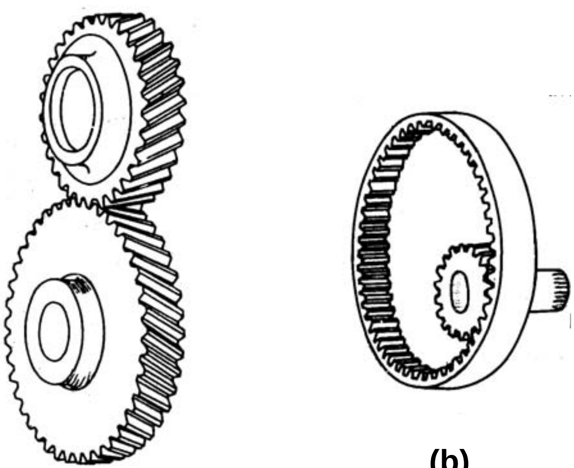
- Speed gear box, feed gear box and some other kinematic units of machine tools
- Speed drives in textile, jute and similar machineries
- Gear boxes of automobiles
- Speed and / or feed drives of several metal forming machines
- Machineries for mining, tea processing etc.
- Large and heavy duty gear boxes used in cement industries, sugar industries, cranes, conveyors etc.
- Precision equipments, clocks and watches
- Industrial robots and toys.

(iii) Types Of Gears And Their Characteristics

Gears are broadly classified

(a) According to configuration (Fig. 7.2.2)

- External gear
- Internal gear



(a) (b)

Fig. 7.2.2 *Configuration of (a) external and (b) internal gears*

(b) According to axes of transmission

- **Spur gears** – transmitting rotation between parallel shafts as shown in Fig. 7.2.3
    - o Straight toothed
    - o Helical toothed
        - — Single helical
        - — double helical (herringbone)

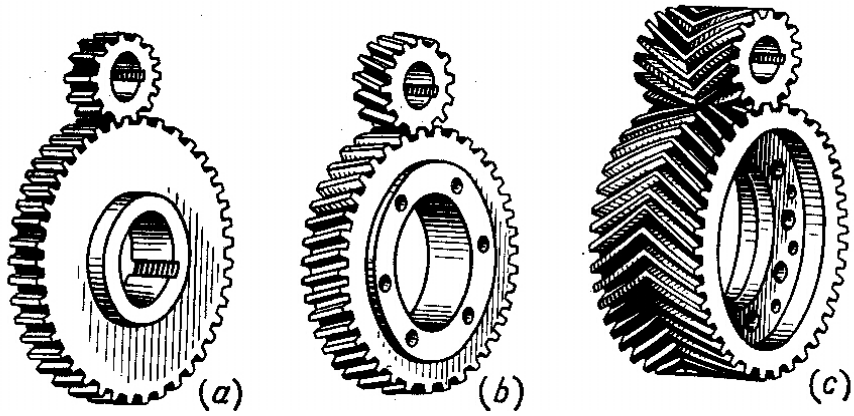


Fig. 7.2.3 *(a) Straight toothed (b)Helical and (c) Double helical gears*

Compared to straight toothed gears, helical toothed gears run more smoothly and can transmit larger torque. Double helical gears are of large size and used for heavy torque transmission.

- Bevel gears – transmitting motion between intersecting shafts (axes) (Fig. 7.2.4)
    - o Straight toothed
    - o Helical toothed
        - — Spiral bevel gear
        - — Hypoid gear

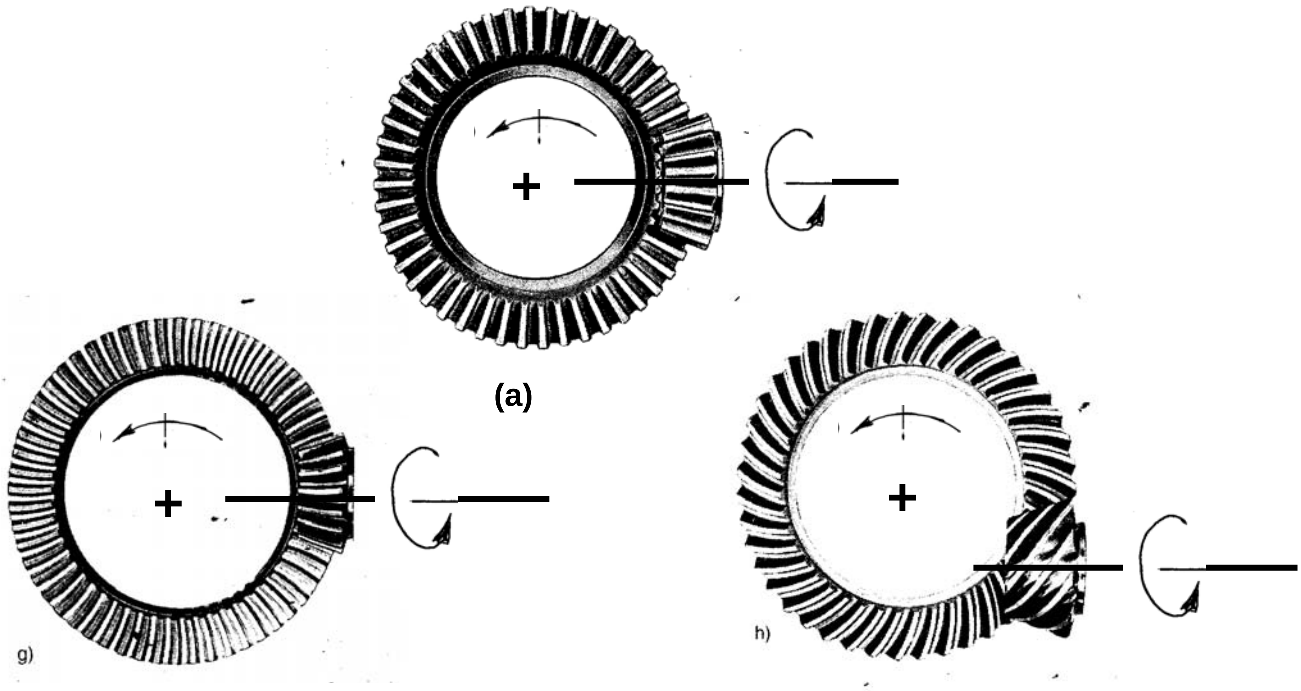
  Helical toothed bevel gears are used for smoother and larger torque transmission.

- Gears transmitting motion and power between non-parallel non-intersecting shafts (Fig. 7.2.5)
    - o Worm and worm wheel
    - o Spiral gears
    - o Skewed or hypoid bevel gears

Worm and worm wheel are generally used for speed reduction but are irreversible i.e., rotation can be transmitted only from the worm to the worm wheel unless the helix angle is tool large.
Spiral gears are used when torque or power to be transmitted is insignificant.

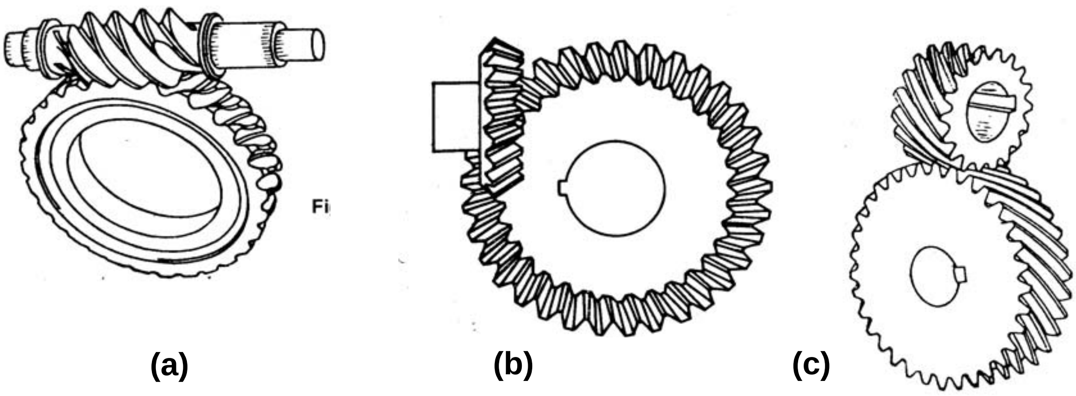
(c) According to pattern of motion

- Rotation to rotation : - (Fig. 7.2.6) wheel type gears
- Rotation to translation or vice versa – e.g. rack and pinion
    - Straight toothed
    - Helical toothed



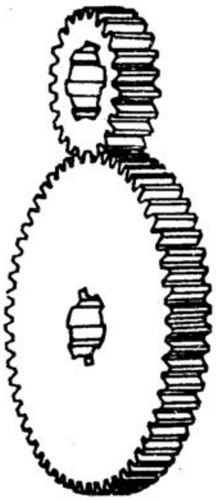
(b) (c)

Fig. 7.2.4 Bevel gears; (a) straight toothed, (b) spiral and hypoid gears



(a) (b) (c)

Fig. 7.2.5 Gears transmitting power between non-parallel non intersecting shafts. (a) worm and worm wheel, (b) hypoid gear and (c) spiral gears.


(a)

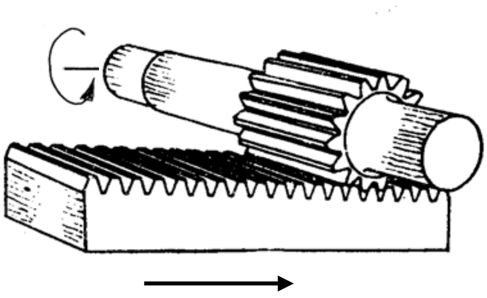

(b)

Fig. 7.2.6 *Gearing systems transforming (a) rotation to rotation and (b) rotation to translation*

(iv) Specification Of Gears

Gears are generally specified by their
- Type; e.g. spur, bevel, spiral etc.
- Material
- Size or dimensions
- Geometry
- Special features, if any

- **Type of gears** – has already been discussed in the previous section (iii)

- **Gear materials**

The materials of most of the gears used for transmitting reasonable torque and speed mainly need to be mechanically strong in shear and bending, sufficiently tough and resistant to wear, fatigue and chemical degradation.
However, the material for any gear is selected based on,
- o The working condition ie, power, speed and torque to be transmitted
- o Working environment, i.e., temperature, vibration, chemical etc.
- o Ease of manufacture
- o Overall cost of material and manufacture

The materials generally used for making gears are :

Δ Ferrous metals – for high loads
- Grey cast iron – preferred for reasonable strength and wear resistance, ease of casting and machining and low cost
- Forged or rolled high carbon steels and alloy steels (Ni-Cr, Mo etc.) which are either fully hardened or surface hardened for use under high stresses and speed.

- ∆ Non ferrous metals – for light load
  - Aluminium, bronze and brass are used for making gears having fine teeth and working at very light load – e.g., in equipments, toys etc. or against hard steel mating gears
  - Aluminium alloys like aluminium bronze, Zinc – Al. alloy etc.

- ∆ Non-metals – widely used for light load, non-precision and noiseless operation. Polymers (plastics) : both themoplastic and thermosetting type and various composites (metals, graphite, wood dust or ceramic powders dispersed in thermosetting plastics)

- **Size or major dimensions**

The dimensional features that are used to express or specify the gears are ;

- ∆ For spur gears and worm wheels
  - — number of teeth, z
  - — module, m
  - — helix angle, if any (θ)
  - — width (b)

For example, pitch circle diameter (PCD) = $mZ/\cos\theta$

- ∆ For worm (single or double toothed gears)
  - — number of start
  - — module helix angle length

- **Gear geometry**

Some geometrical features also need to be mentioned while specifying gears, such as,

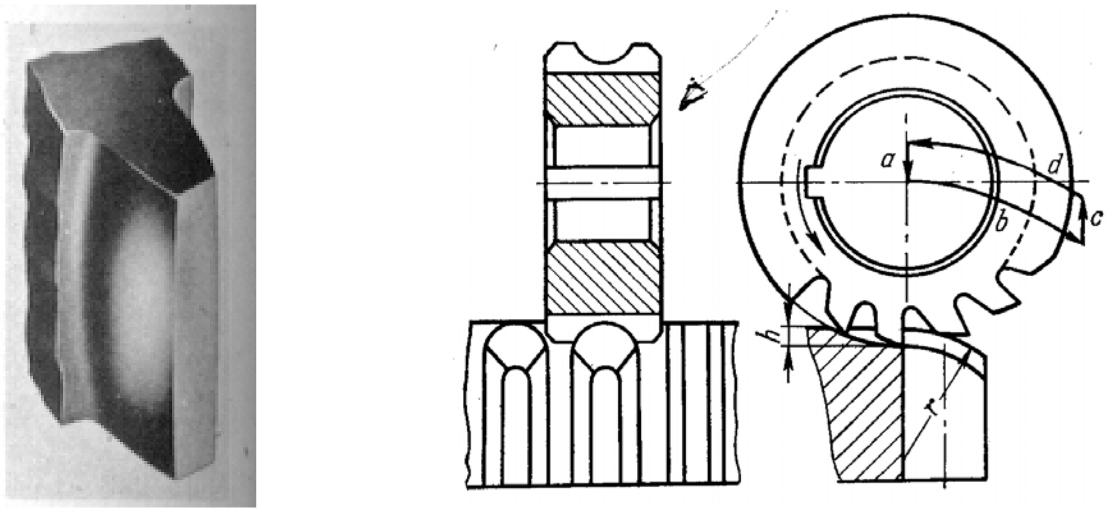
- ∆ Pressure angle
- ∆ Addendum and dedendum

- **Special features**

If there be any special feature, that also has to be included with gear specification, such as

- — Tooth bevelling for safe handling
- — Tooth crowning for uniform wear and long service life
- — Tooth rounding for easy engagement

as indicated in Fig. 7.2.7



(a) (b)

Fig. 7.2.7 Modification of spur gear tooth; (a) crowning and (b) tooth rounding

(V) Manufacture Of Gears

Manufacture of gears needs several processing operations in sequential stages depending upon the material and type of the gears and quality desired. Those stages generally are :

- — Preforming the blank without or with teeth
- — Annealing of the blank, if required, as in case of forged or cast steels
- — Preparation of the gear blank to the required dimensions by machining
- — Producing teeth or finishing the preformed teeth by machining
- — Full or surface hardening of the machined gear (teeth), if required
- — Finishing teeth, if required, by shaving, grinding etc.
- — Inspection of the finished gears.

In this section, performing, producing teeth by machining and gear teeth finishing have been discussed in detail.

Preforming Gear Blanks

- **Casting**

Gear blanks and even gears along with teeth requiring substantial to little machining or finishing are produced by various casting processes.

- o **Sand casting**
  The blanks of large cast iron gears, if required to be made one or few pieces, are produced by sand casting. Then the blank is prepared to appropriate dimensions and the teeth are produced by machining that cast preform. Complete gears with teeth can also be directly produced by such casting and used at low speed in machineries like farm

machinery and hand operated devices where gear accuracy and finish are not that much required.

- **Metal mould casting**
  Medium size steel gears with limited accuracy and finish are often made in single or few pieces by metal mould casting. Such unfinished gears are used in several agro-industries. For general and precision use the cast preforms are properly machined.

- **Die casting**
  Large lot or mass production of small gears of low melting point alloys of Al, Zn, Cu, Mg etc. are done mainly by die casting. Such reasonably accurate gears are directly or after little further finishing are used under light load and moderate speeds, for example in instruments, camera, toys.

- **Investment casting**
  This near-net-shape method is used for producing small to medium size gears of exotic materials with high accuracy and surface finish hardly requiring further finishing. These relatively costly gears are generally used under heavy loads and stresses.

- **Shell mould casting**
  Small gears in batches are also often produced by this process. The quality provided by this process lies in between that of sand casting and investment casting.

- **Centrifugal casting**
  The solid blanks or the outer rims (without teeth) of worm wheels made of cast iron, phosphor bronze or even steel are preferably preformed by centrifugal casting. The performs are machined to form the gear blank of proper size. Then the teeth are developed by machining.

- **Manufacture of gears by rolling**

The straight and helical teeth of disc or rod type external steel gears of small to medium diameter and module are generated by cold rolling by either flat dies or circular dies as shown in Fig. 7.2.8. Such rolling imparts high accuracy and surface integrity of the teeth which are formed by material flow unlike cutting. Gear rolling is reasonably employed for high productivity and high quality though initial machinery costs are relatively high. Larger size gears are formed by hot rolling and then finished by machining

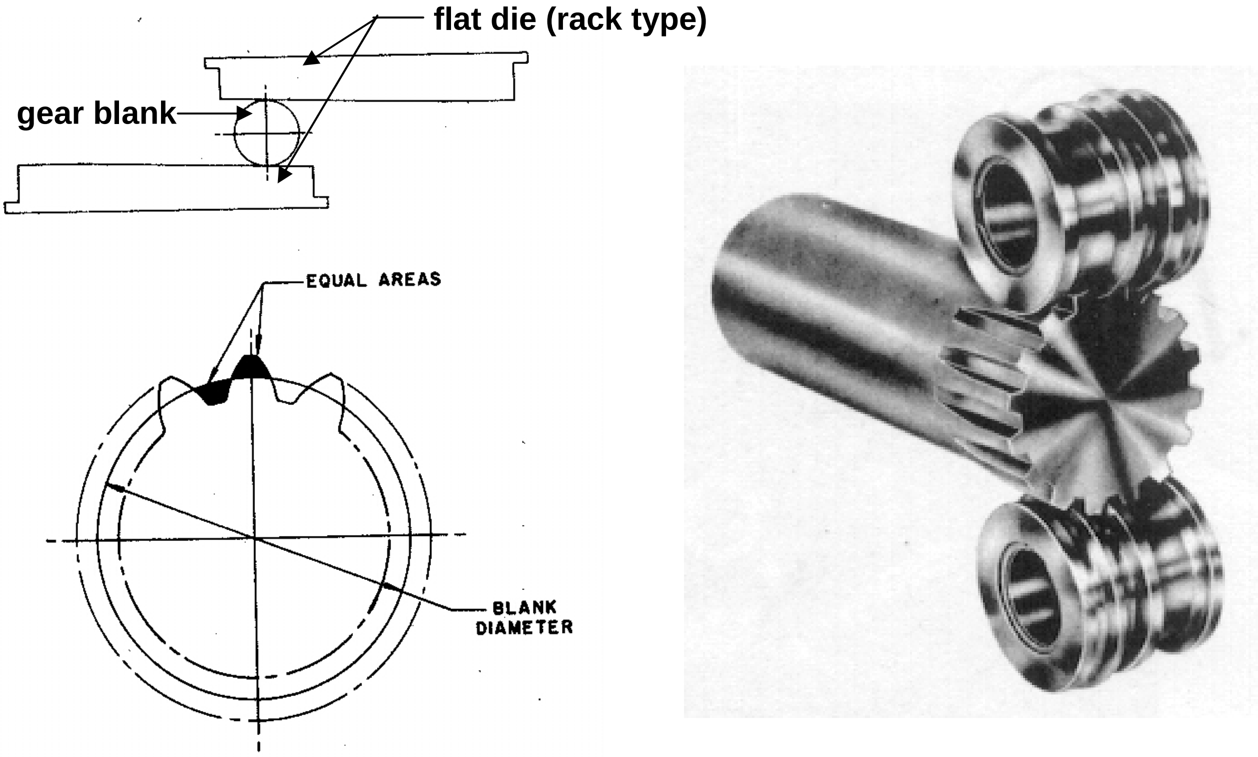


Fig. 7.2.8   Production of teeth of spur gears by rolling.

- **Powder metallurgy**

Small size high quality external or internal spur, bevel or spiral gears are also produced by powder metallurgy process. Large size gears are rolled after briquetting and sintering for more strength and life. Powder metallurgically produced gears hardly require any further finishing work.

- **Blanking in Press tool**

Mass production of small and thin metallic gears requiring less accuracy and finish are often done by blanking from sheets by suitably designed die and punch. Such gears are used for clocks, watches, meters, toys etc. However, quality gears can also be produced by slight finishing (shaving) after blanking.

- **Plastic moulding**

Small to medium size plastic gears with or without metal core are manufactured in large quantity by injection moulding. Such moderately accurate and less noisy gears, both external and internal types, are used under light loads such as equipments, toys, meters etc.

- **Extrusion process**

High quality small metallic or non metallic external gears are often produced in large quantity by extrusion. Number of gears of desired width are obtained by parting from the extruded rod of gear – section.

- **Wire EDM**

Geometrically accurate but moderately finished straight toothed metallic spur gears, both external and internal type, can be produced by wire type Electro-discharge Machining (EDM) as shown in Fig. 7.2.9

Fig. 7.2.9 *Production of teeth of external and internal spur gears by Wire-Electrodischarge machining (EDM)*

Production of Gear Teeth by Machining

It appears from the previous section that gears are manufactured in several routes ;

- Δ The preformed blanks of approximate shape and irregular surface are machined to desired dimensions and finish and then the teeth are produced generally by machining and occasionally by rolling.
- Δ Full gears with teeth are made by different processes and then finished by further machining and / or grinding
- Δ Accurate gears in finished form are directly produced by near – net – shape process like rolling, plastic moulding, powder metallurgy etc. requiring slight or no further finishing.

The most commonly practiced method is preforming the blank by casting, forging etc. followed by pre-machining to prepare the gear blank to desired dimensions and then production of the teeth by machining and further finishing by grinding if necessary.

Gear teeth are produced by machining based on

- o **Forming** – where the profile of the teeth are obtained as the replica of the form of the cutting tool (edge); e.g., milling, broaching etc.
- o **Generation** – where the complicated tooth profile are provided by much simpler form cutting tool (edges) through rolling type, tool – work motions, e.g., hobbing, gear shaping etc.

- **Methods of production of gear teeth by machining on Forming principle**

  - **Shaping, planing and slotting**

Fig. 7.2.10 schematically shows how teeth of straight toothed spur gear can be produced in shaping machine, if necessary. Both productivity and product quality are very low in this process which therefore, is used, if at all, for making one or few teeth on one or two pieces of gears as and when required for repair and maintenance purpose. In principle planning and slotting machines work on the same principle. Planing machine is used, if required at all, for making teeth of large gears whereas slotting, generally, for internal gears.

  - **Milling**

Gear teeth can be produced by both disc and end mill type form milling cutter as shown in Fig. 7.2.11

Production of gear teeth by form milling are characterised by :

- use of HSS form milling cutters
- use of ordinary milling machines
- low production rate for
  - — need of indexing after machining each tooth gap
  - — slow speed and feed
- low accuracy and surface finish
- inventory problem – due to need of a set of eight cutters for each module – pressure angle combination.
- End mill type cutters are used for teeth of large gears and / or module.

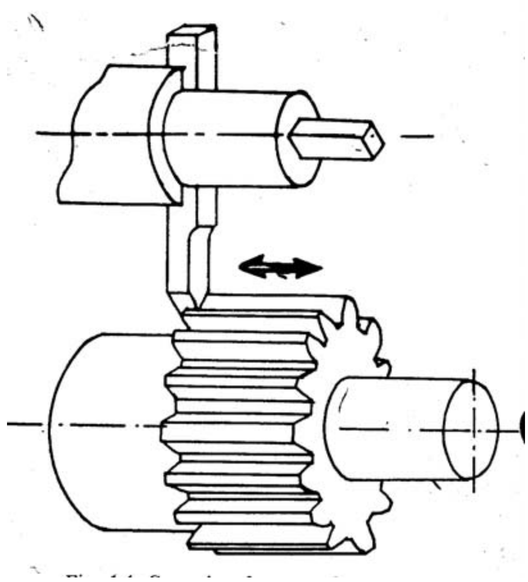


Fig. 7.2.10 *Gear teeth cutting in ordinary shaping machine.*

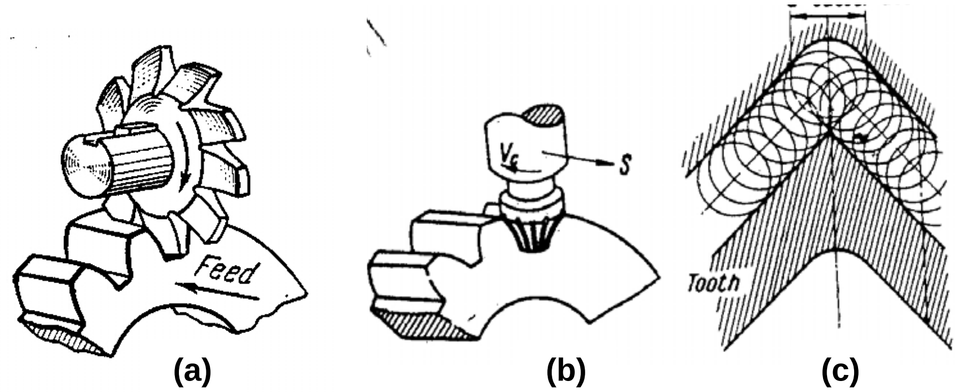
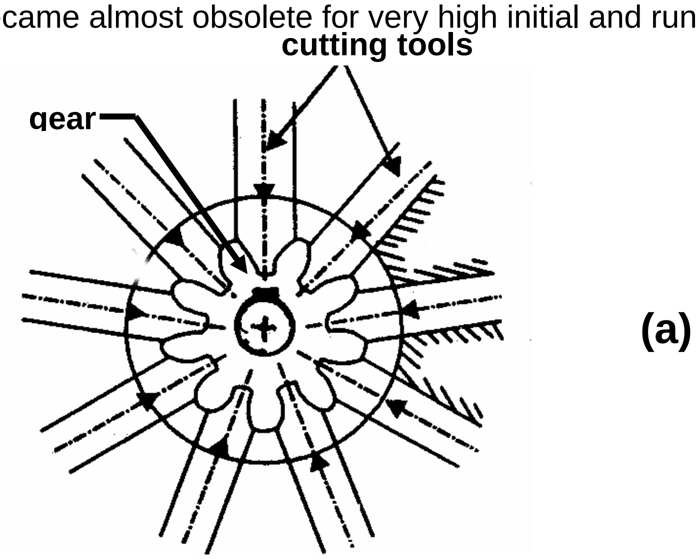


Fig. 7.2.11 *Producing external teeth by form milling cutters (a) disc type and end mill type for (b) single helical and (c) double helical teeth*

- **Fast production of teeth of spur gears**
  - **Parallel multiple teeth shaping**

In principle, it is similar to ordinary shaping but all the tooth gaps are made simultaneously, without requiring indexing, by a set of radially infeeding single point form tools as indicated in Fig. 7.2.12(a). This old process was highly productive but became almost obsolete for very high initial and running costs.



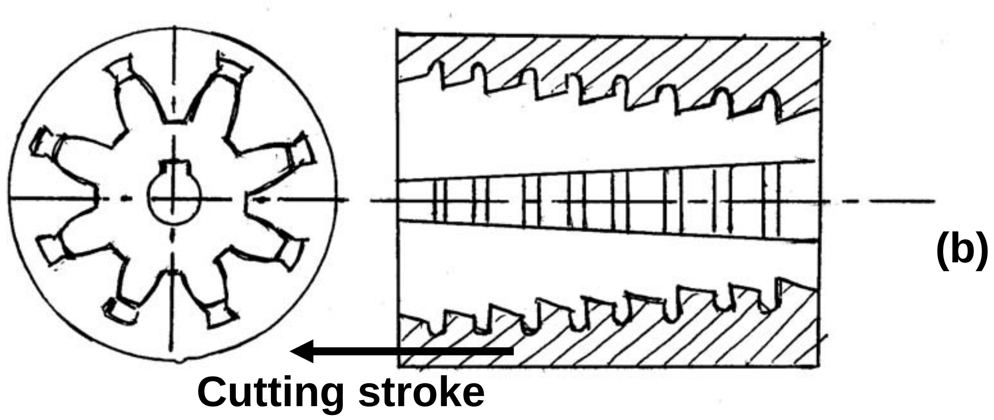


Fig. 7.2.12 *High production of straight teeth of external spur gears by (a) parallel shaping (forming) and (b) broaching*

- **Broaching**

Teeth of small internal and external spur gears; straight or single helical, of relatively softer materials are produced in large quantity by this process. Fig. 7.2.12 (b) schematically shows how external teeth are produced by a broaching in one pass. This method leads to very high productivity and quality but cost of machine and broach are very high.

- **Production of gear teeth by machining on Generation principle**

Generation method is characterised by automatic indexing and ability of a single cutter to cover the entire range of number of teeth for a given combination of module and pressure angle and hence provides high productivity and economy.

- **Sunderland method using rack type cutter**

Fig. 7.2.13 schematically shows the principle of this generation process where the rack type HSS cutter (having rake and clearance angles) reciprocates to accomplish the machining (cutting) action while rolling type interaction with the gear blank like a pair of rack and pinion. The favourable and essential applications of this method (and machine) include :

- moderate size straight and helical toothed external spur gears with high accuracy and finish
- cutting the teeth of double helical or herringbone gears with a central recess (groove)
- cutting teeth of straight or helical fluted cluster gears

However this method needs, though automatic, few indexing operations.

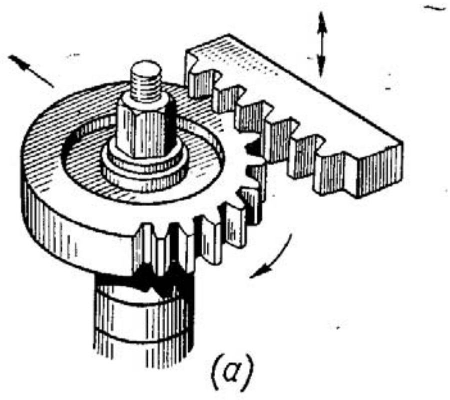


Fig. 7.2.13 *External gear teeth generation by rack type cutter (Sunderland method)*

- **Gear shaping**

In principle, gear shaping is similar to the rack type cutting process, excepting that, the linear type rack cutter is replaced by a circular cutter as indicated in Fig. 7.2.14, where both the cutter and the blank rotate as a pair of spur gears in addition to the reciprocation of the cutter.

Generation method is characterised by automatic indexing and ability of a single cutter to cover the entire range of number of teeth for a given combination of module and pressure angle and hence provides high productivity and economy.
The gear type cutter is made of HSS and possesses proper rake and clearance angles.
The additional advantages of gear shaping over rack type cutting are :

- separate indexing is not required at all
- straight or helical teeth of both external and internal spur gears can be produced with high accuracy and finish
- productivity is also higher.

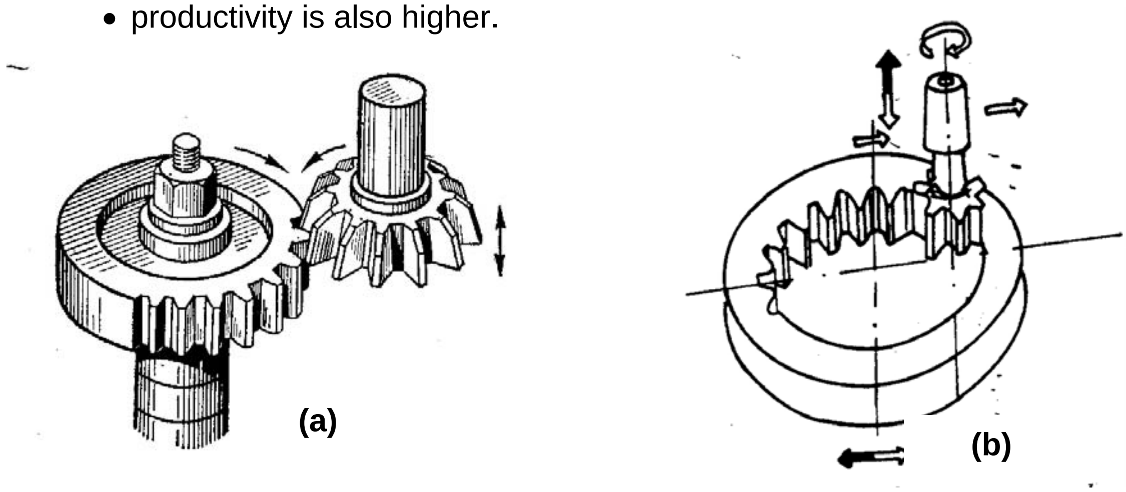


Fig. 7.2.14 *Gear teeth generation by gear shaping (a) external and (b) internal spur gear*

- **Hobbing**

The tool-work configuration and motions in hobbing are shown in Fig. 7.2.15, where the HSS or carbide cutter having teeth like gear milling cutter and the gear blank apparently interact like a pair of worm and worm wheel. The hob (cutter) looks and behaves like a single or multiple start worm. Having lesser number (only three) of tool – work motions, hobbing machines are much more rigid, strong and productive than gear shaping machine. But hobbing provides lesser accuracy and finish and is used only for cutting straight or helical teeth (single) of external spur gears and worm wheels.

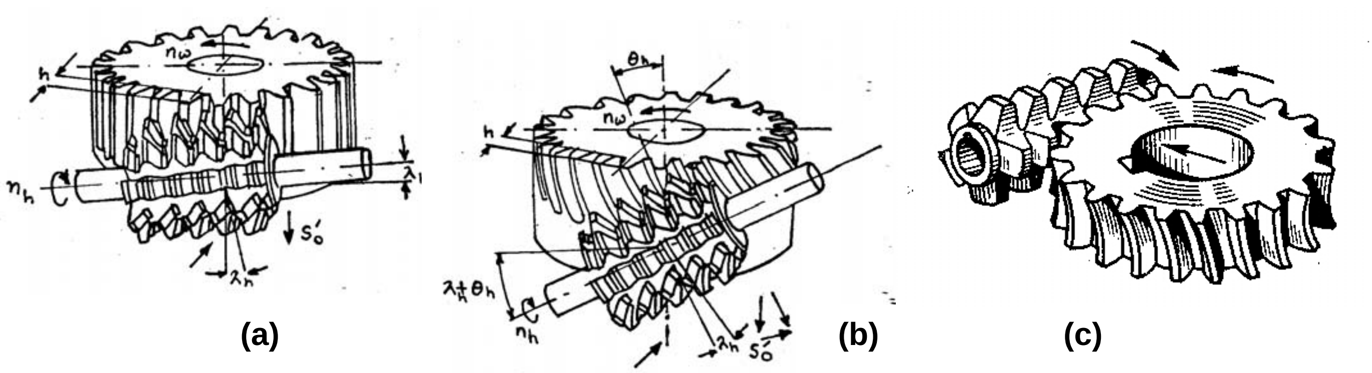


Fig. 7.2.15 *Generation of external gear teeth by Hobbing :*
(a) straight tooth (b) helical tooth and (c) worm wheel

* **Manufacture of worm**

The screw like single or multi-start worms (gears) made of steel are generally made by machining like long thread milling or by cold rolling like thread rolling followed by heat treatment for surface hardening and finishing by grinding.

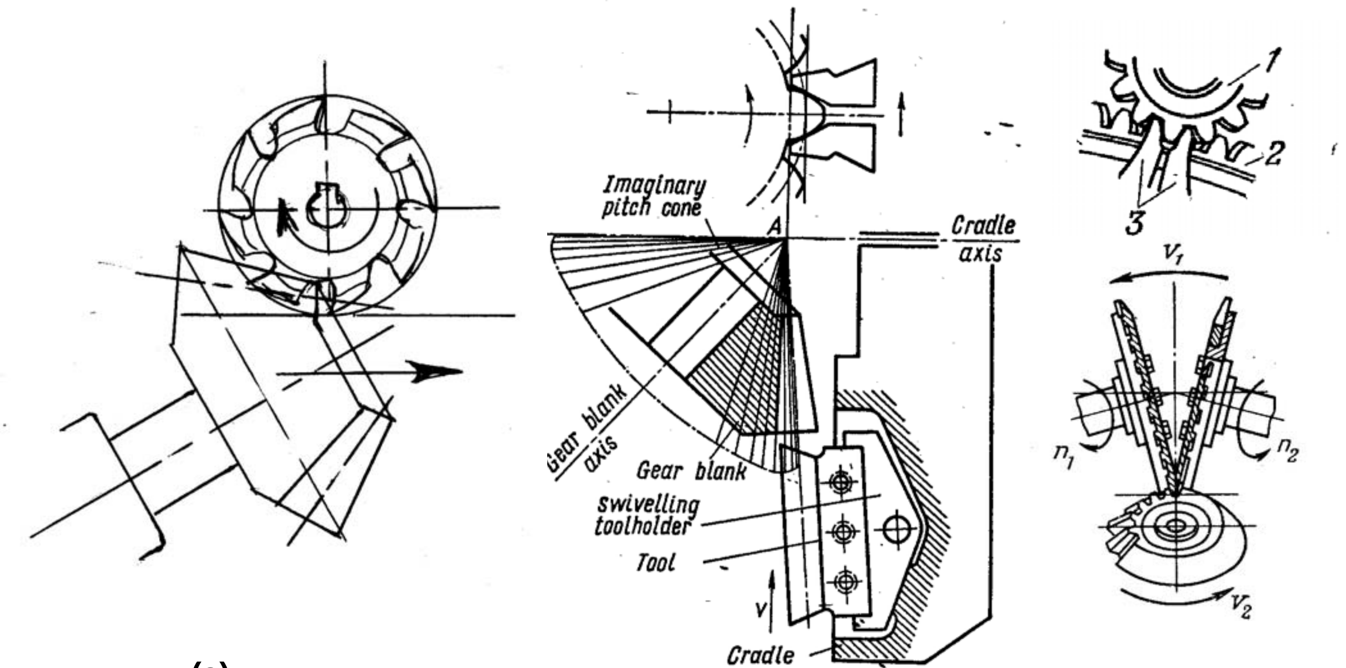
* **Manufacture of bevel gears**

In manufacture of bevel gears, first the blanks are preformed by casting or forging followed by machining to desired dimensions in lathes or special purpose machine.
Then the teeth are produced in the blank by machining. The way of machining and machine tool are chosen based on the form of teeth and volume of production as follows :

- Δ Straight toothed bevel gear
    - o Forming by milling cutter – low productivity and quality hence employed for production requiring less volume and precision
    - o Generation – high accuracy and finish, hence applied for batch to mass production.

Fig. 7.2.16 schematically shows the principle of forming and generation of teeth of straight toothed bevel gear. In generation process, the inner flanks of two adjacent teeth are developed with involute profile by the straight teeth of the cutters under rolling action.

- Δ Teeth of spiral and hypoid bevel gears are produced by almost the same generation principle but the cutter resembles face milling cutter as shown in Fig. 7.2.17.



(a) (b)

Fig. 7.2.16 *Production of teeth of straight toothed spur gear by (a) forming and (b) generation*

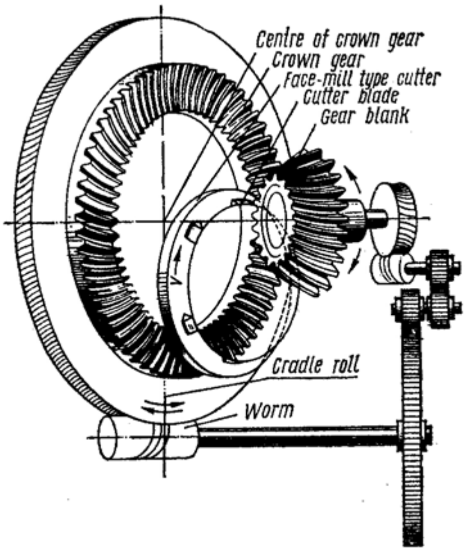


Fig. 7.2.17 *Generation of teeth of spiral and hypoid bevel gear.*

Finishing of Gear Teeth

For smooth running, good performance and long service life, the gears need
- to be accurate in dimensions and forms
- to have high surface finish and
- to be hard and wear resistive at their tooth flanks

which are achieved by some gear teeth finishing work after near accurate preforming and machining. Small gears made by cold rolling generally do not require further finishing. If a rolled gear needs further surface hardening only then little finishing by grinding and / or lapping is done after hardening.
Gears produced to near-net-shape by die casting, powder metallurgy, extrusion, blanking etc. need little finishing.
But machined and hardened gear teeth are essentially finished for accuracy and surface finish.

Common methods of gear teeth finishing

Gear teeth, after preforming and machining, are finished generally by;
- for soft and unhardened gears
  - gear shaving
  - gear rolling or burnishing
- for hard and hardened gears
  - grinding
  - lapping
- for soft but precision gears
  - shaving followed by surface hardening and then lapping

- **Gear shaving**

The teeth of straight or helical toothed external spur gears and worm wheels of moderate size and made of soft materials like aluminium alloy, brass, bronze, cast iron etc. and unhardened steels are mostly finished by shaving process. Fig. 7.2.18 shows the different types of shaving cutters which while their finishing action work apparently as a spur gear, rack or worm in mesh with the conjugate gears to be finished. All those gear, rack or worm type shaving cutters are of hard steel or HSS and their teeth are uniformly serrated as shown in Fig. 7.2.19(a) to generate sharp cutting edges.
While interacting with the gears, the cutting teeth of the shaving cutter keep on smoothening the mating gear flanks by fine machining to high accuracy and surface finish. For such minute cutting action, the shaving teeth need an actual or apparent movement relative to the mating teeth along their length as indicated in Fig. 7.2.19 (b).

- **Gear rolling or burnishing**

In this method the machined gear is rolled under pressure with three hardened master gears of high accuracy and finish. The minute irregularities of the machined gear teeth are smeared off by cold plastic flow, which also helps in improving the surface integrity of the desired teeth.

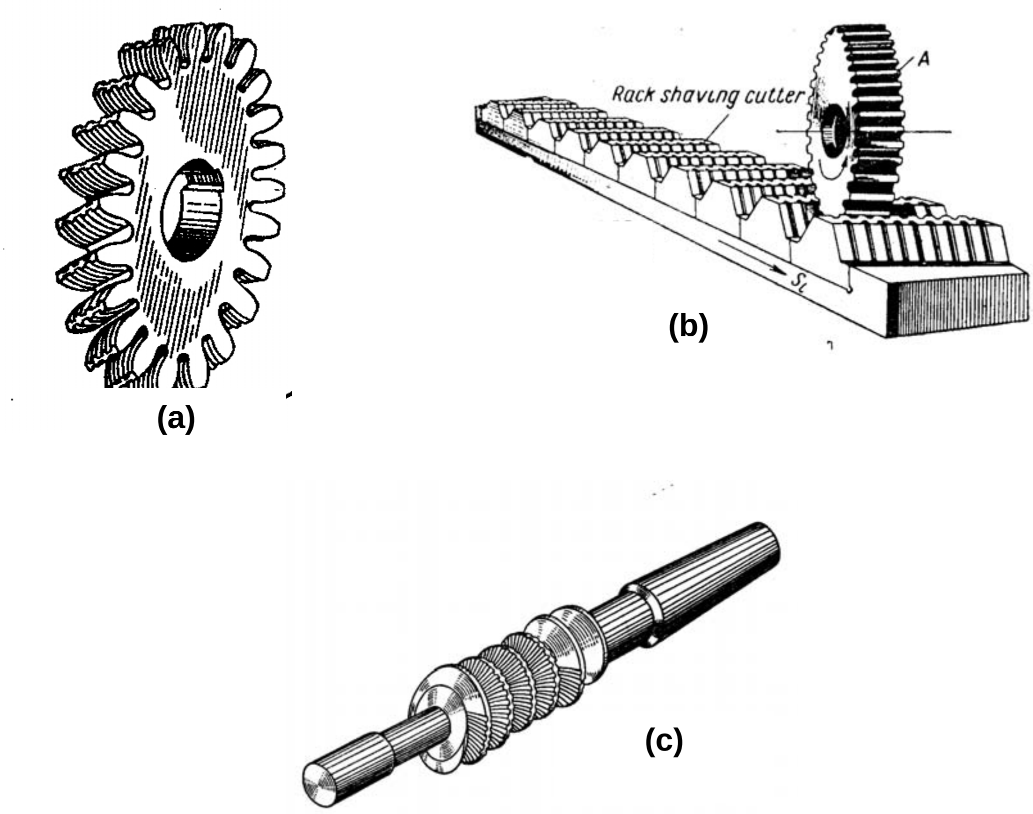
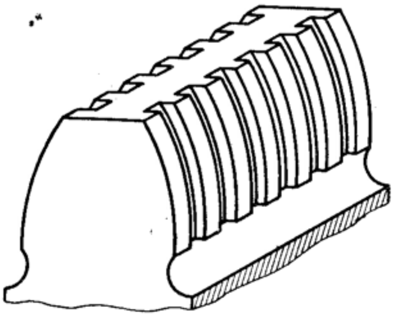
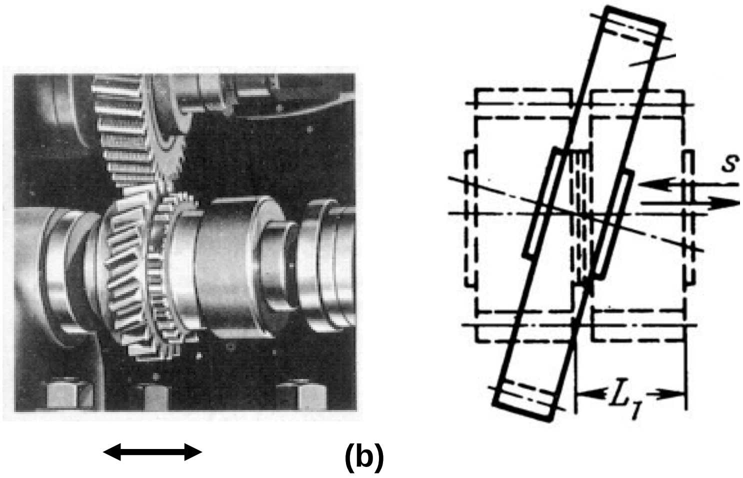


Fig. 7.2.18 Gear shaving cutters of (a) spur gear type (b) rack and (c) worm type



(a)



(b)

Fig. 7.2.19 *Cutting teeth of gear shaving (a) cutter and its (b) action*

- **Gear teeth grinding**

Grinding is a very accurate method and is, though relatively expensive, more widely used for finishing teeth of different type and size of gears of hard material or hardened surfaces. The properly formed and dressed wheel finishes the gear teeth flanks by fine machining or abrading action of the fine abrasives.
Like gear milling, gear grinding is also done on two principles

- Δ Forming
- Δ Generation, which is more productive and accurate

Δ **Gear teeth grinding on forming principle**

This is very similar to machining gear teeth by a single disc type form milling cutter as indicated in Fig. 7.2.20 where the grinding wheel is dressed to the form that is exactly required on the gear. Need of indexing makes the process slow and less accurate. The wheel or dressing has to be changed with change in module, pressure angle and even number of teeth. Form grinding may be used for finishing straight or single helical spur gears, straight toothed bevel gears as well as worm and worm wheels.

Δ **Gear teeth grinding on generation principle**

Fig. 7.2.21 schematically shows the methods of finishing spur gear teeth by grinding on generation principle.
The simplest and most widely used method is very similar to spur gear teeth generation by one or multi-toothed rack cutter. The single or multi-ribbed rotating grinding wheel is reciprocated along the gear teeth as shown. Other tool – work motions remain same as in gear teeth generation by rack type cutter as indicated in Fig. 7.2.13. For finishing large gear teeth a pair of thin dish type grinding wheels are used as shown in Fig. 7.2.21 (c). Whatsoever, the contacting surfaces of the wheels are made to behave as the two flanks of the virtual rack tooth.

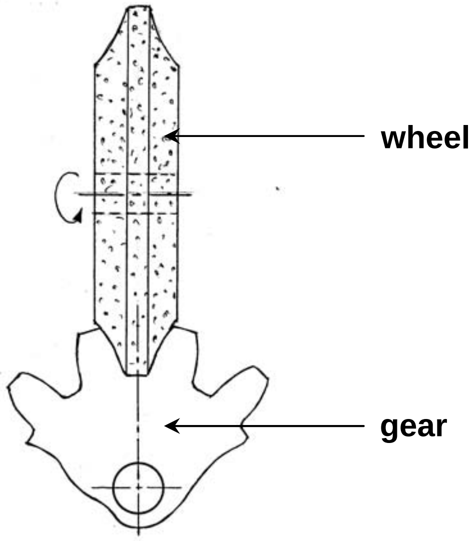


Fig. 7.2.20 *Gear teeth finishing by form grinding*

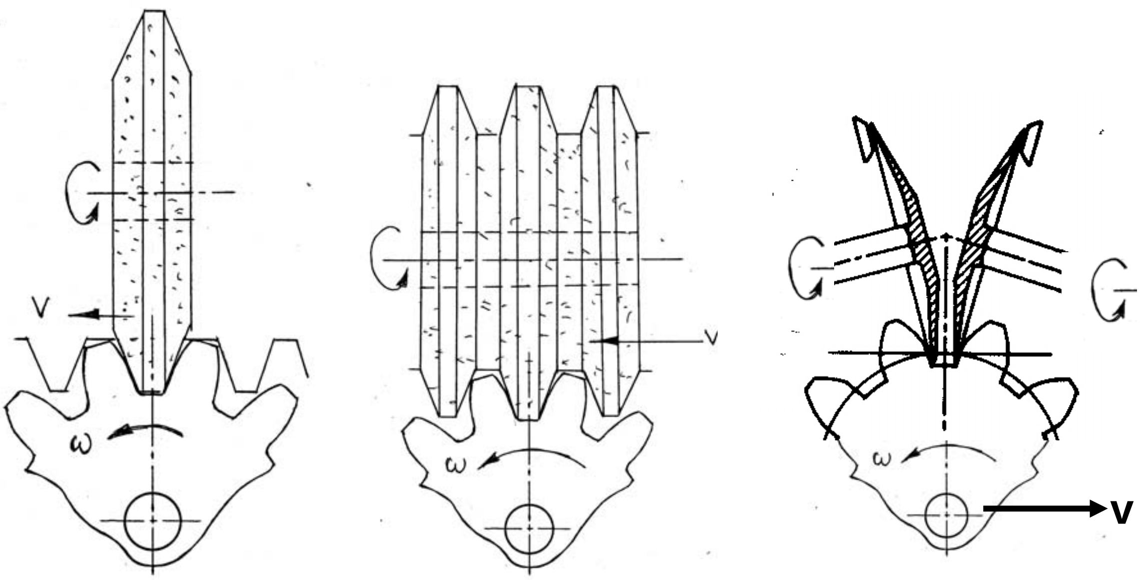


Fig. 7.2.21 *Gear teeth grinding on generation principle.*

Δ Gear teeth finishing by lapping

The lapping process only corrects minute deviations from the desired gear tooth profiles. The gear to be finished after machining and heat treatment and even after grinding is run in mesh with a gear shaped lapping tool or another mating gear of cast iron. An abrasive lapping compound is used in between them. The gear tooth contact substantially improves by such lapping.

Module 8

Jigs and Fixtures for Machine shops

Lesson
33
Purposes of jigs and fixtures and their Design principles

Instructional objectives

This lesson will enable the students

(i) Define Fixture and Jig that aid machining
(ii) Conceive the purposes of use of jigs and fixtures
(iii) State the design considerations for jigs and fixtures
(iv) Illustrate the methods of
  (a) locating
  (b) supporting and
  (c) clamping of blanks
  (d) guidance of cutting tools
 in fixtures and jigs to facilitate machining

(i) Definition Of Fixture And Jig

Fixtures, being used in machine shop, are strong and rigid mechanical devices which enable easy, quick and consistently accurate locating, supporting and clamping, blanks against cutting tool(s) and result faster and accurate machining with consistent quality, functional ability and interchangeability.
Jig is a fixture with an additional feature of tool guidance.

(ii) Purpose Of Using Fixtures And Jigs

For a machining work, like drilling a through hole of given diameter eccentrically in a premachined mild steel disk as shown in Fig. 8.1.1 in a

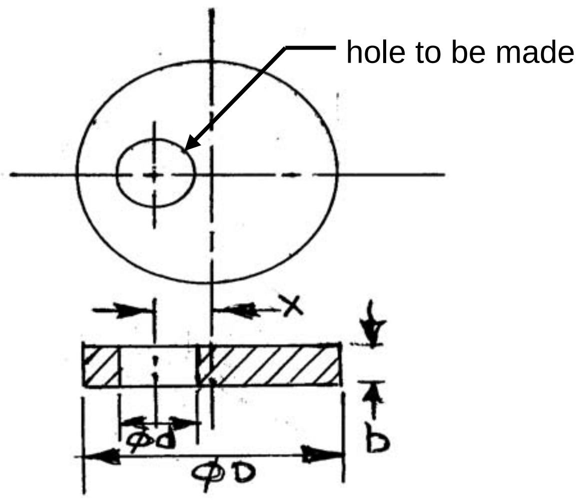


Fig. 8.1.1 *A through hole has to be drilled in a pre-machined mild steel disc.*

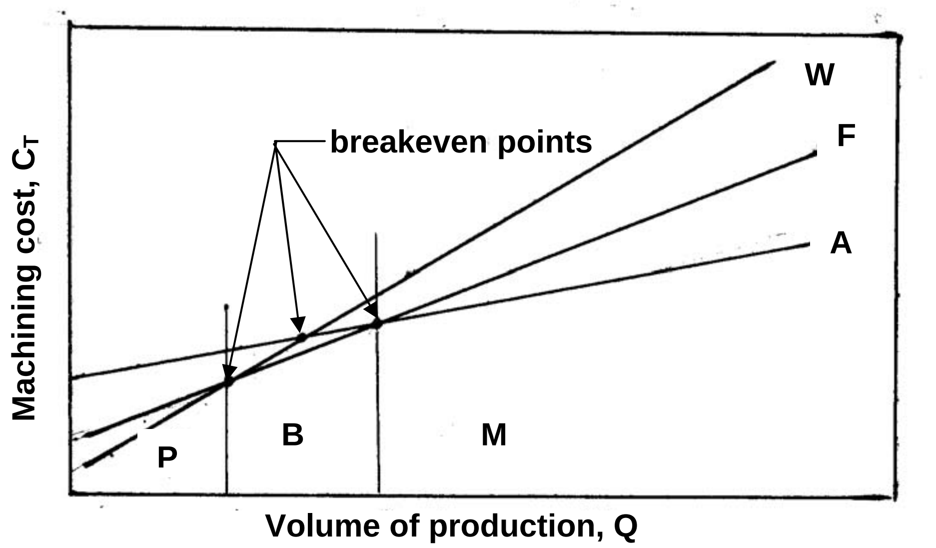
conventional drilling machine without using any fixture or jig, the following elementary steps are to be sequentially followed

- cleaning and deburring the blank (disc)
- marking on the blank showing the location of the hole and its axis on the blank
- punch the centre at the desired location and prick punch the periphery of the hole to be made in the disc
- mount the blank in a drilling vice using parallel block, a small Vee block etc. to provide support and clamp the blank firmly
- position the vice along with the marked blank to bring the hole axis in alignment with the drill axis by
    - Δ either adjusting the vise position w.r.t. the fixed drill axis
    - Δ or moving the drilling machine table and then locking the table position
    - Δ or moving the radial arm and the drilling head, if it is a radial drilling machine
- after fixing the blank, vise and the table, alignment is checked again
- if error, like eccentricity, is found to occur then readjustment of location of the hole – axis is to be done before and even after starting drilling
- drilling is accomplished.

Therefore it appears that so many operations are needed to be carried out carefully and skilfully by the machinist or operator for such a simple job. Even after that there may be inaccuracies in machining. Such tedious and time consuming manual work are eliminated or drastically reduced in mass production by automatic or special purpose machine tools. But such machine tools are quite expensive and hence are economically justified for only huge or mass production and not viable for small lot or batch production. For batch production proper design and use of simple but effective jigs and fixtures are appropriate and economically justified. This is schematically illustrated in Fig. 8.1.2.

The basic purposes of developing and using suitable jigs and fixtures for batch production in machine shops are :

- to eliminate marking, punching, positioning, alignments etc.
- easy, quick and consistently accurate locating, supporting and clamping the blank in alignment of the cutting tool
- guidance to the cutting tool like drill, reamer etc.
- increase in productivity and maintain product quality consistently
- to reduce operator's labour and skill – requirement
- to reduce measurement and its cost
- enhancing technological capacity of the machine tools
- reduction of overall machining cost and also increase in interchangeability.



W – without using jig & fixture
F – using jig and fixture
A – automatic (special purpose) machine
P – piece production
B – batch production
M – mass production

Fig. 8.1.2 *Role of Jigs and Fixtures on machining cost*

(iii) Design Considerations For Jigs And Fixtures

Jigs and fixtures are manually or partially power operated devices. To fulfil their basic purposes, jigs and fixtures are comprised of several elements (as indicated in Fig. 8.1.3) :

- base and body or frame with clamping features
- locating elements for proper positioning and orientation of the blank
- supporting surfaces and base
- clamping elements
- tool guiding frame and bushes (for jig)
- indexing plates or systems, if necessary
- auxiliary elements
- fastening parts

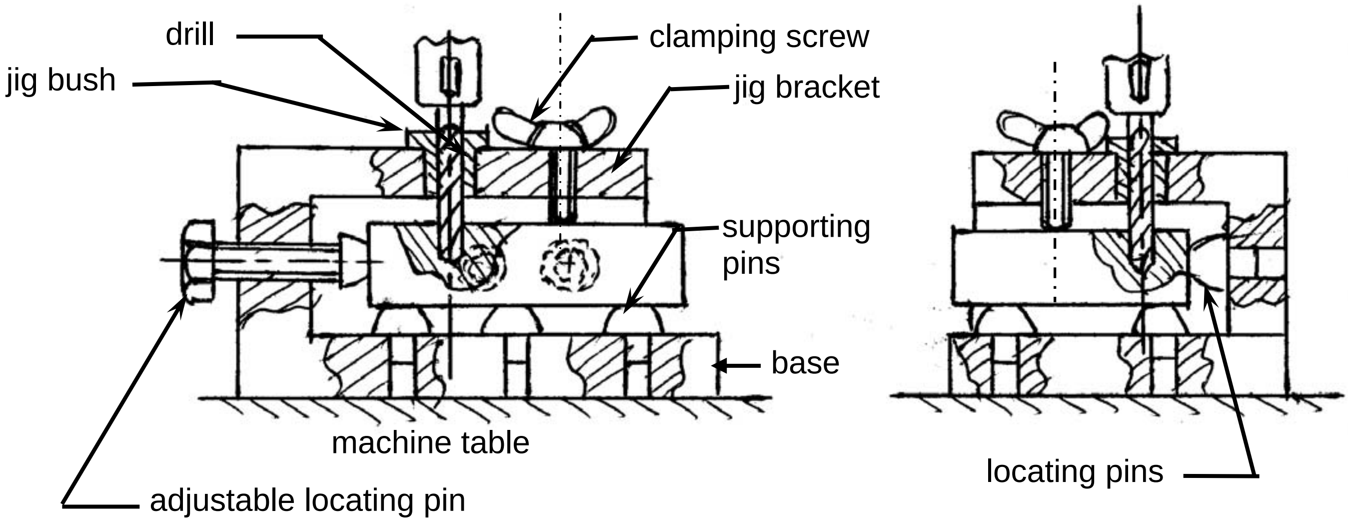


Fig. 8.1.3 *Major elements of jig and fixtures.*

Therefore keeping in view increase in productivity, product quality, repeatability i.e. interchangeability and overall economy in batch production by machining, the following factors are essentially considered during design, fabrication and assembly of jigs and fixtures :

- easy, quick and consistently accurate locating of the blank in the jig or fixture in reference to the cutting tool
- providing strong, rigid and stable support to the blank
- quick, strong and rigid clamping of the blank in the jig or fixture without interrupting any other operations
- tool guidance for slender cutting tools like drills and reamers
- easy and quick loading and unloading the job to and from the jig or fixture
- use of minimum number of parts for making the jig or fixture
- use of standard parts as much as possible
- reasonable amount of flexibility or adjustability, if feasible, to accommodate slight variation in the job - dimensions.
- prevention of jamming of chips, i.e. wide chips-space and easy chip disposal
- easy, quick and accurate indexing system if required.
- easy and safe handling and moving the jig or fixture on the machine table, i.e., their shape, size, weight and sharp edges and corners
- easy and quick removal and replacement of small parts
- manufacturability i.e. ease of manufacture
- durability and maintainability
- service life and overall expenses

(iv) Principles And Methods Of Locating, Supporting And Clamping Blanks And Tool Guidance In Jigs And Fixtures

It is already emphasized that the main functions of the jigs and fixtures are :

(a) easily, quickly, firmly and consistently accurately
- locating
- supporting and
- clamping

the blank (in the jig or fixture) in respect to the cutting tool(s)

(b) providing guidance to the slender cutting tools using proper bushes

There are and can be several methods of locating, supporting and clamping depending upon the size, shape and material of the job, cutting tool and the machining work required. But some basic principles or rules are usually followed while designing for locating, supporting and clamping of blank in fixtures.

(a) Locating, Supporting and Clamping of jobs in jigs and fixtures

Locating – principles and methods

- **Principles or rules of locating in jigs and fixtures**

For accurate machining, the workpiece is to be placed and held in correct position and orientation in the fixture (or jig) which is again appropriately located and fixed with respect to the cutting tool and the machine tool. It has to be assured that the blank, once fixed or clamped, does not move at all.

Any solid body may have maximum twelve degrees of freedom as indicated in Fig. 8.1.4. By properly locating, supporting and clamping the blank its all degrees of freedom are to be arrested as typically shown in Fig. 8.1.5.

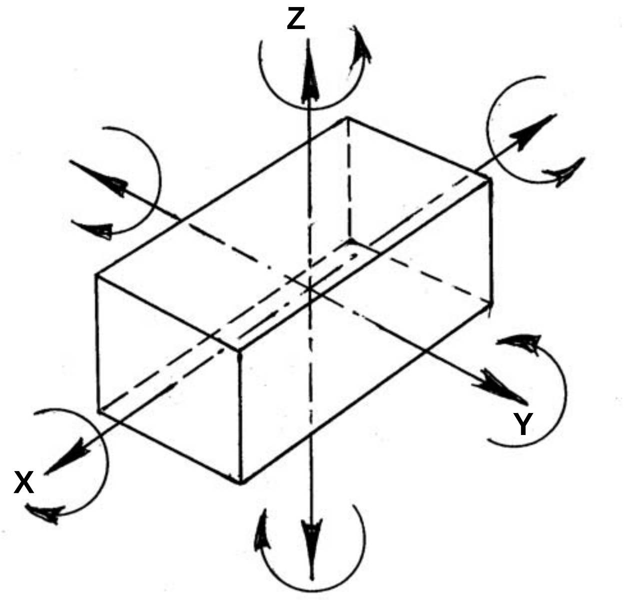


Fig. 8.1.4 *Possible degrees of freedom of a solid body.*

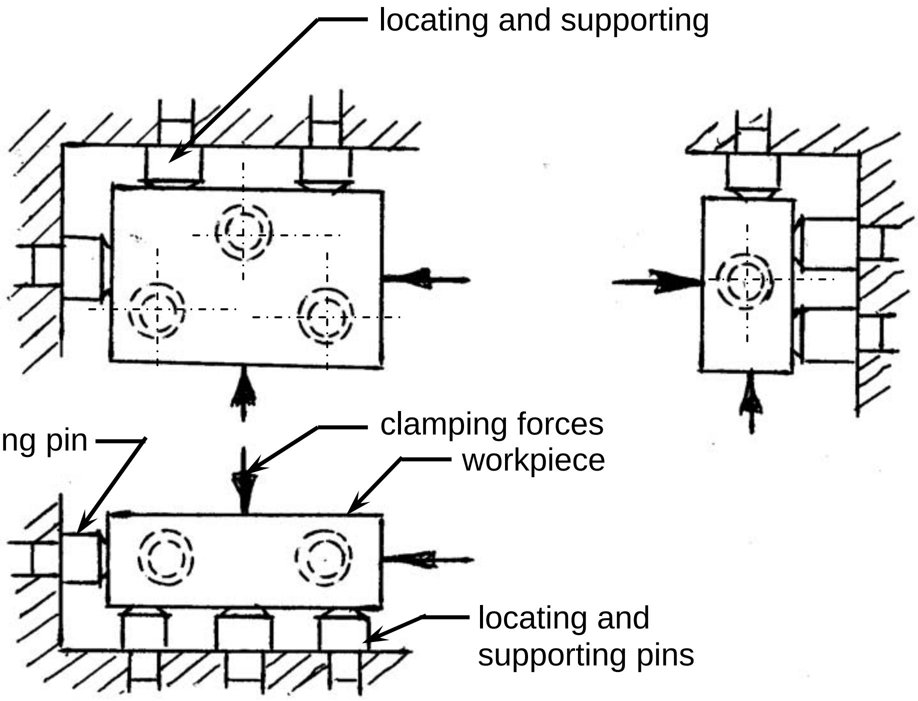


Fig. 8.1.5 *Arresting all degrees of freedom of a blank in a fixture.*

The three adjacent locating surfaces of the blank (workpiece) are resting against 3, 2 and 1 pins respectively, which prevent 9 degrees of freedom. The rest three degrees of freedom are arrested by three external forces usually provided directly by clamping. Some of such forces may be attained by friction.

Some basic principles or rules need to be followed while planning for locating blanks in fixtures, such as;

- One or more surfaces (preferably machined) and / or drilled / bored hole(s) are to be taken for reference
- The reference surfaces should be significant and important feature(s) based on which most of the dimensions are laid down
- Locating should be easy, quick and accurate
- In case of locating by pin, the pins and their mounting and contact points should be strong, rigid and hard
- A minimum of three point must be used to locate a horizontal flat surface
- The locating pins should be as far apart as feasible
- Vee block and cones should be used for self-locating solid and hollow cylindrical jobs as typically shown in **Fig. 8.1.6**
- Sight location is applicable to first – operation location of blank with irregular surfaces produced by casting, forging etc. as indicated in **Fig. 8.1.7** when the bracket is first located on two edges to machine the bottom surface which will be used for subsequent locating.

- Adjustable locating pin(s) as indicated in Fig. 8.1.3 is to be used to accommodate limited part size variation

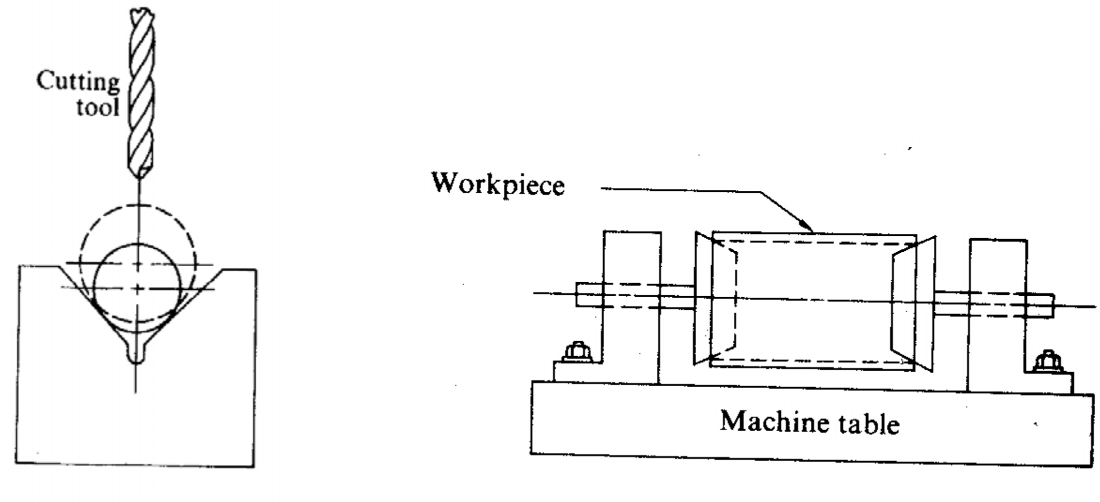


Fig. 8.1.6 *Locating by Vee block and cone.*

- For locating large jobs by rough bottom surface one of the three pins may be replaced by a pivoted arm as indicated in Fig. 8.1.7. The pivoted arm provides wo contact points.

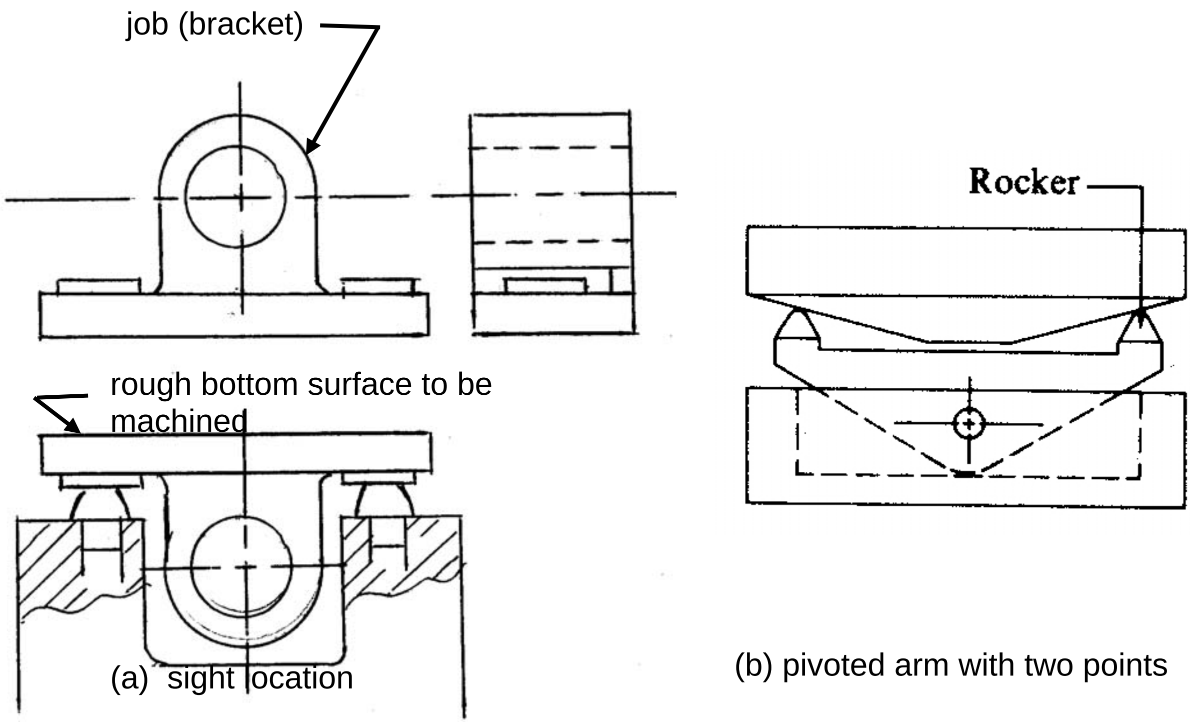


Fig. 8.1.7 *(a) Sight location and (b) location by pivoted points (equalizer)*

- **General methods of locating**

  Δ **Locating blanks for machining in lathes**

In lathes, where the job rotates, the blanks are located by
- fitting into self centering chuck
- fitting into 4 – independent jaw chuck and dead centre
- in self – centering collets
- in between live and dead centres
- by using mandrel fitted into the head stock – spindle
- fitting in a separate fixture which is properly clamped on a driving plate which is coaxially fitted into the lathe spindle.

  Δ **Locating for machining in other than lathes**

In machine tools like drilling machine, boring machine, milling machine, planing machine, broaching machine and surface grinding machine the job remains fixed on the bed or work table of those machine tools.
Fixtures are mostly used in the aforesaid machine tools and jig specially for drilling, reaming etc. for batch production.
For machining in those jigs and fixtures, the blank is located in several ways which include the followings :

- **Locating by flat surfaces**

  Fig. 8.1.8 typically shows locating jobs by their flat surfaces using various types of flat ended pins and buttons.

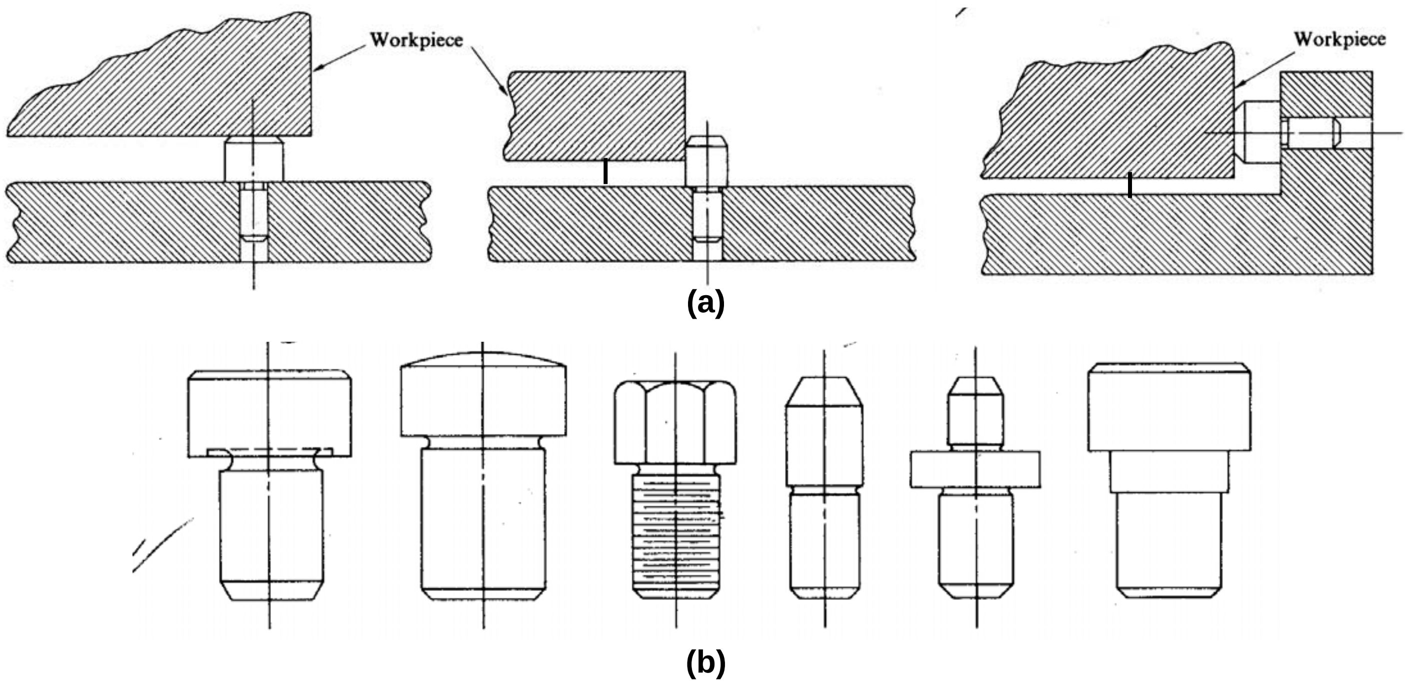
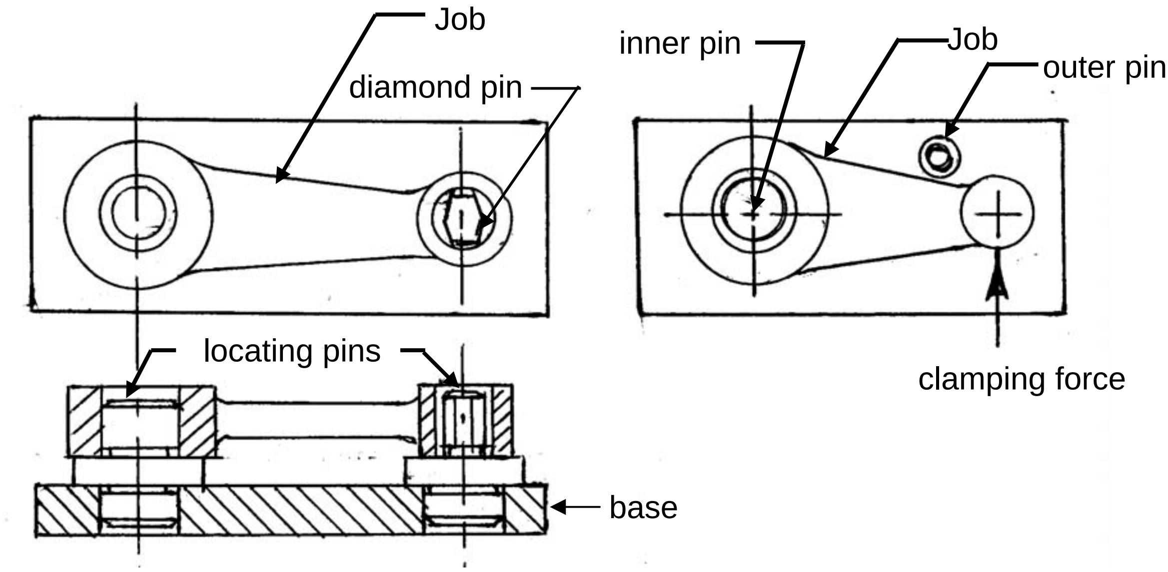


Fig. 8.1.8 *Locating by (a) flat surfaces and (b) types of pins used for that.*

- **Locating by holes**

In several cases, workpieces are located by premachined (drilled, bored or pierced) holes, such as;

* Locating by two holes as shown in Fig. 8.1.9 (a) where one of the pins has to be diamond shaped to accommodate tolerance on the distance between the holes and their diameters
* Locating by one hole and an external pin which presents rotation of the blank around the inner pin as indicated in Fig. 8.1.9 (b)
* Locating by one hole and one Vee-block as shown in Fig. 8.1.10



(a) locating by two holes

(b) locating by one hole

Fig. 8.1.9 *Locating by holes.*

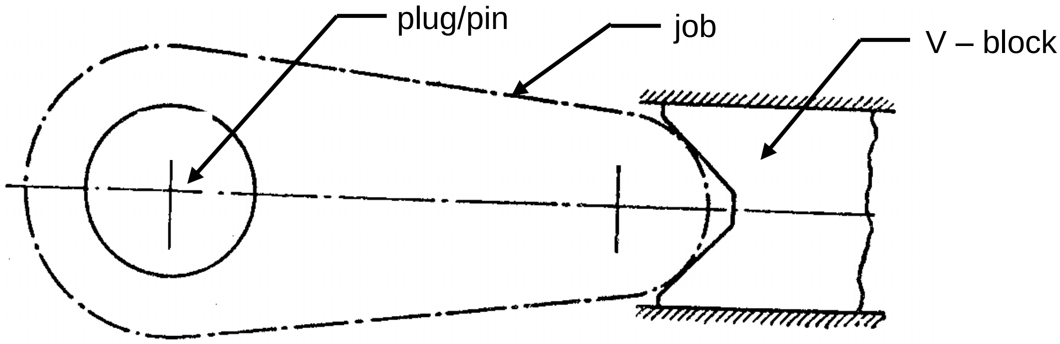


Fig. 8.1.10 *Locating by a pin and Vee block.*

- **Locating on mandrel or plug**

Ring or disc type workpieces are conveniently located on mandrel or single plug as shown in Fig. 8.1.11.

However, there may be several other ways of locating depending upon the machining conditions and requirements.

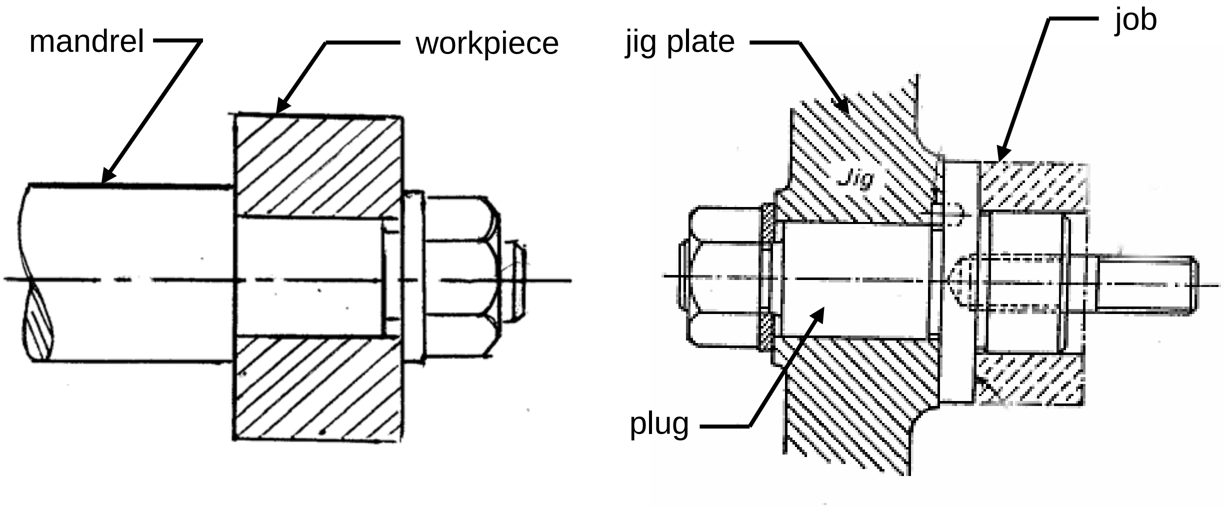


Fig. 8.1.11 *Locating by mandrel or plug.*

 Supporting – principles and methods

A workpiece has to be properly placed in the jig or fixture not only for desired positioning and orientation but also on strong and rigid support such that the blank does not elastically deflect or deform under the actions of the clamping forces, cutting forces and even its own weight.

- **Basic principles or rules to be followed while designing or planning for supporting**
  - supporting should be provided at least at three points
  - supporting elements and system have to be enough strong and rigid to prevent deformation due to clamping and cutting forces
  - unsupported span should not be large to cause sagging as indicated in fig. 8.1.12
  - supporting should keep the blank in stable condition under the forces as indicated in fig. 8.1.13
  - for supporting large flat area proper recess is to be provided, as indicated in fig. 8.1.14, for better and stable support.
  - round or cylindrical workpieces should be supported (along with locating) on strong vee block of suitable size
  - heavy workpieces with pre-machined bottom surface should be supported on wide flat areas, otherwise on flat ended strong pins or plugs.
  - if more than three pins are required for supporting large workpieces then the additional supporting pins are to be spring loaded or adjustable

- additional adjustable supporting pins need to be provided
    - to compensate part size variation
    - when the supporting surface is large and irregular
    - when clamping and cutting forces are large
- ring or disc type jobs, specially requiring indexing should be supported (and located) in mandrel

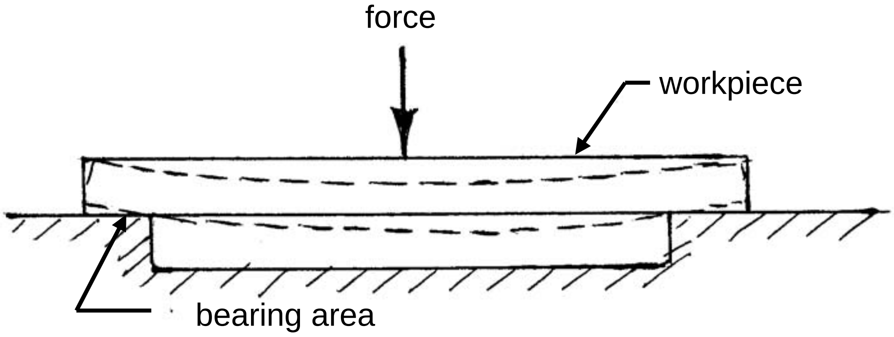


Fig. 8.1.12 *Deflection due to force(s) for wide gap in between supports.*

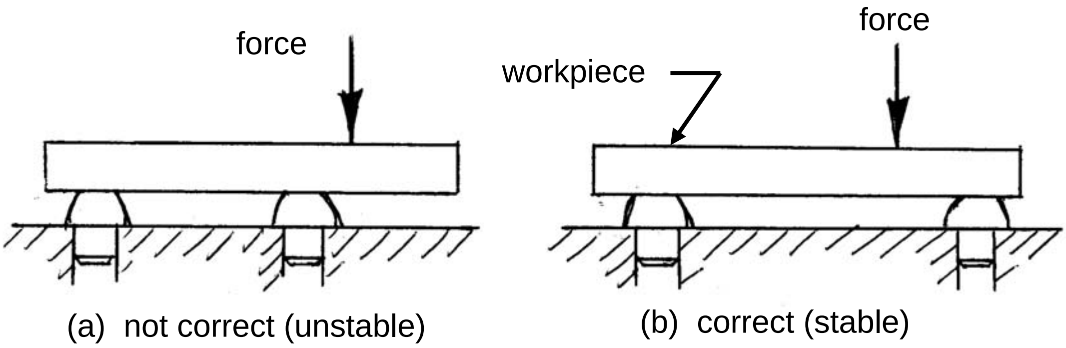


Fig. 8.1.13 *Stability in supporting.*

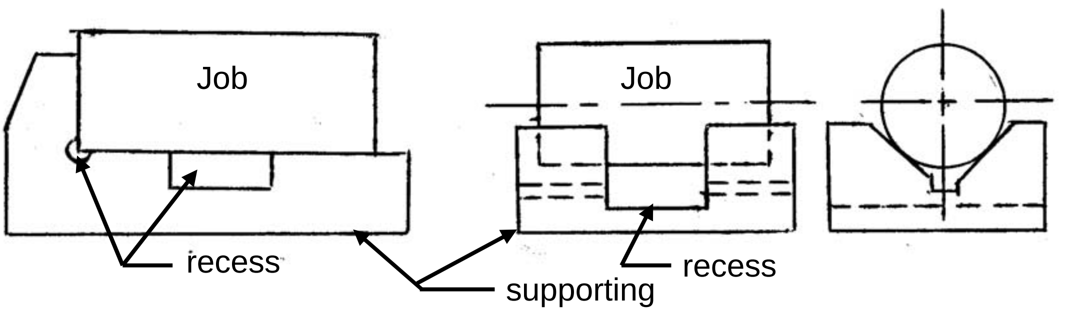


Fig. 8.1.14 *Recess in long span supporting.*

- Common methods of supporting job in fixtures

    - supporting on vices
    - supporting on flat surfaces / blocks (fig. 8.1.15 (a))
    - supporting by fixed pins (fig. 8.1.15 (b))
    - additional supporting by adjustable pins and plugs or jack screws as shown in fig. 8.1.16
    - supporting (and locating) on vee blocks and mandrels (fig. 8.1.11)

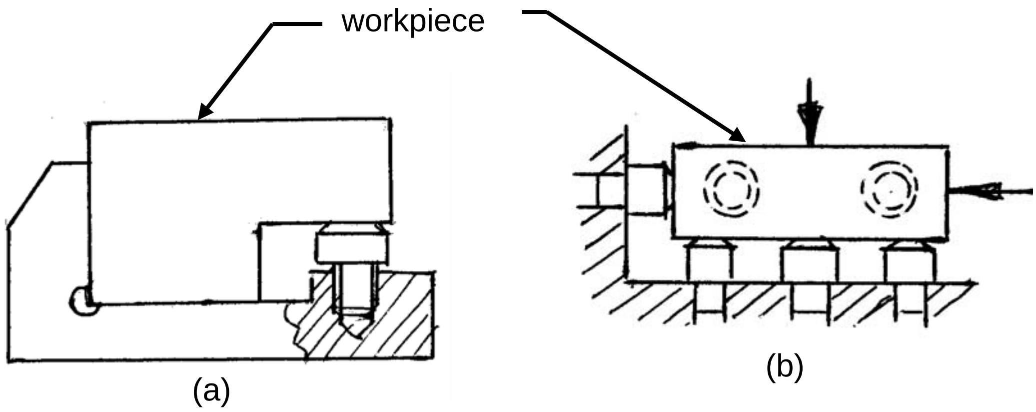


Fig. 8.1.15 *Supporting (a) by flat surface and (b) by pins*

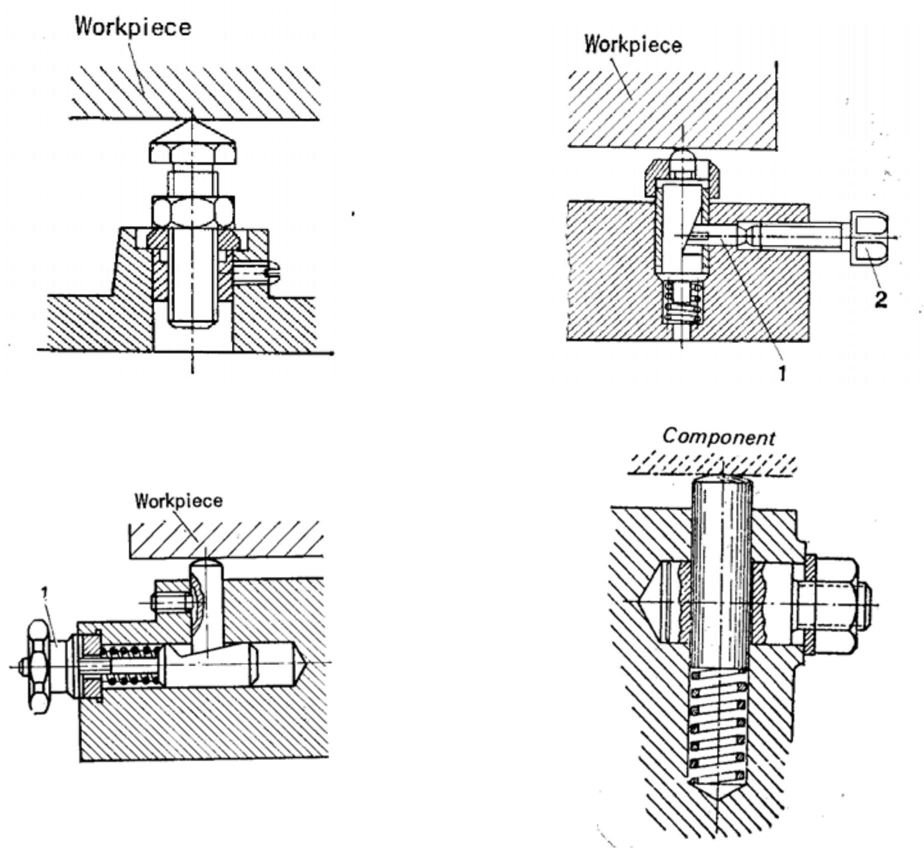


Fig. 8.1.16 *Adjustable supporting pins.*

- ## Clamping of workpiece in fixtures

In jigs and fixtures the workpiece or blank has to be strongly and rigidly clamped against the supporting surfaces and also the locating features so that the blank does not get displaced at all under the cutting forces during machining.

- **While designing for clamping the following factors essentially need to be considered :**
  - clamping need to be strong and rigid enough to hold the blank firmly during machining
  - clamping should be easy, quick and consistently adequate
  - clamping should be such that it is not affected by vibration, chatter or heavy pressure
  - the way of clamping and unclamping should not hinder loading and unloading the blank in the jig or fixture
  - the clamp and clamping force must not damage or deform the workpiece
  - clamping operation should be very simple and quick acting when the jig or fixture is to be used more frequently and for large volume of work
  - clamps, which move by slide or slip or tend to do so during applying clamping forces, should be avoided
  - clamping system should comprise of less number of parts for ease of design, operation and maintenance
  - the wearing parts should be hard or hardened and also be easily replaceable
  - clamping force should act on heavy part(s) and against supporting and locating surfaces
  - clamping force should be away from the machining thrust forces
  - clamping method should be fool proof and safe
  - clamping must be reliable but also inexpensive

- **Various methods of clamping**

Clamping method and system are basically of two categories :

(a) general type without much consideration on speed of clamping operations
(b) quick acting types

(a) General clamping methods of common use :

- Screw operated strap clamps as typically shown in Fig. 8.1.17. The clamping end of the strap is pressed against a spring which enables quick unclamping

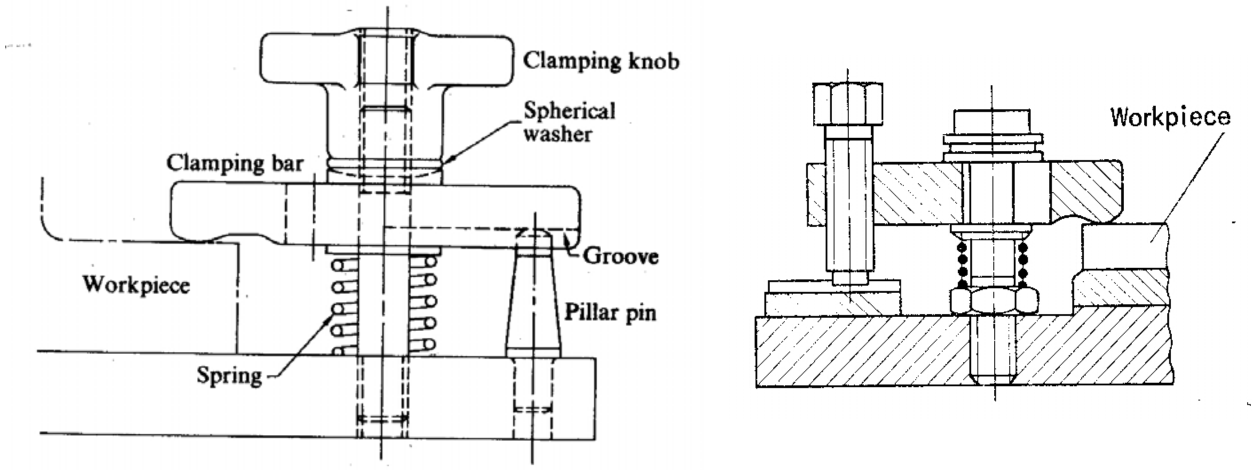


Fig. 8.1.17 *Common strap type clamping.*

- Clamping from side for unobstructed through machining (like milling, planing and broaching) of the top surface. Some commonly used such clamping are shown in Fig. 8.1.18

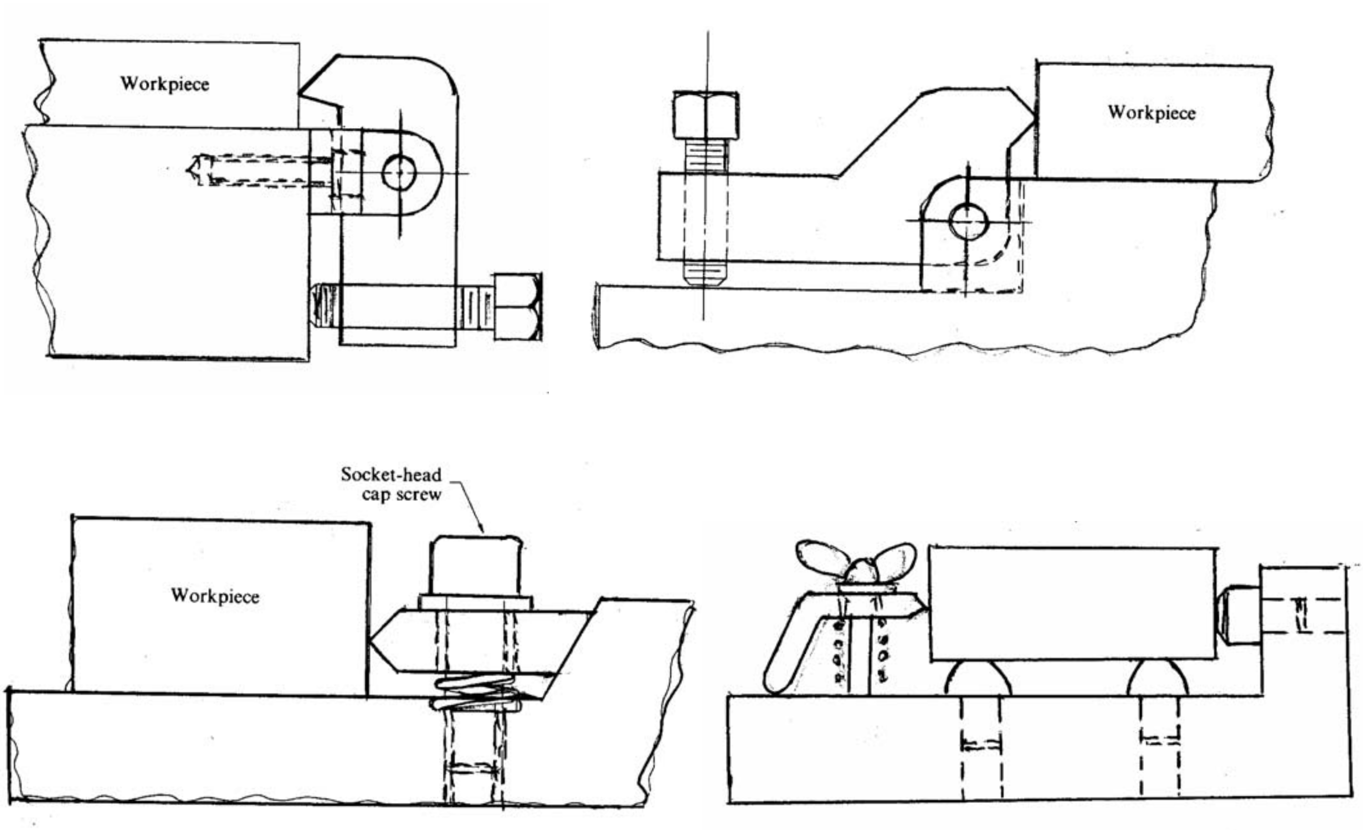


Fig. 8.1.18 *Clamping from side for free machining of the top surface.*

- **Clamping by swing plates**

Such clamping, typically shown in Fig. 8.1.19, are simple and relatively quick in operation but is suitable for jobs of relatively smaller size, simpler shape and requiring lesser clamping forces.

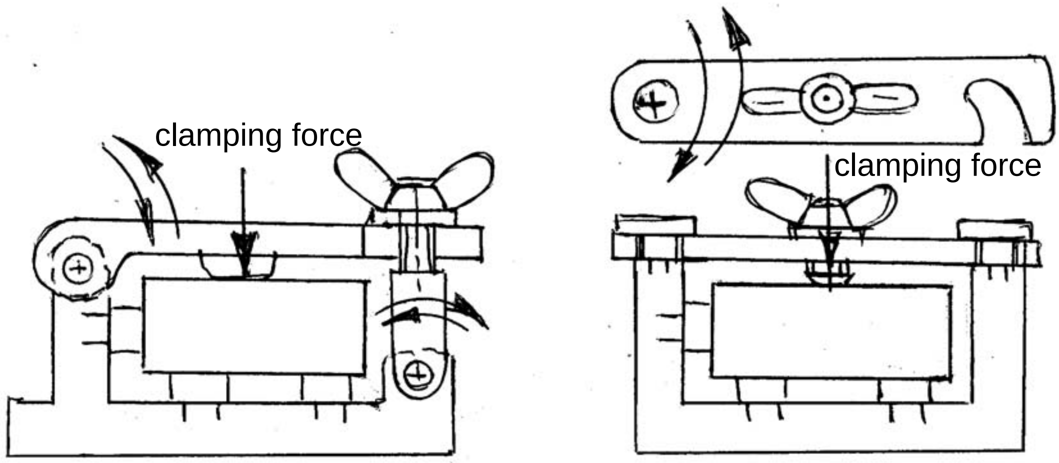


Fig. 8.1.19 *Clamping by swing plates.*

- Other conventional clamping methods include :
  - ∗ Vices like drilling and milling vices
  - ∗ Magnetic chucks
  - ∗ Chucks and collets for lathe work

- **Quick clamping methods and systems**

  - o **Use of quick acting nut** – a typical of such nut and its application is visualised schematically in Fig. 8.1.20

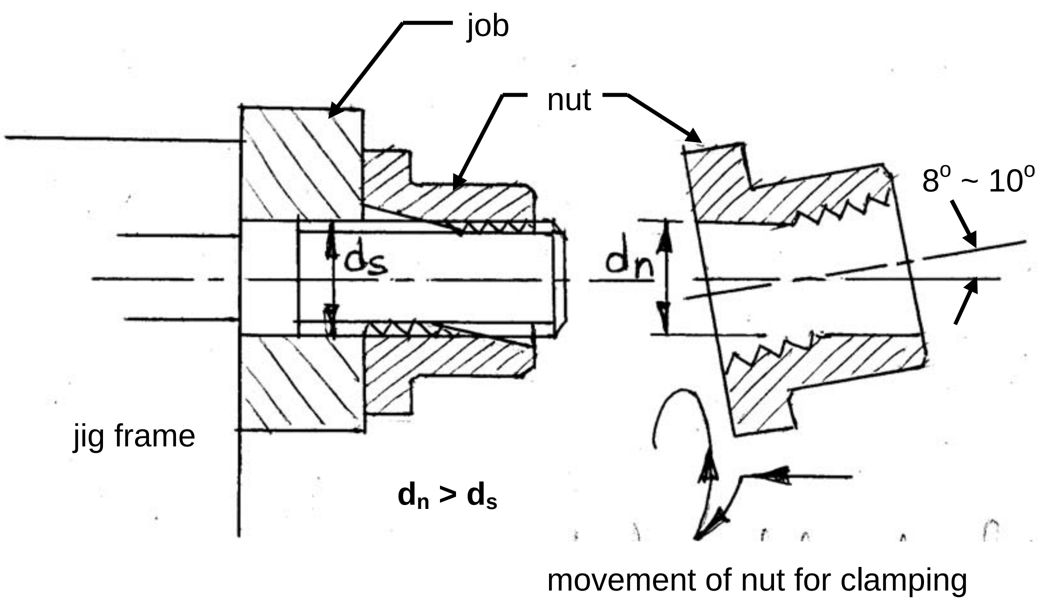
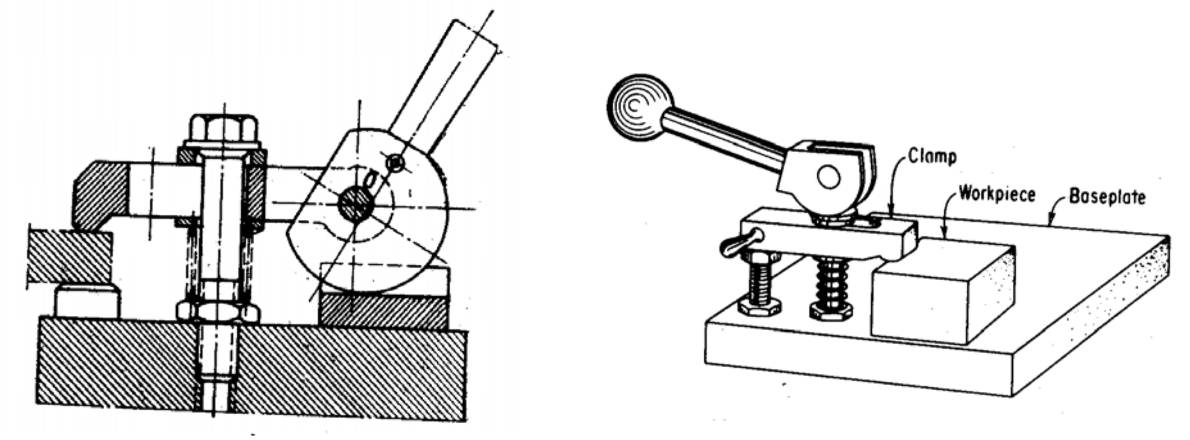


Fig. 8.1.20 *Quick acting nut for rapid clamping.*

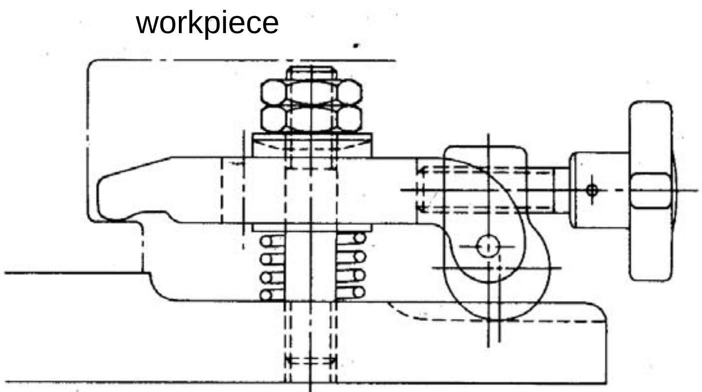
- **Cam clamping**

  Quick clamping by cam is very effective and very simple in operation. Some popular methods and systems of clamping by cam are shown in Fig. 8.1.21

  The cam and screw type clamping system is used for clamping through some interior parts where other simple system will not have access.



(a) clamping by cam



(b) screw and cam clamping from distance

Fig. 8.1.21 *Quick clamping by cams.*

- Quick multiple clamping by pivoted clamps in series and parallel. This method shown in Fig. 8.1.22 is capable to simultaneously clamp number of rods even with slight diameter variation
- Quick clamping by hydraulic and pneumatic force for strong and light clamping respectively
- Light but quick clamping by bayonet type clamp as indicated in Fig. 8.1.23

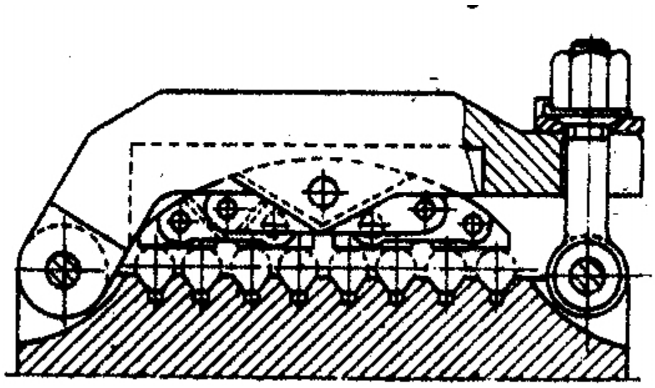


Fig. 8.1.22 *Quick multiple locating and clamping of cylindrical jobs.*

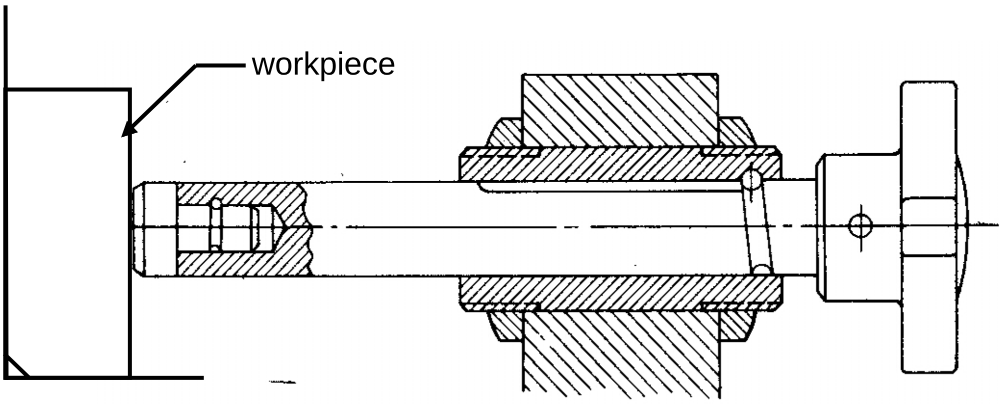


Fig. 8.1.23 *Quick acting screw (bayonet type) clamping.*

(b) Drill – jig bushing

Slender and cantelever type cutting tools, mainly drills, usually suffer from run – out due to possible errors in the drill, sockets and drilling machine spindle and finally in the overall alignment. Such run out causes over sizing, out of roundness and surface roughening of the drilled holes. Such run out aggravates further with the increase in drill speed (rpm) and the thrust force, specially if the drill is not geometrically symmetrical. This often leads to, in addition to poor product quality, breakage of the drill by bending and / or buckling. To reduce such problems, bushes are used in the jigs to guide the drill bits as indicated in Fig. 8.1.3.

- ∆ **The factors to be considered while designing for jig – bushing, are :**
  - o The bushes, used to guide and properly locate drills, reamers etc. are generally made of carbon or alloy steel and made wear resistive by hardening to R_C 60 and above. Often bushes are also made from grey cast iron for antifriction and protection of the tools.

- o The hardened jig bushes are finished outside by grinding and inside by grinding and lapping if high precision is insisted.
- o The bush's length should be sufficient (≥ twice drill diameter) and its diameter should be slightly larger than the drill diameter
- o Design and construction should enable easy and quick proper fitting and removal or replacement of the bushes
- o Bushes should not come out from its seat along with the drill during its return.

∆ Types of jig bushes

Depending upon nature of fitting, quick mounting and replacement, job requirement etc. jig bushes are classified into several types.

- Bushes may be
  - — Press fitted type
  - — Slip type
  - — Screwed type

Press fitted thin sleeve type bushes are generally used for shorter runs and are not renewable. Renewable type slip bushes are used with liner. But screw bushes, though renewable may be used without or with liner.

- Bushes may be
  - — Without head
  - — With head
  - — With a flange being screwed on the bracket

Fig. 8.1.24 shows such various bushes

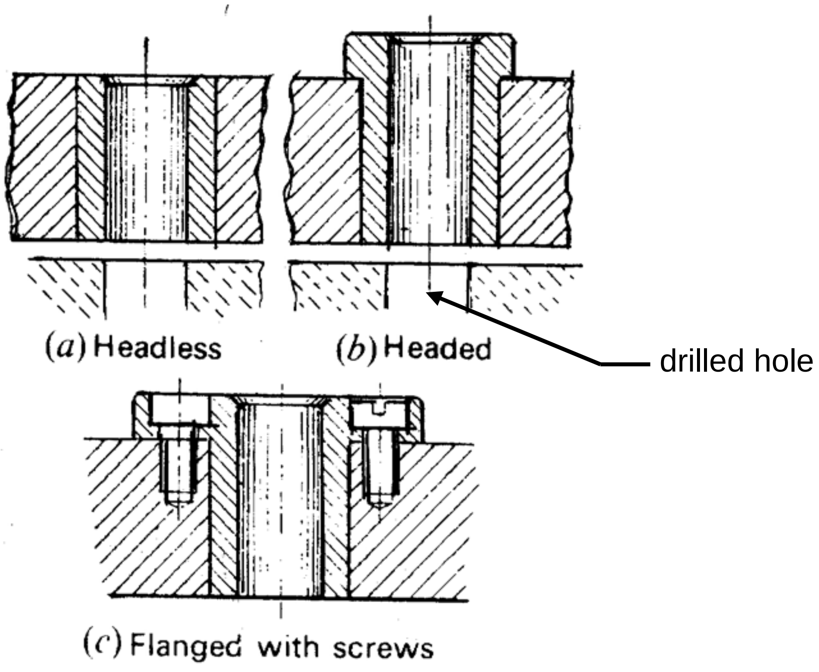


Fig. 8.1.24 *Bushes (a) without head, (b) with head and (c) flange.*

- Frequently replaceable bushes are provided with some locking system as shown in Fig. 8.1.25

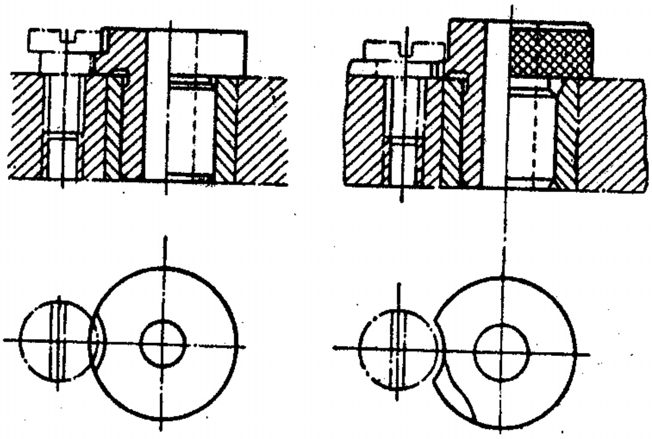
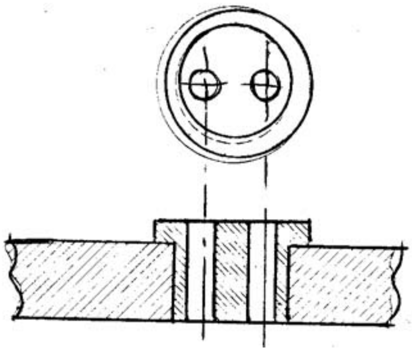
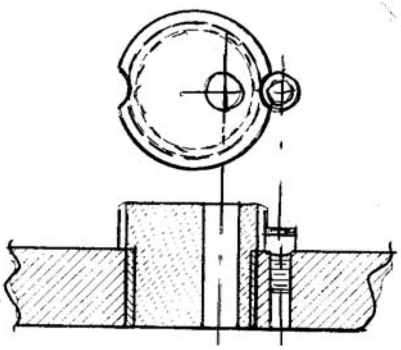


Fig. 8.1.25 *Locking of frequently replaceable bushes.*

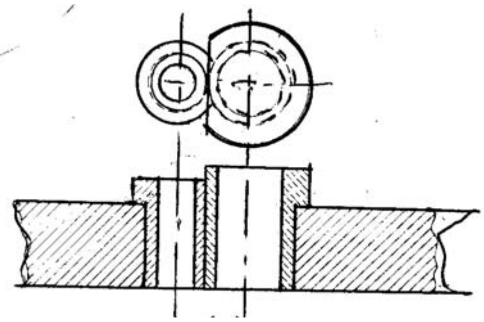
- Some special jig bushings are often designed and used as and when required as indicated in Fig. 8.1.26



(a) two close holes – in one bush



(b) two very close holes – using eccentric bush



(c) two close holes – by two adjacent modified bushes

Fig. 8.1.26 *Special jig – bushes for critical requirements.*

Many other types are possible and made depending upon the working situation and critical requirements.

Module
8
Jigs and Fixtures for Machine shop

Lesson
34
Design and Application of typical jigs and fixtures

Instructional objectives

This lesson will enable the students :

(i) Analyze economic viability and judge necessity of jig – fixture for specific production by machining
(ii) Plan for designing a fixture or jig
(iii) Design fixture or jig (configuration and working) for specific jobs and their machining requirements.

(i) Economic Viability Analysis And Judging Necessity Of Jig – Fixture.

The three possible modes of manufacturing a lot of a product by machining are :

- using ordinary machine and without jig or fixture
- using ordinary machine but with jig or fixture
- using automatic special purpose machine

The selection of the appropriate mode is governed mainly by,

- technological feasibility of those modes
- technical feasibility i.e. availability of the resources and facilities for the different modes
- economical viability, considering
  - Δ cost of manufacturing, based on
    - cost of the basic machine
    - cost of the jig or fixture, if to be used
    - volume of production (i.e. no. of pieces)
    - material and labour cost
  - Δ expected quality of the products and its sale value i.e., revenue
  - Δ total time that will be required to complete the assignment

It is to be borne in mind that sophisticated automatic system not only provides and maintains consistency of quality of the products but also drastically reduces the total time of completing the production, which have substantial socio-economic benefits. Use of jigs and fixtures also help to some extent in saving time and maintaining consistent quality. But sophisticated automatic machines are much more expensive. Use of jigs and fixtures also incur some additional cost.

Selection of appropriate mode for a specific machining task.
A specific case, for example, is taken up as follows to illustrate the selection procedure :

A lot of 120 pieces have to be machined. The estimated cost components in three different modes are as follows :

	Mode	Fixed cost (Rs.)	Machining cost / pc (Rs./piece)
1	W : In ordinary machine without any jig or fixture	200,000.00	5000.00
2	JF : In ordinary machine but with jig or fixture	3,00,000.00	2500.00
3	A : In automatic special purpose machine	6,00,000.00	1000.00

The most appropriate, is to be selected mode and it is to be decided whether use of the jig / fixture will be justified.

Considerations and steps

- assuming uniform quality possible, by all the modes, selection is made on the basis of total production cost
- with the given cost components a graph; total machining cost vs quantity of production, has been plotted as shown in Fig. 8.2.1. From the graph it appears that mode – 1 (W) is most economic when quantity of production i.e., number of pieces to be machined is less than 40 and the mode – 3 (A) will be most economical when the number of pieces exceeds 200. The mode – 2 (JF) appears to be economically most viable if the production volume lies within 41 to 199.
- Since the number of pieces desired to be produced is 120 only, it is clear that for 120 pieces, the mode – 2 (JF) i.e., machining in ordinary machine tool using jig – fixture is most justified.

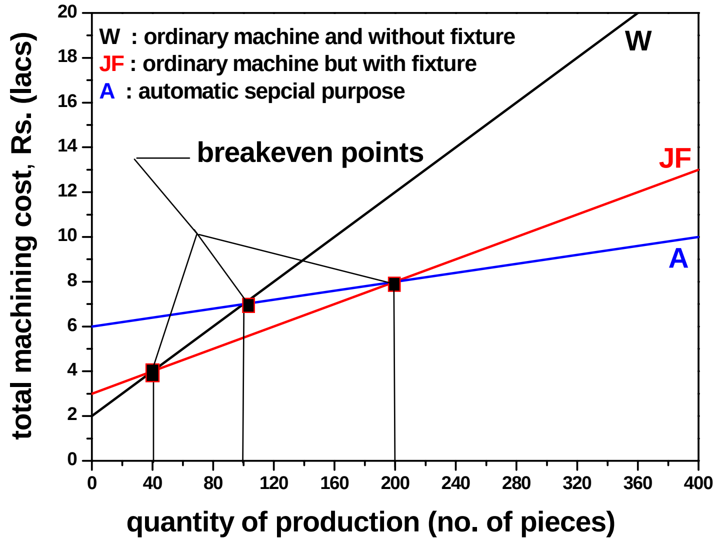


Fig. 8.2.1 *Economic viability of jig and fixture for batch production.*

(ii) Planning Prior To Design And Construction Of A Fixture Or Jig

After reasonably deciding that a jig or fixture will be used for a given machining work, a thorough planning has to be made prior to actual design and construction of the jig or fixture. This is explained by a specific example as follows :

Task : A fixture or jig has to be designed and built for drilling a through hole in pre-machined mild steel pins at a given distance from one end face as indicated in Fig. 8.2.2.

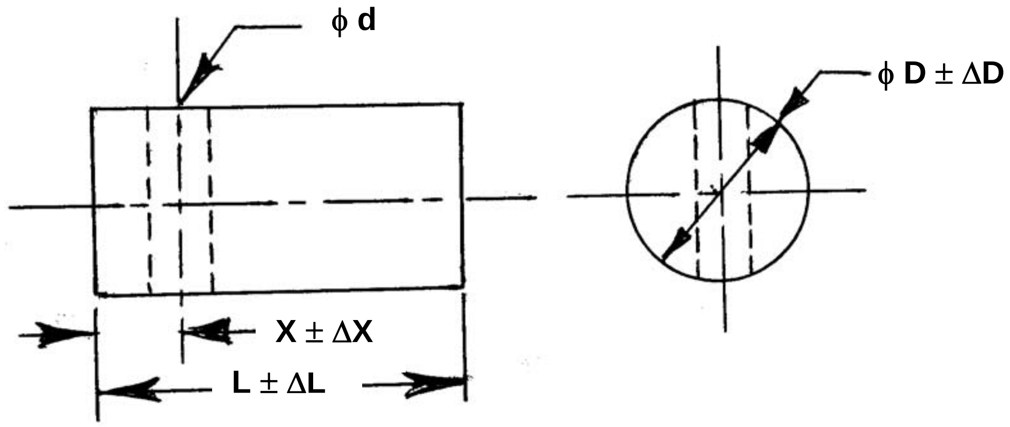


Fig. 8.2.2 *A through transverse hole to be drilled at a distance from end face.*

Planning in steps for design and construction of a jig or fixture suitable for the purpose

- **whether fixture or jig ?**
  Since a hole has to be drilled precisely at a particular location within tolerance a suitable drill – guide will be necessary. So it has to be a jig.
- **Positioning and orientation**
  Since a diametral through hole has to be drilled perpendicular to the rod – axis, and the drill – axis in the machine is vertical, the suitable orientation of the job in the jig and against the drill axis will be horizontal as shown in Fig. 8.2.3 (a)

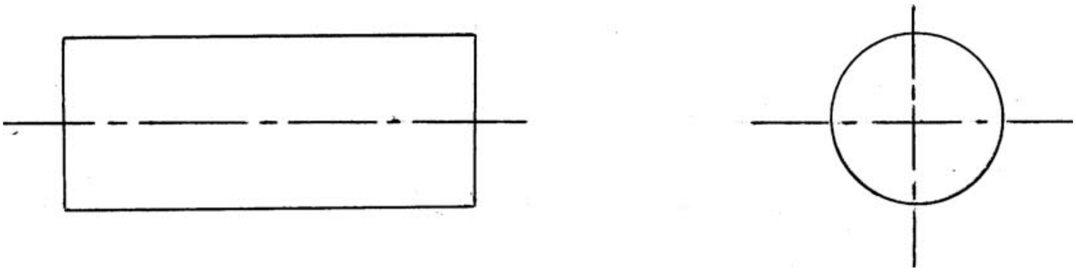


Fig. 8.2.3 (a) Blank and its apparent positioning during drilling

o **Locating the blank in the jig and w.r.t. the drill – axis**

The facts that

- The blanks are straight cylindrical and pre-machined
- Blank diameter may vary though within a tolerance and
- The blank axis is to be horizontal

clearly justify that the basic locating by V – block will be appropriate as indicated in Fig. 8.2.3 (b). To essentially maintain the desired distance of the hole-axis from one machined face of the block, a pin has also to be used for axial location and it should be adjustable type for likely variation in the part length as indicated in Fig. 8.2.3 (b)

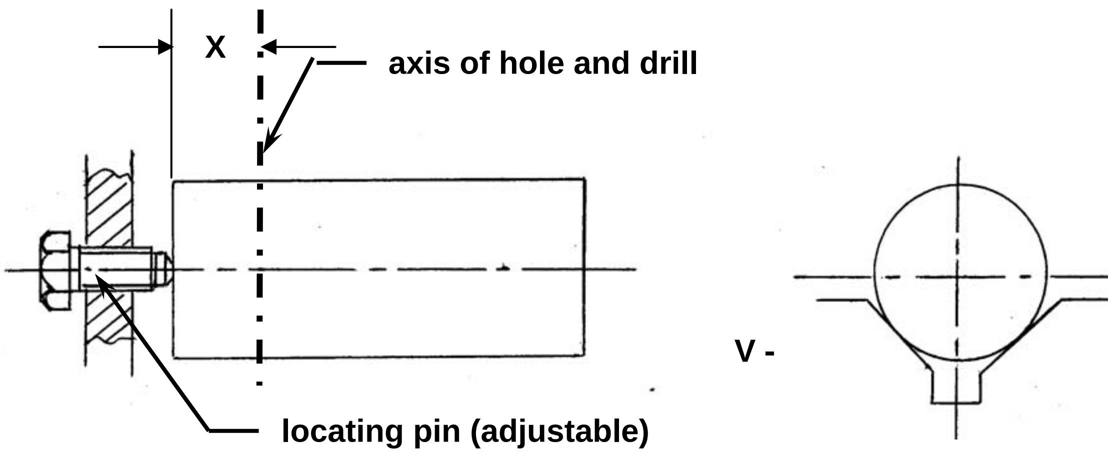


***Fig. 8.2.3** (b) locating by V – block and adjustable pin*

o **Supporting the blank against forces**

Since the blanks are solid steel rods of favourable L/D ratio and it has been reasonably decided to locate it on V – block, the same V – block can be used for the desired support. In that case the V – block need to be enough strong and rigid and also provided with necessary recess or relief at the central portion as indicated in Fig. 8.2.3 (c)

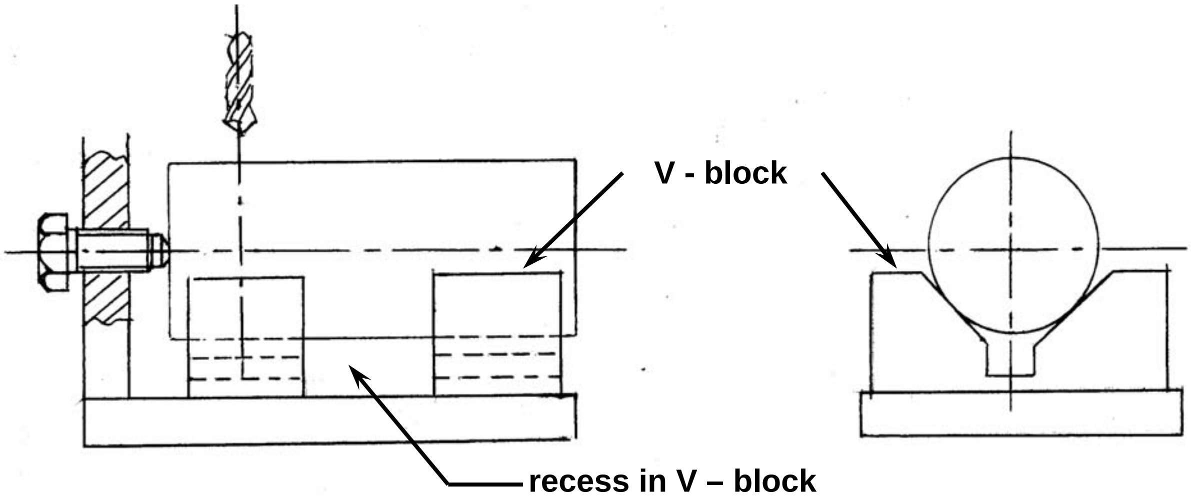


Fig. 8.2.3 *(c) supporting on V - block*

o **Clamping**

Clamping system should be, as far as possible, simple and quick but also need to be strong, rigid and stable. Clamping should not also obstruct or hamper blank's loading and unloading as well as machining work. Keeping all such factors a cam – clamping may be considered as indicated in Fig. 8.2.3 (d). The clamping plug should retreat sufficiently from the blank for its easier removal and entering of the next blank. A spring can be used. For more effective and stable clamping on cylindrical surface, a pivoted clamping would be more suitable as shown in the Fig. 8.2.3 (d).

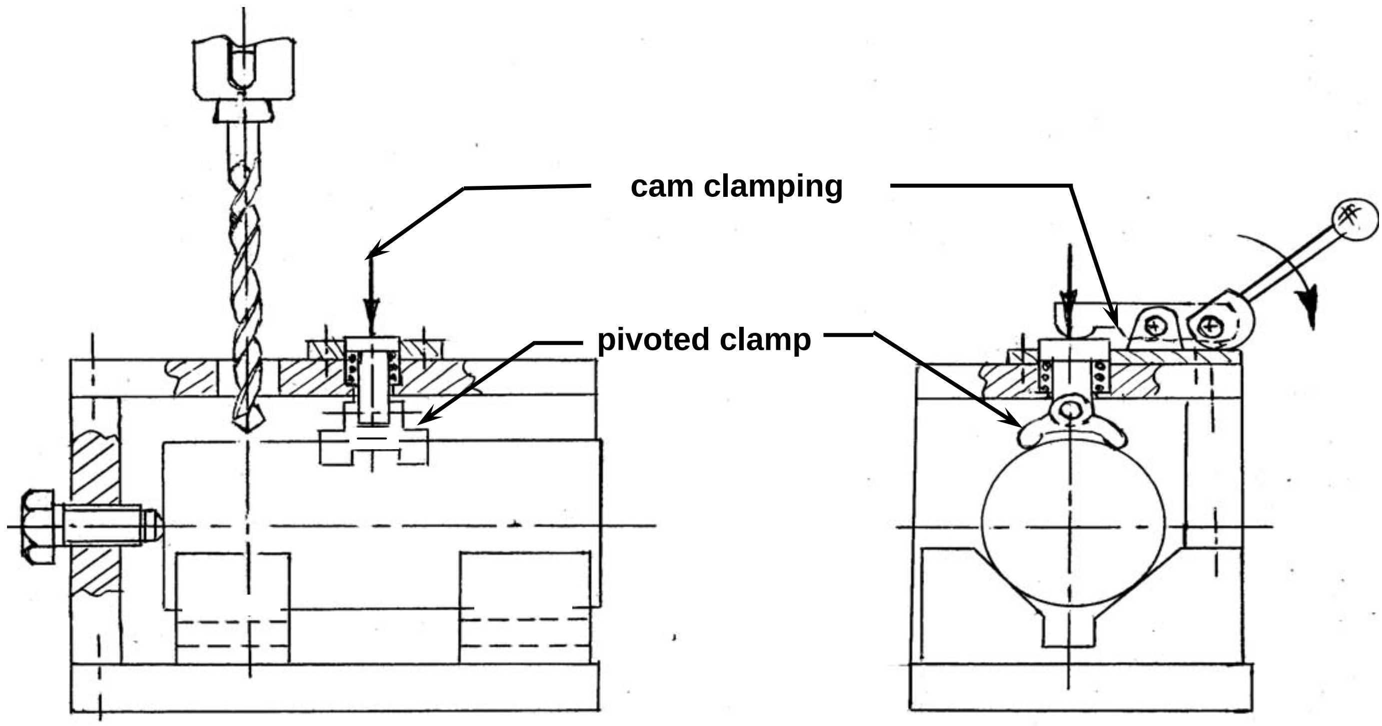


Fig. 8.2.3 *(d) Quick clamping by cam*

o **Tool guidance**

Since it is drilling and over a deep hole, specially on a cylindrical surface, tool guidance must be provided as indicated in Fig. 8.2.3 (e) which also shows holding of the slip type bush by a pin for replacement of the bush.

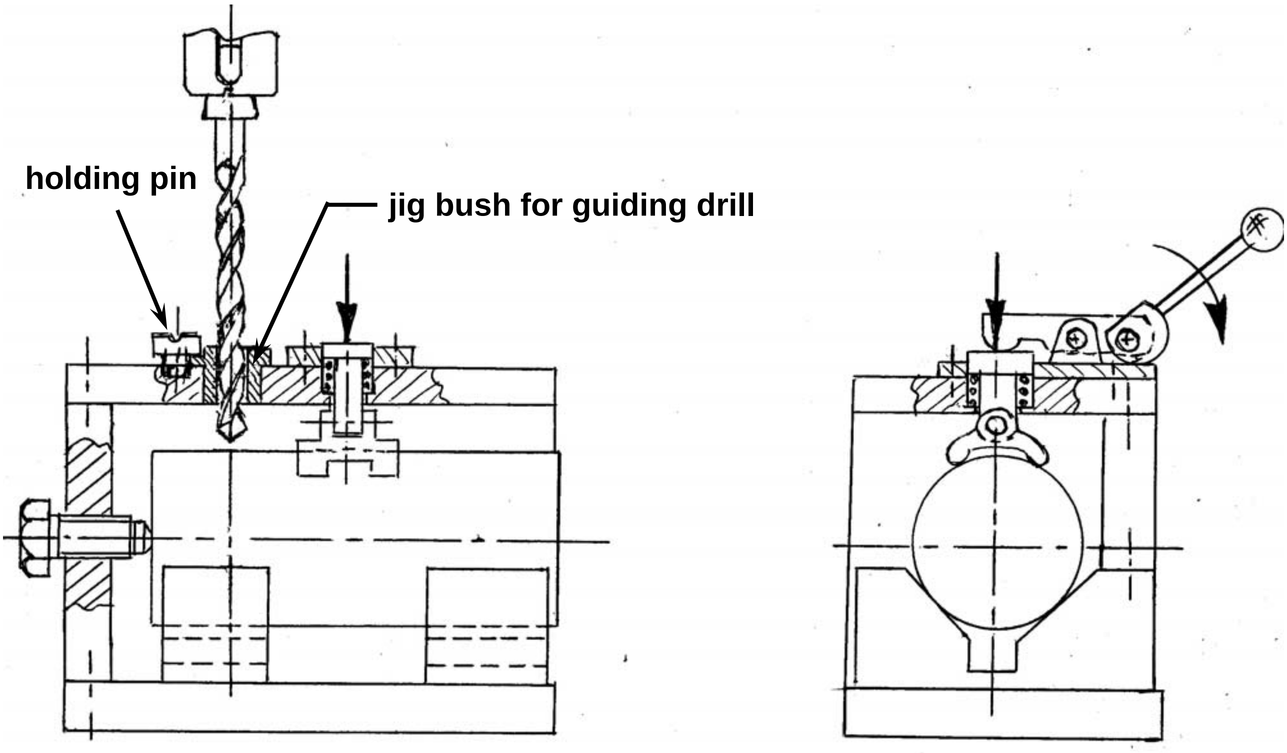


***Fig. 8.2.3** (e) Jig bushing for tool(drill) guidance*

o **Consistent effective locating and ejection**

It is to be assured that the locating pin is in proper contact with the locating surface and preferably under the same amount of force all the time. This can be done by applying a spring loaded force on the blank and against the locating pin as indicated in Fig. 8.2.3 (f). Such pushing system, again, should not hinder placing and removal of the blank in and from the jig or fixture. One of the possible methods has been shown in Fig. 8.2.3 (f) where the swing type lever holding the spring loaded pushing – pin is manually operated with the help of a spring and a stop – pin.

For easy removal of the machined job from the jig or fixture an ejector may be used. Fig. 8.2.3 (f) also shows such an ejector to facilitate unloading of the job after sequentially withdrawing the tool and the clamping unit and shifting the push – lever.

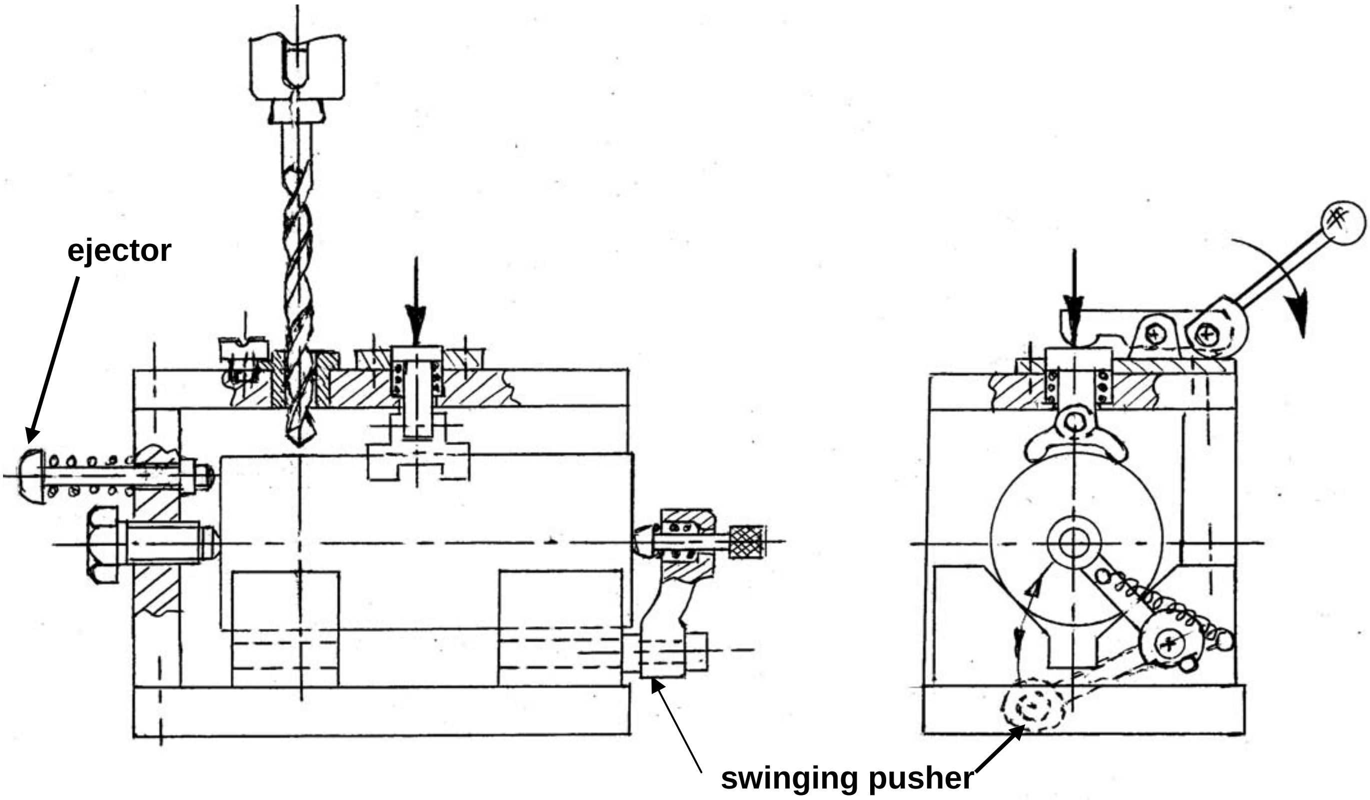


Fig. 8.2.3 *(f) complete jig with assured locating and ejection*

This way, the planning work enables get proper schematic layout of the entire jig or fixture with its vital parts and configuration.
Next step, for the design, will be selection of materials for various parts and determination of their dimensions based on strength and rigidity.

(iii) Design Of Fixtures And Jigs For Some Specific Jobs

Example – 1 In a pre-machined hollow metallic disc six equispaced blind holes have to be drilled radially as indicated in Fig. 8.2.4.

Design the configuration and working method of the fixture or jig for such drilling work in a batch production.

Design – The proposed design is schematically shown in Fig. 8.2.4

- Since the machining requirement is drilling where the tool will essentially need guidance, a jig has to be designed
- Since it is required to produce equi-angular spaced holes by drilling an indexing system has to be considered

- The indexing work can be accomplished by indexing the jig, holding the job clamped inside, manually by bringing the desired hole axis aligned with the fixed drill axis by manual adjustment. Six bushes are fitted equispaced in the jig. The design of the jig is schematically shown in Fig. 8.2.4. The same work could be done by indexing the workpiece only within the fixed jig having only one bush (example 2).

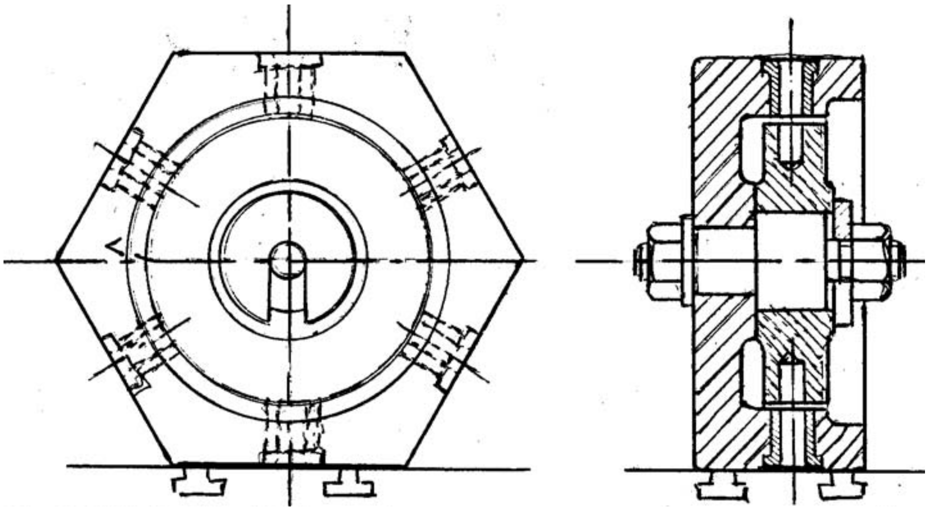


Fig. 8.2.4 *Jig for drilling six equispaced radial blind holes in a disc*.

Example – 2 Four equispaced through holes have to be drilled radially in a disc, (like rotor of radial piston pump) as shown in Fig. 8.2.5 (a). A jig is to be designed for batch production of such discs.

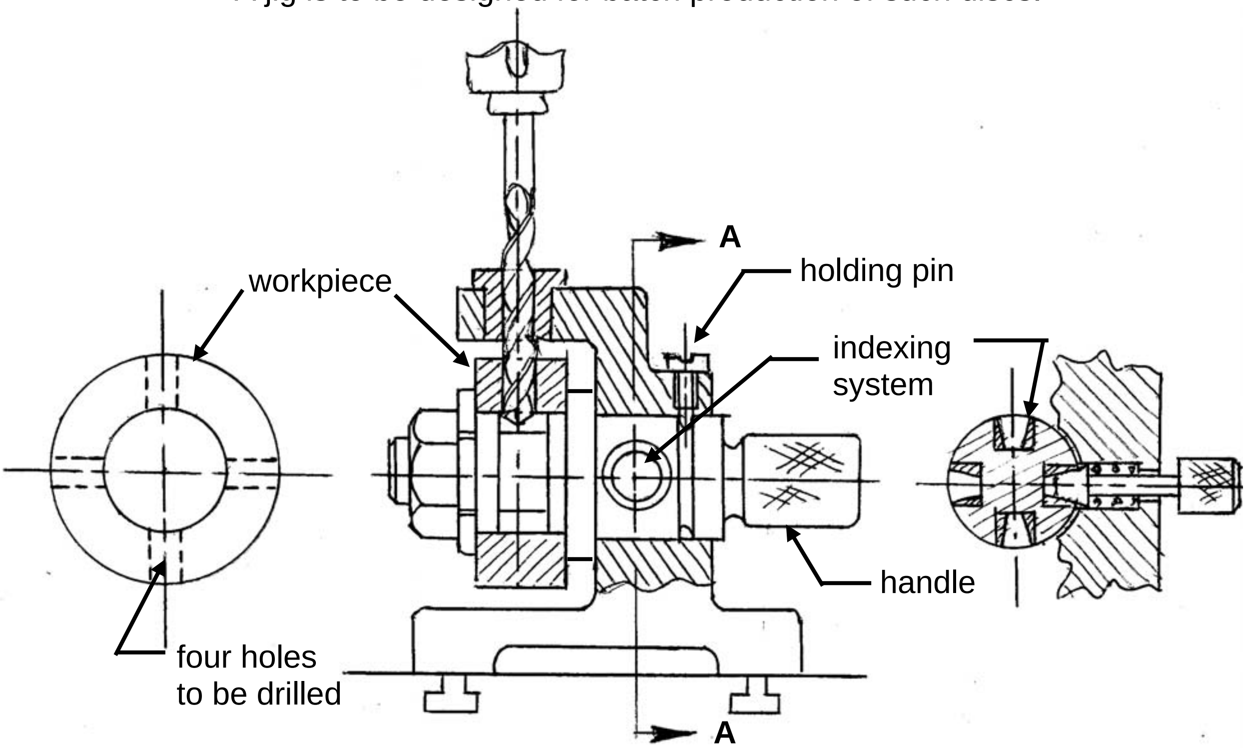


Fig. 8.2.5 *Jig for drilling four equispaced through radial holes in a ring.*

Design : The proposed design is schematically shown in Fig. 8.2.5

- Drilling four equispaced through radial holes will need indexing in the jig to be designed.
- The jig possesses a rotable mandril on which the pre-machined blank (hollow disc) will be mounted as shown
- The axial location of the blank with respect to the axis of the desired hole i.e. drill is provided by the step in the mandril
- The blank gets desirably strong support from the mandril; both radially and axially
- Only one bush is mounted coaxially with the drill for necessary tool guidance
- The blank will be strongly and rigidly clamped by the front nut. A quick acting nut could also be used.
- A suitable indexing system has been incorporated which will enable 90^o – rotation of the blank, within the fixed jig, by unlocking the indexing pin and rotating the mandril with the help of the handle shown. The small fixed (screwed) pin will prevent any axial shift of the mandril during its rotation under unlocked condition.
- This jig will remain clamped on the drilling machine bed (table) with the axis of the bush aligned with that of the drill i.e., spindle

Example – 3 A through rectangular section slot has to be cut on a rod as shown in Fig. 8.2.6 (a). A fixture or jig is to be designed for cutting the slot in batch production

Design : The proposed design is schematically shown in Fig. 8.2.6 (b)

- It will be a fixture, not jig, since there is no need of making holes
- A slot milling cutter of width equal to the width of the slot desired has to be used as shown
- Since the blank is a cylindrical piece, V – block type system has been used for locating and supporting
- The axial location (and supporting) will be accomplished by the axial pin and the contact will be assured by the swing type spring loaded pusher as shown.
- Clamping will be done quickly by the cam pressing the strap as shown
- The fixture holding the workpiece will be properly fixed on the table of the milling machine and will move along that table
- After completion of the work, i.e. cutting of the slot, the fixture will be removed. A spring loaded ejector (cum locator) can also be used as shown in the Fig. 8.2.6 (b).

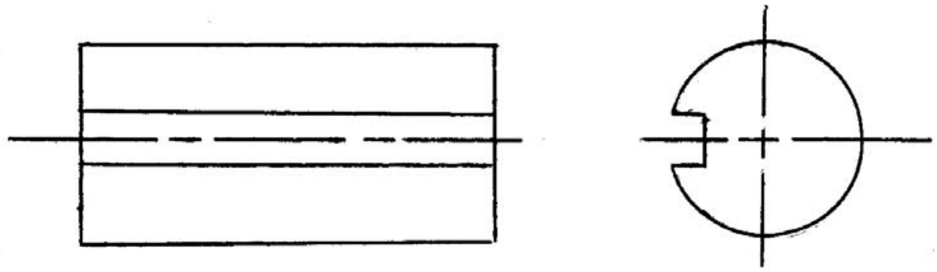


Fig. 8.2.6 *(a) A through slot to be produced on a rod*

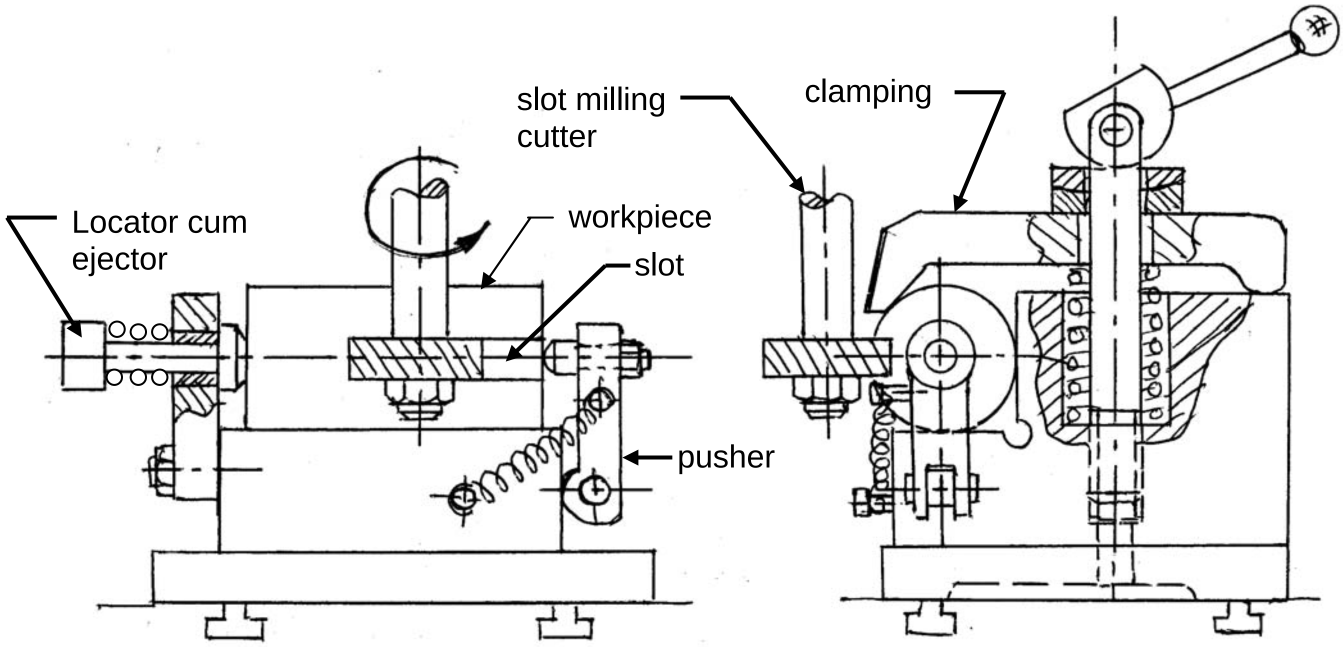


Fig. 8.2.6 *(b) Fixture for milling the slots on the rod.*

It is to be noted, jigs and fixtures are not standard items and are as such not available in the market. It has to be designed and built as and when required based on the exact requirements.

Module
9
Non-conventional machining

Lesson
35
Introduction and Abrasive Jet Machining

Instructional Objectives

i. Identify the characteristics of conventional machining
ii. Identify the characteristics of non traditional machining
iii. Differentiate between conventional and non traditional machining
iv. Classify different non traditional machining processes
v. Identify the need for non traditional machining processes
vi. Describe the basic mechanism of material removal in AJM
vii. Identify major components of AJM equipment
viii. State the working principle of AJM equipment
ix. Draw schematically the AJM equipment
x. Identify the process parameters of AJM
xi. Identify the machining characteristics of AJM
xii. Analyse the effect of process parameters on material removal rate (MRR)
xiii. Draw variation in MRR with different process parameters
xiv. Develop mathematical model relating MRR with abrasive jet machining parameters
xv. List three applications of AJM
xvi. List three limitations of AJM

(i) Introduction

Manufacturing processes can be broadly divided into two groups and they are primary manufacturing processes and secondary manufacturing processes. The former ones provide basic shape and size to the material as per designer's requirement. Casting, forming, powder metallurgy are such processes to name a few. Secondary manufacturing processes provide the final shape and size with tighter control on dimension, surface characteristics etc. Material removal processes are mainly the secondary manufacturing processes.

Material removal processes once again can be divided into mainly two groups and they are "Conventional Machining Processes" and "Non-Traditional Manufacturing Processes".

Examples of conventional machining processes are turning, boring, milling, shaping, broaching, slotting, grinding etc. Similarly, Abrasive Jet Machining (AJM), Ultrasonic Machining (USM), Water Jet and Abrasive Water Jet Machining (WJM and AWJM), Electro-discharge Machining (EDM) are some of the Non Traditional Machining (NTM) Processes.

(ii) Classification of Non Traditional Machining Processes

To classify Non Traditional Machining Processes (NTM), one needs to understand and analyse the differences and similar characteristics between conventional machining processes and NTM processes.

Conventional Machining Processes mostly remove material in the form of chips by applying forces on the work material with a wedge shaped cutting tool that is harder than the work material under machining condition. Such forces induce plastic deformation within the work piece leading to shear deformation along the shear plane and chip formation. Fig. 9.1.1 depicts such chip formation by shear deformation in conventional machining.

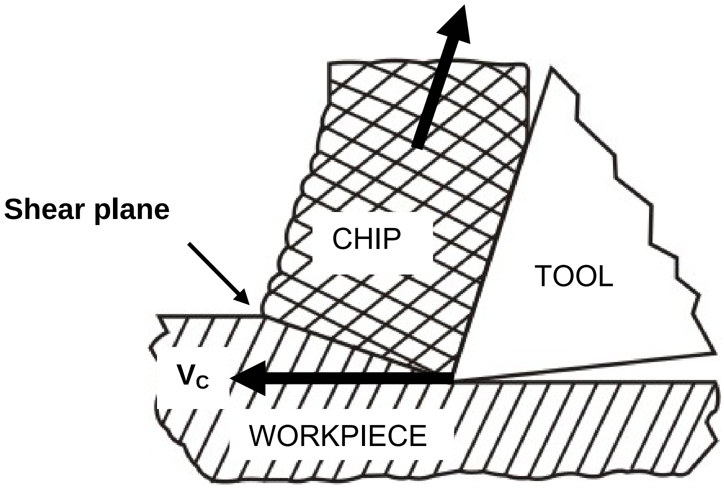


Fig.9.1.1 *Shear deformation in conventional machining leading to chip formation.*

Thus the major characteristics of conventional machining are:

- Generally macroscopic chip formation by shear deformation
- Material removal takes place due to application of cutting forces – energy domain can be classified as mechanical
- Cutting tool is harder than work piece at room temperature as well as under machining conditions

Non Traditional Machining (NTM) Processes on the other hand are characterised as follows:

- Material removal may occur with chip formation or even no chip formation may take place. For example in AJM, chips are of microscopic size and in case of Electrochemical machining material removal occurs due to electrochemical dissolution at atomic level
- In NTM, there may not be a physical tool present. For example in laser jet machining, machining is carried out by laser beam. However in Electrochemical Machining there is a physical tool that is very much required for machining
- In NTM, the tool need not be harder than the work piece material. For example, in EDM, copper is used as the tool material to machine hardened steels.
- Mostly NTM processes do not necessarily use mechanical energy to provide material removal. They use different energy domains to provide machining. For example, in USM, AJM, WJM mechanical energy is used to machine material, whereas in ECM electrochemical dissolution constitutes material removal.

Thus classification of NTM processes is carried out depending on the nature of energy used for material removal. The broad classification is given as follows:

- Mechanical Processes
    - Abrasive Jet Machining (AJM)
    - Ultrasonic Machining (USM)
    - Water Jet Machining (WJM)
    - Abrasive Water Jet Machining (AWJM)
- Electrochemical Processes
    - Electrochemical Machining (ECM)
    - Electro Chemical Grinding (ECG)
    - Electro Jet Drilling (EJD)
- Electro-Thermal Processes
    - Electro-discharge machining (EDM)

— Laser Jet Machining (LJM)
— Electron Beam Machining (EBM)

- Chemical Processes
  — Chemical Milling (CHM)
  — Photochemical Milling (PCM) etc.

Fig. 9.1.2 schematically depicts some of the NTM processes:

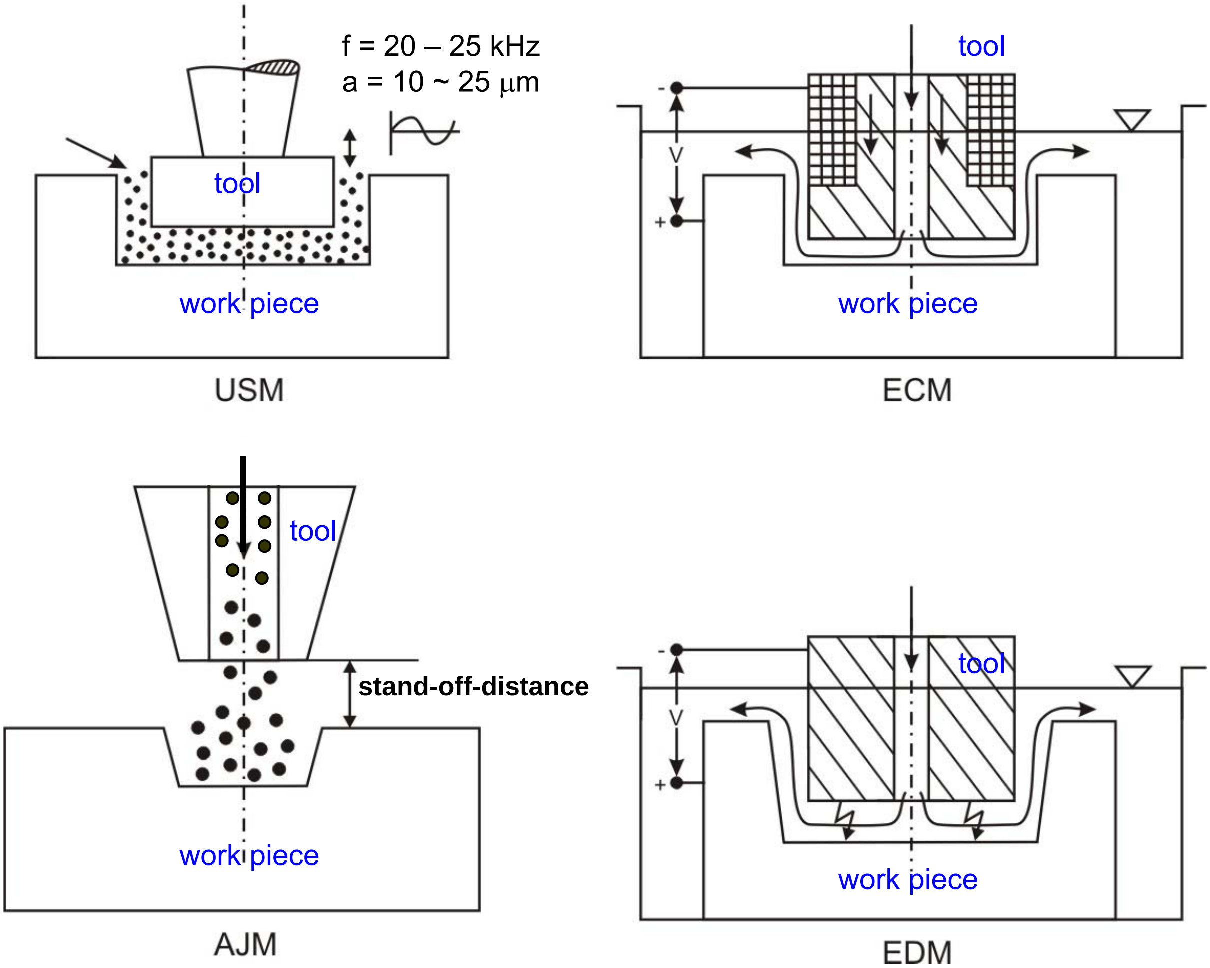


Fig. 9.1.2 *Schematic representation of various metal cutting operations.*

(iii) Need for Non Traditional Machining

Conventional machining sufficed the requirement of the industries over the decades. But new exotic work materials as well as innovative geometric design of products and components were putting lot of pressure on capabilities of conventional machining processes to manufacture the components with desired tolerances economically. This led to the development and establishment of NTM processes in the industry as efficient and economic alternatives to conventional ones. With development in the NTM processes, currently there are often the first choice and not an alternative to conventional processes for certain technical requirements. The following examples are provided where NTM processes are preferred over the conventional machining process:

- Intricate shaped blind hole – e.g. square hole of 15 mmx15 mm with a depth of 30 mm
- Difficult to machine material – e.g. same example as above in Inconel, Ti-alloys or carbides.
- Low Stress Grinding – Electrochemical Grinding is preferred as compared to conventional grinding
- Deep hole with small hole diameter – e.g. ϕ 1.5 mm hole with l/d = 20
- Machining of composites.

(iv) Abrasive Jet Machining

In Abrasive Jet Machining (AJM), abrasive particles are made to impinge on the work material at a high velocity. The jet of abrasive particles is carried by carrier gas or air. The high velocity stream of abrasive is generated by converting the pressure energy of the carrier gas or air to its kinetic energy and hence high velocity jet. The nozzle directs the abrasive jet in a controlled manner onto the work material, so that the distance between the nozzle and the work piece and the impingement angle can be set desirably. The high velocity abrasive particles remove the material by micro-cutting action as well as brittle fracture of the work material. Fig. 9.1.3 schematically shows the material removal process.

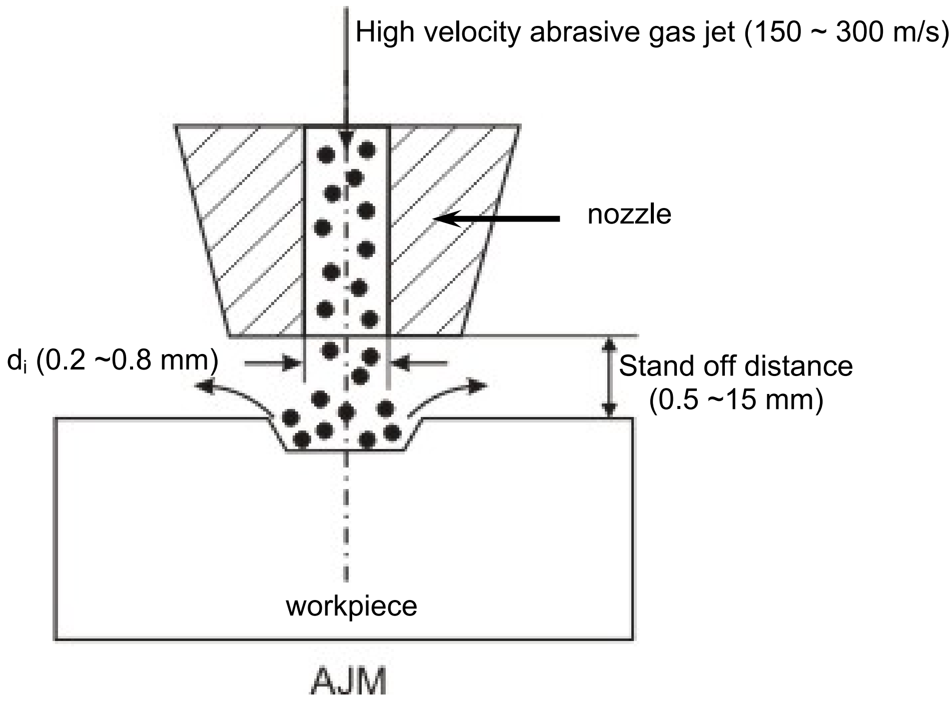


Fig. 9.1.3 *Schematic representation of AJM*

AJM is different from standard shot or sand blasting, as in AJM, finer abrasive grits are used and the parameters can be controlled more effectively providing better control over product quality.

In AJM, generally, the abrasive particles of around 50 μm grit size would impinge on the work material at velocity of 200 m/s from a nozzle of I.D. of 0.5 mm with a stand off distance of around 2 mm. The kinetic energy of the abrasive particles would be sufficient to provide material removal due to brittle fracture of the work piece or even micro cutting by the abrasives.

(v) Equipment

In AJM, air is compressed in an air compressor and compressed air at a pressure of around 5 bar is used as the carrier gas as shown in Fig. 9.1.4. Fig. 9.1.4 also shows the other major parts of the AJM system. Gases like CO_2, N_2 can also be used as carrier gas which may directly be issued from a gas cylinder. Generally oxygen is not used as a carrier gas. The carrier gas is

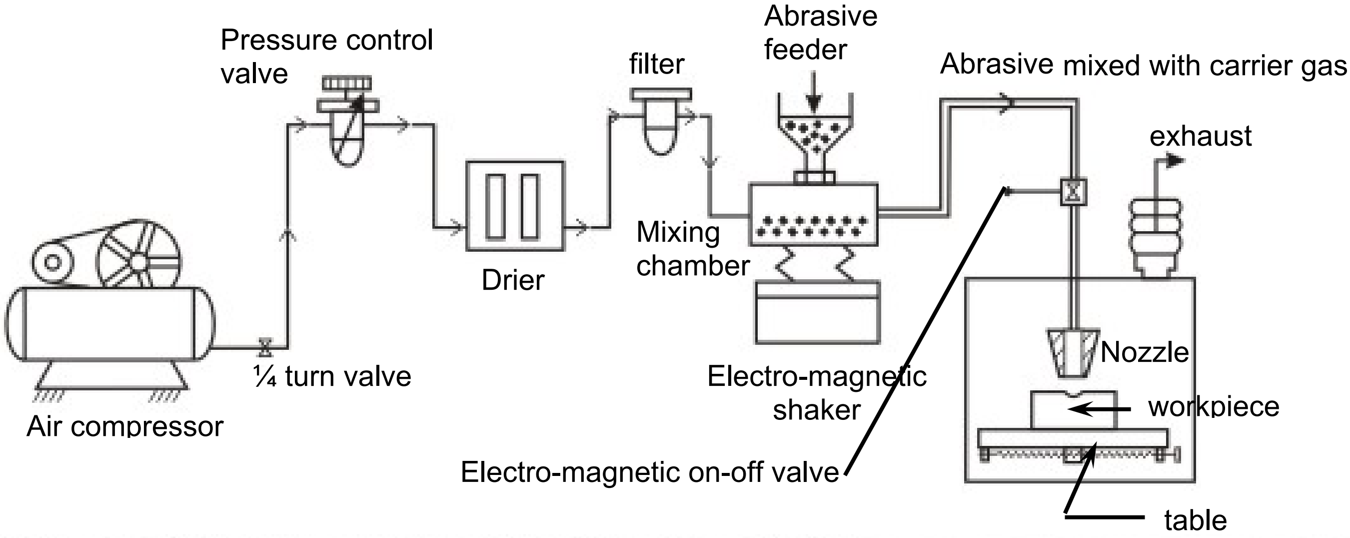


Fig. 9.1.4 *AJM set-up*

first passed through a pressure regulator to obtain the desired working pressure. The gas is then passed through an air dryer to remove any residual water vapour. To remove any oil vapour or particulate contaminant the same is passed through a series of filters. Then the carrier gas enters a closed chamber known as the mixing chamber. The abrasive particles enter the chamber from a hopper through a metallic sieve. The sieve is constantly vibrated by an electromagnetic shaker. The mass flow rate of abrasive (15 gm/min) entering the chamber depends on the amplitude of vibration of the sieve and its frequency. The abrasive particles are then carried by the carrier gas to the machining chamber via an electro-magnetic on-off valve. The machining enclosure is essential to contain the abrasive and machined particles in a safe and eco-friendly manner. The machining is carried out as high velocity (200 m/s) abrasive particles are issued from the nozzle onto a work piece traversing under the jet.

(vi) Process Parameters and Machining Characteristics.

The process parameters are listed below:

- Abrasive
  - — Material – Al_2O_3 / SiC / glass beads
  - — Shape – irregular / spherical
  - — Size – 10 ~ 50 μm
  - — Mass flow rate – 2 ~ 20 gm/min
- Carrier gas
  - — Composition – Air, CO_2, N_2
  - — Density – Air ~ 1.3 kg/m^3

— Velocity – 500 ~ 700 m/s
— Pressure – 2 ~ 10 bar
— Flow rate – 5 ~ 30 lpm

- Abrasive Jet
  — Velocity – 100 ~ 300 m/s
  — Mixing ratio – mass flow ratio of abrasive to gas – $\left(\frac{M_{abr}}{M_{gas}}\right)$
  — Stand-off distance – 0.5 ~ 5 mm
  — Impingement Angle – 60^0 ~ 90^0
- Nozzle
  — Material – WC / sapphire
  — Diameter – (Internal) 0.2 ~ 0.8 mm
  — Life – 10 ~ 300 hours

The important machining characteristics in AJM are

- The material removal rate (MRR) mm^3/min or gm/min
- The machining accuracy
- The life of the nozzle

Fig. 9.1.5 depicts the effect of some process parameters on MRR

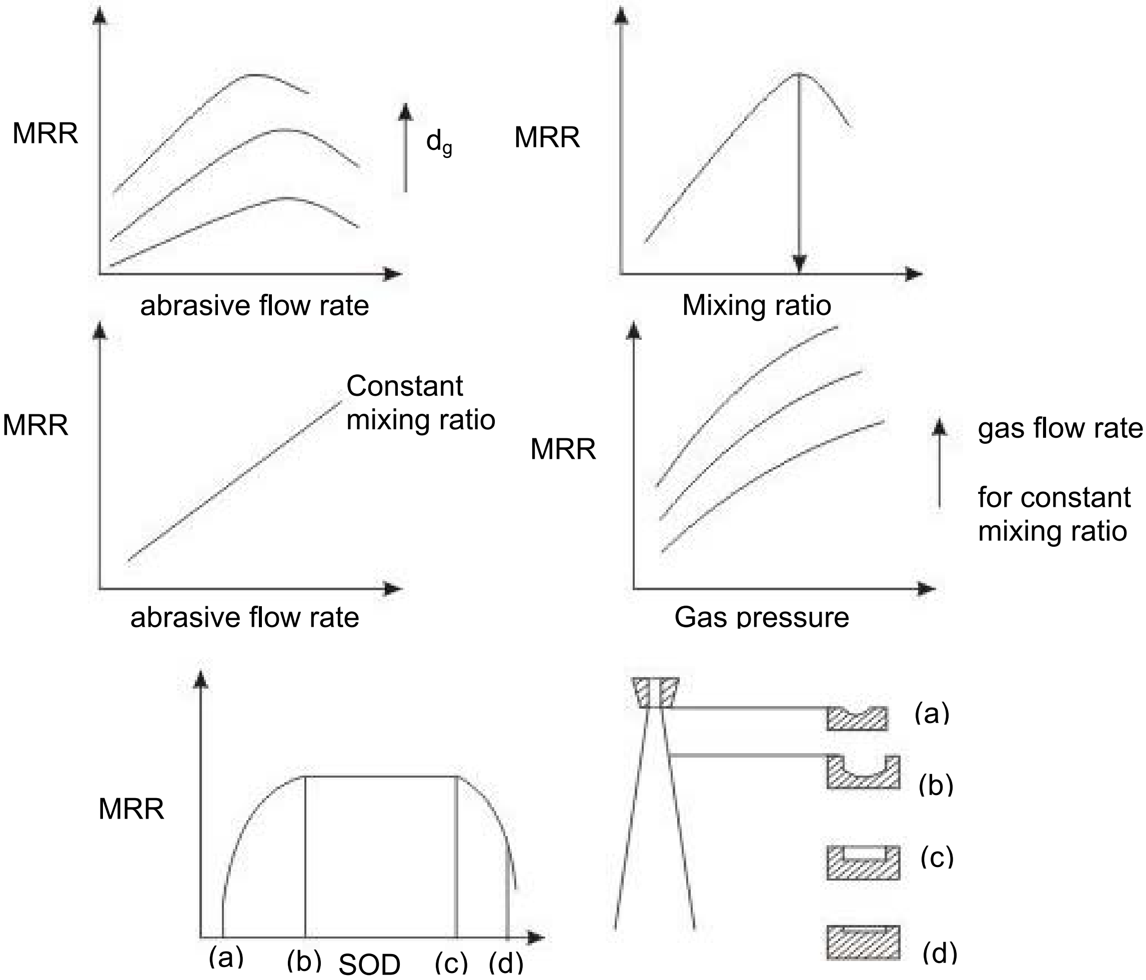


Fig. 9.1.5 *Effect of process parameters MRR*

(vii) Modelling of material removal

As mentioned earlier, material removal in AJM takes place due to brittle fracture of the work material due to impact of high velocity abrasive particles.
Modelling has been done with the following assumptions:

(i) Abrasives are spherical in shape and rigid. The particles are characterised by the mean grit diameter
(ii) The kinetic energy of the abrasives are fully utilised in removing material
(iii) Brittle materials are considered to fail due to brittle fracture and the fracture volume is considered to be hemispherical with diameter equal to chordal length of the indentation
(iv) For ductile material, removal volume is assumed to be equal to the indentation volume due to particulate impact.

Fig. 9.1.6 schematically shows the interaction of the abrasive particle and the work material in AJM.

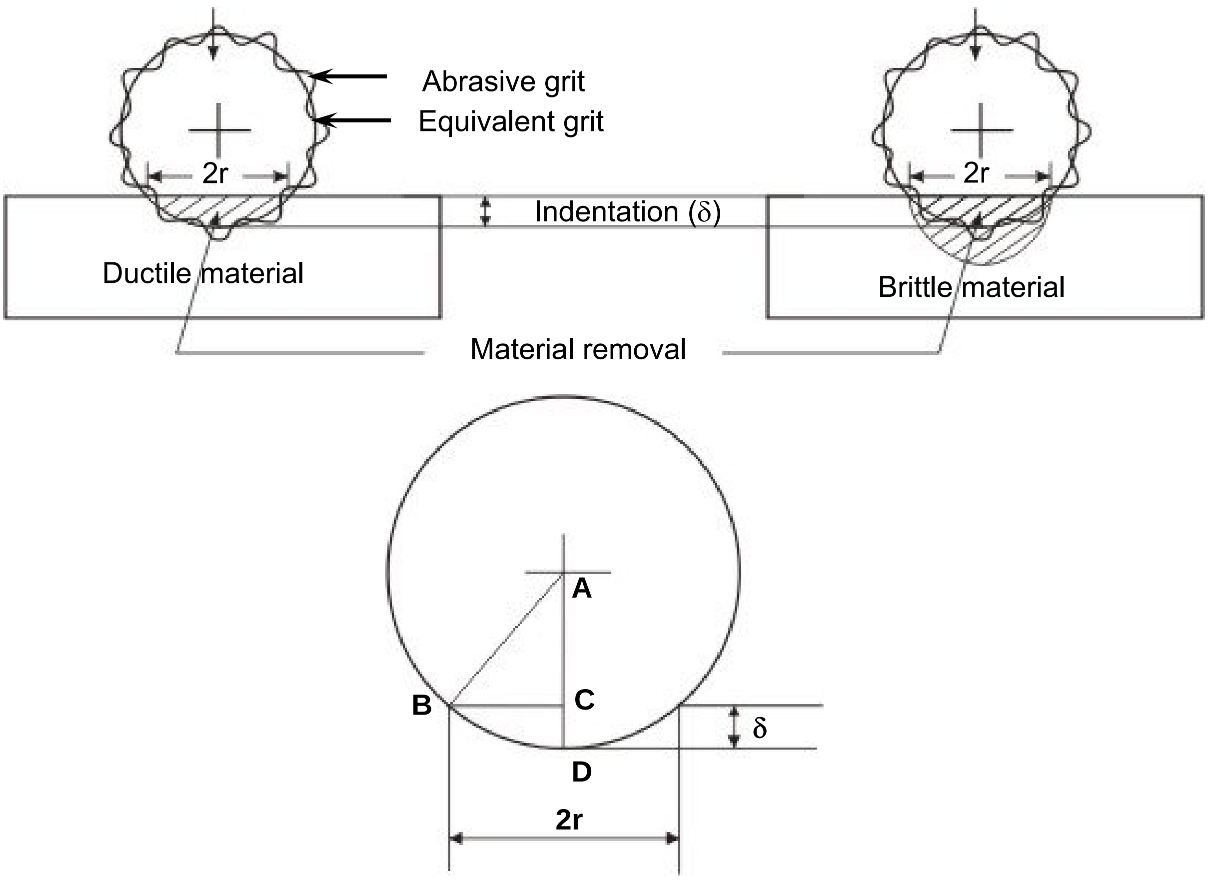


Fig. 9.1.6 *Interaction of abrasive particles with workpiece*

From the geometry of the indentation

$$AB^2 = AC^2 + BC^2$$

$$BC^2 = r^2 = AB^2 - AC^2$$

$$r^2 = \left(\frac{d_g}{2}\right)^2 - \left\{\frac{d_g}{2} - \delta\right\}^2$$

$$r^2 = -\delta^2 + d_g\delta \cong d_g\delta$$

$$r = \sqrt{d_g\delta}$$

∴ Volume of material removal in brittle material is the volume of the hemispherical impact crater and is given by:

$$\Gamma_B = \frac{2}{3}\pi r^3 = \frac{2\pi}{3}(d_g\delta)^{3/2}$$

For ductile material, volume of material removal in single impact is equal to the volume of the indentation and is expressed as:

$$\Gamma_D = \pi\delta^2\left[\frac{d_g}{2} - \frac{\delta}{3}\right] = \frac{\pi\delta^2 d_g}{2}$$

Kinetic energy of a single abrasive particle is given by

$$K.E._g = \frac{1}{2}m_g v^2 = \frac{1}{2}\left\{\frac{\pi}{6}{d_g}^3\rho_g\right\}v^2 = \frac{\pi}{12}{d_g}^3\rho_g v^2$$

where, v = velocity of the abrasive particle
m_g = mass of a single abrasive grit
d_g = diameter of the grit
ρ_g = density of the grit

On impact, the work material would be subjected to a maximum force **F** which would lead to an indentation of 'δ'. Thus the work done during such indentation is given by

$$W = \frac{1}{2}F\delta$$

Now considering H as the hardness or the flow strength of the work material, the impact force (F) can be expressed as:

$$F = \text{indentation area x hardness}$$

$$F = \pi r^2 H$$

where, r = the indentation radius

$$\therefore W = \frac{1}{2}F\delta = \frac{1}{2}\pi r^2 H\delta$$

Now, as it is assumed that the K.E. of the abrasive is fully used for material removal, then the work done is equated to the energy

$$W = K.E.$$

$$\frac{1}{2}\pi r^2 \delta H = \frac{\pi}{12} d_g^3 \rho_g v^2$$

$$\delta = \frac{d_g^3 \rho_g v^2}{6r^2 H} \qquad now\ r = \sqrt{d_g \delta} \quad \Rightarrow r^2 = d_g \delta$$

$$\delta^2 = \frac{d_g^2 \rho_g v^2}{6H}$$

$$\delta = d_g v \left(\frac{\rho_g}{6H}\right)^{1/2}$$

Now MRR in AJM of brittle materials can be expressed as:

$$MRR_B = \Gamma_B x \text{ Number of impacts by abrasive grits per second } = \Gamma_B N$$

$$MRR_B = \Gamma_B \frac{\dot{m}_a}{\text{mass of a grit}} = \frac{\dot{m}_a}{\frac{\pi}{6} d_g^3 \rho_g} = \frac{6\Gamma_B \dot{m}_a}{\pi d_g^3 \rho_g} \qquad as\ \Gamma_B = \frac{2\pi}{3}(d_g\delta)^{3/2}$$

$$= \frac{6x\frac{2\pi}{3}(d_g\delta)^{3/2}\dot{m}_a}{\pi d_g^3 \rho_g} = \frac{4\dot{m}_a}{\rho_g}\left(\frac{\delta}{d_g}\right)^{3/2}$$

$$MRR_B = \left(\frac{4\dot{m}_a}{\rho_g}\right)\left(\frac{\delta}{d_g}\right)^{3/2}$$

$$as \quad \delta = d_g v \left(\frac{\rho_g}{6H}\right)^{1/2}$$

$$MRR_B = \frac{4\dot{m}_a}{\rho_g} \cdot \left(\frac{d_g v}{d_g}\right)^{3/2} \left(\frac{\rho_g}{6H}\right)^{3/4}$$

$$MRR_B = \frac{4\dot{m}_a v^{3/2}}{6^{3/4}\rho_g^{1/4} H^{3/4}} \approx \frac{\dot{m}_a v^{3/2}}{\rho_g^{1/4} H^{3/4}}$$

as $\Gamma_D = \frac{\pi\delta^2 d_g}{2}$ MRR for ductile material can be simplified as:

$$MRR_D = \Gamma_D N = \Gamma_D \frac{6\dot{m}_a}{\pi d_g^3 \rho_g} = \frac{\pi\delta^2 d_g 6\dot{m}_a}{2\pi d_g^3 \rho_g}$$

$$MRR_D = \frac{6\pi\delta^2 \dot{m}_a}{2\pi d_g{}^2 \rho_g}$$

$$as \quad \delta = d_g v \left(\frac{\rho_g}{6H}\right)^{1/2}$$

$$MRR_D = \frac{6 \dot{m}_a d_g{}^2 v^2}{2 d_g{}^2 \rho_g}\left(\frac{\rho_g}{6H}\right)$$

$$MRR_D = \frac{1}{2}\frac{\dot{m}_a v^2}{H}$$

(viii) Applications

- For drilling holes of intricate shapes in hard and brittle materials
- For machining fragile, brittle and heat sensitive materials
- AJM can be used for drilling, cutting, deburring, cleaning and etching.
- Micro-machining of brittle materials

(ix) Limitations

- MRR is rather low (around ~ 15 mm^3/min for machining glass)
- Abrasive particles tend to get embedded particularly if the work material is ductile
- Tapering occurs due to flaring of the jet
- Environmental load is rather high.

Quiz Test.

1. AJM nozzles are made of
   (a) low carbon steel
   (b) HSS
   (c) WC
   (d) Stainless steel

2. Material removal in AJM of glass is around
   (a) 0.1 mm^3/min
   (b) 15 mm^3/min
   (c) 15 mm^3/s
   (d) 1500 mm^3/min

3. Material removal takes place in AJM due to
   (a) electrochemical action
   (b) mechanical impact
   (c) fatigue failure of the material
   (d) sparking on impact

4. As the stand off distance increases, the depth of penetration in AJM
   (a) increases
   (b) decreases
   (c) does not change
   (d) initially increases and then remains steady

Problem

1. Estimate the material removal rate in AJM of a brittle material with flow strength of 4 GPa. The abrasive flow rate is 2 gm/min, velocity is 200 m/s and density of the abrasive is 3 gm/cc.
2. Material removal rate in AJM is 0.5 mm^3/s. Calculate material removal per impact if mass flow rate of abrasive is 3 gm/min, density is 3 gm/cc and grit size is 60 μm as well as indentation radius.

Solutions to the Quiz problems

1 – (c)
2 – (b)
3 – (b)
4 – (b)

Solutions to the Problems

Solution of Prob. 1

$$MRR_B \approx \frac{\dot{m}_a v^{3/2}}{\rho_g^{1/4} H^{3/4}} = \frac{\frac{2x10^{-3}}{60} x(200)^{3/2}}{(3000)^{1/4} x(4x10^9)^{3/4}}$$

$$MRR_B = 8x10^{-10} m^3/s = 8x10^{-1} x60 \quad mm^3/s \cong 48 \quad mm^3/\min$$

Solution of Prob. 2

$$Mass\ of\ grit = \frac{\pi}{6} d_g^{\ 3}.\rho_g$$

$$\therefore No.\ of\ impact\ /\ time = \frac{\dot{m}_a}{\frac{\pi}{6} d_g^{\ 3} \rho_g} = \frac{6x\frac{3x10^{-3}}{60}}{\pi x(50x10^{-6})^3 x3000}$$

N = 254648

$$\Gamma_B = \frac{MRR}{N} = \frac{0.5mm^3/s}{2546648/s} = 1.96x10^{-6} mm^3 = 1960 \mu m^3$$

$$\text{Indentation volume} = \frac{2}{3}\pi r^3 = 1960 \quad \mu m^3$$

Indentation radius, $r \approx 9.78 \approx 10\mu m$

Module
9
Non-conventional machining

Lesson 36

Ultrasonic Machining (USM)

Instructional Objectives

i. Describe the basic mechanism of material removal in USM
ii. Identify the process parameters of USM
iii. Identify the machining characteristics of USM
iv. Analyse the effect of process parameters on material removal rate (MRR)
v. Develop mathematical model relating MRR with USM parameters
vi. Draw variation in MRR with different process parameters
vii. Identify major components of USM equipment
viii. State the working principle of USM equipment
ix. Draw schematically the USM equipment
x. List three applications of USM
xi. List three limitations of USM

1. Introduction

Ultrasonic machining is a non-traditional machining process. USM is grouped under the mechanical group NTM processes. Fig. 9.2.1 briefly depicts the USM process.

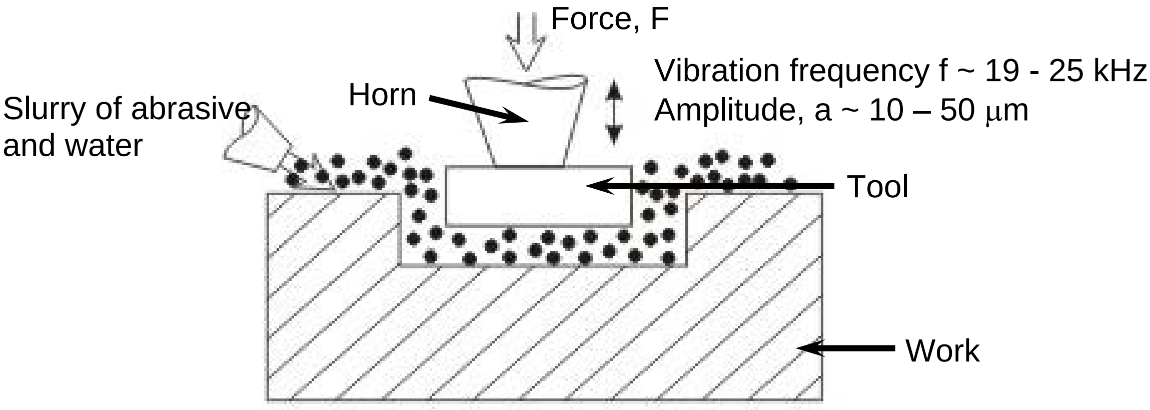


Fig. 9.2.1 *The USM process*

In ultrasonic machining, a tool of desired shape vibrates at an ultrasonic frequency (19 ~ 25 kHz) with an amplitude of around 15 – 50 μm over the workpiece. Generally the tool is pressed downward with a feed force, F. Between the tool and workpiece, the machining zone is flooded with hard abrasive particles generally in the form of a water based slurry. As the tool vibrates over the workpiece, the abrasive particles act as the indenters and indent both the work material and the tool. The abrasive particles, as they indent, the work material, would remove the same, particularly if the work material is brittle, due to crack initiation, propagation and brittle fracture of the material. Hence, USM is mainly used for machining brittle materials {which are poor conductors of electricity and thus cannot be processed by Electrochemical and Electro-discharge machining (ECM and ED)}.

2. Mechanisms of Material Removal in USM and its modelling

As has been mentioned earlier, USM is generally used for machining brittle work material. Material removal primarily occurs due to the indentation of the hard abrasive grits on the brittle work material. As the tool vibrates, it leads to indentation of the abrasive grits. During indentation, due to Hertzian contact stresses, cracks would develop just below the contact site, then as indentation progresses the cracks would propagate due to increase in stress and ultimately lead to brittle fracture of the work material under each individual interaction site between the abrasive grits and the workpiece. The tool material should be such that indentation by the abrasive grits does not lead to brittle failure. Thus the tools are made of tough, strong and ductile materials like steel, stainless steel and other ductile metallic alloys.

Other than this brittle failure of the work material due to indentation some material removal may occur due to free flowing impact of the abrasives against the work material and related solid-solid impact erosion, but it is estimated to be rather insignificant. Thus, in the current model, material removal would be assumed to take place only due to impact of abrasives between tool and workpiece, followed by indentation and brittle fracture of the workpiece. The model does consider the deformation of the tool.

In the current model, all the abrasives are considered to be identical in shape and size. An abrasive particle is considered to be spherical but with local spherical bulges as shown in Fig. 9.2.2. The abrasive particles are characterised by the average grit diameter, d_g. It is further assumed that the local spherical bulges have a uniform diameter, d_b and which is related to the grit diameter by $d_b = \mu d_g^2$. Thus an abrasive is characterised by μ and d_g.

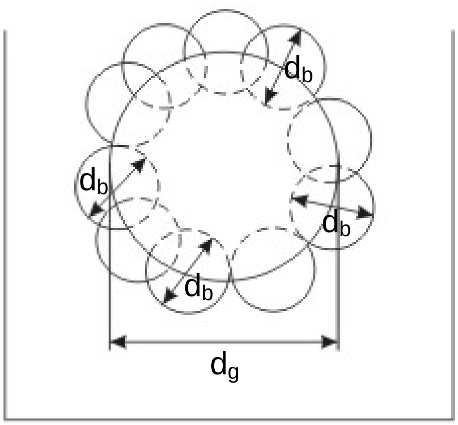


Fig. 9.2.2 *Schematic representation of abrasive grit*

During indentation by the abrasive grit onto the workpiece and the tool, the local spherical bulges contact the surfaces and the indentation process is characterised by d_b rather than by d_g. Fig. 9.2.3 shows the interaction between the abrasive grit and the workpiece and tool.

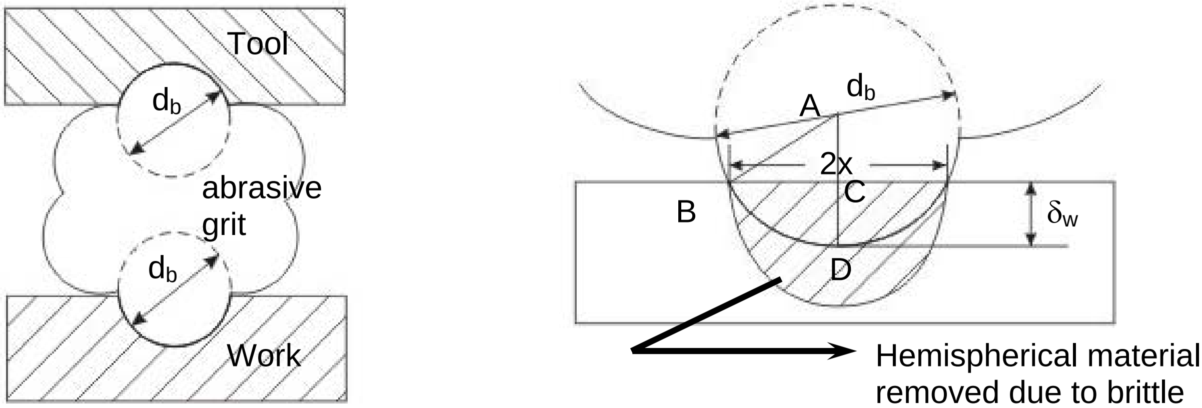


***Fig. 9.2.3** Interaction between grit and workpiece and tool*

As the indentation proceeds, the contact zone between the abrasive grit and workpiece is established and the same grows. The contact zone is circular in nature and is characterised by its diameter '2x'. At full indentation, the indentation depth in the work material is characterised by δ_w. Due to the indentation, as the work material is brittle, brittle fracture takes place leading to hemi-spherical fracture of diameter '2x' under the contact zone. Therefore material removal per abrasive grit is given as

$$\Gamma_w = \frac{2}{3}\pi x^3$$

Now from Fig. 9.2.3 $\quad AB^2 = AC^2 + BC^2$

$$\left(\frac{d_b}{2}\right)^2 = \left(\frac{d_b}{2} - \delta_w\right)^2 + x^2$$

$$x^2 = d_b\delta_w \text{ neglecting } \delta_w^2 \text{ as } \delta_w << d_b$$

$$\therefore \Gamma_w = \frac{2}{3}\pi(d_b\delta_w)^{3/2}$$

If at any moment of time, there are an average 'n' of grits and the tool is vibrating at a frequency 'f' then material removal rate can be expressed as

$$MRR_w = \Gamma_w .n.f$$

$$= \frac{2}{3}\pi\left(\delta_w d_b\right)^{3/2} nf$$

Now as the tool and workpiece would be pressing against each other, contact being established via the abrasive grit, both of them would deform or wear out. As the tool vibrates, for sometime, it vibrates freely; then it comes in contact with the abrasive, which is already in contact with the job.

And then the indentation process starts and finally completes with an indentation of δ_w and δ_t on the work and tool respectively. Fig. 9.2.4

schematically depicts the same assuming the work to be rigid for easy depiction. The tool vibrates in a harmonic motion. Thus only during its first quarter of its cycle it can derive an abrasive towards interaction with the tool and workpiece as shown in Fig. 9.2.5. Out of this quarter cycle, some part is used to engage the tool with abrasive particle as shown in Fig. 9.2.4. Thus the time of indentation τ can be roughly estimated as

$$\frac{\delta}{a_o} = \frac{\tau}{T/4} \Rightarrow \quad \tau = \frac{T\delta}{4a_o} = \frac{T(\delta_w + \delta_t)}{4a_o}$$

Now during machining, the impulse of force on the tool and work would be balanced. Thus total impulse on the tool can be expressed as

$$I_t = n.f.\frac{1}{2}F_{max}\tau$$

where F_{max} is the maximum indentation force per abrasive.
Now in the USM, the tool is fed with an average force F

Thus $F = \frac{1}{2}F_{max}\tau.n.f$

Again, if the flow strength of work material is taken as σ_w, then

$$F_{max} = \sigma_w \pi x^2$$

$$\therefore F = \frac{1}{2}\sigma_w \pi x^2 \tau nf$$

$$F = \frac{1}{2}nf\sigma_w \pi x^2 \frac{T(\delta_w + \delta_t)}{4a_o}$$

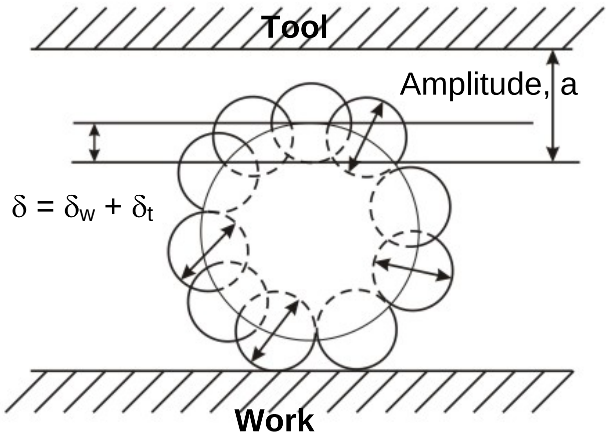


Fig. 9.2.4 *Interaction between grit and workpiece and tool to depict the workpiece and tool deformations*

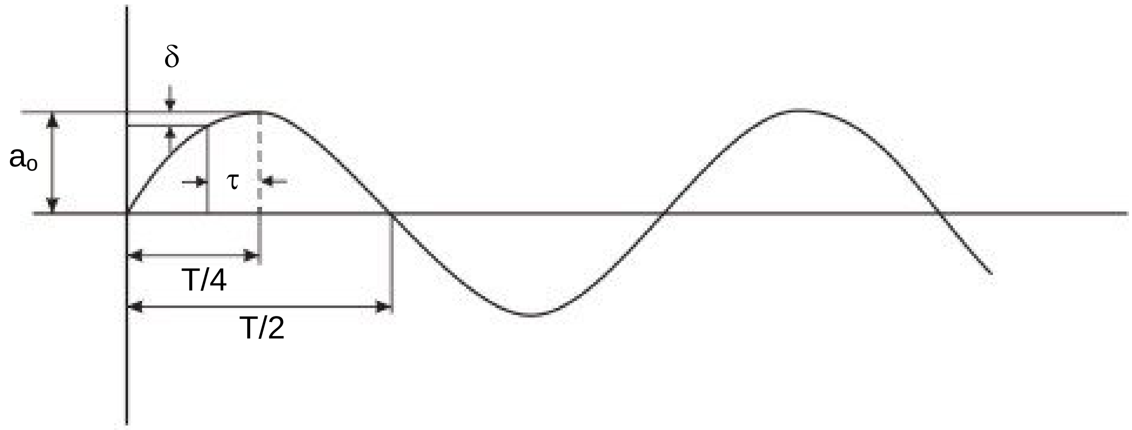


***Fig.9.2.5** Change in tool position due to ultrasonic vibration of the tool*

If 'A' is total surface area of the tool facing the workpiece, then volume of abrasive slurry of one grit thickness is

$$Ad_g$$

If n is the number of grits then the total volume of n grits is

$$\frac{\pi d_g^{\ 3}}{6} n$$

Thus the concentration of abrasive grits in the slurry is related as follows:

$$n\frac{\pi d_g^3}{6} = Ad_g C$$

$$C = \frac{\frac{\pi d_g^3}{6} n}{Ad_g} = \frac{\pi d_g^2}{6A} n$$

$$\therefore \quad n = \frac{6AC}{\pi d_g^2}$$

Now it is expected that indentation would be inversely proportional to the flow strength then,

$$\frac{\delta_t}{\delta_w} = \frac{\sigma_w}{\sigma_t} = \lambda$$

Again combining, 'F' can be written as

$$F = \frac{1}{2} nf\sigma_w \pi x^2 \frac{T}{4a_o}\delta_w (1+\lambda)$$

$$F = \frac{1}{2}\frac{6AC}{\pi d_g^2}.f.\sigma_w.\pi d_b \delta_w \frac{T}{4a_o}\delta_w (1+\lambda)$$

$$F = \frac{3AC}{d_g^2}.(fT).\frac{\sigma_w}{4a_o} d_b \delta_w^2 (1+\lambda)$$

$$F = \frac{3AC}{d_g^2}(fT).\frac{\sigma_w}{4a_o}\mu d_g^2 \delta_w^2 (1+\lambda)$$

$$\delta_w^2 = \frac{4a_o F}{3\mu AC\sigma_w (1+\lambda)}$$

Now,

$$MRR = \Gamma_w nf$$

$$= \frac{2}{3}\pi x^3 n.f$$

$$= \frac{2}{3}\pi \frac{6cA}{\pi d_g{}^2}.f.x^3$$

$$= 4\pi \frac{cA}{\pi d_g{}^2}.f.(d_b \delta_w)^{3/2} = \frac{4cA}{d_g{}^2}.f.\left(\mu d_g{}^2 \delta_w\right)^{3/2}$$

$$= 4cAd_g \mu^{3/2}.f.\left\{\frac{4Fa_o}{3\mu Ac\sigma_w (1+\lambda)}\right\}^{3/4}$$

$$MRR \quad \alpha \quad \frac{c^{1/4} A^{1/4} F^{3/4} a_o{}^{3/4} d_g f}{\sigma_w{}^{3/4} (1+\lambda)^{3/4}} \mu^{3/4}$$

$$\alpha \quad d_g f \frac{c^{1/4} A p^{3/4} a_o{}^{3/4}}{\sigma_w{}^{3/4} (1+\lambda)^{3/4}} \mu^{3/4}$$

3. Process Parameters and their Effects.

During discussion and analysis as presented in the previous section, the process parameters which govern the ultrasonic machining process have been identified and the same are listed below along with material parameters

- Amplitude of vibration (a_o) – 15 – 50 μm
- Frequency of vibration (f) – 19 – 25 kHz
- Feed force (F) – related to tool dimensions
- Feed pressure (p)
- Abrasive size – 15 μm – 150 μm
- Abrasive material – Al_2O_3
  - SiC
  - B_4C
  - Boronsilicarbide
  - Diamond
- Flow strength of work material
- Flow strength of the tool material
- Contact area of the tool – A
- Volume concentration of abrasive in water slurry – C

Fig. 9.2.6 depicts the effect of parameters on MRR.

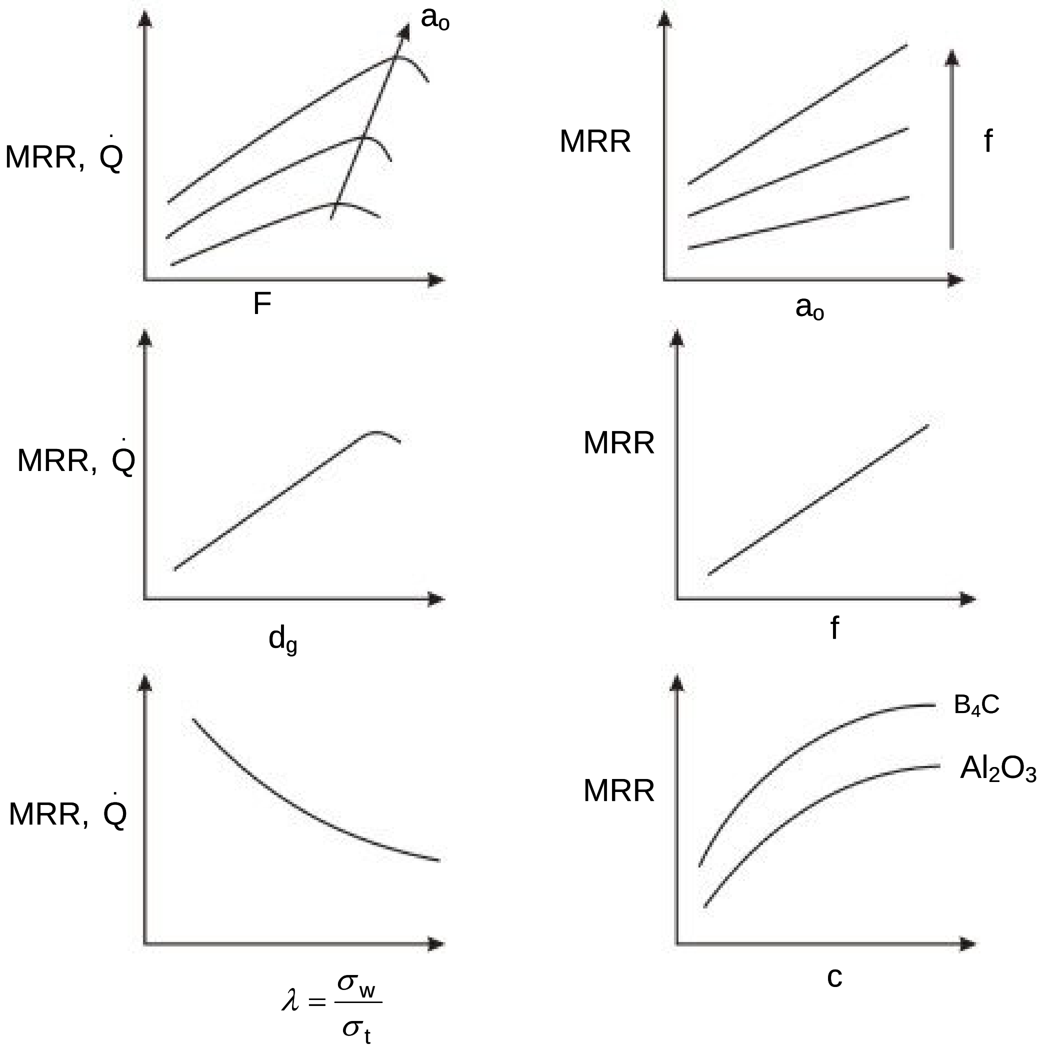


Fig. 9.2.6 *Effect of machining parameters on MRR*

4. Machine

The basic mechanical structure of an USM is very similar to a drill press. However, it has additional features to carry out USM of brittle work material. The workpiece is mounted on a vice, which can be located at the desired position under the tool using a 2 axis table. The table can further be lowered or raised to accommodate work of different thickness. The typical elements of an USM are (Fig. 9.2.7)

- Slurry delivery and return system
- Feed mechanism to provide a downward feed force on the tool during machining
- The transducer, which generates the ultrasonic vibration

- The horn or concentrator, which mechanically amplifies the vibration to the required amplitude of 15 – 50 μm and accommodates the tool at its tip.

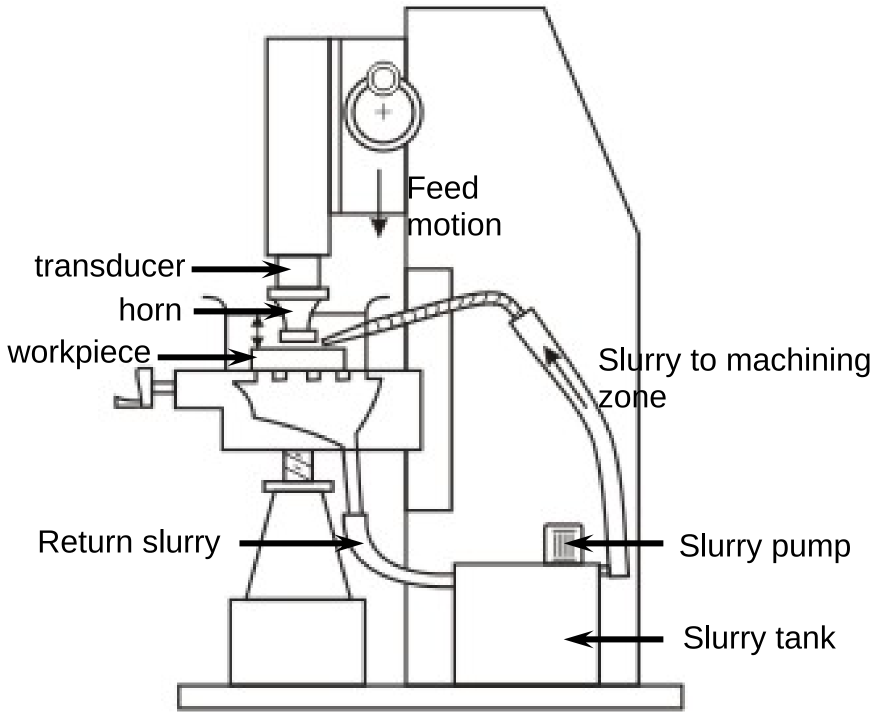


Fig. 9.2.7 *Schematic view of an Ultrasonic Machine*

The ultrasonic vibrations are produced by the transducer. The transducer is driven by suitable signal generator followed by power amplifier. The transducer for USM works on the following principle

- Piezoelectric effect
- Magnetostrictive effect
- Electrostrictive effect

Magnetostrictive transducers are most popular and robust amongst all. Fig. 9.2.8 shows a typical magnetostrictive transducer along with horn. The horn or concentrator is a wave-guide, which amplifies and concentrates the vibration to the tool from the transducer.

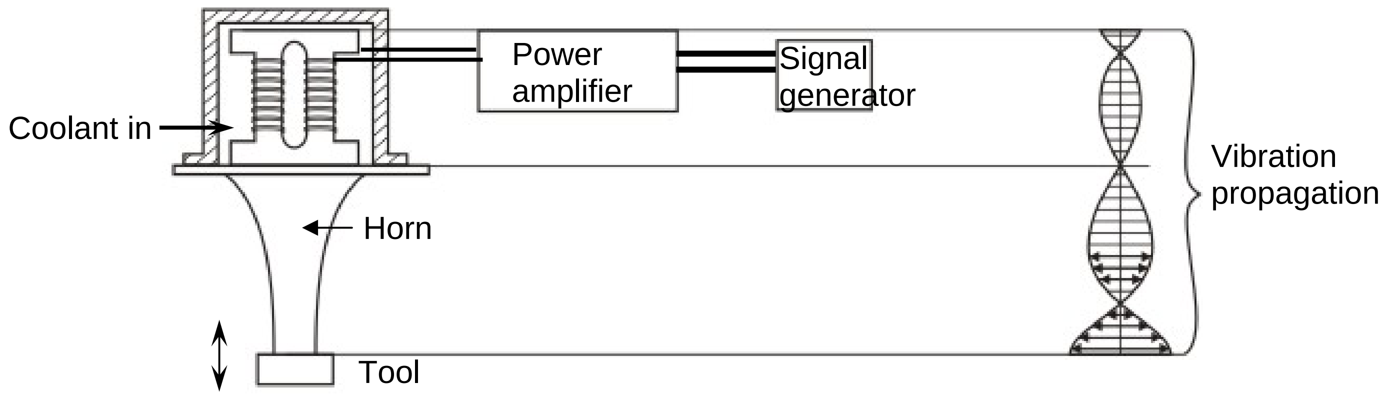


Fig. 9.2.8 *Working of horn as mechanical amplifier of amplitude of vibration*

The horn or concentrator can be of different shape like

- Tapered or conical
- Exponential
- Stepped

Machining of tapered or stepped horn is much easier as compared to the exponential one. Fig. 9.2.9 shows different horns used in USM

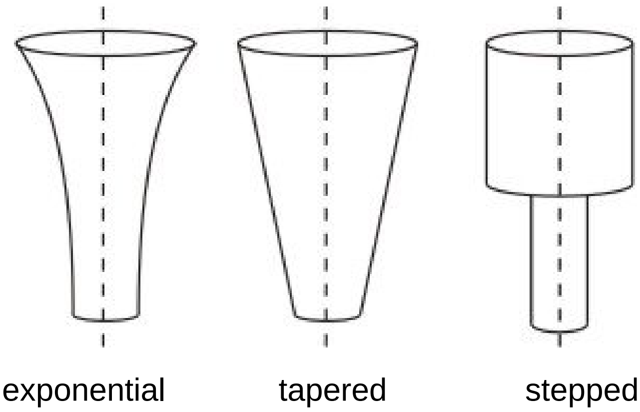


Fig. 9.2.9 *Different Horns used in USM*

5. Applications

- Used for machining hard and brittle metallic alloys, semiconductors, glass, ceramics, carbides etc.
- Used for machining round, square, irregular shaped holes and surface impressions.
- Machining, wire drawing, punching or small blanking dies.

6. Limitations

- Low MRR
- Rather high tool wear
- Low depth of hole

Quiz Test

1. Which of the following material is not generally machined by USM
   (i) Copper
   (ii) Glass
   (iii) Silicon
   (iv) Germanium
2. Tool in USM is generally made of
   (i) Glass
   (ii) Ceramic
   (iii) Carbides
   (iv) Steel
3. Increasing volume concentration of abrasive in slurry would affect MRR in the following manner
   (i) increase MRR
   (ii) decrease MRR
   (iii) would not change MRR
   (iv) initially decrease and then increase MRR
4. USM can be classified as the following type of non-traditional machining process
   (i) electrical
   (ii) optical
   (iii) mechanical
   (iv) chemical

Problems

1. Glass is being machined at a MRR of 6 mm^3/min by Al_2O_3 abrasive grits having a grit dia of 150 μm. If 100 μm grits were used, what would be the MRR?

2. For the above problem, from the initial setting the frequency is increased from 20 kHz to 25 kHz. Determine new MRR.

3. For the first problem, the feed force is increased by 50% along with a reduction in concentration by 70%. What would be the effect on MRR.

Answers to the Quiz

1 – (a)
2 – (d)
3 – (a)
4 – (c)

Solutions to the Problems

Soln. to Prob. 1

$$MRR \,\alpha\, \frac{c^{1/4}F^{3/4}a_o^{3/4}A^{1/4}d_g f}{\sigma_w{}^{3/4}(1+\lambda)^{3/4}}\mu^{3/4}$$

Thus MRR = kd_g keeping all other variables unchanged

$$\therefore \quad \frac{MRR_1}{MRR_2} = \frac{d_{g1}}{d_{g2}} \quad \Rightarrow \quad MRR_2 = MRR_1 \frac{d_{g2}}{d_{g1}}$$

$$MRR_2 = 6x\frac{100}{150} = 4 \text{ mm}^3\text{/min} \qquad \text{Ans.}$$

Soln. to Prob. 2

$$MRR \,\alpha\, \frac{c^{1/4}F^{3/4}a_o^{3/4}A^{1/4}d_g f}{\sigma_w{}^{3/4}(1+\lambda)^{3/4}}\mu^{3/4}$$

MRR = kf keeping all other variables same

$$\therefore \quad MRR_{NEW} = \frac{f_{new}}{f_{old}}.MRR_{OLD} = \frac{25}{20}x6 = 7.5 \text{ mm}^3\text{/min} \quad \text{Ans.}$$

Soln. to Prob. 3

$$MRR \,\alpha\, \frac{c^{1/4}F^{3/4}a_o^{3/4}A^{1/4}d_g f}{\sigma_w{}^{3/4}(1+\lambda)^{3/4}}\mu^{3/4}$$

$MRR = kC^{1/4}F^{3/4}$ Keeping all other variables constant

$$\therefore \quad MRR_{NEW} = \left(\frac{C_{NEW}}{C_{OLD}}\right)^{1/4} . \left(\frac{F_{NEW}}{F_{OLD}}\right)^{3/4} MRR_{OLD}$$

$$= (0.3)^{1/4} x (1.5)^{3/4} x6 = 6.02 \text{ mm}^3 / \text{min}$$

Almost no change in MRR.

Module 9

Non conventional Machining

Lesson
37
Water Jet and Abrasive Water Jet Machining

Instructional Objectives

- o List four different non conventional machining processes
- o Differentiate between water and abrasive water jet machining
- o List different WJM and AWJM systems
- o List ten different modules of AWJM systems
- o List four applications of AWJM
- o List three advantages of AWJM
- o List materials that can be processed by AWJM
- o Mention functions of different elements of AWJM
- o Identify mechanism of material removal
- o Develop models for mechanism of material removal
- o Identify parameters related to product quality
- o Identify five limitations of AWJM
- o Identify environmental issues in the area of AWJM

Introduction

Water Jet Machining (WJM) and Abrasive Water Jet Machining (AWJM) are two non-traditional or non-conventional machining processes. They belong to mechanical group of non-conventional processes like Ultrasonic Machining (USM) and Abrasive Jet Machining (AJM). In these processes (WJM and AJWM), the mechanical energy of water and abrasive phases are used to achieve material removal or machining. The general grouping of some of the typical non-traditional processes are shown below:

- o Mechanical Processes
  - — USM
  - — AJM
  - — WJM and AWJM
- o Thermal Processes
  - — EBM
  - — LBM
  - — PAM
  - — EDM and WEDM
- o Electrical Processes
  - — ECM
  - — EDG
  - — EJD
- o Chemical Processes
  - — Chemical milling
  - — Photo chemical machining

WJM and AWJM can be achieved using different approaches and methodologies as enumerated below:

- WJM - Pure
- WJM - with stabilizer
- AWJM – entrained – three phase – abrasive, water and air
- AWJM – suspended – two phase – abrasive and water

- o Direct pumping
- o Indirect pumping
- o Bypass pumping

However in all variants of the processes, the basic methodology remains the same. Water is pumped at a sufficiently high pressure, 200-400 MPa (2000-4000 bar) using intensifier technology. An intensifier works on the simple principle of pressure amplification using hydraulic cylinders of different cross-sections as used in "**Jute Bell Presses**". When water at such pressure is issued through a suitable orifice (generally of 0.2- 0.4 mm dia), the potential energy of water is converted into kinetic energy, yielding a high velocity jet (1000 m/s). Such high velocity water jet can machine thin sheets/foils of aluminium, leather, textile, frozen food etc.
In pure WJM, commercially pure water (tap water) is used for machining purpose. However as the high velocity water jet is discharged from the orifice, the jet tends to entrain atmospheric air and flares out decreasing its cutting ability.
Hence, quite often stabilisers (long chain polymers) that hinder the fragmentation of water jet are added to the water.
In AWJM, abrasive particles like sand (SiO_2), glass beads are added to the water jet to enhance its cutting ability by many folds. AWJ are mainly of two types – entrained and suspended type as mentioned earlier. In entrained type AWJM, the abrasive particles are allowed to entrain in water jet to form abrasive water jet with significant velocity of 800 m/s. Such high velocity abrasive jet can machine almost any material. Fig. 1 shows the photographic view of a commercial CNC water jet machining system along with close-up view of the cutting head.

Fig. 1 *Commercial CNC water jet machining system and cutting heads (Photograph Courtesy – Omax Corporation, USA)*

Application

The applications and materials, which are generally machined using WJ and AWJ, are given below:

Application

- Paint removal
- Cleaning
- Cutting soft materials
- Cutting frozen meat
- Textile, Leather industry
- Mass Immunization
- Surgery
- Peening
- Cutting
- Pocket Milling
- Drilling
- Turning
- Nuclear Plant Dismantling

Materials

- Steels
- Non-ferrous alloys
- Ti alloys, Ni- alloys
- Polymers
- Honeycombs
- Metal Matrix Composite
- Ceramic Matrix Composite
- Concrete
- Stone – Granite
- Wood
- Reinforced plastics
- Metal Polymer Laminates
- Glass Fibre Metal Laminates

The cutting ability of water jet machining can be improved drastically by adding hard and sharp abrasive particles into the water jet. Thus, WJM is typically used to cut so called “softer” and “easy-to-machine” materials like thin sheets and foils, non-ferrous metallic alloys, wood, textiles, honeycomb, polymers, frozen meat, leather etc, but the domain of “harder and “difficult-to-machine” materials like thick plates of steels, aluminium and other commercial materials, metal matrix and ceramic matrix composites, reinforced plastics, layered composites etc are reserved for AWJM.

Other than cutting (machining) high pressure water jet also finds application in paint removal, cleaning, surgery, peening to remove residual stress etc. AWJM can as well be used besides cutting for pocket milling, turning, drilling etc. One of the strategic areas where robotic AWJM is finding critical application is dismantling of nuclear plants.

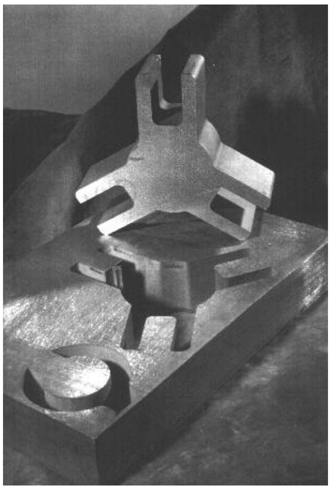


Fig. 2 *Stainless steel plate (50 mm thick) machined with AWJ*
(Photograph Courtesy – Omax Corporation, USA)

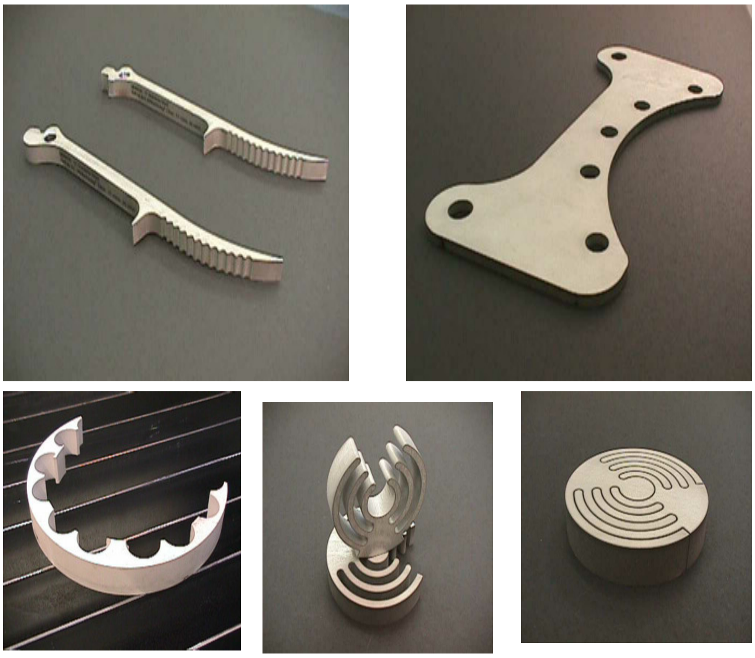


Fig. 3 *Different engineering components machined with AWJ*
(Photograph Courtesy – Omax Corporation, USA)

Fig. 2 depicts a typical example of AWJM, where 50 mm thick stainless steel has been machined. Fig. 3 shows the obtainable accuracy and precision with AWJM. Some of the job shop industries and manufacturers claim to have successfully used AWJM in free form surface generation by milling as shown in the following web page:

WJM and AWJM have certain advantageous characteristics, which helped to achieve significant penetration into manufacturing industries.

- Extremely fast set-up and programming
- Very little fixturing for most parts
- Machine virtually any 2D shape on any material
- Very low side forces during the machining
- Almost no heat generated on the part
- Machine thick plates

Machine

Any standard abrasive water jet machining (AWJM) system using entrained AWJM methodology consists of following modules.

- LP booster pump
- Hydraulic unit
- Additive Mixer
- Intensifier
- Accumulator
- Flexible high pressure transmission line
- On-off valve
- Orifice
- Mixing Chamber
- Focussing tube or inserts
- Catcher
- CNC table
- Abrasive metering device
- Catcher

1. LP Booster
2. Hydraulic drive
3. Additive mixer
4. Direction control
5. Intensifier
5A. LP Intensifier
5B. HP Intensifier
6. Accumulator

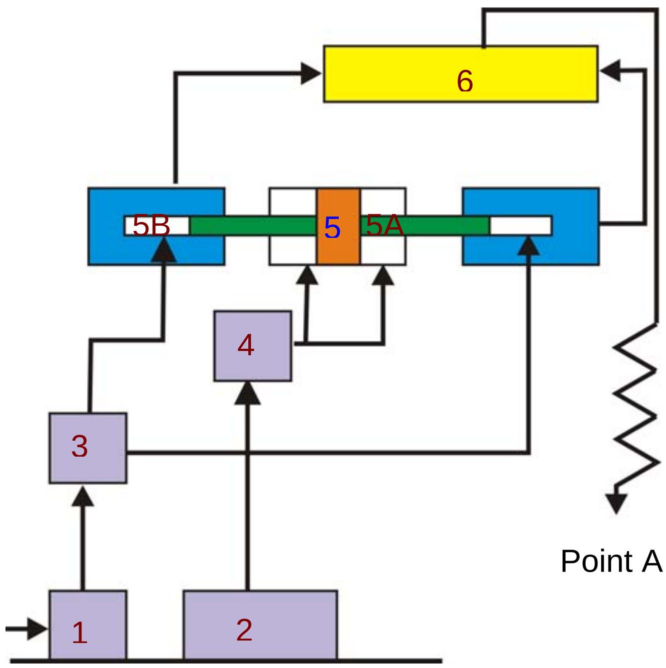


Fig. 4 *Schematic set-up of AWJM*

Intensifier, shown in Fig. 5 is driven by a hydraulic power pack. The heart of the hydraulic power pack is a positive displacement hydraulic pump. The power packs in modern commercial systems are often controlled by microcomputers to achieve programmed rise of pressure etc.

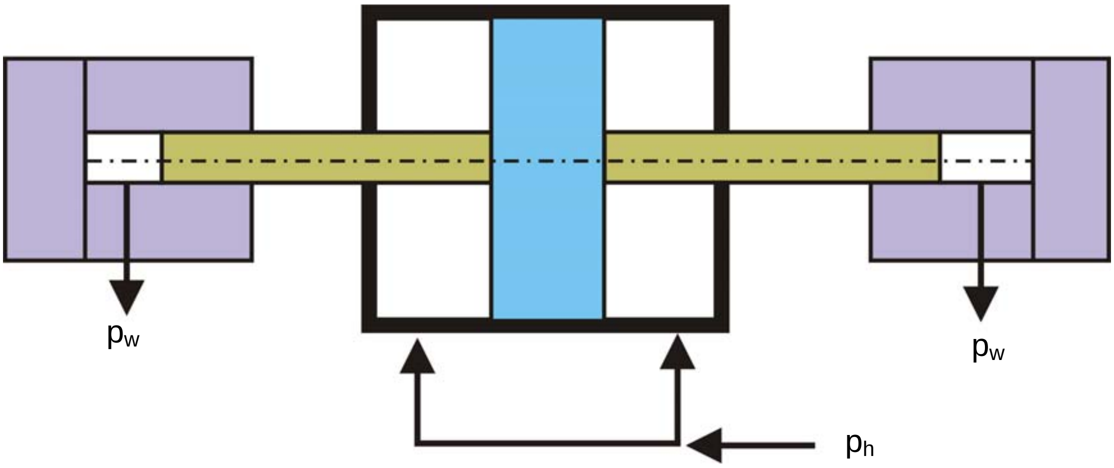


Fig. 5 *Intensifier – Schematic*

The hydraulic power pack delivers the hydraulic oil to the intensifier at a pressure of p_h . The ratio of cross-section of the two cylinders in the intensifier is say ***A** ratio* ***(A = A** large* ***/ A** small* ***)***. Thus, pressure amplification would take place at the small cylinder as follows.

$$p_h \times A_{large} = p_w \times A_{small}$$

$$p_w = p_h \times \frac{A_{large}}{A_{small}}$$

$$p_w = p_h \times A_{ratio}$$

Thus, if the hydraulic pressure is set as 100 bar and area ratio is 40, p_w = 100 x 40 = 4000 bar. By using direction control valve, the intensifier is driven by the hydraulic unit. The water may be directly supplied to the small cylinder of the intensifier or it may be supplied through a booster pump, which typically raises the water pressure to 11 bar before supplying it to the intensifier. Sometimes water is softened or long chain polymers are added in "additive unit".

Thus, as the intensifier works, it delivers high pressure water (refer Fig. 6). As the larger piston changes direction within the intensifier, there would be a drop in the delivery pressure. To counter such drops, a thick cylinder is added to the delivery unit to accommodate water at high pressure. This is called an "accumulator" which acts like a "fly wheel" of an engine and minimises fluctuation of water pressure

High-pressure water is then fed through the flexible stainless steel pipes to the cutting head. It is worth mentioning here that such pipes are to carry water at 4000 bar (400 MPa) with flexibility incorporated in them with joints but without any leakage. Cutting head consists of orifice, mixing chamber and focussing tube or insert where water jet is formed and mixed with abrasive particles to form abrasive water jet.

Fig. 6 shows a cutting head or jet former both schematically and photographically. Typical diameter of the flexible stainless steel pipes is of 6 mm. Water carried through the pipes is brought to the jet former or cutting head.

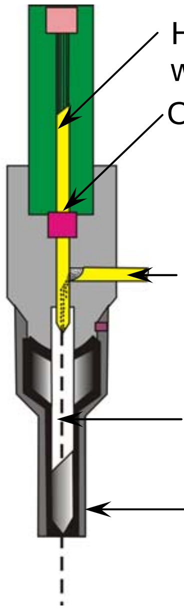


Fig. 6 *Schematic and photographic view of the cutting head (Photograph Courtesy – Omax Corporation, USA)*

The potential or pressure head of the water is converted into velocity head by allowing the high-pressure water to issue through an orifice of small diameter (0.2 – 0.4 mm). The velocity of the water jet thus formed can be estimated, assuming no losses as $v_{wj} = (2p_w / \rho_w)^{1/2}$ using Bernoulli's equation where, p_w is the water pressure and ρ_w is the density of water. The orifices are typically made of sapphire. In commercial machines, the life of the sapphire orifice is typically around 100 – 150 hours. In WJM this high velocity water jet is used for the required application where as in AWJM it is directed into the mixing chamber. The mixing chamber has a typical dimension of inner diameter 6 mm and a length of 10 mm. As the high velocity water is issued from the orifice into the mixing chamber, low pressure (vacuum) is created within the mixing chamber. Metered abrasive particles are introduced into the mixing chamber through a port.

The abrasive particles are metered using different techniques like vibratory feeder or toothed belt feeder. The reader may consult standard literature on transportation of powders.

Mixing

Fig. 7 schematically shows the mixing process. Mixing means gradual entrainment of abrasive particles within the water jet and finally the abrasive water jet comes out of the focussing tube or the nozzle.

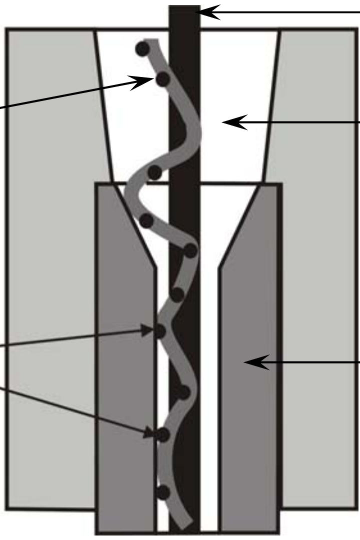


Fig. 7 *Schematic view of mixing process*

During mixing process, the abrasive particles are gradually accelerated due to transfer of momentum from the water phase to abrasive phase and when the jet finally leaves the focussing tube, both phases, water and abrasive, are assumed to be at same velocity.

The mixing chamber, as shown in Fig. 7 and Fig. 8, is immediately followed by the focussing tube or the inserts. The focussing tube is generally made of tungsten carbide (powder metallurgy product) having an inner diameter of 0.8 to 1.6 mm and a length of 50 to 80 mm. Tungsten carbide is used for its abrasive resistance. Abrasive particles during mixing try to enter the jet, but they are reflected away due to interplay of buoyancy and drag force. They go on interacting with the jet and the inner walls of the mixing tube, until they are accelerated using the momentum of the water jet.

Mixing process may be mathematically modelled as follows. Taking into account the energy loss during water jet formation at the orifice, the water jet velocity may be given as,

$$v_{wj} = \Psi \sqrt{\frac{2 p_w}{\rho_w}} \quad \text{.................. (1)}$$

where,

Ψ = Velocity coefficient of the orifice

The volume flow rate of water may be expressed as

$$\dot{q}_w = \phi \times v_{wj} \times A_{orifice}$$

$$\dot{q}_w = \phi \times v_{wj} \times \frac{\Pi}{4} d_o^{\,2}$$

$$\dot{q}_w = \phi \times \frac{\Pi}{4} d_o^{\,2} \times \Psi \sqrt{\frac{2\,p_w}{\rho_w}}$$

$$\dot{q}_w = c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2\,p_w}{\rho_w}}$$

where,

ϕ = Coefficient of "vena-contracta"
c_d = Discharge coefficient of the orifice

Thus, the total power of the water jet can be given as

$$P_{wj} = p_w \times q_w$$

$$P_{wj} = p_w \times c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2\,p_w}{\rho_w}}$$

$$P_{wj} = c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2\,p_w^{\,3}}{\rho_w}}$$

During mixing process as has been discussed both momentum and energy are not conserved due to losses that occur during mixing. But initially it would be assumed that no losses take place in momentum, i.e., momentum of the jet before and after mixing is conserved.

$$\sum\left(\dot{m}\,v\right)_{before} = \sum\left(\dot{m}\,v\right)_{after}$$

$$\left(\dot{m}_{air}\,v_{air} + \dot{m}_w\,v_{wj} + \dot{m}_{abr}\,v_{abr}\right)_{before} = \left(\dot{m}_{air}\,v_{air} + \dot{m}_w\,v_{wj} + \dot{m}_{abr}\,v_{abr}\right)_{after}$$

The momentum of air before and after mixing will be neglected due to very low density. Further, it is assumed that after mixing both water and abrasive phases attain the same velocity of v_{wj}. Moreover, when the abrasive particles are fed into the water jet through the port of the mixing chamber, their velocity is also very low and their momentum can be neglected.

$$\therefore \dot{m}_w v_{wj} = \left(\dot{m}_w + \dot{m}_{abr}\right) v_{awj}$$

$$v_{awj} = \frac{\dot{m}_w}{\left(\dot{m}_w + \dot{m}_{abr}\right)} v_{wj}$$

$$v_{awj} = \frac{1}{\left(1 + R\right)} v_{wj}$$

where,

$$R = \text{loading factor} = \frac{\dot{m}_{abr}}{\dot{m}_w}$$

As during mixing process momentum loss occurs as the abrasives collide with the water jet and at the inner wall of the focussing tube multiple times before being entrained, velocity of abrasive water jet is given as,

$$v_{awj} = \eta \frac{1}{\left(1 + R\right)} v_{wj}$$

where, η = momentum loss factor.

Suspension Jet

In entrained AWJM, the abrasive water jet, which finally comes from the focussing tube or nozzle, can be used to machine different materials.

In suspension AWJM the abrasive water jet is formed quite differently. There are three different types of suspension AWJ formed by direct, indirect and Bypass pumping method as already given in Table. 2. Fig. 8 shows the working principle of indirect and Bypass pumping system of suspension AWJM system.

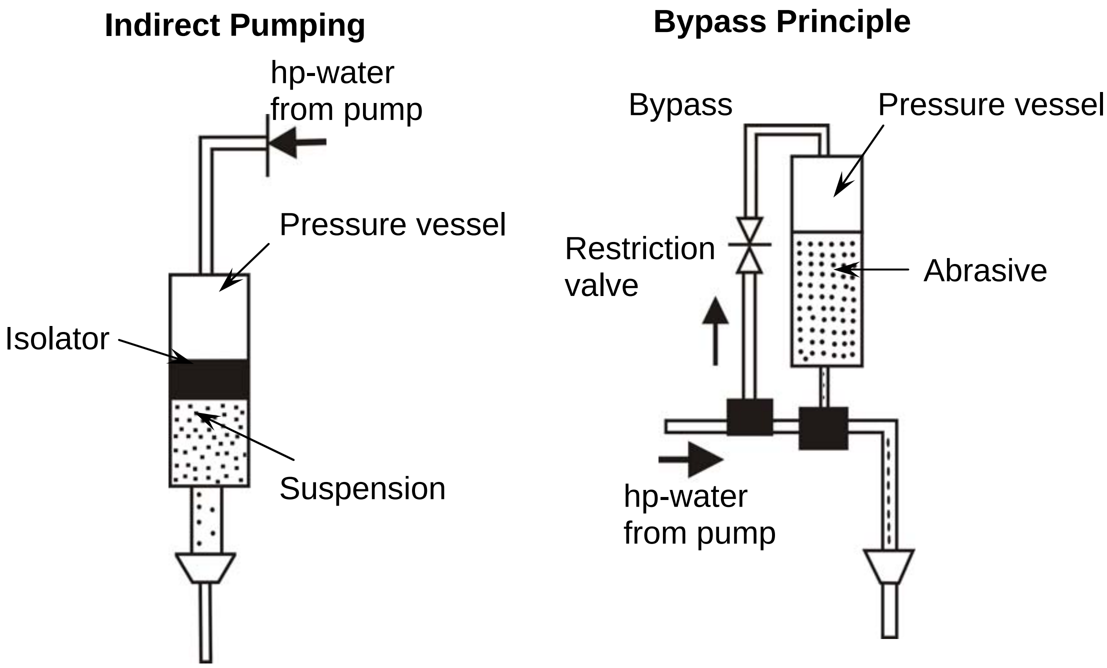
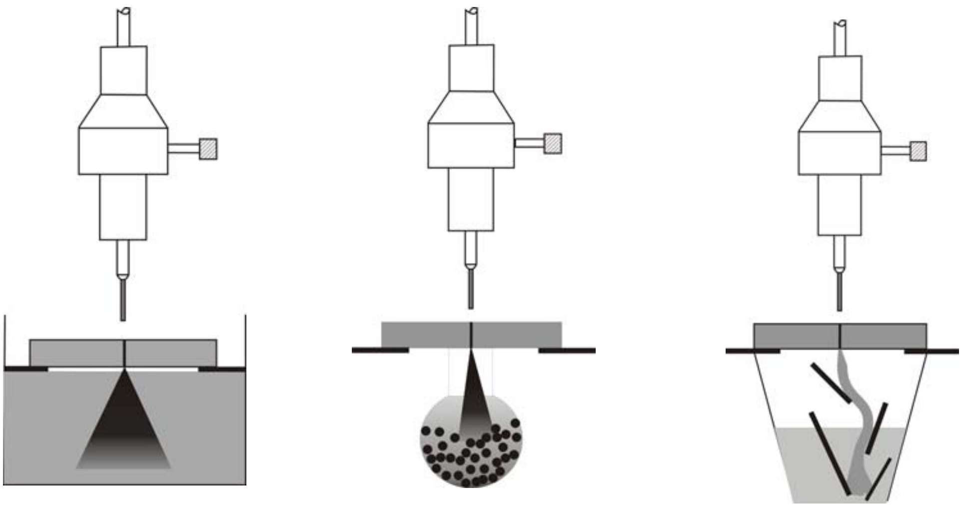


Fig. 8
Schematic of AWJM (Suspension type)

In suspension AWJM, preformed mixture of water and abrasive particles is pumped to a sufficiently high pressure and store in pressure vessel. Then the premixed high-pressure water and abrasive is allowed to discharge from a nozzle to form abrasive water jet.

Catcher

Once the abrasive jet has been used for machining, they may have sufficiently high level of energy depending on the type of application. Such high-energy abrasive water jet needs to be contained before they can damage any part of the machine or operators. "Catcher" is used to absorb the residual energy of the AWJ and dissipate the same. Fig. 9 shows three different types of catcher – water basin type, submerged steel balls and TiB_2 plate type.



(a) water basin (b) steel/WC/ceramic balls (c) catcher plates (TiB_2)

Fig. 9 *Some typical catchers*

Moreover the catcher can be of pocket type or line type. In pocket type, the catcher basin travels along the jet. In line type, the catcher basin only travels along one axis of the CNC table and its length covers the width of the other axis of the CNC table.

Mechanism of material removal

The general domain of parameters in entrained type AWJ machining system is given below:

- Orifice – Sapphires – 0.1 to 0.3 mm
- Focussing Tube – WC – 0.8 to 2.4 mm
- Pressure – 2500 to 4000 bar
- Abrasive – garnet and olivine - #125 to #60
- Abrasive flow - 0.1 to 1.0 Kg/min
- Stand off distance – 1 to 2 mm
- Machine Impact Angle – 60^{o} to 90^{0}
- Traverse Speed – 100 mm/min to 5 m/min
- Depth of Cut – 1 mm to 250 mm

Mechanism of material removal in machining with water jet and abrasive water jet is rather complex. In AWJM of ductile materials, material is mainly removed by low angle impact by abrasive particles leading to ploughing and micro cutting. Such process has been studied in detail initially by Finnie[1] as available in the edited volume by Engels[1]. Further at higher angle of impact, the material removal involves plastic failure of the material at the sight of impact, which was studied initially by Bitter[2,3]. Hashish[4] unified such models as applicable under AWJM at a later stage. In case of AWJM of brittle materials, other than the above two models, material would be removed due to crack initiation and propagation because of brittle failure of the material. Kim et al [5] have studied this in detail in the context of AWJM.

In water jet machining, the material removal rate may be assumed to be proportional to the power of the water jet.

$$MRR \propto P_{wj} \propto c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2 p_w^{\,3}}{\rho_w}}$$

$$MRR = u \times c_d \times \frac{\Pi}{4} d_o^{\,2} \times \sqrt{\frac{2 p_w^{\,3}}{\rho_w}}$$

The proportionality constant *u* is the specific energy requirement and would be a property of the work material.

Fig. 10, Fig. 11, Fig. 12 and Fig. 13 show the cut generated by an AWJM in different sections. It is called a kerf.

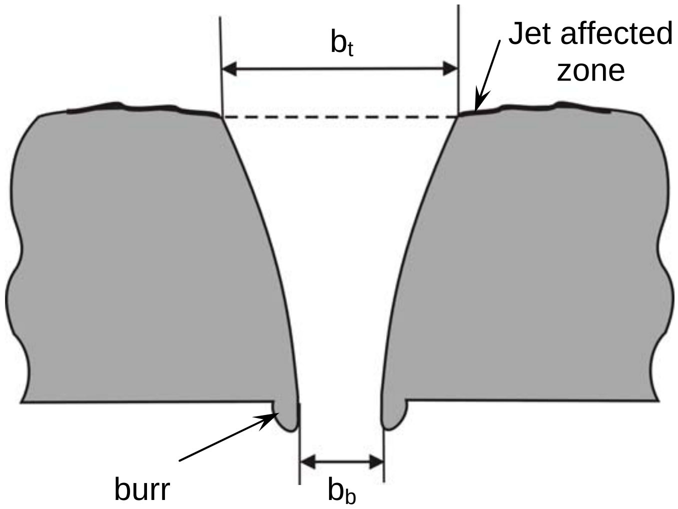


Fig. 10 *Schematic of AWJM kerf*

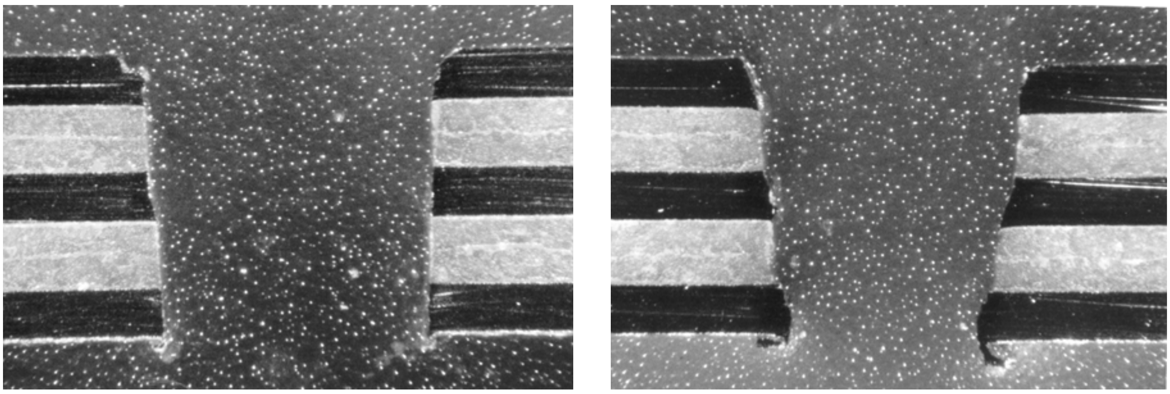


Fig. 11 *Photographic view of kerf (cross section)*

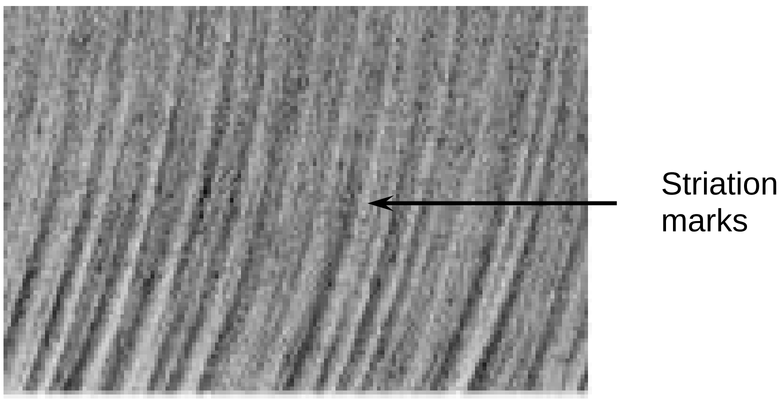


Fig. 12 *Photographic view of kerf (longitudinal section)*

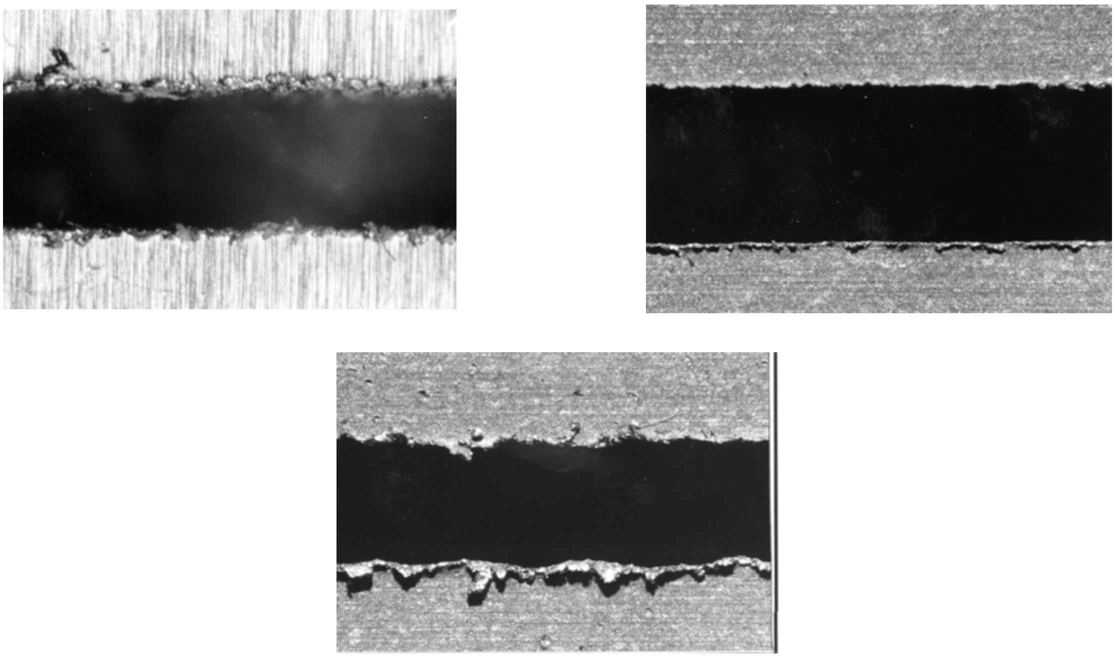


Fig. 13 *Photographic view of the kerf (back side)*

The top of the kerf is wider than the bottom of the kerf. Generally the top width of the kerf is equal to the diameter of the AWJ. Once again, diameter of the AWJ is equal to the diameter of the focussing tube or the insert if the stand-off distance is around 1 to 5mm. The taper angle of the kerf can be reduced by increasing the cutting ability of the AWJ. Fig. 12 shows the longitudinal section of the kerf. It may be observed that the surface quality at the top of the kerf is rather good compared to the bottom part. At the bottom there is repeated curved line formation. At the top of the kerf, the material removal is by low angle impact of the abrasive particle; where as at the bottom of the kerf it is by plastic failure. Striation formation occurs due to repeated plastic failure.

Fig. 13 shows the exit side of the kerf. Though all three of them were machined with the same AWJ diameter, their widths are different due to tapering of the kerf. Further, severe burr formation can be observed at the exit side of the kerf.

Thus, in WJM and AWJM the following are the important product quality parameters.

- striation formation
- surface finish of the kerf
- tapering of the kerf
- burr formation on the exit side of the kerf

Models proposed by Finnie, Bitter, Hashish and Kim though are very comprehensive and provide insight into the mechanism of material removal, require substantial information on different aspects and parameters which may not be readily available.

Thus a more workable, simple but reliable model for predicting depth of penetration as proposed by the group working in TU Delft, the Netherlands is being presented here.

The power of the abrasive phase of the abrasive water jet can be estimated as,

$$P_{abr} = \frac{1}{2}\dot{m}_{abr}\, v_{awj}^2$$

$$P_{abr} = \frac{1}{2}\dot{m}_{abr}\left\{\eta \frac{1}{\left(1+R\right)} v_{wj}\right\}^2$$

$$P_{abr} = \frac{1}{2}\dot{m}_{w}\, R\left\{\eta \frac{1}{\left(1+R\right)} v_{wj}\right\}^2$$

$$P_{abr} = \frac{1}{2}c_d \times \frac{\Pi}{4} d_o^{\ 2} \rho_w v_{wj} R\eta^2 \left(\frac{1}{1+R}\right)^2 v_{wj}^2$$

$$P_{abr} = c_d \times \frac{\Pi}{8} d_o^{\ 2} \rho_w R\eta^2 \left(\frac{1}{1+R}\right)^2 v_{wj}^3$$

$$P_{abr} = c_d \times \frac{\Pi}{8} d_o^{\ 2} \rho_w R\eta^2 \left(\frac{1}{1+R}\right)^2 \left(\frac{2p_w}{\rho_w}\right)^{3/2}$$

$$P_{abr} = c_d \times \frac{\sqrt{2}\Pi}{4} d_o^{\ 2} R\eta^2 \left(\frac{1}{1+R}\right)^2 \frac{p_w^{3/2}}{\rho_w^{1/2}}$$

$$P_{abr} = c_d \times \frac{\Pi}{4} d_o^{\ 2} R\left(\frac{\eta}{1+R}\right)^2 p_w^{3/2}\sqrt{\frac{2}{\rho_w}}$$

Thus it may be assumed that the material removal rate is proportional to the power of abrasive phase of AWJ. The water phase does not contribute to material removal in AWJM.

$$MRR = \dot{Q} = \frac{P_{abr}}{u_{job}}$$

where,

u_{job} = specific energy requirement in machining a material in AWJM

Now

$MRR = h_t w v_f$

Where,

h_t = depth of penetration

w = width of the kerf
= $(w_{top} + w_{bottom}) / 2$
$\approx d_i$, the diameter of the focussing tube or nozzle or the insert

v_f = traverse speed of the AWJ or cutting speed

Therefore,

$MRR = h_t d_i v_f$

$$\therefore h_t = c_d \times \frac{\Pi}{4} d_o^{\,2} R \left(\frac{\eta}{1+R} \right)^2 \frac{p_w^{3/2}}{u_{job} d_i v_f} \sqrt{\frac{2}{\rho_w}}$$

Generally,

$$MRR = \xi \frac{P_{abr}}{u_{job}}$$

where, ξ is a coefficient, which takes into account several factors like sharpness or dullness of the abrasive, friability of the abrasives, stand-off distance, process inhomogenities etc

Therefore,

$$\therefore h_t = \xi c_d \times \frac{\Pi}{4} d_o^{\,2} R \left(\frac{\eta}{1+R} \right)^2 \frac{p_w^{3/2}}{u_{job} d_i v_f} \sqrt{\frac{2}{\rho_w}}$$

Now the manufacturing strategy should be selected in such a way so that maximization of h_t takes place.

$R = \frac{\dot{m}_{abr}}{m_w}$, is the loading parameter .

Optimal loading ratio is required to be determined by differentiating with respect to the loading ratio, *R*

$$h_t = \overline{K}\frac{R^2}{(1+R)^2}$$

Where, $\overline{K}$ is the constant.

$$\frac{\partial h_t}{\partial R} = \overline{K}(1+R)^2 - 2R - 2(1+R).R^2 = 0$$

$$(1+R) - 2R = 0$$

$$1 - R = 0 \Rightarrow R = 1$$

Thus, theoretically maximum depth of penetration occurs at R = 1. The variation in h_t with R is shown in Fig. 14.However, in practice maximum h_t is obtained at R = 0.5 to 0.6 for all other parameters remaining same. Fig. 15 also provides some indications to increase depth of cut.

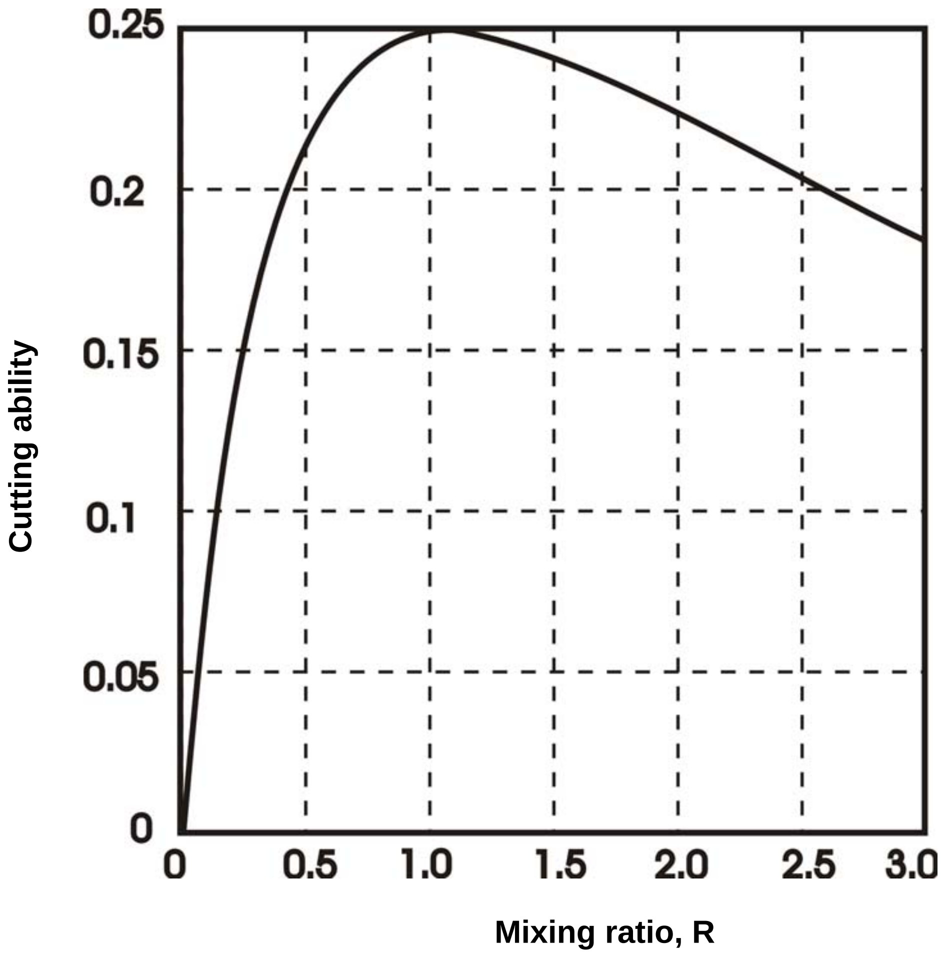


Fig. 14 *Variation in cutting ability of AWJM with mixing ratio*

Environmental issues and future

Nowadays, every manufacturing process is being re-evaluated in terms of its impact on the environment. For example, use of conventional coolants in machining and grinding is being looked upon critically from the point of view of its impact on environment. The environmental issues relevant to AWJM are,

- water recycling
- spent water disposal
- chip recovery
- abrasive recovery and reuse

Environmental issues and concerns have lead the researchers to use such mediums and abrasives that do not require disposal, recycling or lead to pollution. Work is going on in the area of high-pressure cryogenic jet machining (Fig. 16) where liquid nitrogen replaces the water phase and dry ice crystals (solid CO_2 crystals) replace the abrasive

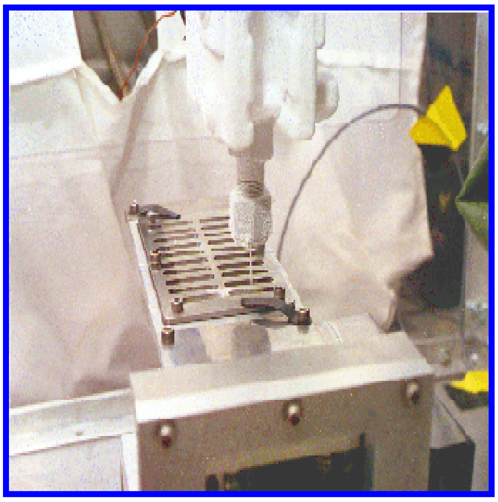


Fig. 15 *Cryogenic Abrasive Jet Machining*

phase leading to no need of disposal or waste generation. The removed work material in the form of microchips can be collected much easily reducing the chances of environmental degradation.

Problems

1. Assuming no losses, determine water jet velocity, when the water pressure is 4000 bar, being issued from an orifice of diameter 0.3 mm

Ans:
$$v_w = \sqrt{\frac{2p}{\rho_w}} = \sqrt{\frac{2x4000x10^5}{1000}} = 894m/s$$

2. Determine the mass flow rate of water for the given problem assuming all related coefficients to be 1.

Ans:
$$m_w = \rho_w.Q_w = \rho_w \frac{\pi}{4} d_o^2 v_w$$
$$= 1000x\frac{\pi}{4}x(0.3x10^{-3})^2 x894$$
$$= 0.0631 \quad kg/s$$
$$= 0.0631x60 = 3.79 \quad kg/\min$$

3. If the mass flow rate of abrasive is 1 kg/min, determine the abrasive water jet velocity assuming no loss during mixing process using the above data (data of Question. 1, 2 and 3)

Ans:

$$v_{awj} = \left(\frac{1}{1+R}\right)v_{wj} = \left(\frac{1}{1+\frac{m_{abr}}{m_w}}\right)v_{wj} = \left(\frac{1}{1+\frac{1}{3.79}}\right)x894 = 707m/s$$

4. Determine depth of penetration, if a steel plate is AWJ machined at a traverse speed of 300 mm/min with an insert diameter of 1 mm. The specific energy of steel is 13.6 J/mm^3.

Ans:

$$h_t = \frac{\pi}{4} d_o^2 R\left(\frac{1}{1+R}\right)^2 \frac{p^{3/2}}{u_{job} d_i V_f} \sqrt{\frac{2}{\rho_w}}$$

$$h_t = \frac{\pi}{4}(0.3x10^{-3})^2 \frac{1}{3.8}\left(\frac{1}{1+\frac{1}{3.8}}\right)^2 \frac{\left(4000x10^5\right)^{3/2}}{13.6x10^9 x1x10^{-3} x\frac{300}{60}x10^{-3}} \sqrt{\frac{2}{1000}}$$

$$h_t = 77.6 \quad mm$$

Quiz Questions

1. WJM cannot be used to machine

   (a) frozen food
   (b) plywood
   (c) leather
   (d) steel plates ANSWER (d)

2. In AWJM mixing process takes place in

   (a) intensifier
   (b) catcher
   (c) mixing chamber
   (d) orifice ANSWER (c)

3. Abrasive water jet velocity increases with (keeping all other parameters unchanged)

   (a) increasing traverse velocity of the job
   (b) decreasing mass flow rate of abrasive
   (c) decreasing traverse velocity of the job
   (d) increasing mass flow rate of abrasive

   ANSWER (b)

4. In an environment friendly development concerning AWJM, the following is used as abrasive

   (a) dry ice
   (b) cubic boron nitrite
   (c) diamond
   (d) tungsten carbide ANSWER (a)

Test Items

1. List different modules of AWJM systems

Ans:

- LP booster pump
- Hydraulic unit
- Additive Mixer
- Intensifier
- Accumulator
- Flexible high pressure transmission line
- On-off valve
- Orifice
- Mixing Chamber
- Focussing tube or inserts
- Catcher

- CNC table
- Abrasive metering device
- Catcher

2. List different WJM and AWJM systems

Ans:

- WJM - Pure
- WJM - with stabilizer
- AWJM – entrained – three phase – abrasive, water and air
- AWJM – suspended – two phase – abrasive and water
  - Direct pumping
  - Indirect pumping
  - Bypass pumping

3. Identify the limitations of AWJM from environmental issues

Ans:

- water recycling
- spent water disposal
- chip recovery
- abrasive recovery and reuse

4. List quality parameters associated with AWJM

Ans:

- striation formation
- surface finish of the kerf
- tapering of the kerf
- burr formation on the exit side of the kerf

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Module
9
Non conventional Machining

Lesson
38
Electro Chemical Machining

Instructional Objectives

(i) Identify electro-chemical machining (ECM) as a particular type of non-tradition processes
(ii) Describe the basic working principle of ECM process
(iii) Draw schematically the basics of ECM
(iv) Draw the tool potential drop
(v) Describe material removal mechanism in ECM
(vi) Identify the process parameters in ECM
(vii) Develop models for material removal rate in ECM
(viii) Analyse the dynamics of ECM process
(ix) Identify different modules of ECM equipment
(x) List four application of ECM
(xi) Draw schematics of four such ECM applications

1. Introduction

Electrochemical Machining (ECM) is a non-traditional machining (NTM) process belonging to Electrochemical category. ECM is opposite of electrochemical or galvanic coating or deposition process. Thus ECM can be thought of a controlled anodic dissolution at atomic level of the work piece that is electrically conductive by a shaped tool due to flow of high current at relatively low potential difference through an electrolyte which is quite often water based neutral salt solution.
Fig. 1 schematically shows the basic principle of ECM.

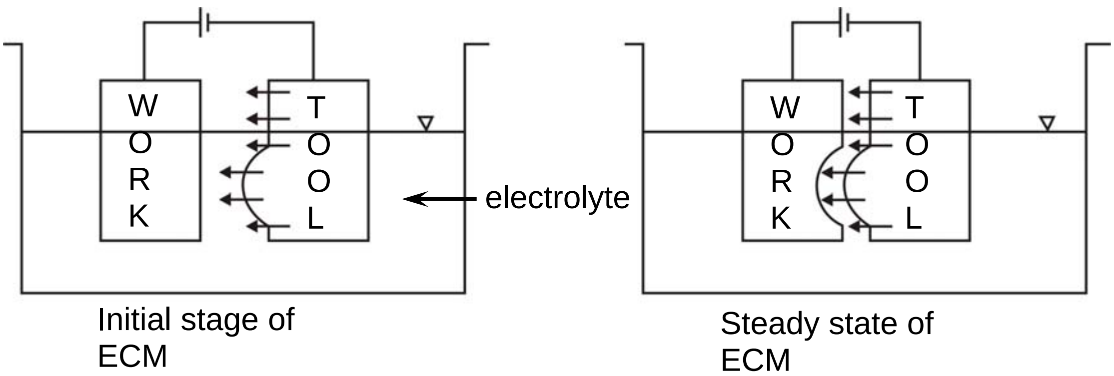


Fig. 1 *Schematic principle of Electro Chemical Machining (ECM)*

2. Process

During ECM, there will be reactions occurring at the electrodes i.e. at the anode or workpiece and at the cathode or the tool along with within the electrolyte.
Let us take an example of machining of low carbon steel which is primarily a ferrous alloy mainly containing iron. For electrochemical machining of steel, generally a neutral salt solution of sodium chloride (NaCl) is taken as the electrolyte. The electrolyte and water undergoes ionic dissociation as shown below as potential difference is applied

$$NaCl \leftrightarrow Na^+ + Cl^-$$
$$H_2O \leftrightarrow H^+ + (OH)^-$$

As the potential difference is applied between the work piece (anode) and the tool (cathode), the positive ions move towards the tool and negative ions move towards the workpiece.
Thus the hydrogen ions will take away electrons from the cathode (tool) and from hydrogen gas as:

$$2H^+ + 2e^- = H_2\uparrow \text{ at cathode}$$

Similarly, the iron atoms will come out of the anode (work piece) as:

$$Fe = Fe^{++} + 2e^-$$

Within the electrolyte iron ions would combine with chloride ions to form iron chloride and similarly sodium ions would combine with hydroxyl ions to form sodium hydroxide

$$Na^+ + OH^- = NaOH$$

In practice $FeCl_2$ and $Fe(OH)_2$ would form and get precipitated in the form of sludge. In this manner it can be noted that the work piece gets gradually machined and gets precipitated as the sludge. Moreover there is not coating on the tool, only hydrogen gas evolves at the tool or cathode. Fig. 2 depicts the electro-chemical reactions schematically. As the material removal takes place due to atomic level dissociation, the machined surface is of excellent surface finish and stress free.

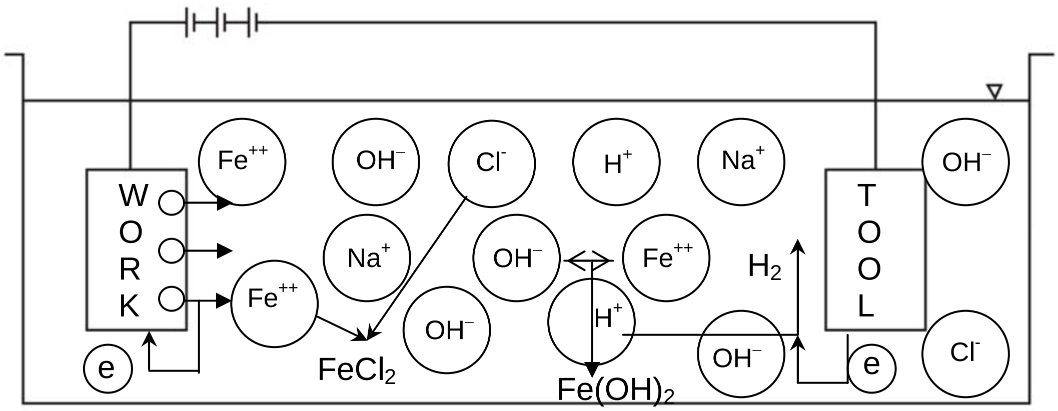


Fig. 2 *Schematic representation of electro-chemical reactions*

The voltage is required to be applied for the electrochemical reaction to proceed at a steady state. That voltage or potential difference is around 2 to 30 V. The applied potential difference, however, also overcomes the following resistances or potential drops. They are:

- The electrode potential
- The activation over potential
- Ohmic potential drop
- Concentration over potential
- Ohmic resistance of electrolyte

Fig. 3 shows the total potential drop in ECM cell.

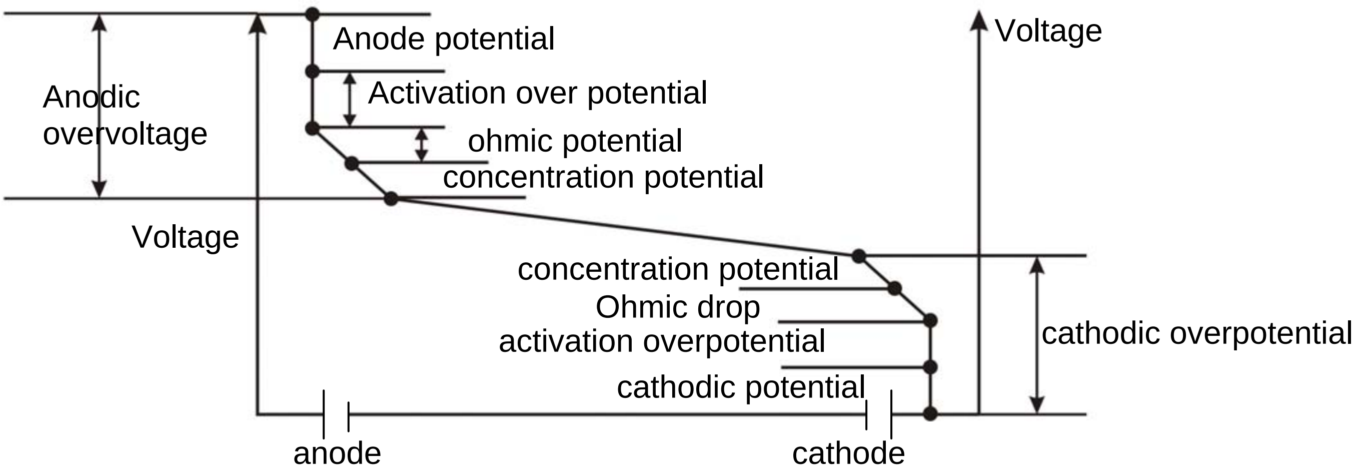


Fig. 3 *Total potential drop in ECM cell*

3. Equipment

The electrochemical machining system has the following modules:

- Power supply
- Electrolyte filtration and delivery system
- Tool feed system
- Working tank

Fig. 4 schematically shows an electrochemical drilling unit.

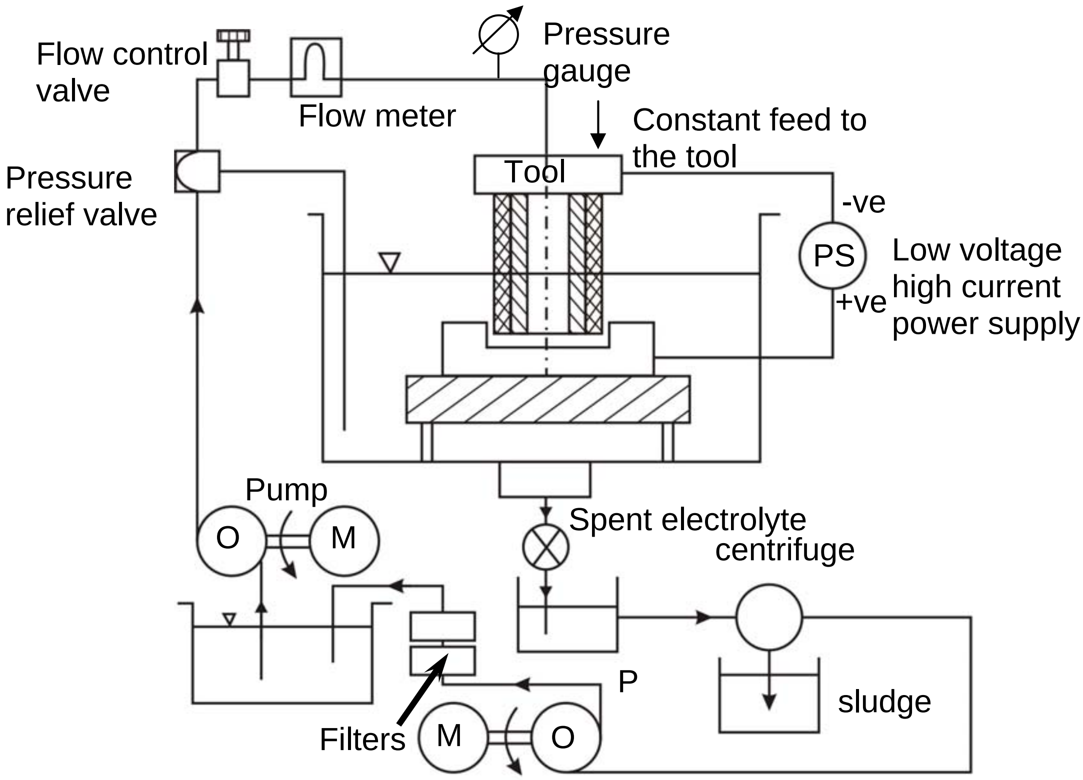


Fig. 4 *Schematic diagram of an electrochemical drilling unit*

4. Modelling of material removal rate

Material removal rate (MRR) is an important characteristic to evaluate efficiency of a non-traditional machining process.

In ECM, material removal takes place due to atomic dissolution of work material. Electrochemical dissolution is governed by Faraday's laws.

The first law states that the amount of electrochemical dissolution or deposition is proportional to amount of charge passed through the electrochemical cell, which may be expressed as:

$$m \propto Q,$$

where m = mass of material dissolved or deposited

Q = amount of charge passed

The second law states that the amount of material deposited or dissolved further depends on Electrochemical Equivalence (ECE) of the material that is again the ratio of the atomic weight and valency. Thus

$$m \ \alpha \ ECE \ \alpha \ \frac{A}{\nu}$$

Thus $m \ \alpha \ \frac{QA}{\nu}$

where F = Faraday's constant

= 96500 coulombs

$$\therefore \quad m = \frac{ItA}{F\nu}$$

$$\therefore \quad MRR = \frac{m}{t\rho} = \frac{IA}{F\rho\nu}$$

where I = current

ρ= density of the material

The engineering materials are quite often alloys rather than element consisting of different elements in a given proportion.

Let us assume there are 'n' elements in an alloy. The atomic weights are given as A_1, A_2, ………….., A_n with valency during electrochemical dissolution as ν_1, ν_2, …………, ν_n. The weight percentages of different elements are α_1, α_2, ………….., α_n (in decimal fraction)

Now for passing a current of I for a time t, the mass of material dissolved for any element 'i' is given by

$$m_i = \Gamma_a \rho \alpha_i$$

where Γ_a is the total volume of alloy dissolved. Each element present in the alloy takes a certain amount of charge to dissolve.

$$m_i = \frac{Q_i A_i}{F\nu_i}$$

$$\Rightarrow Q_i = \frac{F m_i \nu_i}{A_i}$$

$$\Rightarrow Q_i = \frac{F\Gamma_a \rho \alpha_i \nu_i}{A_i}$$

The total charge passed

$$Q_T = It = \sum Q_i$$

$$\therefore \quad Q_T = It = F\Gamma_a \rho \sum \frac{\alpha_i \nu_i}{A_i}$$

Now

$$MRR = \frac{\Gamma_a}{t} = \frac{1}{F\rho} \cdot \frac{I}{\sum \frac{\alpha_i \nu_i}{A_i}}$$

5. Dynamics of Electrochemical Machining

ECM can be undertaken without any feed to the tool or with a feed to the tool so that a steady machining gap is maintained. Let us first analyse the dynamics with NO FEED to the tool. Fig. 5 schematically shows the machining (ECM) with no feed to the tool and an instantaneous gap between the tool and workpiece of ‘h’.

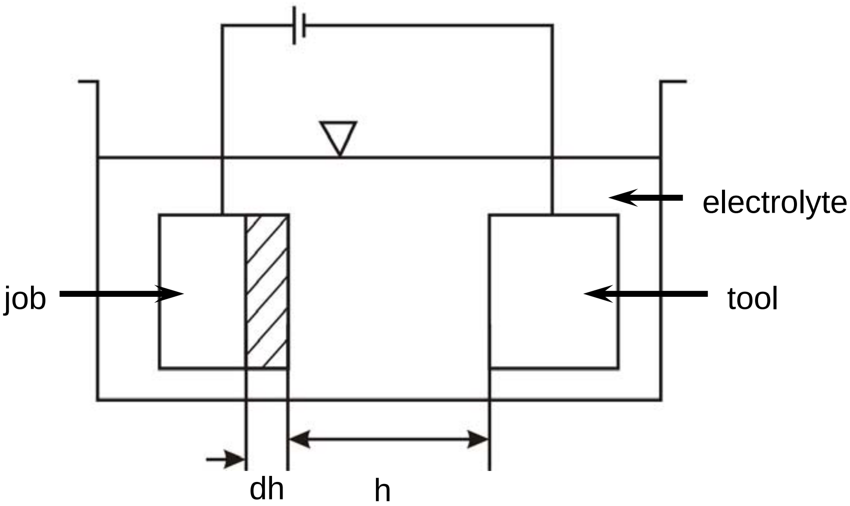


Fig. 5 *Schematic representation of the ECM process with no feed to the tool*

Now over a small time period ‘dt’ a current of I is passed through the electrolyte and that leads to a electrochemical dissolution of the material of amount ‘dh’ over an area of S

$$\therefore \quad I = \frac{V}{R} = \frac{V}{\frac{rh}{s}} = \frac{Vs}{rh}$$

then $\dfrac{dh}{dt} = \dfrac{1}{F} \cdot \dfrac{A_x}{\rho \nu_x}\left(\dfrac{Vs}{rh} \cdot \dfrac{1}{s}\right)$

$$= \frac{1}{F} \cdot \frac{A_x}{\rho \nu_x} \cdot \frac{V}{rh}$$

for a given potential difference and alloy

$$\frac{dh}{dt} = \frac{A_x V}{F \rho \nu_x r} \cdot \frac{1}{h} = \frac{c}{h}$$

where c = constant

$$= \frac{A_x V}{F \rho \nu_x r}$$

$$c = \frac{V}{F \rho r \sum \frac{\alpha_i \nu_i}{A_i}}$$

$$\therefore \quad \frac{dh}{dt} = \frac{c}{h}$$

$$hdh = cdt$$

At t = 0, h = h_o and at t = t_1 and h = h_1

$$\therefore \quad \int_{h_o}^{h_1} hdh = c \int_0^t dt$$

$$\therefore \quad h_1^2 - h_o^2 = 2ct$$

That is the tool – workpiece gap under zero feed condition grows gradually following a parabolic curve as shown in Fig. 6

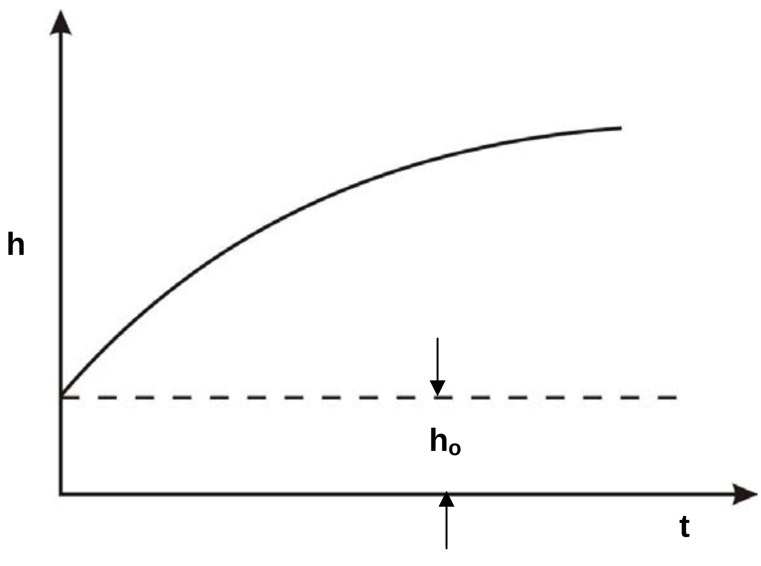


Fig. 6 Variation of tool-workpiece gap under zero feed condition

As $\frac{dh}{dt} = \frac{c}{h}$

Thus dissolution would gradually decrease with increase in gap as the potential drop across the electrolyte would increase

Now generally in ECM a feed (f) is given to the tool

$$\therefore \quad \frac{dh}{dt} = \frac{c}{h} - f$$

Now if the feed rate is high as compared to rate of dissolution, then after sometime the gap would diminish and may even lead to short circuiting. Under steady state condition the gap is uniform i.e. the approach of the tool is compensated by dissolution of the work material. Thus with respect to the tool, the workpiece is not moving

Thus $\frac{dh}{dt} = 0 = \frac{c}{h} = f$

$$\therefore \quad f = \frac{c}{h}$$

or h* = steady state gap = c/f

Now under practical ECM condition it is not possible to set exactly the value of h* as the initial gap. Thus it is required to be analysed if the initial gap value would have any effect on progress of the process

Now $\frac{dh}{dt} = \frac{c}{h} - f$

Now $h' = \frac{h}{h^*} = \frac{hf}{c}$

And $t' = \frac{ft}{h^*} = \frac{f^2 t}{c}$

$$\therefore \quad \frac{dh'}{dt'} = \frac{f/c}{f^2/c}.\frac{dh}{dt} = \frac{1}{f}.\frac{dh}{dt}$$

Thus $\frac{dh}{dt} = \frac{c}{h} - f$

$$\Rightarrow \quad f\frac{dh'}{dt'} = \frac{c}{h'h^*} - f = \frac{cf}{h'c} - f$$

$$\Rightarrow \quad f\frac{dh'}{dt'} = f\left(\frac{1-h'}{h'}\right)$$

$$\Rightarrow \quad \frac{dh'}{dt'} = \frac{1-h'}{h'}$$

$$\therefore \quad dt' = \frac{h'}{1-h'}dh'$$

Now integrating between t' = 0 to t' = t' when h' changes from h_o' to h_1'

$$\therefore \quad \int_0^{t'} dt' = \int_{h_o'}^{h_1'} \frac{h'}{1-h'}dh'$$

$$\therefore \quad t' = \int_{h_o'}^{h_1'} -\frac{d(1-h')}{(1-h')} + \int_{h_o'}^{h_1'} d(1-h')$$

$$t' = h_o' - h_1' + \ln\frac{h_o' - 1}{h_1' - 1}$$

now for different value of h_o', h_1' seems to approach 1 as shown in Fig. 7

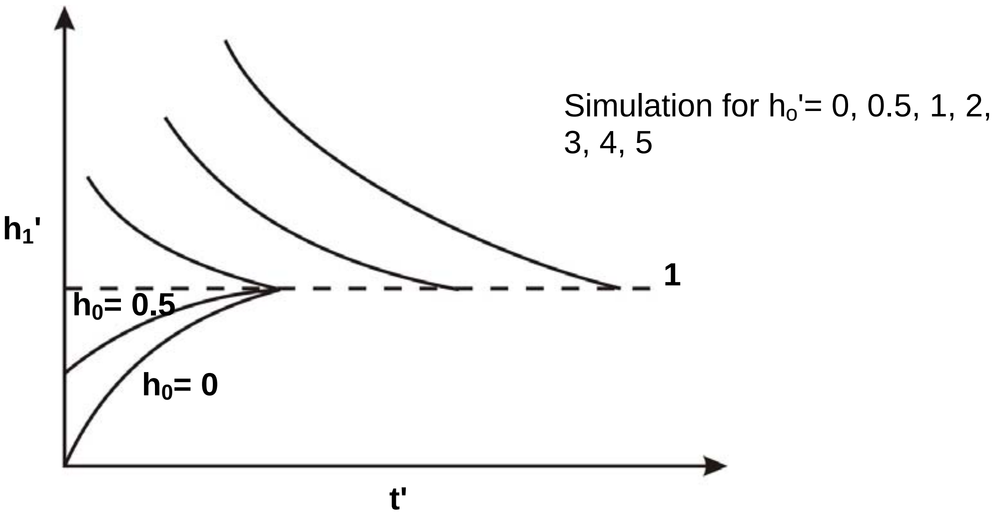


Fig. 7 *Variation in steady state gap with time for different initial gap*

Thus irrespective of initial gap

$$h' = \frac{h}{h^*} = 1 \qquad \Rightarrow \frac{fh}{c} = 1$$

$$\therefore \quad h = \frac{c}{f}$$

or $$f = \frac{c}{h} = \frac{A_x V}{F\rho v_x r} \cdot \frac{1}{h}$$

$$\therefore \quad f = \frac{A_x}{F\rho v_x} \cdot \frac{V}{rh} = \frac{A_x}{F\rho v_x} \cdot \frac{i}{s}$$

$$\therefore \quad f = \frac{A_x}{F\rho v_x} \cdot \frac{I}{s} = MRR \text{ in } mm/s$$

Thus it seems from the above equation that ECM is self regulating as MRR is equal to feed rate.

6. Applications

ECM technique removes material by atomic level dissolution of the same by electrochemical action. Thus the material removal rate or machining is not dependent on the mechanical or physical properties of the work material. It only depends on the atomic weight and valency of the work material and the condition that it should be electrically conductive. Thus ECM can machine any electrically conductive work material irrespective of their hardness, strength or even thermal properties. Moreover

as ECM leads to atomic level dissolution, the surface finish is excellent with almost stress free machined surface and without any thermal damage.
ECM is used for

- Die sinking
- Profiling and contouring
- Trepanning
- Grinding
- Drilling
- Micro-machining

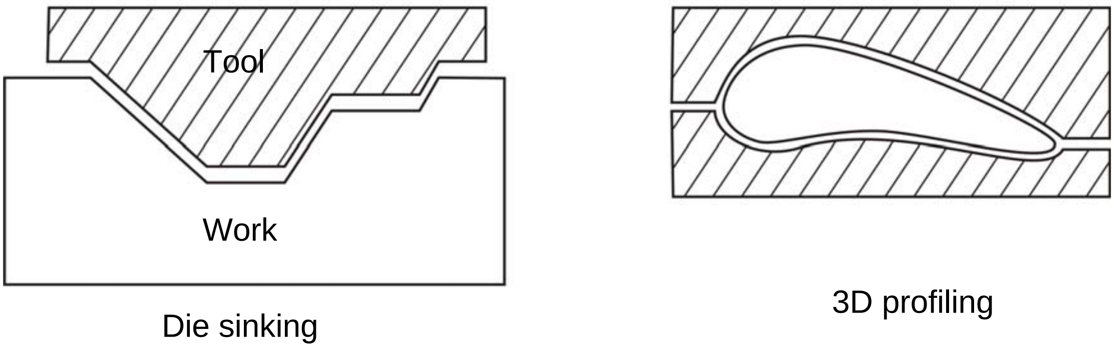
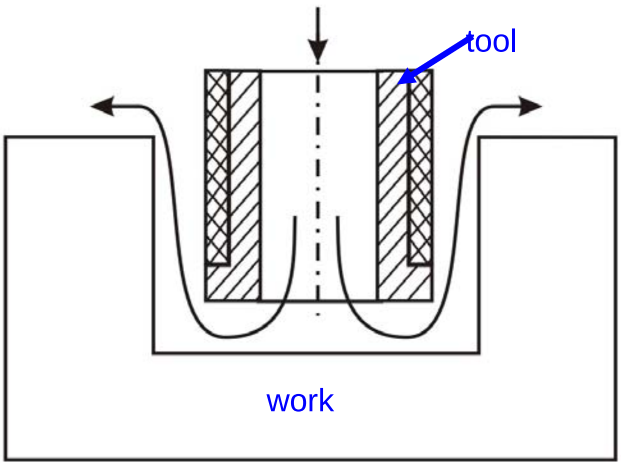


Fig. 8 *Different applications of Electro Chemical Machining*



(drilling)

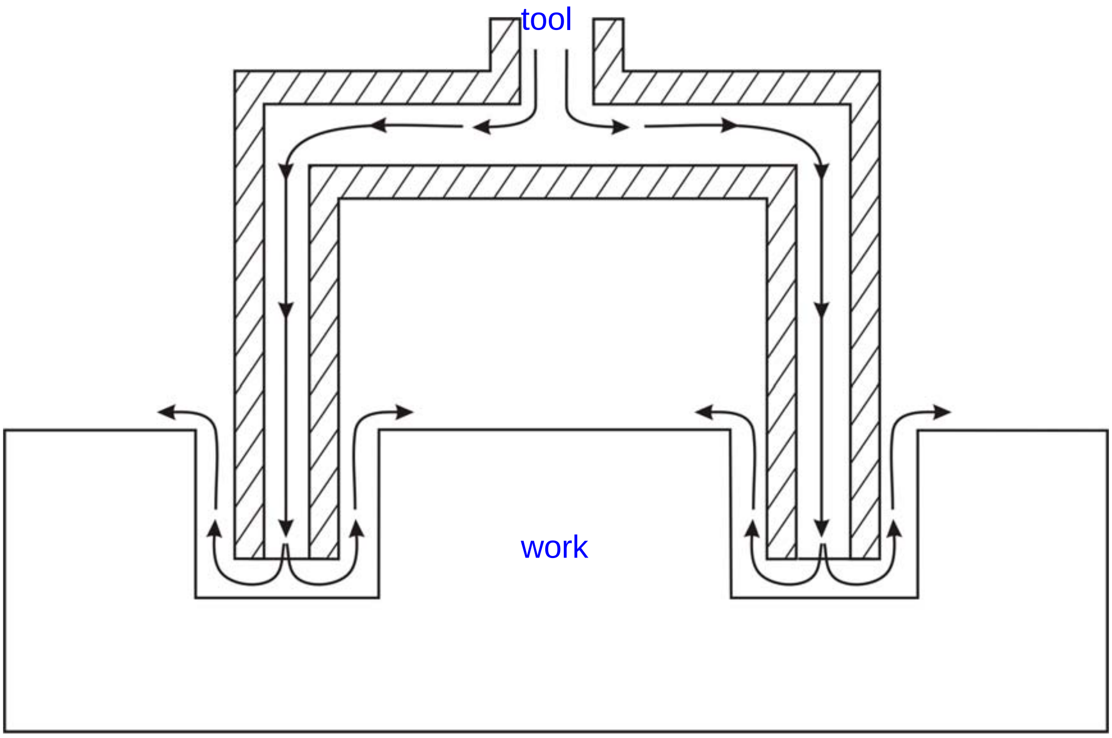


Fig. 9 *Drilling and Trepanning by ECM*

7. Process Parameters

Power Supply	
Type	direct current
Voltage	2 to 35 V
Current	50 to 40,000 A
Current density	0.1 A/mm^2 to 5 A/mm^2
Electrolyte	
Material	NaCl and $NaNO_3$
Temperature	20^{o}C – 50^{o}C
Flow rate	20 lpm per 100 A current
Pressure	0.5 to 20 bar
Dilution	100 g/l to 500 g/l
Working gap	0.1 mm to 2 mm
Overcut	0.2 mm to 3 mm
Feed rate	0.5 mm/min to 15 mm/min
Electrode material	Copper, brass, bronze
Surface roughness, R_a	0.2 to 1.5 μm

Quiz Test

1. For ECM of steel which is used as the electrolyte
   (a) kerosene
   (b) NaCl
   (c) Deionised water
   (d) HNO_3

2. MRR in ECM depends on
   (a) Hardness of work material
   (b) atomic weight of work material
   (c) thermal conductivity of work material
   (d) ductility of work material

3. ECM cannot be undertaken for
   (a) steel
   (b) Nickel based superalloy
   (c) Al_2O_3
   (d) Titanium alloy

4. Commercial ECM is carried out at a combination of
   (a) low voltage high current
   (b) low current low voltage
   (c) high current high voltage
   (d) low current low voltage

Problems

1. In electrochemical machining of pure iron a material removal rate of 600 mm^3/min is required. Estimate current requirement.
2. Composition of a Nickel superalloy is as follows:

   Ni = 70.0%, Cr = 20.0%, Fe = 5.0% and rest Titanium

   Calculate rate of dissolution if the area of the tool is 1500 mm^2 and a current of 2000 A is being passed through the cell. Assume dissolution to take place at lowest valency of the elements.

$A_{Ni} = 58.71$	$\rho_{Ni} = 8.9$	$\nu_{Ni} = 2$
$A_{Cr} = 51.99$	$\rho_{Cr} = 7.19$	$\nu_{Cr} = 2$
$A_{Fe} = 55.85$	$\rho_{Fe} = 7.86$	$\nu_{Fe} = 2$
$A_{Ti} = 47.9$	$\rho_{Ti} = 4.51$	$\nu_{Ti} = 3$

3. In ECM operation of pure iron an equilibrium gap of 2 mm is to be kept. Determine supply voltage, if the total overvoltage is 2.5 V. The resistivity of the electrolyte is 50 Ω-mm and the set feed rate is 0.25 mm/min.

Answers

Answers to Quiz Test

1 – (b)
2 – (b)
3 – (c)
4 – (a)

Solution to Prob. 1

$$MRR = \dot{m} = \frac{m}{t} = \frac{AI}{F\nu}$$

$$\therefore \quad MRR = \dot{\Gamma} = \frac{m}{\rho t} = \frac{AI}{F\rho\nu}$$

MRR = 600 mm^3/min = 600/60 mm^3/s = 10 mm^3/s = $10x10^{-3}$cc/s

$$\therefore \quad 10x10^{-3} = \frac{56xI}{96500x7.8x2}$$

As A_{Fe} = 56
ν_{Fe} = 2
F = 96500 coulomb
ρ = 7.8 gm/cc

$$\therefore \quad I = \frac{96500x10x10^{-3}x7.8x2}{56}$$

I = 268.8 A **Answer**

Solution of Problem 2

$$\text{Now, } \rho_{alloy} = \frac{1}{\sum \frac{\alpha_i}{\rho_i}}$$

$$= \frac{1}{\frac{\alpha_{Ni}}{\rho_{Ni}} + \frac{\alpha_{Cr}}{\rho_{Cr}} + \frac{\alpha_{Fe}}{\rho_{Fe}} + \frac{\alpha_{Ti}}{\rho_{Ti}}}$$

$$= \frac{1}{\frac{0.7}{8.9} + \frac{0.2}{7.19} + \frac{0.05}{7.86} + \frac{0.05}{4.51}} = 8.07\ gm/cc$$

$$\text{Now } MRR = \frac{m}{\rho t} = \frac{I}{F\rho \sum \frac{\alpha_i \nu_i}{A_i}}$$

$$= \frac{1000}{96500x8.07x\left\{\frac{0.75x2}{58.71} + \frac{0.2x2}{51.99} + \frac{0.05x2}{55.85} + \frac{0.05x3}{47.9}\right\}}$$

= 0.0356 cc/sec
= 2.14 cc/min
= 2140 mm^3/min

$$\therefore \text{Rate of dissolution} = \frac{MRR}{Area} = \frac{2140}{1500} = 1.43\ mm/min$$ **answer**

Solution to Prob. 3

$$h^* = \frac{c}{f}$$

where $c = \frac{VA_{Fe}}{F\rho_{Fe} r \nu_{Fe}}$

$$C = \frac{(V-2.5)x55.85}{96500x7.8x10^{-3}x50x2}$$

$$= \frac{(V-2.5)}{1347.7}$$

$$h^* = 2 = \frac{c}{f} = \frac{(V-2.5)}{1347x\frac{0.25}{60}}$$

$$2 = \frac{V-2.5}{5.615}$$

$\therefore \quad V = 8.73$ Volt. **Answer**

Module
9
Non conventional Machining

Lesson
39

Electro Discharge Machining

Instructional Objectives

(i) Identify electro-discharge machining (EDM) as a particular type of non-tradition processes
(ii) Describe the basic working principle of EDM process
(iii) Draw schematically the basics of EDM
(iv) Describe spark initiation in EDM
(v) Describe material removal mechanism in EDM
(vi) Draw the basic electrical waveform used in EDM
(vii) Identify the process parameters in EDM
(viii) Describe the characteristics of EDM
(ix) Identify the purpose of dielectric fluid in EDM
(x) List two common dielectric fluid
(xi) Analyse the required properties of EDM tool
(xii) List four common tool material for EDM
(xiii) Develop models for material removal rate in EDM
(xiv) Identify the machining characteristics in EDM
(xv) Analyse the effect of process variables on surface roughness
(xvi) Analyse taper cut and over cut in EDM
(xvii) Identify different modules of EDM system
(xviii) Draw schematic representation of different electrical generators used in EDM
(xix) Analyse working principle of RC type EDM generator

1. Introduction

Electro Discharge Machining (EDM) is an electro-thermal non-traditional machining process, where electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark.

EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. EDM can be used to machine difficult geometries in small batches or even on job-shop basis. Work material to be machined by EDM has to be electrically conductive.

2. Process

Fig. 1 shows schematically the basic working principle of EDM process.

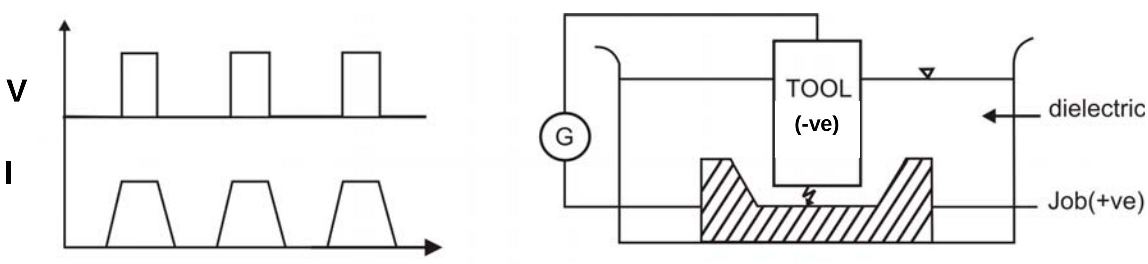


Fig. 1 *Schematic representation of the basic working principle of EDM process.*

In EDM, a potential difference is applied between the tool and workpiece. Both the tool and the work material are to be conductors of electricity. The tool and the work material are immersed in a dielectric medium. Generally kerosene or deionised water is used as the dielectric medium. A gap is maintained between the tool and the workpiece. Depending upon the applied potential difference and the gap between the tool and workpiece, an electric field would be established. Generally the tool is connected to the negative terminal of the generator and the workpiece is connected to positive terminal. As the electric field is established between the tool and the job, the free electrons on the tool are subjected to electrostatic forces. If the work function or the bonding energy of the electrons is less, electrons would be emitted from the tool (assuming it to be connected to the negative terminal). Such emission of electrons are called or termed as cold emission. The "cold emitted" electrons are then accelerated towards the job through the dielectric medium. As they gain velocity and energy, and start moving towards the job, there would be collisions between the electrons and dielectric molecules. Such collision may result in ionisation of the dielectric molecule depending upon the work function or ionisation energy of the dielectric molecule and the energy of the electron. Thus, as the electrons get accelerated, more positive ions and electrons would get generated due to collisions. This cyclic process would increase the concentration of electrons and ions in the dielectric medium between the tool and the job at the spark gap. The concentration would be so high that the matter existing in that channel could be characterised as "plasma". The electrical resistance of such plasma channel would be very less. Thus all of a sudden, a large number of electrons will flow from the tool to the job and ions from the job to the tool. This is called avalanche motion of electrons. Such movement of electrons and ions can be visually seen as a spark. Thus the electrical energy is dissipated as the thermal energy of the spark.

The high speed electrons then impinge on the job and ions on the tool. The kinetic energy of the electrons and ions on impact with the surface of the job and tool respectively would be converted into thermal energy or heat flux. Such intense localised heat flux leads to extreme instantaneous confined rise in temperature which would be in excess of $10,000^{o}C$.

Such localised extreme rise in temperature leads to material removal. Material removal occurs due to instant vapourisation of the material as well as due to melting. The molten metal is not removed completely but only partially.

As the potential difference is withdrawn as shown in Fig. 1, the plasma channel is no longer sustained. As the plasma channel collapse, it generates pressure or shock waves, which evacuates the molten material forming a crater of removed material around the site of the spark.

Thus to summarise, the material removal in EDM mainly occurs due to formation of shock waves as the plasma channel collapse owing to discontinuation of applied potential difference.

Generally the workpiece is made positive and the tool negative. Hence, the electrons strike the job leading to crater formation due to high temperature and melting and material removal. Similarly, the positive ions impinge on the tool leading to tool wear.

In EDM, the generator is used to apply voltage pulses between the tool and the job. A constant voltage is not applied. Only sparking is desired in EDM rather than arcing. Arcing leads to localised material removal at a particular point whereas sparks get distributed all over the tool surface leading to uniformly distributed material removal under the tool.

3. Process Parameters

The process parameters in EDM are mainly related to the waveform characteristics. Fig. 2 shows a general waveform used in EDM.

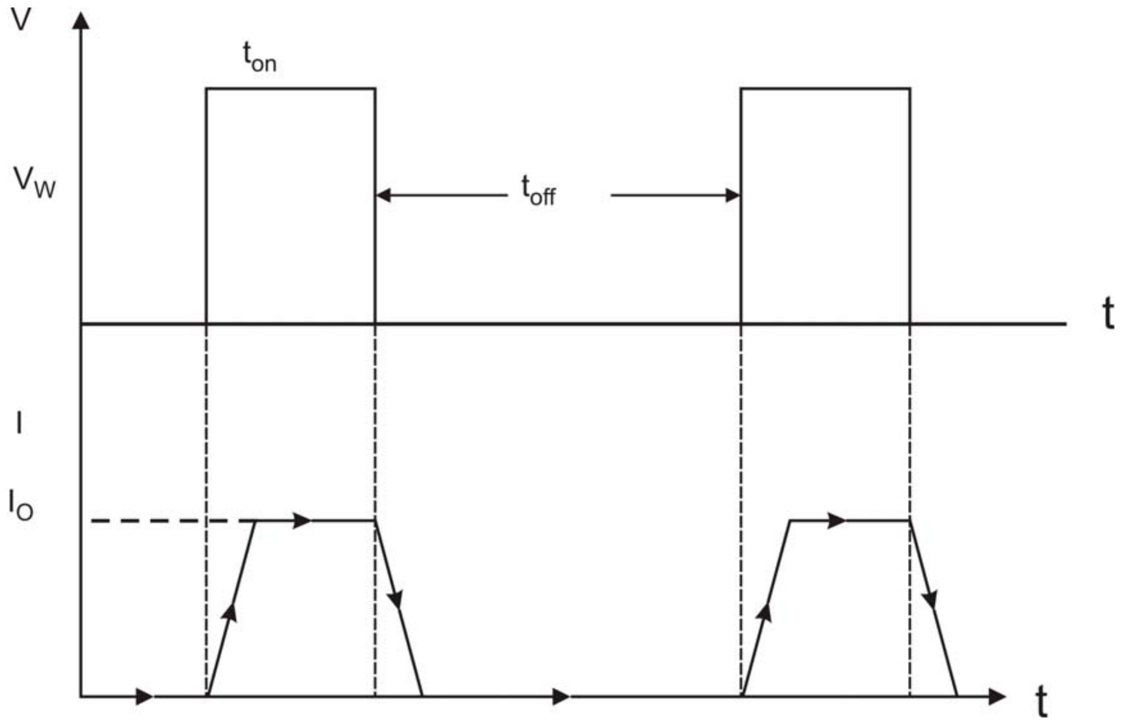


Fig. 2 *Waveform used in EDM*

The waveform is characterised by the

- The open circuit voltage - V_o
- The working voltage - V_w
- The maximum current - I_o
- The pulse on time – the duration for which the voltage pulse is applied - t_{on}
- The pulse off time - t_{off}
- The gap between the workpiece and the tool – spark gap - δ
- The polarity – straight polarity – tool (-ve)
- The dielectric medium
- External flushing through the spark gap.

4. Characteristics of EDM

(a) The process can be used to machine any work material if it is electrically conductive
(b) Material removal depends on mainly thermal properties of the work material rather than its strength, hardness etc
(c) In EDM there is a physical tool and geometry of the tool is the positive impression of the hole or geometric feature machined
(d) The tool has to be electrically conductive as well. The tool wear once again depends on the thermal properties of the tool material
(e) Though the local temperature rise is rather high, still due to very small pulse on time, there is not enough time for the heat to diffuse and thus almost no increase in bulk temperature takes place. Thus the heat affected zone is limited to 2 – 4 μm of the spark crater

(f) However rapid heating and cooling and local high temperature leads to surface hardening which may be desirable in some applications
(g) Though there is a possibility of taper cut and overcut in EDM, they can be controlled and compensated.

5. Dielectric

In EDM, as has been discussed earlier, material removal mainly occurs due to thermal evaporation and melting. As thermal processing is required to be carried out in absence of oxygen so that the process can be controlled and oxidation avoided. Oxidation often leads to poor surface conductivity (electrical) of the workpiece hindering further machining. Hence, dielectric fluid should provide an oxygen free machining environment. Further it should have enough strong dielectric resistance so that it does not breakdown electrically too easily but at the same time ionise when electrons collide with its molecule. Moreover, during sparking it should be thermally resistant as well.
Generally kerosene and deionised water is used as dielectric fluid in EDM. Tap water cannot be used as it ionises too early and thus breakdown due to presence of salts as impurities occur. Dielectric medium is generally flushed around the spark zone. It is also applied through the tool to achieve efficient removal of molten material.

6. Electrode Material

Electrode material should be such that it would not undergo much tool wear when it is impinged by positive ions. Thus the localised temperature rise has to be less by tailoring or properly choosing its properties or even when temperature increases, there would be less melting. Further, the tool should be easily workable as intricate shaped geometric features are machined in EDM. Thus the basic characteristics of electrode materials are:

- High electrical conductivity – electrons are cold emitted more easily and there is less bulk electrical heating
- High thermal conductivity – for the same heat load, the local temperature rise would be less due to faster heat conducted to the bulk of the tool and thus less tool wear
- Higher density – for the same heat load and same tool wear by weight there would be less volume removal or tool wear and thus less dimensional loss or inaccuracy
- High melting point – high melting point leads to less tool wear due to less tool material melting for the same heat load
- Easy manufacturability
- Cost – cheap

The followings are the different electrode materials which are used commonly in the industry:

- Graphite
- Electrolytic oxygen free copper
- Tellurium copper – 99% Cu + 0.5% tellurium
- Brass

7. Modelling of Material Removal and Product Quality

Material removal in EDM mainly occurs due to intense localised heating almost by point heat source for a rather small time frame. Such heating leads to melting and crater formation as shown in Fig. 3.

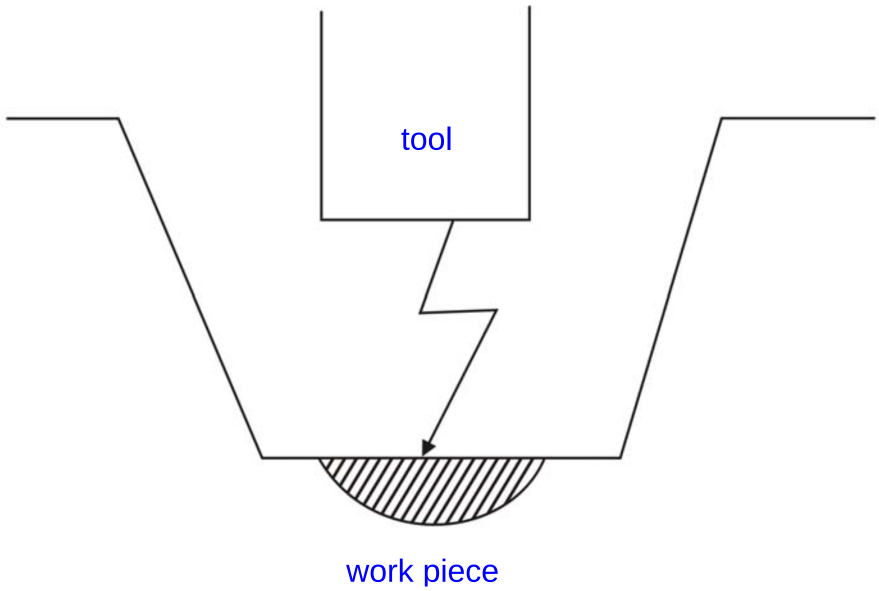


Fig. 3 *Schematic representation of crater formation in EDM process.*

The molten crater can be assumed to be hemispherical in nature with a radius r which forms due to a single pulse or spark. Hence material removal in a single spark can be expressed as

$$\Gamma_s = \frac{2}{3}\pi r^3$$

Now as per Fig. 2, the energy content of a single spark is given as

$$E_s = VIt_{on}$$

A part of this spark energy gets lost in heating the dielectric, and rest is distributed between the impinging electrons and ions. Thus the energy available as heat at the workpiece is given by

$$E_w \quad \alpha \quad E_s$$

$$E_w = kE_s$$

Now it can be logically assumed that material removal in a single spark would be proportional to the spark energy. Thus

$$\Gamma_s \quad \alpha \quad E_s \quad \alpha \quad E_w$$

$$\therefore \quad \Gamma_s = gE_s$$

Now material removal rate is the ratio of material removed in a single spark to cycle time.

Thus

$$MRR = \frac{\Gamma_s}{t_c} = \frac{\Gamma_s}{t_{on} + t_{off}}$$

$$MRR = g\frac{VIt_{on}}{t_{on} + t_{off}} = g\frac{VI}{\left(1 + \frac{t_{off}}{t_{on}}\right)}$$

The model presented above is a very simplified one and linear relationship is not observed in practice. But even then such simplified model captures the complexity of EDM in a very efficient manner. MRR in practice does increase with increase in working voltage, current, pulse on time and decreases with increase in pulse off time. Product quality is a very important characteristic of a manufacturing process along with MRR. The followings are the product quality issues in EDM

- Surface finish
- Overcut
- Tapercut

No two sparks take place side by side. They occur completely randomly so that over time one gets uniform average material removal over the whole tool cross section. But for the sake of simplicity, it is assumed that sparks occur side by side as shown in Fig. 4.

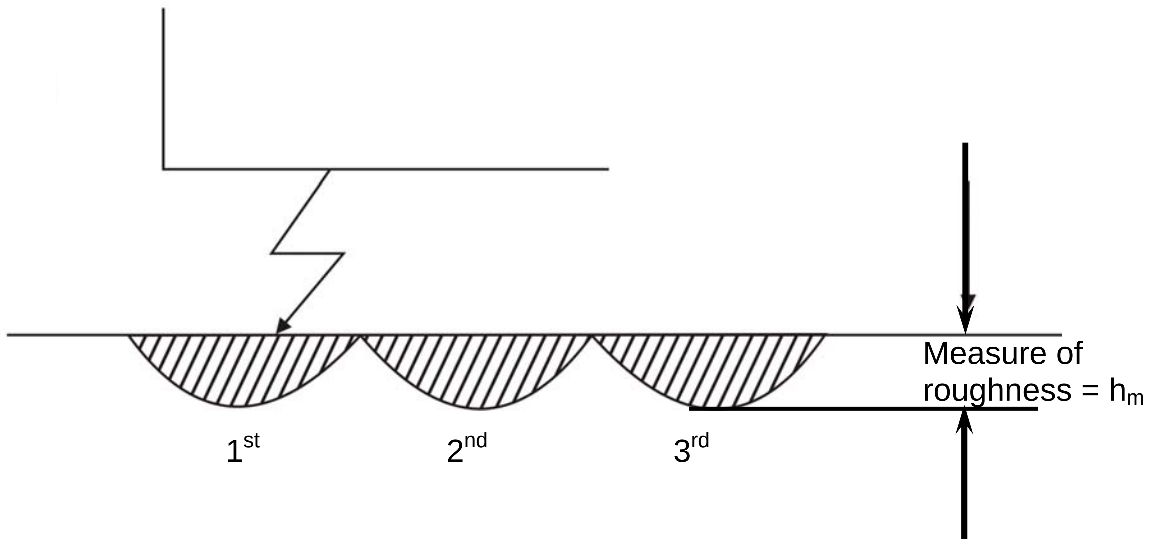


Fig. 4 *Schematic representation of the sparks in EDM process.*

Thus

$$h_m = r \quad \text{and} \quad \Gamma_s = \frac{2}{3}\pi r^3$$

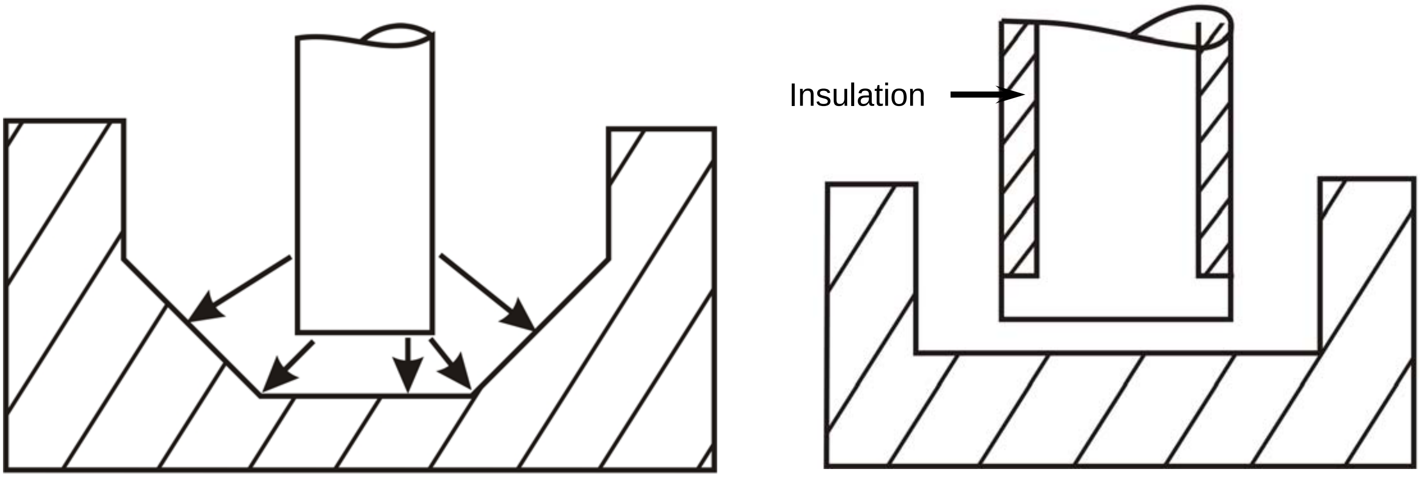
$$\therefore \quad r = h_m = \left(\frac{3}{2}\Gamma_s\right)^{1/3}$$

Now $\quad \Gamma_s = gE_s = gVIt_{on}$

$$\therefore \quad h_m \quad \alpha \quad (\Gamma_s)^{1/3} \quad \alpha \quad \{VIt_{on}\}^{1/3}$$

Thus it may be noted that surface roughness in EDM would increase with increase in spark energy and surface finish can be improved by decreasing working voltage, working current and pulse on time.

In EDM, the spark occurs between the two nearest point on the tool and workpiece. Thus machining may occur on the side surface as well leading to overcut and tapercut as depicted in Fig. 5. Taper cut can be prevented by suitable insulation of the tool. Overcut cannot be prevented as it is inherent to the EDM process. But the tool design can be done in such a way so that same gets compensated.



tapercut and overcut   tapercut prevention

Fig. 5 *Schematic depiction of taper cut and over cut and control of taper cut*

8. Equipment

Fig. 6 shows an EDM machine. EDM machine has the following major modules

- Dielectric reservoir, pump and circulation system
- Power generator and control unit
- Working tank with work holding device
- X-y table accommodating the working table
- The tool holder
- The servo system to feed the tool

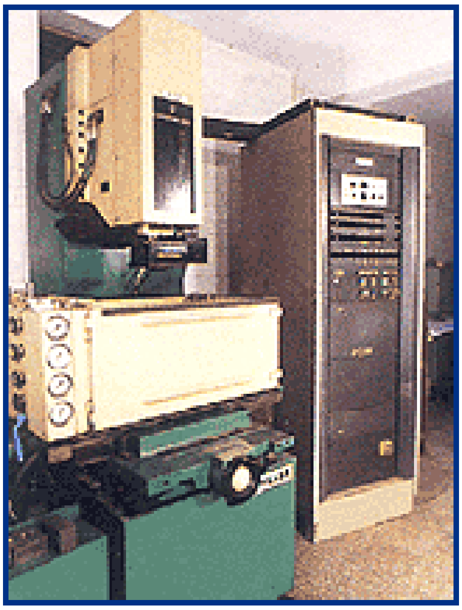


Fig. 6 *Commercial Electro-discharge Machine*

9. Power generator

Fig. 2 depicted general nature of voltage pulses used in electro-discharge machining. Different power generators are used in EDM and some are listed below:

- Resistance-capacitance type (RC type) Relaxation generator
- Rotary impulse type generator
- Electronic pulse generator
- Hybrid EDM generator

Fig. 7 shows the basic circuit for different type of EDM generators

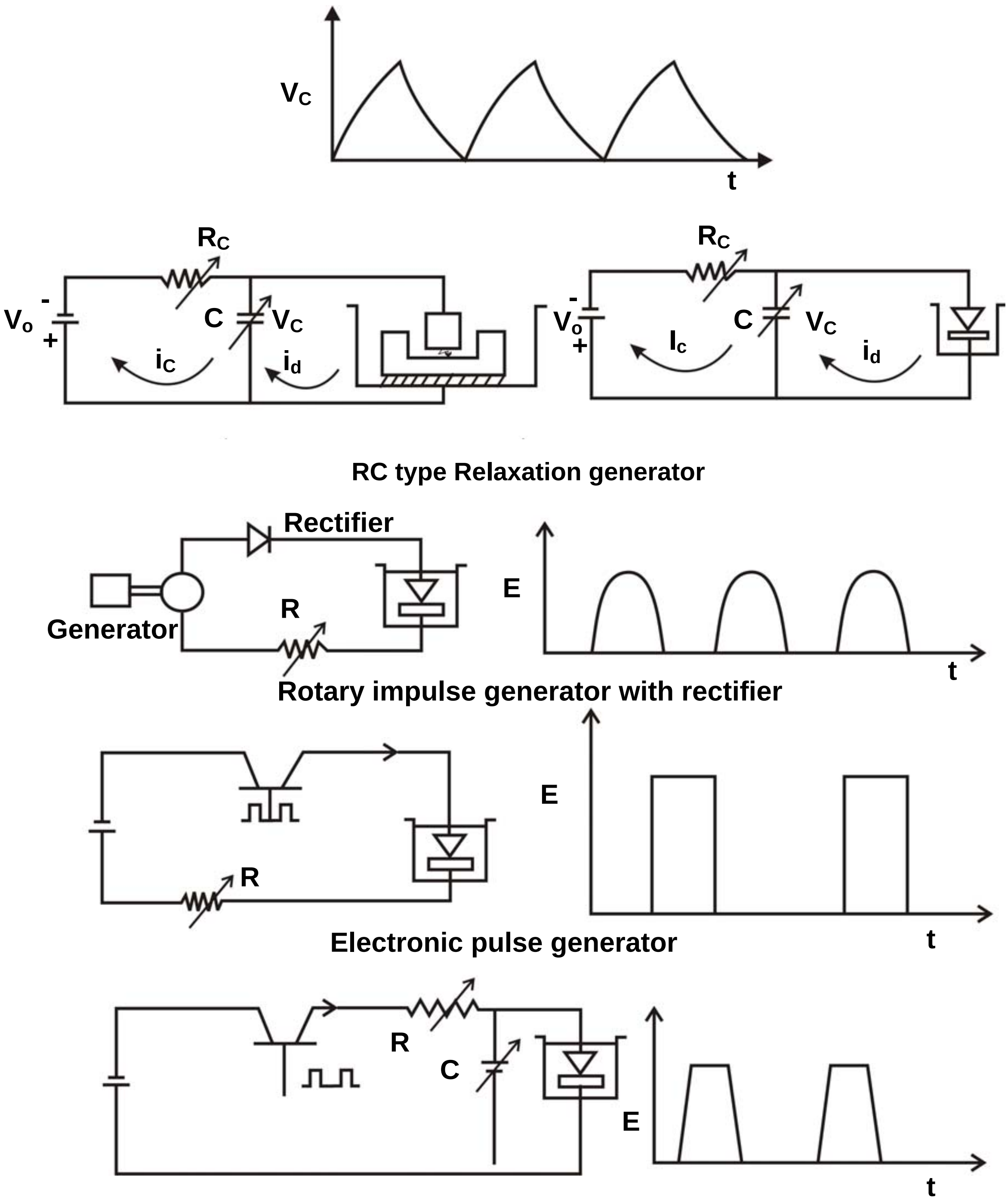


Fig. 7 *Basic circuits for different types of EDM generators.*

10. Analysis of RC type Relaxation EDM Generator

In RC type generator, the capacitor is charged from a DC source. As long as the voltage in the capacitor is not reaching the breakdown voltage of the dielectric medium under the prevailing machining condition, capacitor would continue to charge. Once the breakdown voltage is reached the capacitor would start discharging and a spark would be established between the tool and workpiece leading to machining. Such discharging would continue as long as the spark can be sustained. Once the voltage becomes too low to sustain the spark, the charging of the capacitor would continue. Fig. 8 shows the working of RC type EDM relaxation.

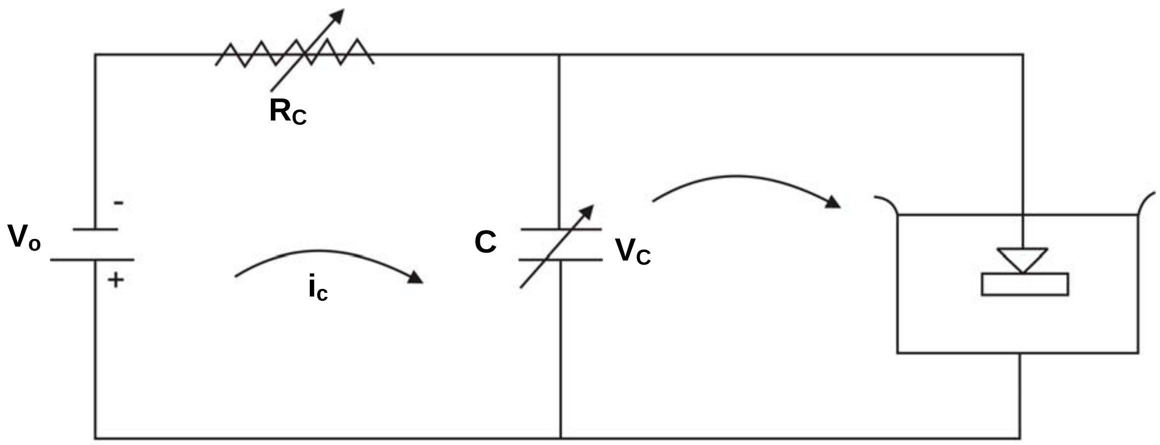


Fig. 8 *Schematic of the working principle of RC type EDM relaxation circuit.*

During charging, at any instant, from circuit theory,

or $$\frac{dV}{V_o - V_c} = \frac{1}{CR_c} dt$$

At t=0, V_c=0 and t = t_c, V_c=V_c*

$$\therefore \int_0^{V_c^*} \frac{dV_c}{V_o - V_c} = \frac{1}{CR_c} \int_0^{t_c} dt$$

$$\Rightarrow \quad -\frac{t_c}{R_c} = \left| \ln\left(V_o - V_c\right) \right|_o^{V_c^*}$$

$$\therefore \quad V_c^* = V_o \left\{ 1 - e^{-\frac{t_c}{R_c C}} \right\}$$

$$\text{or} \quad V_c = V_o \left\{ 1 - e^{-\frac{t}{R_c C}} \right\}$$

where, I_c = charging current
V_o= open circuit voltage
R_c= charging resistance
C = capacitance
V_c= instantaneous capacitor voltage during charging

Thus at any instant charging current, i_c, can be given as:

$$i_c = \frac{V_o - V_c}{R_c} = \frac{V_o - V_o\left(1 - e^{-\frac{t}{R_c C}}\right)}{R_c}$$

$$i_c = \frac{V_o e^{-\frac{t}{R_c C}}}{R_c} = i_o . e^{-\frac{t}{R_c C}}$$

During discharging, the electrical load coming from the EDM may be assumed a totally resistive and is characterised by a machine resistance of R_m. then the current passing through the EDM machine is given by

$$i_d = \frac{V_c}{R_m} = -C\frac{dV_c}{dt}$$

where, I_d = discharge current or current flowing through the machine
V_c= instantaneous capacitor voltage during discharging
R_m= machine resistance

The negative sign in front of the derivative of the voltage represents that the V_c is gradually decreasing during discharging.

Now at t = 0 (i.e. at the start of discharging, i.e. initiation of the spark), $V_c=V_c^*$ and at t = t_d, $V_c=V_d^*$

$$\int_{V_c^*}^{V_d^*} \frac{dV_c}{V_c} = -\frac{1}{CR_m}\int_0^{t_d} dt$$

$$\therefore \quad -\frac{t_d}{CR_m} = \ln\frac{V_d^*}{V_c^*}$$

$$\therefore \quad V_d^* = \frac{V_c^*}{R_m} . e^{-\frac{t_d}{R_m C}}$$

$\therefore$ The discharging or the machining current I_d is given by

$$i_d = \frac{V_d}{R_m} = \frac{V_c^*}{R_m} . e^{-\frac{t}{R_m C}}$$

Thus the voltage and the current pulses during charging and discharging is given in Fig. 9.

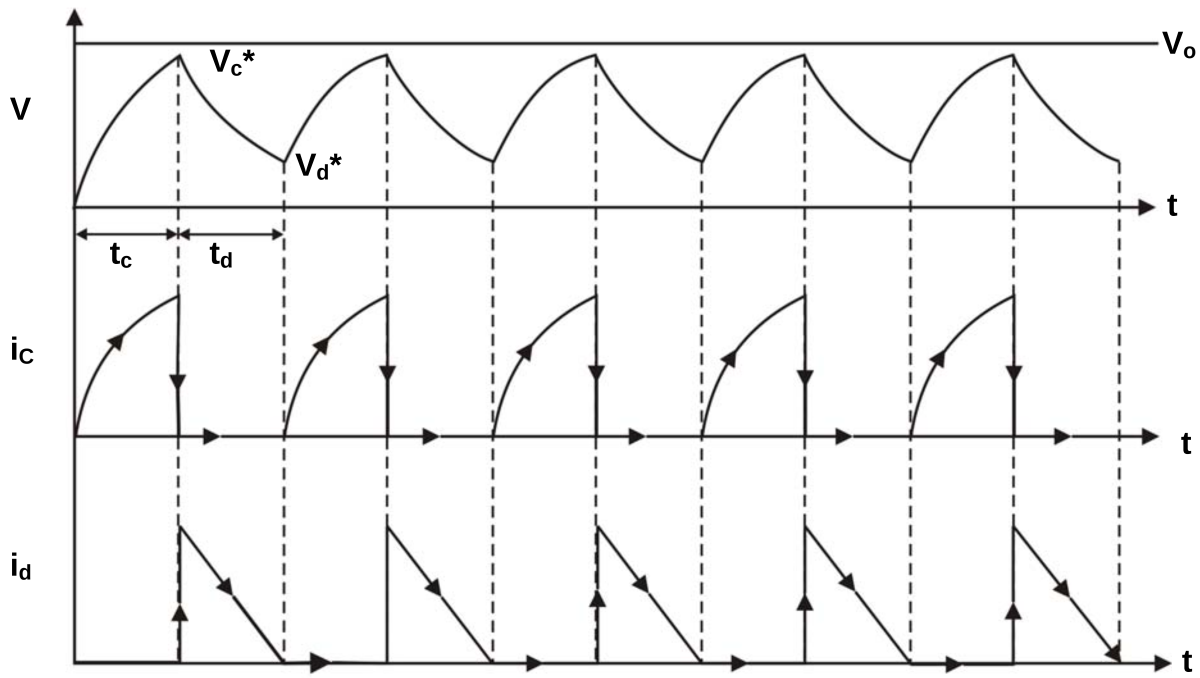


Fig. 9 *Schematic representation of the current pulses during charging and discharging in EDM process.*

For maximum power dissipation in RC type EDM generator $V_c^* = 0.716\ V_o$.
The charging time or idle time or off time, t_c, can be expressed as

$$t_c = -\frac{R_c C}{\ln\left(1 - \frac{V_c^*}{V_c}\right)}$$

The discharging time or machining time or on time can be expressed as

$$t_d = -\frac{R_m C}{\ln\left(\frac{V_d}{V_c^*}\right)^*}$$

$\therefore$ Frequency of operation, f

$$f = \frac{1}{t_c + t_d} = \frac{1}{\frac{R_c C}{\ln\left(1 - \frac{V_c^*}{V_c}\right)} + \frac{R_m C}{\ln\left(\frac{V_d}{V_c^*}\right)}}$$

Total energy discharged through spark gap

$$= \int_0^{t_d} i_d^2 R_m dt = \int_0^{t_d} \frac{V_c^{*2}}{R_m^2} R_m e^{-\frac{2t}{R_m C}} dt$$

$$= \frac{V_c^{*2}}{R_m} \int_o^{t_d} e^{-\frac{2t}{R_m C}} dt$$

$$= \frac{V_c^{*2}}{R_m} \cdot \frac{R_m C}{2t} \left| -e^{-\frac{2t}{R_m C}} \right|_0^{t_d}$$

$$= \frac{1}{2} C V_c^{*2} \left\{ 1 - e^{-\frac{2t_d}{R_m C}} \right\}$$

$$\cong \frac{1}{2} C V_c^{*2}$$

Quiz Test

1. Which of the following material cannot be machined by EDM
   (a) steel
   (b) WC
   (c) Titanium
   (d) Glass

2. w(W)hich of the following is used as dielectric medium in EDM
   (a) tap water
   (b) kerosene
   (c) NaCL solution
   (d) KOH solution

3. Tool should not have
   (a) low thermal conductivity
   (b) high machinability
   (c) high melting point
   (d) high specific heat

Problems

1. In a RC type generator, the maximum charging voltage is 80 V and the charging capacitor is 100 μF. Determine spark energy.

2. If in a RC type generator, to get an idle time of 500 μs for open circuit voltage of 100 V and maximum charging voltage of 70 V, determine charging resistance. Assume C = 100 μF.

3. For a RC type generator to get maximum power dissipation during charging $V_c^* = V_o x 0.716$. Determine idle time for R_c = 10 Ω and C = 200 μF

4. Determine on time or discharge time if V_o = 100 V and V_d^* = 15 V.
   Spark energy = 0.5 J. Generator is expected for maximum power during charging.
   Machine resistance = 0.5 Ω.

Solution to the Quiz Test

1 – (d)
2 – (b)
3 – (a)

Solutions to the Problems

Solution to Prob. 1

$$E_s = \frac{1}{2}CV^2 = \frac{1}{2}x100x10^{-6}x80^2 = 0.32J \qquad \textbf{answer}$$

Solution to Prob. 2

$$t_c = -\frac{R_c C}{\ln\left(1 - \frac{V_c{}^*}{V_c}\right)}$$

$$500x10^{-6} = -\frac{R_c x100x10^{-6}}{\ln\left(1 - \frac{70}{100}\right)}$$

$$R_C \cong 6\ \Omega \qquad \textbf{Answer}$$

Solution to Prob. 3

$$t_c = -\frac{R_c C}{\ln\left(1 - \frac{V_c^*}{V_o}\right)} = -\frac{10x200x10^{-6}}{\ln(1 - 0.716)}$$

t_c = 1.58 ms **answer**

Solution to Prob. 4

$$V_c^* = 0.716V_o = 71.6\ V$$

$$E_s = \frac{1}{2}CV^2 = 0.5\ J$$

$$\therefore \quad C = 2x0.5x\frac{1}{(71.6)^2} = 195\ \mu F$$

$$t_d = -\frac{R_m C}{\ln\left(\frac{V_d^*}{V_c^*}\right)} = 62\ \mu F \qquad \textbf{answer}$$

Module
9
Non conventional Machining

Lesson
40
Electron Beam and Laser Beam Machining

Instructional Objectives

i. Describe the basic mechanism of material removal in EBM & LBM
ii. Identify major components of EBM & LBM equipment
iii. State the working principle of EBM & LBM equipment
iv. Draw schematically the EBM & LBM equipment
v. Identify the process parameters of EBM & LBM
vi. Identify the machining characteristics of EBM & LBM
vii. List three applications of EBM & LBM
viii. List three limitations of EBM & LBM

1. Introduction

Electron Beam Machining (EBM) and Laser Beam Machining (LBM) are thermal processes considering the mechanisms of material removal. However electrical energy is used to generate high-energy electrons in case of Electron Beam Machining (EBM) and high-energy coherent photons in case of Laser Beam Machining (LBM). **Thus these two processes are often classified as electro-optical-thermal processes.**

There are different jet or beam processes, namely Abrasive Jet, Water Jet etc. These two are mechanical jet processes. There are also thermal jet or beams. A few are oxyacetylene flame, welding arc, plasma flame etc. EBM as well as LBM are such thermal beam processes. Fig. 9.6.1 shows the variation in power density vs. the characteristic dimensions of different thermal beam processes. Characteristic length is the diameter over which the beam or flame is active. In case of oxyacetylene flame or welding arc, the characteristic length is in mm to tens of mm and the power density is typically low. Electron Beam may have a characteristic length of tens of microns to mm depending on degree of focusing of the beam. In case of defocused electron beam, power density would be as low as 1 Watt/mm^2. But in case of focused beam the same can be increased to tens of kW/mm^2. Similarly as can be seen in Fig. 9.6.1, laser beams can be focused over a spot size of 10 – 100 μm with a power density as high as 1 MW/mm^2. Electrical discharge typically provides even higher power density with smaller spot size.

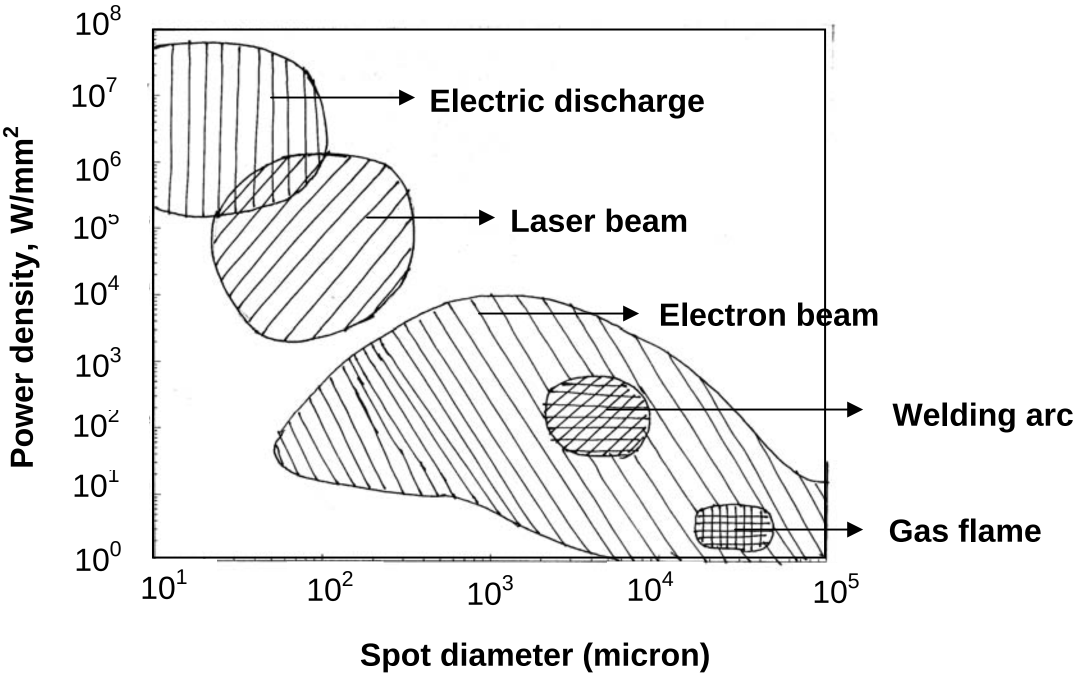
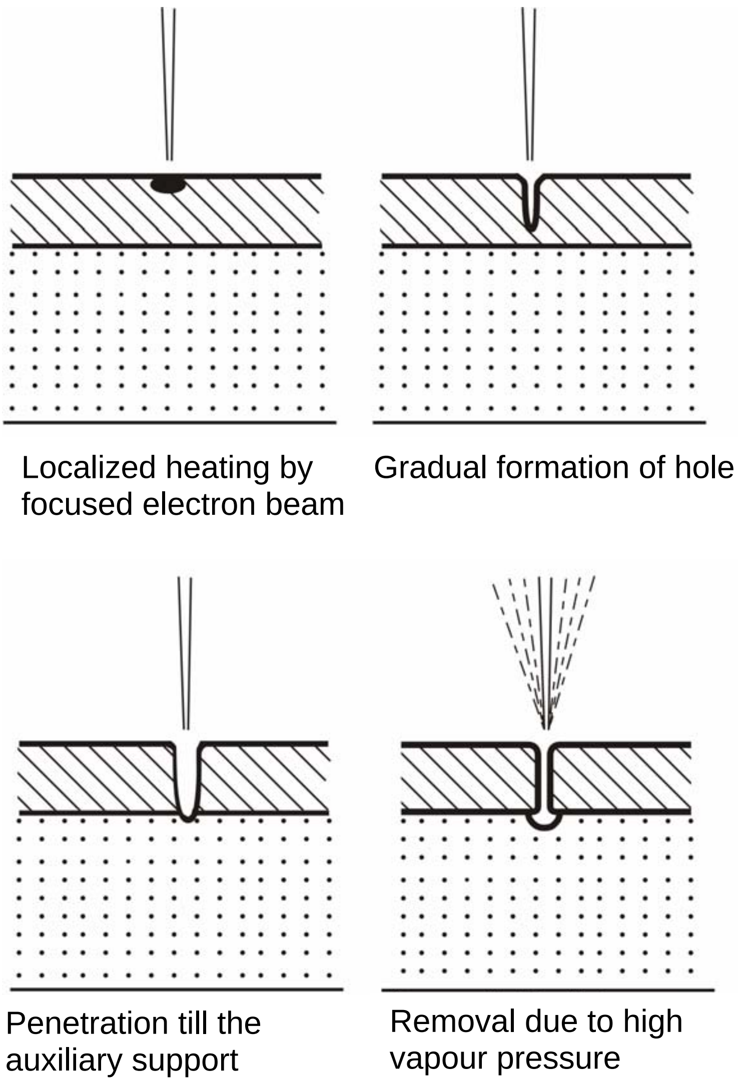


Fig. 9.6.1 *Variation in energy density with spot diameter of thermal beam processes*

EBM and LBM are typically used with higher power density to machine materials. The mechanism of material removal is primarily by melting and rapid vaporisation due to intense heating by the electrons and laser beam respectively.

2. Electron Beam Machining – Process

Electron beam is generated in an electron beam gun. The construction and working principle of the electron beam gun would be discussed in the next section. Electron beam gun provides high velocity electrons over a very small spot size. Electron Beam Machining is required to be carried out in vacuum. Otherwise the electrons would interact with the air molecules, thus they would loose their energy and cutting ability. Thus the workpiece to be machined is located under the electron beam and is kept under vacuum. The high-energy focused electron beam is made to impinge on the workpiece with a spot size of 10 – 100 μm. The kinetic energy of the high velocity electrons is converted to heat energy as the electrons strike the work material. Due to high power density instant melting and vaporisation starts and "melt – vaporisation" front gradually progresses, as shown in Fig. 9.6.2. Finally the molten material, if any at the top of the front, is expelled from the cutting zone by the high vapour pressure at the lower part. Unlike in Electron Beam Welding, the gun in EBM is used in pulsed mode. Holes can be drilled in thin sheets using a single pulse. For thicker plates, multiple pulses would be required. Electron beam can also be manoeuvred using the electromagnetic deflection coils for drilling holes of any shape.



*`**Fig. 9.6.2** Mechanism of Material Removal in Electron Beam Machining*

3. Electron Beam Machining – Equipment

Fig. 9.6.3 shows the schematic representation of an electron beam gun, which is the heart of any electron beam machining facility. The basic functions of any electron beam gun are to generate free electrons at the cathode, accelerate them to a sufficiently high velocity and to focus them over a small spot size. Further, the beam needs to be manoeuvred if required by the gun.
The cathode as can be seen in Fig. 9.6.3 is generally made of tungsten or tantalum. Such cathode filaments are heated, often inductively, to a temperature of around 2500^0C. Such heating leads to thermo-ionic emission of electrons, which is further enhanced by maintaining very low vacuum within the chamber of the electron beam gun. Moreover, this cathode cartridge is highly negatively biased so that the thermo-ionic electrons are strongly repelled away form the cathode. This cathode is often in the form of a cartridge so that it can be changed very quickly to reduce down time in case of failure.

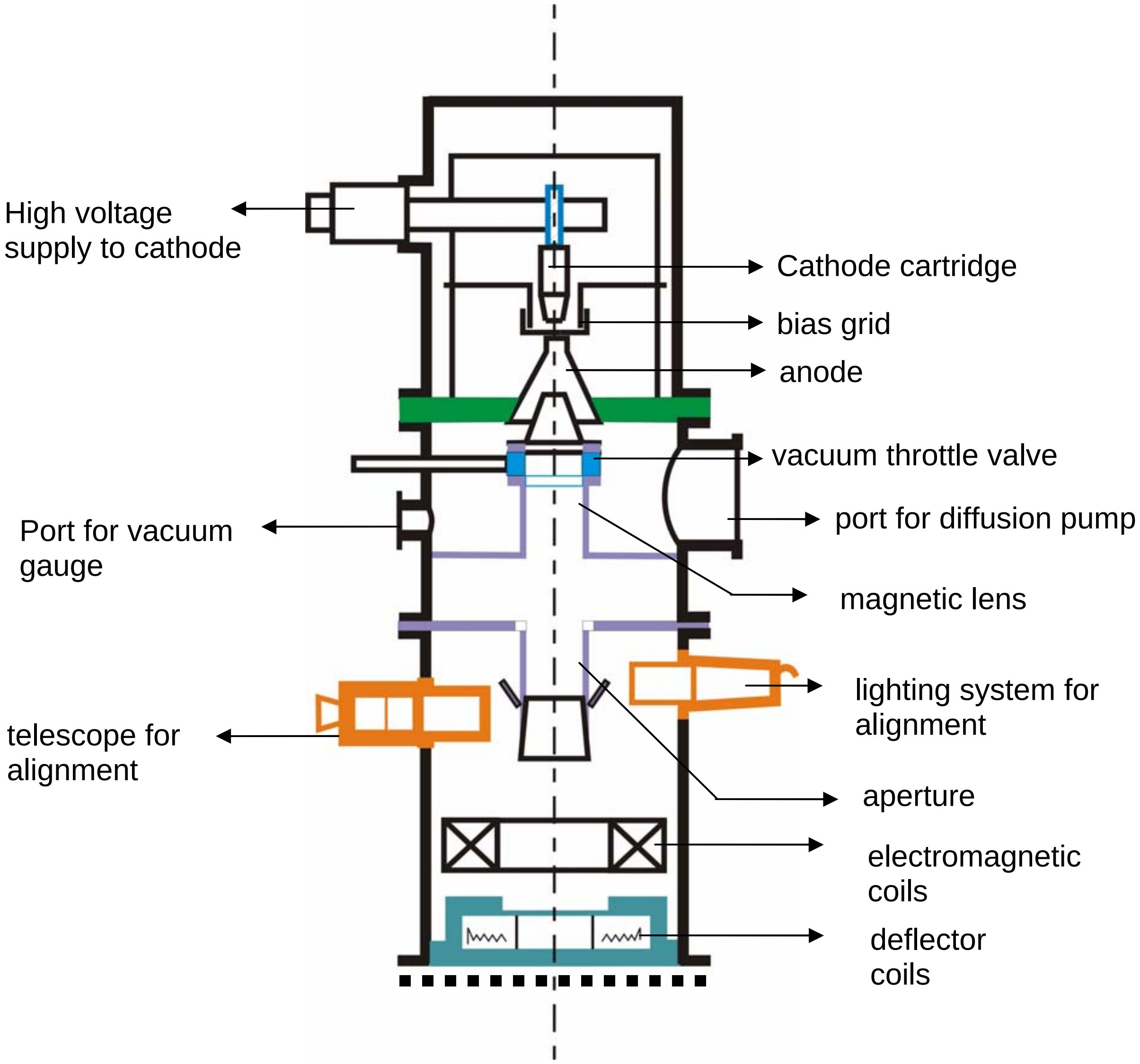


Fig. 9.6.3 *Electron Beam Gun*

Just after the cathode, there is an annular bias grid. A high negative bias is applied to this grid so that the electrons generated by this cathode do not diverge and approach the next element, the annular anode, in the form of a beam. The annular anode now attracts the electron beam and gradually gets accelerated. As they leave the anode section, the electrons may achieve a velocity as high as half the velocity of light.

The nature of biasing just after the cathode controls the flow of electrons and the biased grid is used as a switch to operate the electron beam gun in pulsed mode.

After the anode, the electron beam passes through a series of magnetic lenses and apertures. The magnetic lenses shape the beam and try to reduce the divergence. Apertures on the other hand allow only the convergent electrons to pass and capture the divergent low energy electrons from the fringes. This way, the aperture and the magnetic lenses improve the quality of the electron beam.

Then the electron beam passes through the final section of the electromagnetic lens and deflection coil. The electromagnetic lens focuses the electron beam to a desired spot. The deflection coil can manoeuvre the electron beam, though by small amount, to improve shape of the machined holes.

Generally in between the electron beam gun and the workpiece, which is also under vacuum, there would be a series of slotted rotating discs. Such discs allow the electron beam to pass and machine materials but helpfully prevent metal fumes and vapour generated during machining to reach the gun. Thus it is essential to synchronize the motion of the rotating disc and pulsing of the electron beam gun.

Electron beam guns are also provided with illumination facility and a telescope for alignment of the beam with the workpiece.

Workpiece is mounted on a CNC table so that holes of any shape can be machined using the CNC control and beam deflection in-built in the gun.

One of the major requirements of EBM operation of electron beam gun is maintenance of desired vacuum. Level of vacuum within the gun is in the order of 10^{-4} to 10^{-6} Torr. *{1 Torr = 1mm of Hg}* Maintenance of suitable vacuum is essential so that electrons do not loose their energy and a significant life of the cathode cartridge is obtained. Such vacuum is achieved and maintained using a combination of rotary pump and diffusion pump. Diffusion pump, as shown in Fig. 9.6.4 is attached to the diffusion pump port of the electron beam gun (vide Fig. 9.6.3).

Diffusion pump is essentially an oil heater. As the oil is heated the oil vapour rushes upward where gradually converging structure as shown in Fig. 9.6.4 is present. The nozzles change the direction of motion of the oil vapour and the oil vapour starts moving downward at a high velocity as jet. Such high velocity jets of oil vapour entrain any air molecules present within the gun. This oil is evacuated by a rotary pump via the backing line. The oil vapour condenses due to presence of cooling water jacket around the diffusion pump.

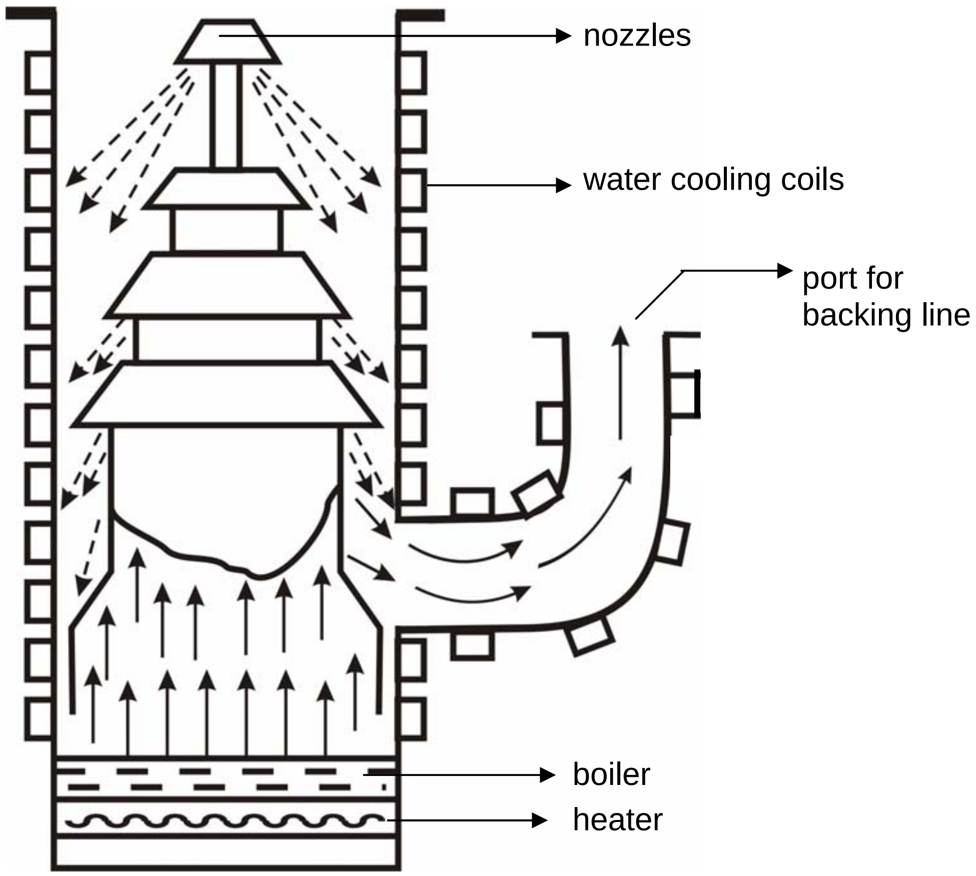


Fig. 9.6.4 Working of a Diffusion Pump

4. Electron Beam Process – Parameters

The process parameters, which directly affect the machining characteristics in Electron Beam Machining, are:

- The accelerating voltage
- The beam current
- Pulse duration
- Energy per pulse
- Power per pulse
- Lens current
- Spot size
- Power density

As has already been mentioned in EBM the gun is operated in pulse mode. This is achieved by appropriately biasing the biased grid located just after the cathode. Switching pulses are given to the bias grid so as to achieve pulse duration of as low as 50 μs to as long as 15 ms.
Beam current is directly related to the number of electrons emitted by the cathode or available in the beam. Beam current once again can be as low as 200 μamp to 1 amp.

Increasing the beam current directly increases the energy per pulse. Similarly increase in pulse duration also enhances energy per pulse. High-energy pulses (in excess of 100 J/pulse) can machine larger holes on thicker plates.

The energy density and power density is governed by energy per pulse duration and spot size. Spot size, on the other hand is controlled by the degree of focusing achieved by the electromagnetic lenses. A higher energy density, i.e., for a lower spot size, the material removal would be faster though the size of the hole would be smaller.

The plane of focusing would be on the surface of the workpiece or just below the surface of the workpiece. This controls the kerf shape or the shape of the hole as schematically shown in Fig. 9.6.5.

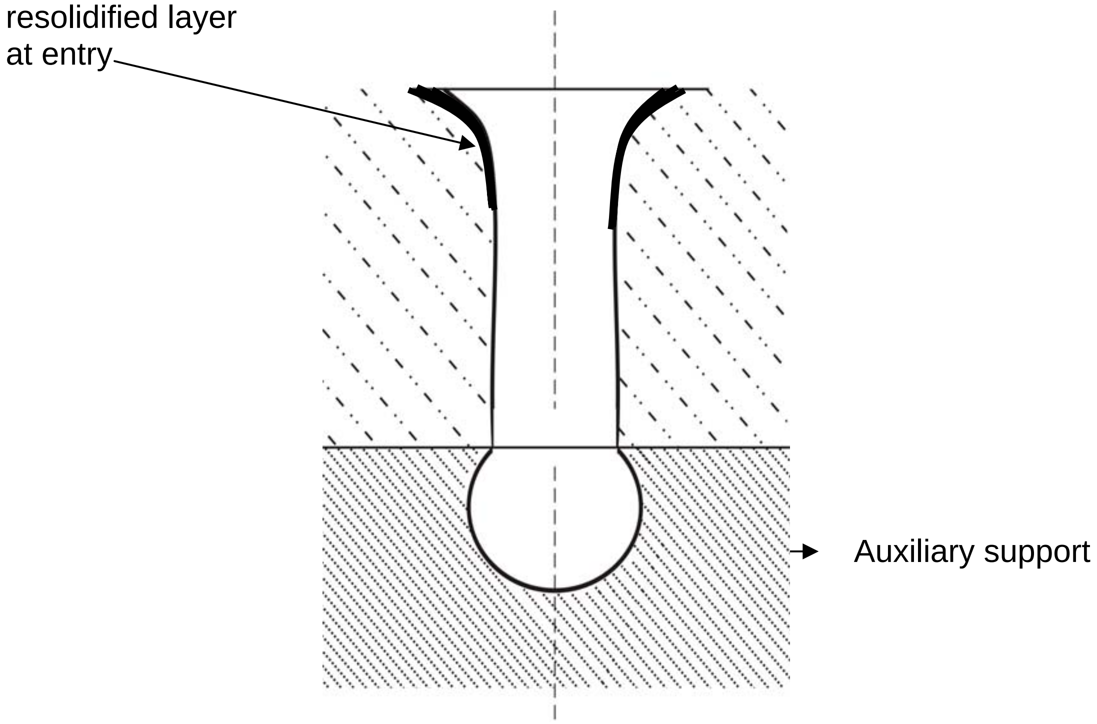


Fig. 9.6.5 *Typical kerf shape of electron beam drilled hole*

As has been indicated earlier, the final deflection coil can manoeuvre the electron beam providing holes of non-circular cross-section as required.

5. Electron Beam Process Capability

EBM can provide holes of diameter in the range of 100 μm to 2 mm with a depth upto 15 mm, i.e., with a l/d ratio of around 10. Fig. 9.6.5 schematically represents a typical hole drilled by electron beam. The hole can be tapered along the depth or barrel shaped. By focusing the beam below the surface a reverse taper can also be obtained. Typically as shown in Fig. 9.6.5, there would be an edge rounding at the entry point along with presence of recast layer. Generally burr formation does not occur in EBM.

A wide range of materials such as steel, stainless steel, Ti and Ni super-alloys, aluminium as well as plastics, ceramics, leathers can be machined successfully using electron beam. As the mechanism of material removal is thermal in nature as for example in electro-discharge machining, there would be thermal damages associated with EBM. However, the heat-affected zone is rather narrow due to shorter pulse duration in EBM. Typically the heat-affected zone is around 20 to 30 μm.

Some of the materials like Al and Ti alloys are more readily machined compared to steel. Number of holes drilled per second depends on the hole diameter, power density and depth of the hole as well as material type as mentioned earlier. Fig. 9.6.6 depicts the variation in drilling speed against volume of material removed for steel and Aluminium alloy.

EBM does not apply any cutting force on the workpieces. Thus very simple work holding is required. This enables machining of fragile and brittle materials by EBM. Holes can also be drilled at a very shallow angle of as less as 20 to 30^0.

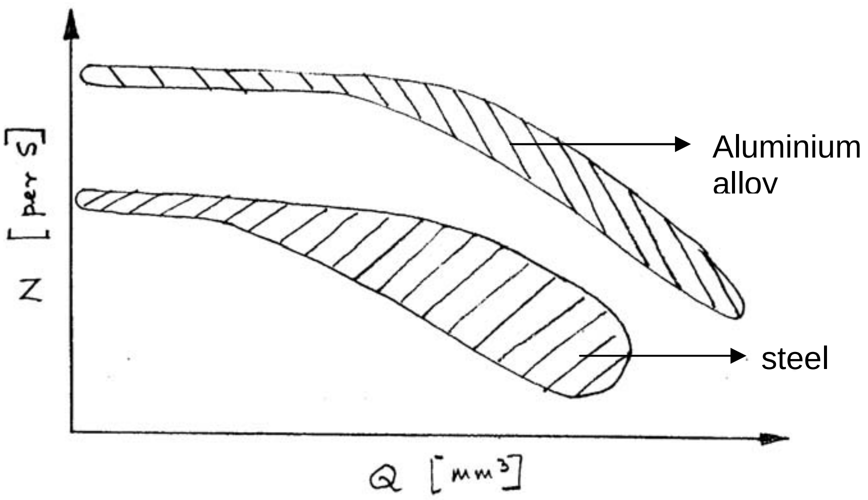


Fig. 9.6.6 Variation in drilling speed with volume of material removal for steels and aluminium

6. Electron Beam Machining – Advantages and Limitations

EBM provides very high drilling rates when small holes with large aspect ratio are to be drilled. Moreover it can machine almost any material irrespective of their mechanical properties. As it applies no mechanical cutting force, work holding and fixturing cost is very less. Further for the same reason fragile and brittle materials can also be processed. The heat affected zone in EBM is rather less due to shorter pulses. EBM can provide holes of any shape by combining beam deflection using electromagnetic coils and the CNC table with high accuracy.

However, EBM has its own share of limitations. The primary limitations are the high capital cost of the equipment and necessary regular maintenance applicable for any equipment using vacuum system. Moreover in EBM there is significant amount of non-productive pump down period for attaining desired vacuum. However this can be reduced to some extent using vacuum load locks. Though heat affected zone is rather less in EBM but recast layer formation cannot be avoided.

7. Laser Beam Machining – Introduction

Laser Beam Machining or more broadly laser material processing deals with machining and material processing like heat treatment, alloying, cladding, sheet metal bending etc. Such processing is carried out utilizing the energy of coherent photons or laser beam, which is mostly converted into thermal energy upon interaction with most of the materials. Nowadays, laser is also finding application in regenerative machining or rapid prototyping as in processes like stereo-lithography, selective laser sintering etc.

Laser stands for light amplification by stimulated emission of radiation. The underline working principle of laser was first put forward by Albert Einstein in 1917 though the first industrial laser for experimentation was developed around 1960s.

Laser beam can very easily be focused using optical lenses as their wavelength ranges from half micron to around 70 microns. Focussed laser beam as indicated earlier can have power density in excess of 1 MW/mm^2. As laser interacts with the material, the energy of the photon is absorbed by the work material leading to rapid substantial rise in local temperature. This in turn results in melting and vaporisation of the work material and finally material removal.

8. Laser Beam Machining – the lasing process

Lasing process describes the basic operation of laser, i.e. generation of coherent (both temporal and spatial) beam of light by “light amplification” using “stimulated emission”.

In the model of atom, negatively charged electrons rotate around the positively charged nucleus in some specified orbital paths. The geometry and radii of such orbital paths depend on a variety of parameters like number of electrons, presence of neighbouring atoms and their electron structure, presence of electromagnetic field etc. Each of the orbital electrons is associated with unique energy levels. At absolute zero temperature an atom is considered to be at ground level, when all the electrons occupy their respective lowest potential energy. The electrons at ground state can be excited to higher state of energy by absorbing energy form external sources like increase in electronic vibration at elevated temperature, through chemical reaction as well as via absorbing energy of the photon. Fig. 9.6.7 depicts schematically the absorption of a photon by an electron. The electron moves from a lower energy level to a higher energy level.

On reaching the higher energy level, the electron reaches an unstable energy band. And it comes back to its ground state within a very small time by releasing a photon. This is called spontaneous emission. Schematically the same is shown in Fig. 9.6.7 and Fig. 9.6.8. The spontaneously emitted photon would have the same frequency as that of the “exciting” photon.

Sometimes such change of energy state puts the electrons in a meta-stable energy band. Instead of coming back to its ground state immediately (within tens of ns) it stays at the elevated energy state for micro to milliseconds. In a material, if more number of electrons can be somehow pumped to the higher meta-stable energy state as compared to number of atoms at ground state, then it is called “population inversion”. Such electrons,

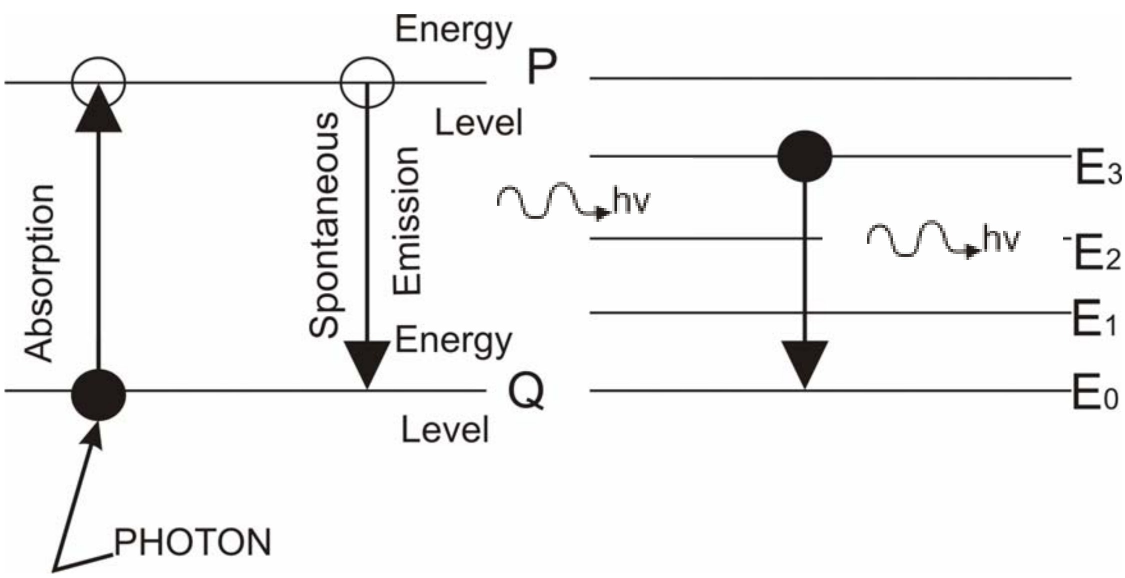


Fig. 9.6.7 *Energy bands in materials*

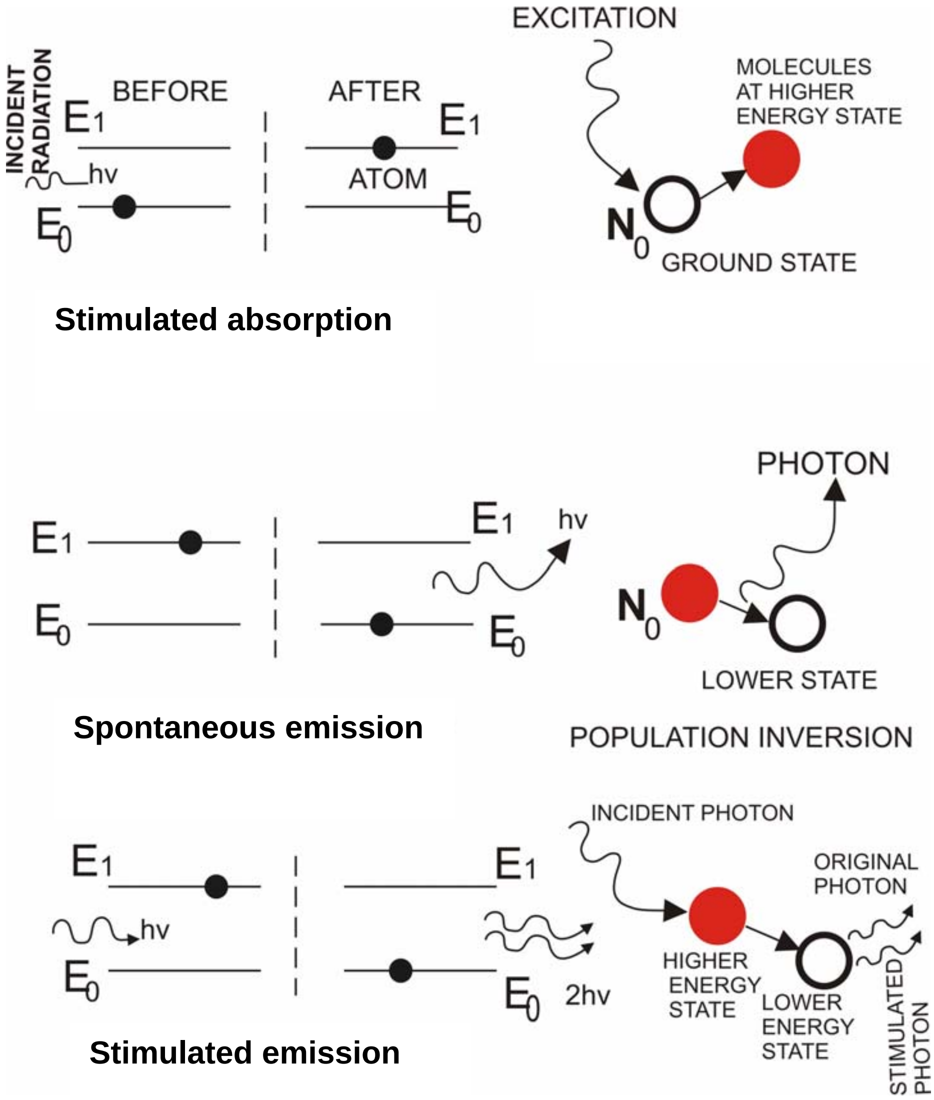


Fig. 9.6.8 *Spontaneous and stimulated emissions*

at higher energy meta-stable state, can return to the ground state in the form of an avalanche provided stimulated by a photon of suitable frequency or energy. This is called stimulated emission. Fig. 9.6.8 shows one such higher state electron in meta-stable orbit. If it is stimulated by a photon of suitable energy then the electron will come down to the lower energy state and in turn one original photon, another emitted photon by stimulation having some temporal and spatial phase would be available. In this way coherent laser beam can be produced.

Fig. 9.6.9 schematically shows working of a laser. There is a gas in a cylindrical glass vessel. This gas is called the lasing medium. One end of the glass is blocked with a 100% reflective mirror and the other end is having a partially reflective mirror. Population inversion can be carried out by exciting the gas atoms or molecules by pumping it with flash lamps. Then stimulated emission would initiate lasing action. Stimulated emission of photons could be in all directions. Most of the stimulated photons, not along the longitudinal direction would be lost and generate waste heat. The photons in the longitudinal direction would form coherent, highly directional, intense laser beam.

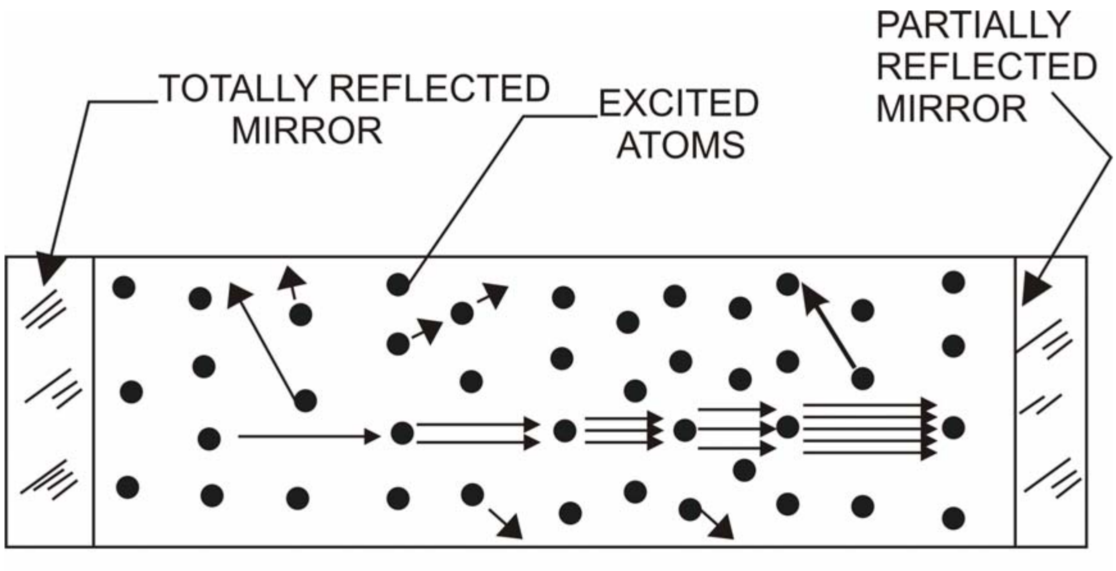


Fig. 9.6.9 *Lasing action*

9. Lasing Medium

Many materials can be used as the heart of the laser. Depending on the lasing medium lasers are classified as solid state and gas laser. Solid-state lasers are commonly of the following type

- Ruby which is a chromium – alumina alloy having a wavelength of 0.7 μm
- Nd-glass lasers having a wavelength of 1.64 μm
- Nd-YAG laser having a wavelength of 1.06 μm

These solid-state lasers are generally used in material processing.

The generally used gas lasers are

- Helium – Neon
- Argon
- CO_2 etc.

Lasers can be operated in continuous mode or pulsed mode. Typically CO_2 gas laser is operated in continuous mode and Nd – YAG laser is operated in pulsed mode.

10. Laser Construction

Fig. 9.6.10 shows a typical Nd-YAG laser. Nd-YAG laser is pumped using flash tube. Flash tubes can be helical, as shown in Fig. 9.6.10, or they can be flat. Typically the lasing material is at the focal plane of the flash tube. Though helical flash tubes provide better pumping, they are difficult to maintain.

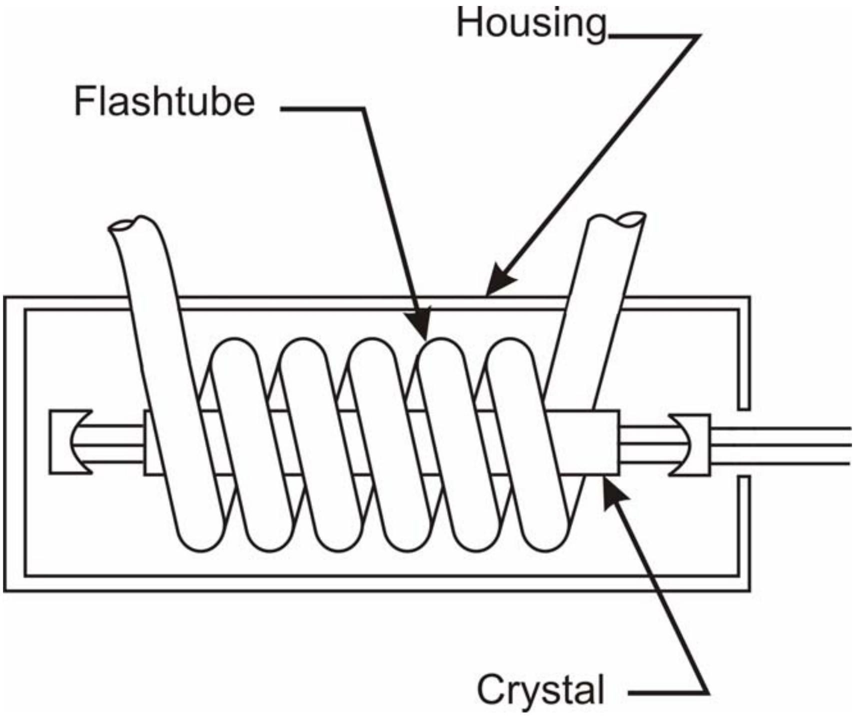


Fig. 9.6.10 Solid-state laser with its optical pumping unit

Fig. 9.6.11 shows the electrical circuit for operation of a solid-state laser. The flash tube is operated in pulsed mode by charging and discharging of the capacitor. Thus the pulse on time is decided by the resistance on the flash tube side and pulse off time is decided by the charging resistance. There is also a high voltage switching supply for initiation of pulses.

Fig. 9.6.12 shows a CO_2 laser. Gas lasers can be axial flow, as shown in Fig. 9.6.12, transverse flow and folded axial flow as shown in Fig. 9.6.13. The power of a CO_2 laser is typically around 100 Watt per metre of tube length. Thus to make a high power laser, a rather long tube is required which is quite inconvenient. For optimal use of floor space, high-powered CO_2 lasers are made of folded design.

In a CO_2 laser, a mixture of CO_2, N_2 and He continuously circulate through the gas tube. Such continuous recirculation of gas is done to minimize

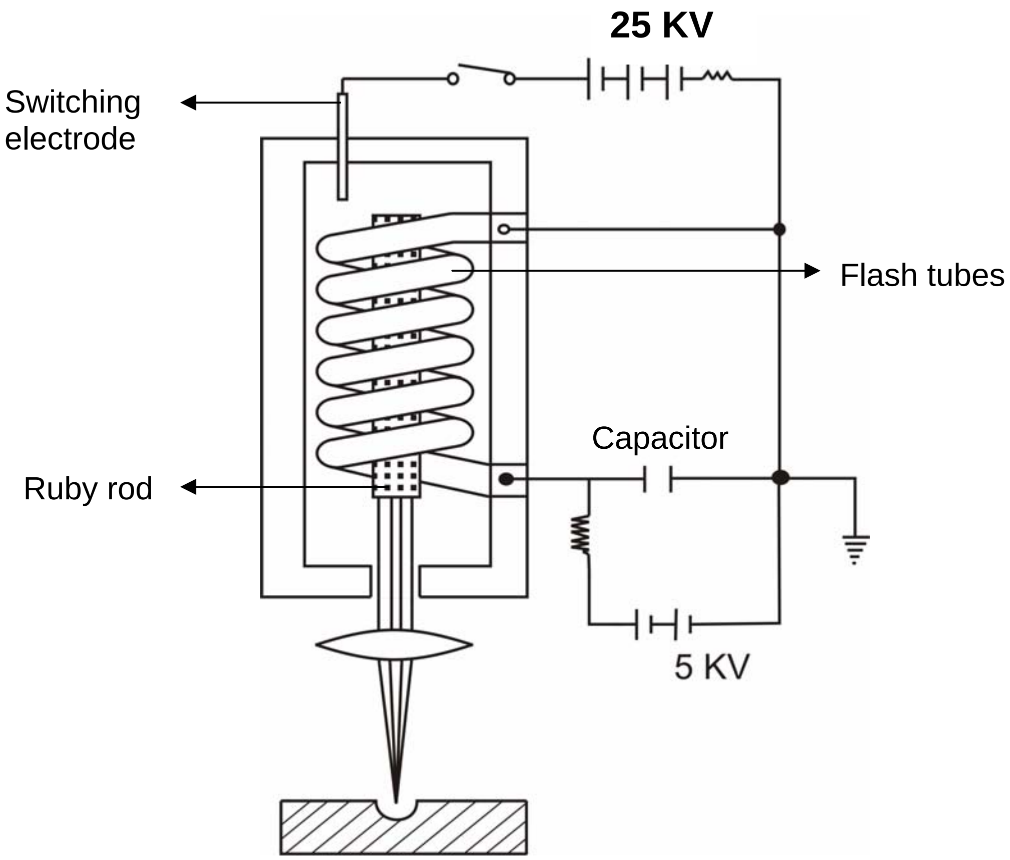


Fig. 9.6.11 *Working of a solid-state laser*

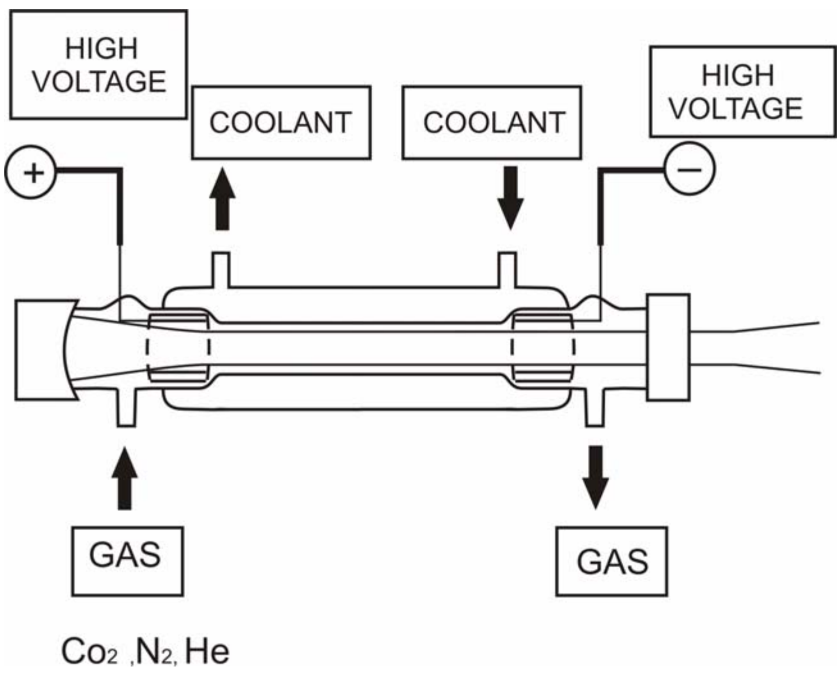


Fig. 9.6.12 *Construction of a CO_2 laser*

consumption of gases. CO_2 acts as the main lasing medium whereas Nitrogen helps in sustaining the gas plasma. Helium on the other hand helps in cooling the gases.

As shown in Fig. 9.6.12 high voltage is applied at the two ends leading to discharge and formation of gas plasma. Energy of this discharge leads to population inversion and lasing action. At the two ends of the laser we have one 100% reflector and one partial reflector. The 100% reflector redirects the photons inside the gas tube and partial reflector allows a part of the laser beam to be issued so that the same can be used for material processing. Typically the laser tube is cooled externally as well.

As had been indicated earlier CO_2 lasers are folded to achieve high power. Fig. 9.6.13 shows a similar folded axial flow laser. In folded laser there would be a few 100% reflective turning mirrors for manoeuvring the laser beam from gas supply as well as high voltage supply as shown in Fig. 9.6.13.

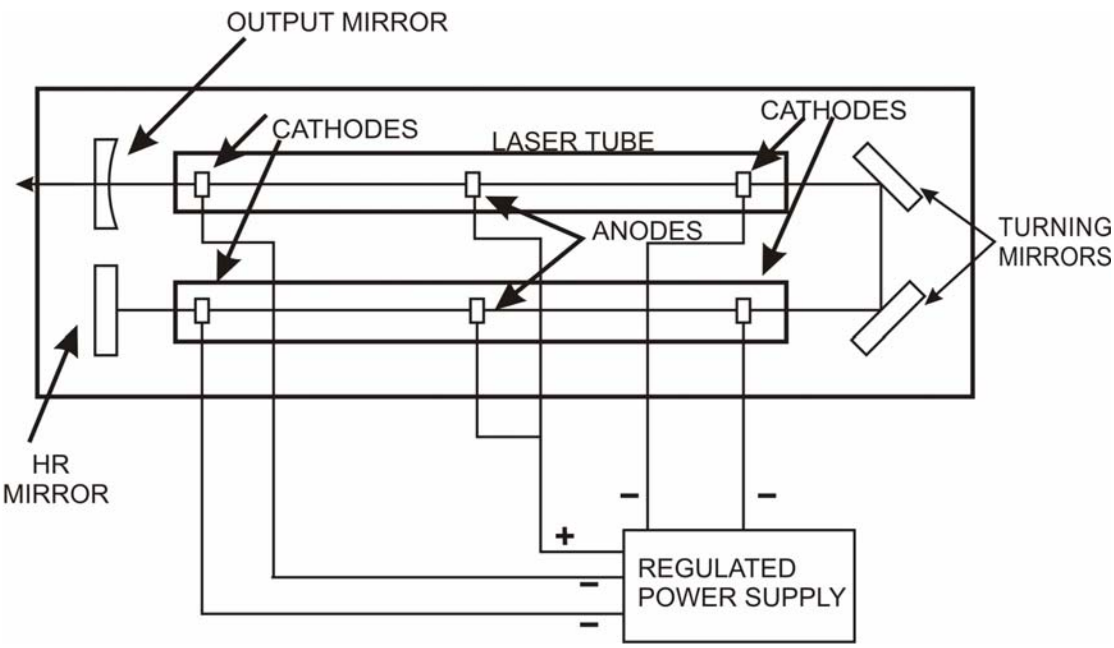


Fig. 9.6.13 *Construction of folded gas laser*

Table 9.6.1 shows the capability and characteristics of common lasers.

Table 9.6.1 Process characteristics of different lasers

Application	Type of laser
Large holes upto 1.5 mm dia. Large holes (trepanned) Small holes > 0.25 mm dia. Drilling (punching or percussion)	Ruby, Nd-glass, Nd-YAG Nd-YAG, CO_2 Ruby, Nd-glass, Nd-YAG Nd-YAG, Ruby
Thick cutting Thin slitting of metals Thin slitting of plastics	CO_2 with gas assist Nd-YAG CO_2
Plastics Metals Organics, Non-metal Ceramics	CO_2 Nd-YAG, ruby, Nd-glass Pulsed CO_2 Pulsed CO_2, Nd-YAG

Lasing materials	Ruby	**Nd-YAG**	Nd-glass	**CO_2**
Type	Solid state	**Solid state**	Solid state	**Gas**
Composition	0.03 – 0.7% Nd in Al_3O_2	**1% Nd doped Yttrium – Aluminium-Garnet**	2-6% Nd in glass	**CO_2+He+N_2 (3:8:4)**
Wavelength (radiation)	0.69 μm	**1.064 μm**	1.064 μm	**10.6 μm**
Efficiency	1% max.	**2%**	2%	**10-15%**
Beam mode	Pulsed or CW	**Pulsed or CW**	Pulsed	**Pulsed or CW**
Spot size	0.015 mm	**0.015 mm**	0.025 mm	**0.075 mm**
Pulse repetition rate (normal operation).	1-10 pps	**1-300 pps or CW**	1-3 pps	**CW**
Beam output	10-100 W	**10-1000 W**	10 – 100 W	**0.1 – 10 kW**
Peak power	200 kW	**400 kW**	200 kW	**100 kW**

11. Laser Beam Machining – Application

Laser can be used in wide range of manufacturing applications

- Material removal – drilling, cutting and tre-panning
- Welding
- Cladding
- Alloying

Drilling micro-sized holes using laser in difficult – to – machine materials is the most dominant application in industry. In laser drilling the laser beam is focused over the desired spot size. For thin sheets pulse laser can be used. For thicker ones continuous laser may be used.

12. Laser Beam Machining – Advantages

- In laser machining there is no physical tool. Thus no machining force or wear of the tool takes place.
- Large aspect ratio in laser drilling can be achieved along with acceptable accuracy or dimension, form or location
- Micro-holes can be drilled in difficult – to – machine materials
- Though laser processing is a thermal processing but heat affected zone specially in pulse laser processing is not very significant due to shorter pulse duration.

13. Laser Beam Machining – Limitations

- High initial capital cost
- High maintenance cost
- Not very efficient process
- Presence of Heat Affected Zone – specially in gas assist CO_2 laser cutting
- Thermal process – not suitable for heat sensitive materials like aluminium glass fibre laminate as shown in Fig.9.6.14

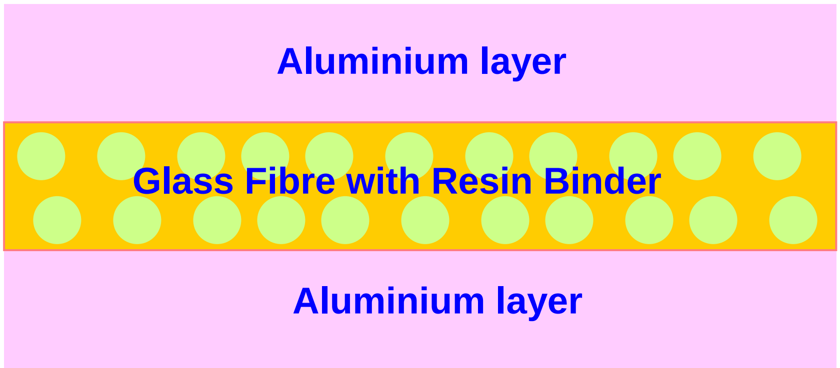


Fig. 9.6.14 Aluminium Glass Fibre Laminate – heat sensitive glass fibre layer due to presence of resin as binder

Quiz Questions

1. Mechanism of material removal in Electron Beam Machining is due to

a) Mechanical erosion due to impact of high of energy electrons
b) Chemical etching by the high energy electron
c) Sputtering due to high energy electrons
d) Melting and vaporisation due to thermal effect of impingement of high energy electron

Answer – (d)

2. Mechanism of material removal in Laser Beam Machining is due to

a) Mechanical erosion due to impact of high of energy photons
b) Electro-chemical etching
c) Melting and vaporisation due to thermal effect of impingement of high energy laser beam
d) Fatigue failure

Answer – (c)

3. Generally Electron Beam Gun is operated at

a) Atmospheric pressure
b) At 1.2 bar pressure above atmosphere
c) At 10 – 100 mTorr pressure
d) At 0.01 – 0.001 mTorr pressure

Answer – (d)

4. Laser Beam is produced due to

a) Spontaneous emission
b) Stimulated emission followed by spontaneous emission
c) Spontaneous emission followed by Spontaneous absorption
d) Spontaneous absorption leading to "population inversion" and followed by stimulated emission

Answer – (d)