Jigs & Fixtures

Introduction:

- The world’s demand for manufactured goods is growing rapidly.
- From the evolution of CNC and CAM, the art of manufacturing has undergone many dramatic changes and advances.
- Every industry is finding the way of increasing their production to its maximum. These changes have created a need of for most cost-effective and efficient work holding methods and devices.
- Despite the many advancements and changes in cutting tools, machine tools, and production methods, the basic requirement of holding the workpiece has remained constant.

Introduction:

- The accuracy of any product manufactured by machining is based on various cutting parameters, skill of operator, alignment of machine tool, relative movement between job and how the job and tool are clamped with respect to one another.

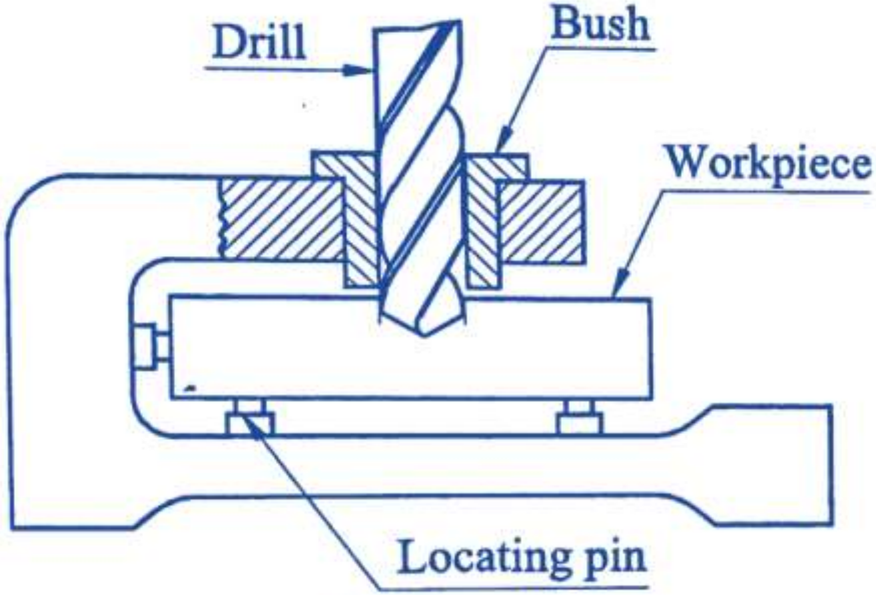
- Mainly arrangement for clamping the tool is made in all the machine tools while for clamping the work piece arrangement is to be done.

- The equipments used for clamping and holding the workpiece are called Jigs & Fixtures.

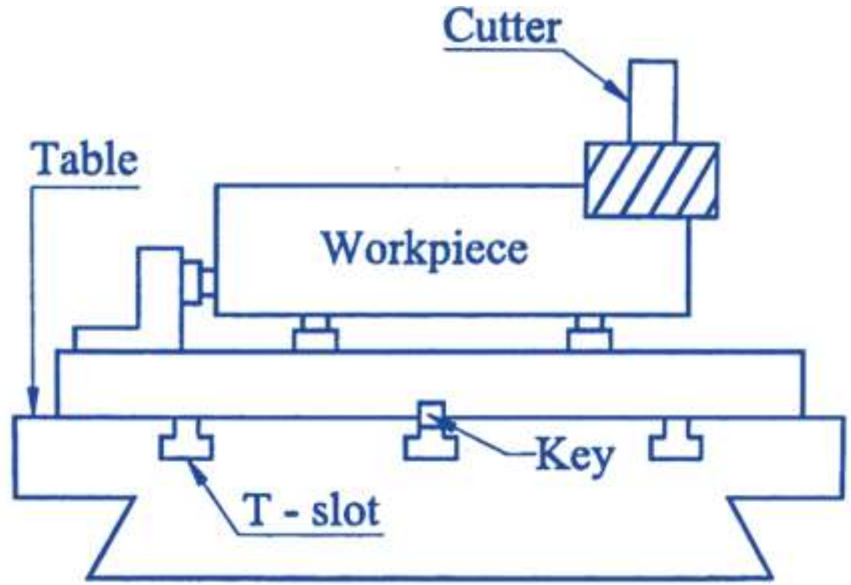
- The equipments generally used for holding the workpiece like chuck, mandrel, different types of vices, collets, etc., are easily available in the market so there is no need of designing them.

Concept:

- **The Jigs and Fixtures are the equipments for obtaining required accuracy of the product.**
- **They arrange the job with respect to cutting tool as needed and hold it firmly.**
- **This will not allow the job to move during machining operations and intended operations can be performed at right place and obtaining the required result.**
- **Jig also performs the additional function of guiding the tool.**
- **The basic aim of using jigs and fixtures is to produce the components or workpiece economically & as per required quality level.**


Drill
Bush
Workpiece
Locating pin

Jig


Cutter
Table
Workpiece
Key
T - slot

Fixture

Definitions:

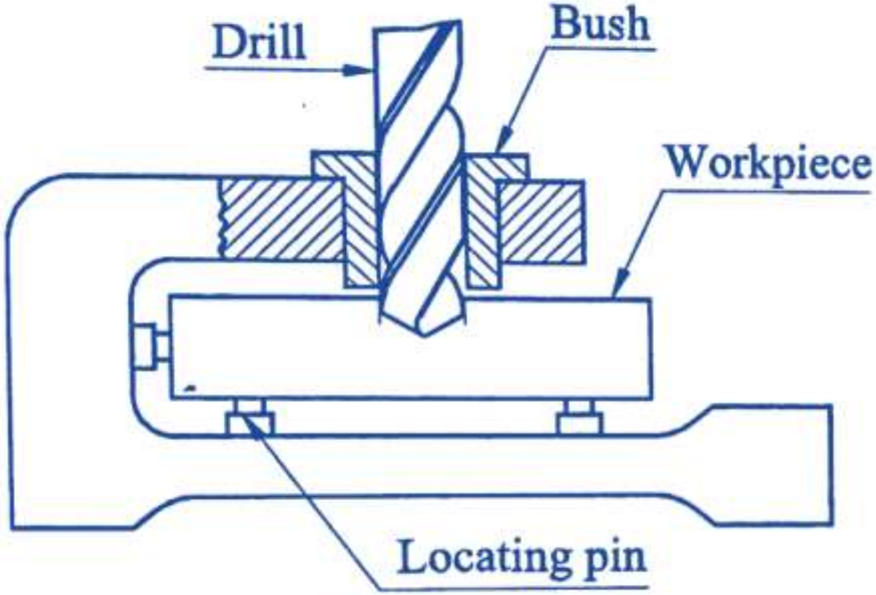
- **Jigs: A jig may be defined as a work holding device generally used in a drill press in conjunction with drill bushings for guiding the tools so that drills will produce holes only where the bushing are located in the drill jig.**

- **A jig may be also defined as a device used in mass production for increasing the productivity by correctly location & firmly holding the workpiece as well as guiding the cutting tool.**

Definitions:

- **Fixture:** **A fixture may be defined as a device used to increase manufacturing efficiency and productivity in mass production. It locate the workpiece in correct position and hold it firmly but it does not have provision for guiding the cutting tool.**

- **Set blocks and feeler or thickness gauges are used with fixtures to reference the cutter to the workpiece**


Drill
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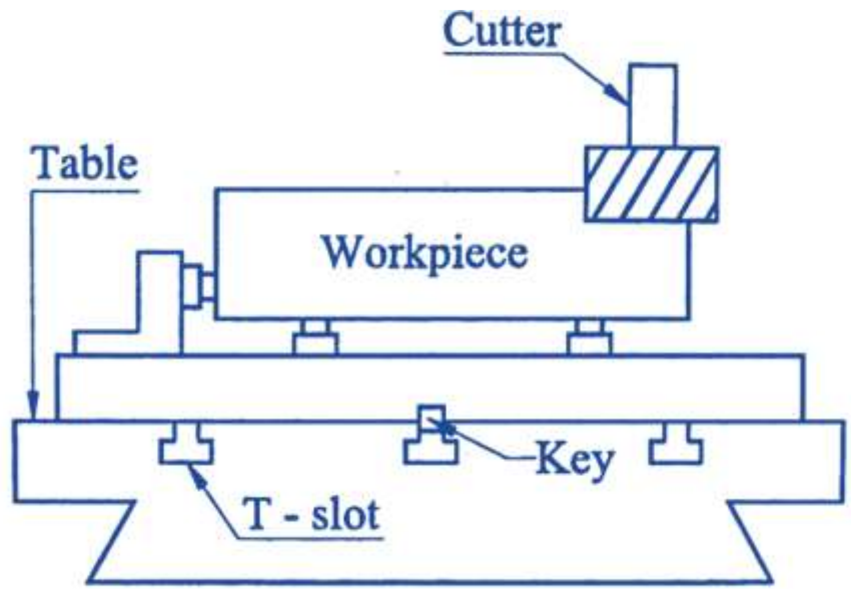
Jig


Cutter
Table
Workpiece
Key
T - slot

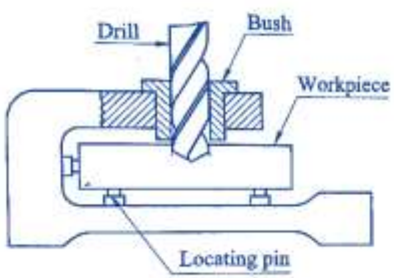
Fixture

General Principles of Jig & Fixture Design:

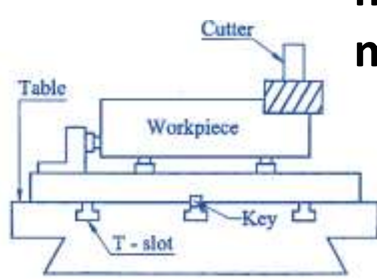
1. **Easy & Simple.**
2. **Reduction in ideal time.**
3. **Strength & Rigidity.**
4. **Method of object removal.**
5. **Control of wear.**
6. **Effect of heat.**
7. **Tool Guiding.**
8. **Tool Setting.**
9. **Table Fixing.**
10. **Clearance.**
11. **Location.**
12. **Swarf Clearance.**
13. **Clamping.**
14. **Fool-proofing.**
15. **Safety.**
16. **Accuracy.**
17. **Fatigue.**
18. **Handling, etc.**

Difference between Jig & Fixture Design:

Jig	Fxture
1. It guides the cutting tool.	1. It does not guides the cutting tool.
2. It is mostly attached to the machine table.	2. It is always attached with the machine table.
3. It is generally light in weight than the fixture.	3. Fixture is generally heavier than the Jig.
4. Jig feet is used in its construction.	4. In its construction such feet is not used.
5. Bushes are used in a jig for guiding the cutting tool.	5. Bushes are not used in fixtures.
6. It is specially used for drilling, reaming & boring operations.	6. It is specially used for milling, turning, grinding & broaching operations.
7. Jig is widely used on drilling machine.	7. Fixture is widely used on lathe, milling, grinding and broaching machines.



Jig



Fixture

Importance of Jigs & Fixtures:

- Total cycle time reduces. This reduction becomes possible due to saving in layout time and machining time. Less time is required for tool adjustment and wastage becomes negligible, therefore, productivity increases.
- Productivity also increases as simultaneous machining on more than one components can be done as well as more than one cutting tool can be used at a time.
- The marking and tool setting for individual component & machining operation is not required. The workpiece gets automatically located in right position. Tool is also guided and its setting is readily available, therefore manufacturing tolerances are maintained and interchangeable parts are produced.

Importance of Jigs & Fixtures:

- The use of jigs and fixtures helps in producing similar products hence the role in standardization is important.
- The process of standardization is made successful by them.
- Standard parts used in jigs and fixtures saves the design time and cost and make the production method simple.
- Inspection process become simple and fast.
- Therefore efficiency and economy is obtain by standardization.

Main Elements of Jigs and Fixtures :

1.Body : it is a frame, plate or box type structure that holds the work piece. It should be rigid and stable.

2.Locating system : This system is used to locate the work piece properly in relation to cutting or forming tools.

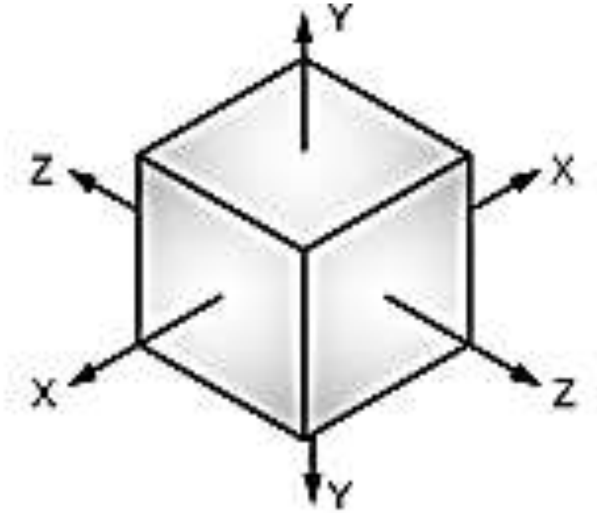
3.Clamping system : Work piece is clamped firmly in located position with the help of clamping elements.

4.Guiding and setting elements : These elements are used to guide the tool in the case of jigs and help in proper setting of the tool in fixtures.

5.Positioning elements : These consist of different fastening devices needed for securing the jig or fixture to the machine.

6.Indexing elements : These are not needed always but are necessary for the jigs and fixtures used for machining work pieces involving operation at many places on the work piece surface.

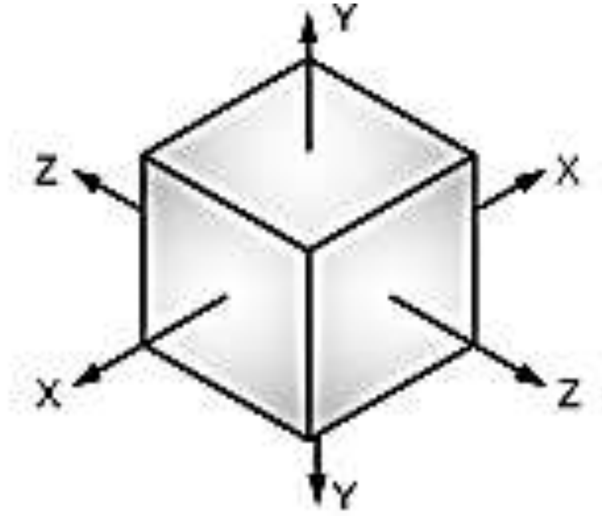
Three-Two-One Locating Principle



- All possible movements of an object in space can be described with reference to linear motions along three perpendicular axes defining space and three rotations about these axes.

- These six basic movements can take place in a total of 12 different directions.

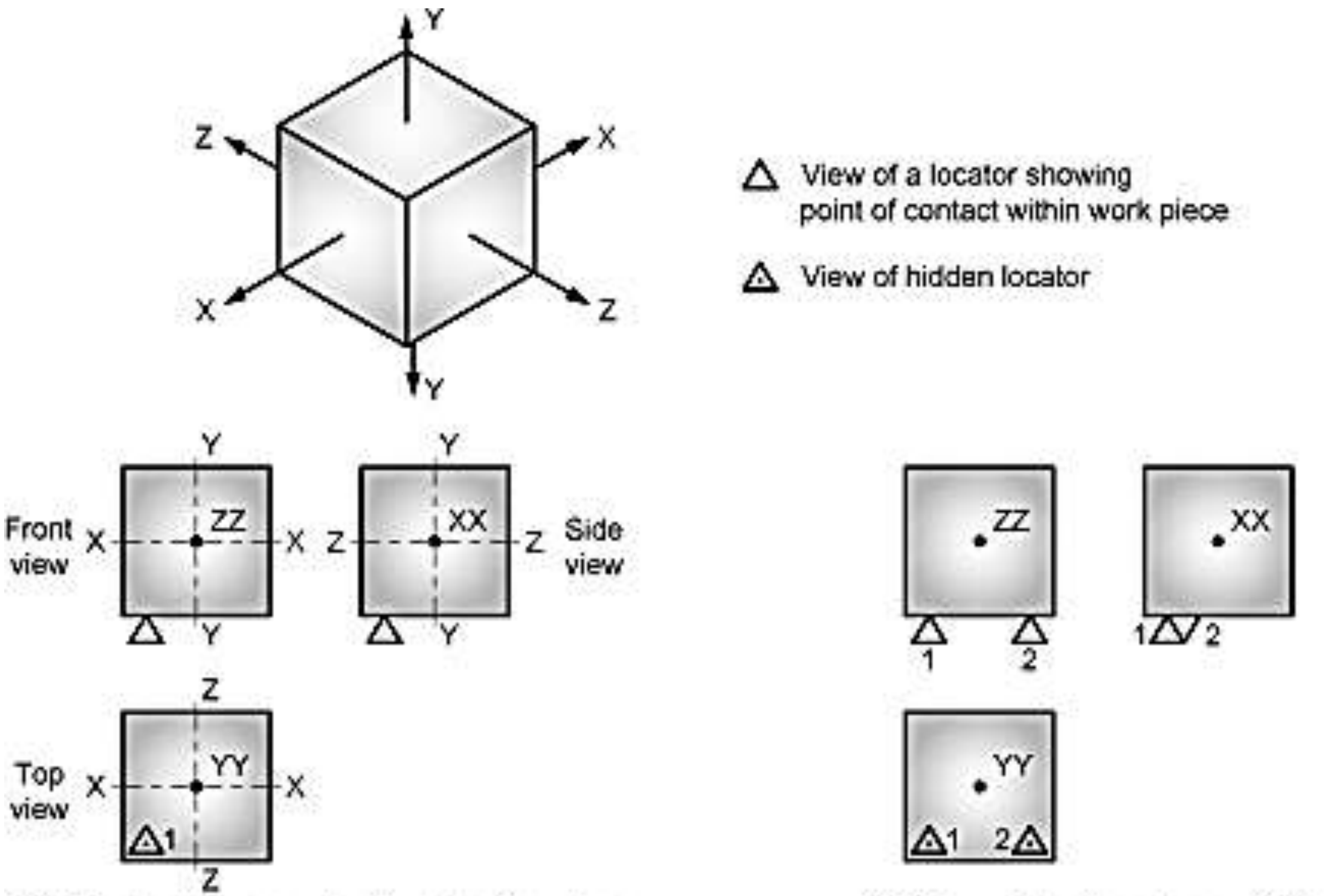
Three-Two-One Locating Principle



•The location system must stop movement in six directions of movements and the clamping forces must stop the others in the opposite directions.

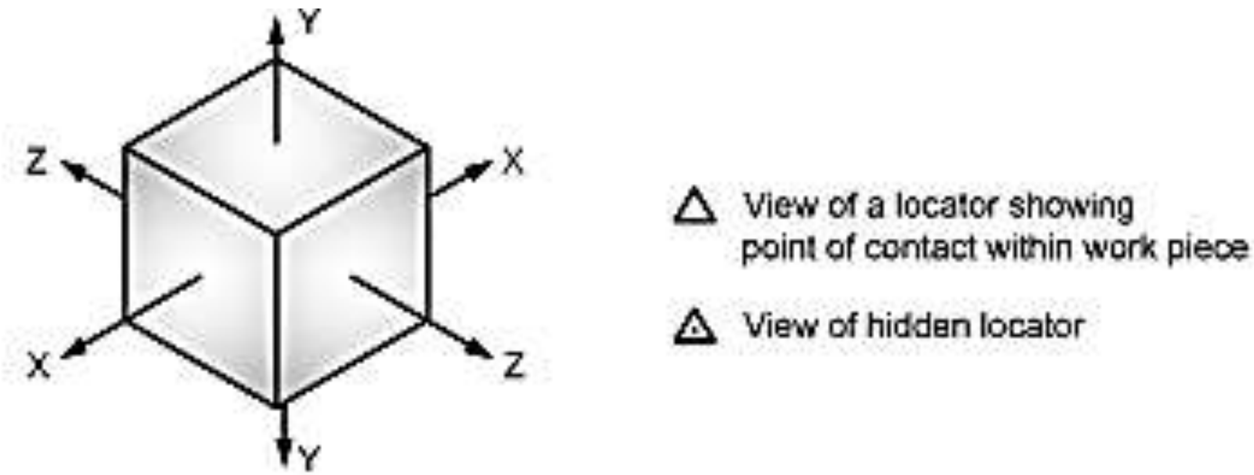
•A definite pattern of placement of locators should be developed to constrain the movement of a body in space.

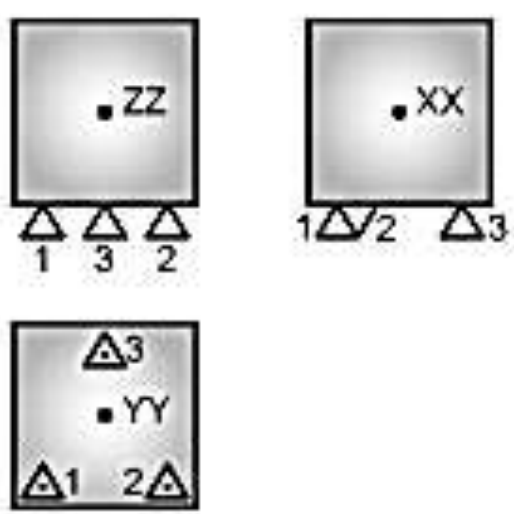
•To illustrate the system of location, the movements of a cube in space are considered. The pattern of arrangement is called the 3-2-1 location system. A triangle symbol is used to schematically represent a locator.



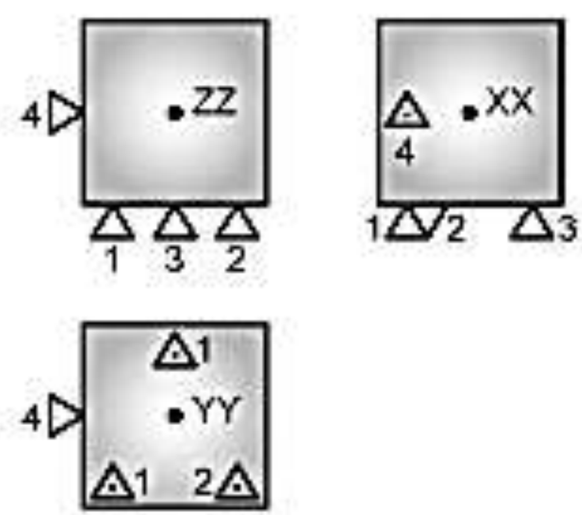
(a) One locator on cube. One locator stops linear movement downward along axis Y-Y

(b) Second locator stops rotation about Z-Z axis

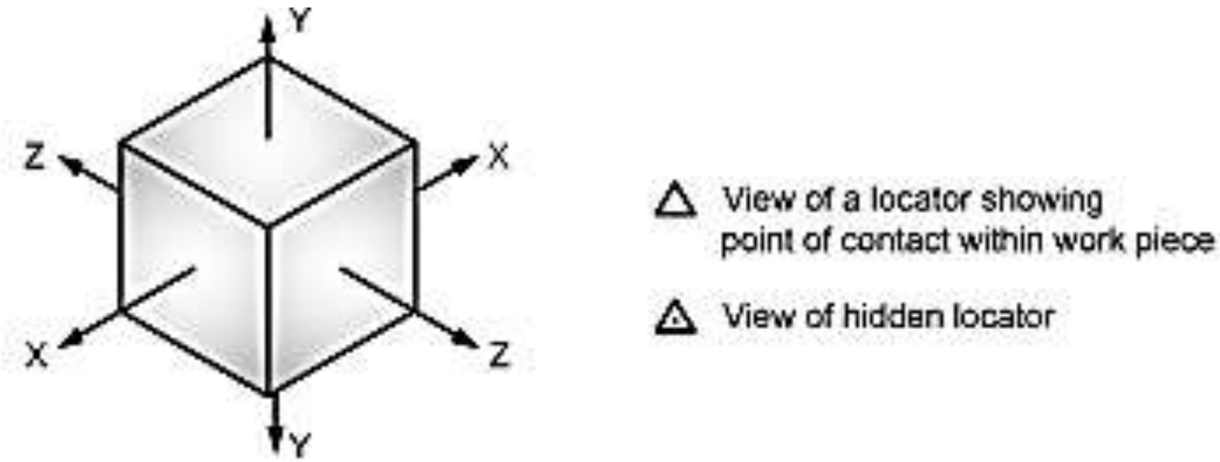


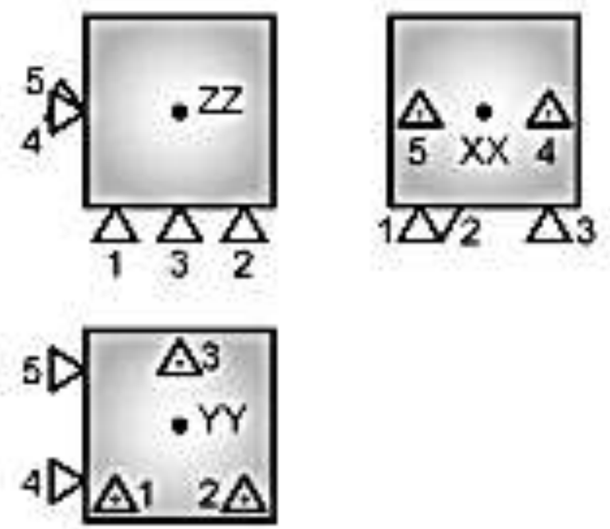


(c) Third locator stops rotation about X-X axis

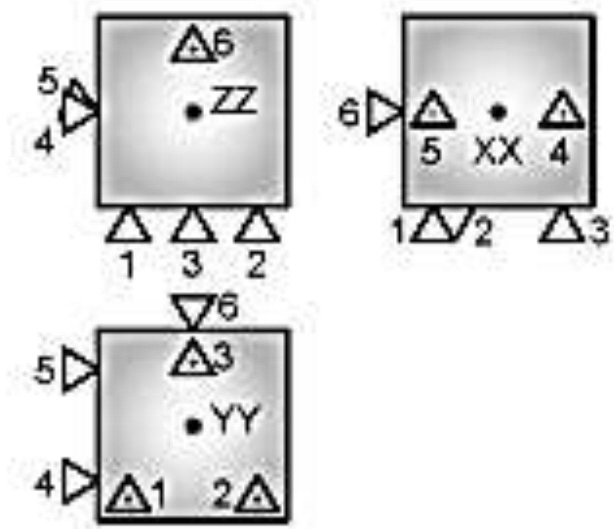


(d) Fourth locator stops linear motion along X-X to the left





(c) Fifth locator stops rotation about Y-Y axis



(f) Sixth locator stops linear motion inward along axis Z-Z

The Location System:

- Locators are parts of a jig or fixture that ensure that the work piece is located in a proper position.
- Locators are designed depending on the shape and requirements of the work.
- Locators are usually made separate from the jig or fixture and consist of units made from tough or case hardened steel accurately ground to size and precisely positioned in the jig or fixture body where required.
- Locator shape is a function of the work piece feature used for location.

Pads, pins and buttons :

- These locators control the work piece from flat surfaces or from a profile.
- A round pin or button is used to support the job firmly and hold it in position.
- The main difference between pins and buttons is in length. Buttons are shorter in length than pins and are generally used for vertical location.
- Larger sizes of pins are sometimes referred to as Plugs.
- The locator is an interference fit in the base and a good seat is provided by chamfering the location bore and under cutting the pad under the head

Pads, pins and buttons :

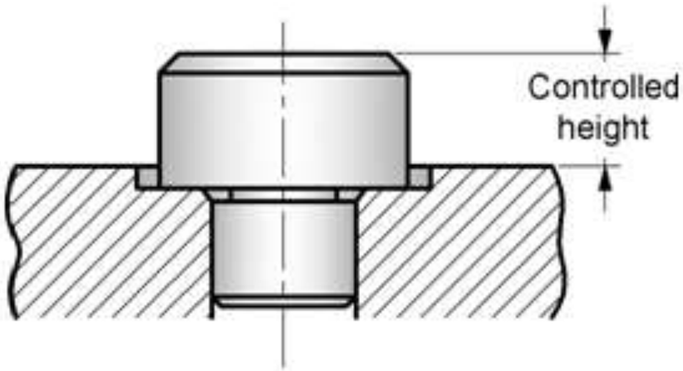


Fig. 5.3.4 : Location pad

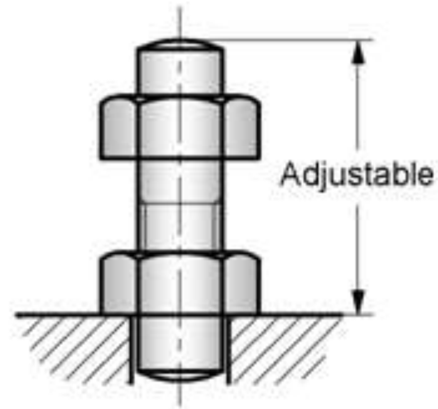


Fig. 5.3.5 : Adjustable pin (pad)

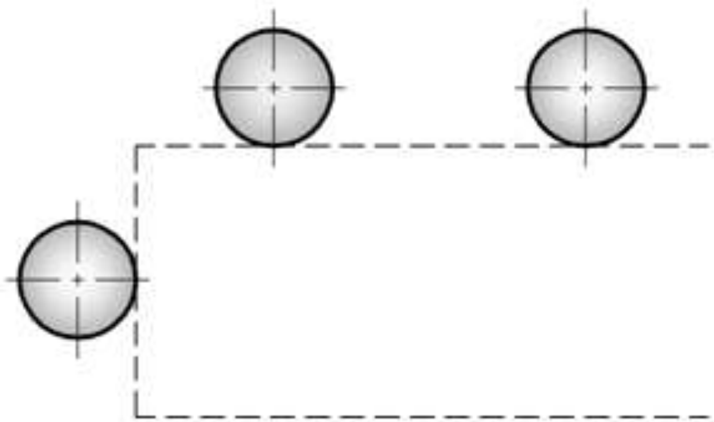


Fig. 5.3.6 : Pins used to locate a rectangular work piece

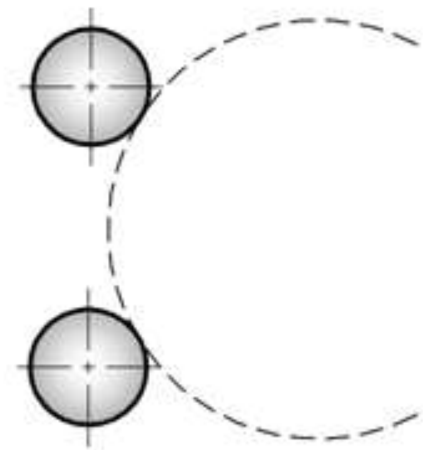


Fig. 5.3.7 : Pins used to locate cylindrical work piece

Cylindrical locators :

- These locators control the work piece from flat surfaces or from a profile.

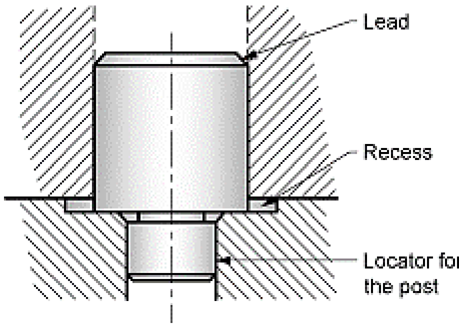
- A round pin or button is used to support the job firmly and hold it in position.

- The main difference between pins and buttons is in length. Buttons are shorter in length than pins and are generally used for vertical location.

- Larger sizes of pins are sometimes referred to as Plugs.

- The locator is an interference fit in the base and a good seat is provided by chamfering the location bore and under cutting the pad under the head

Cylindrical locators :



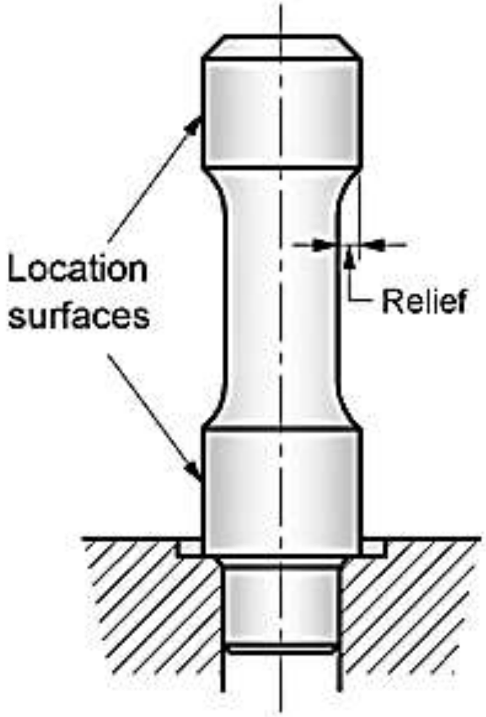


Fig. 5.3.9 : Long location post with central portion relieved

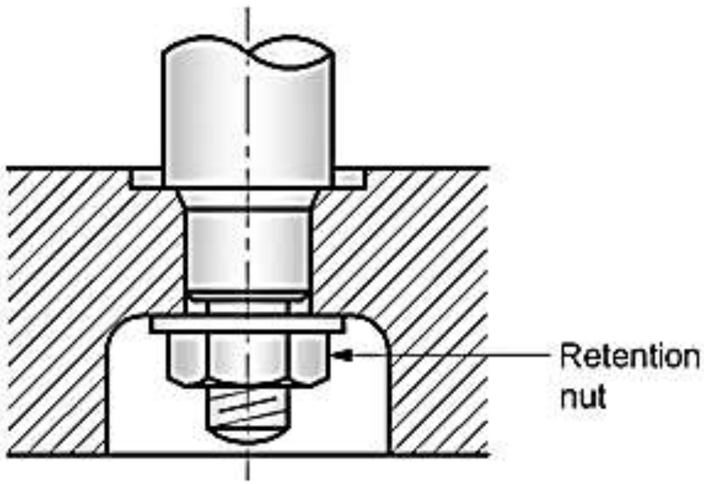
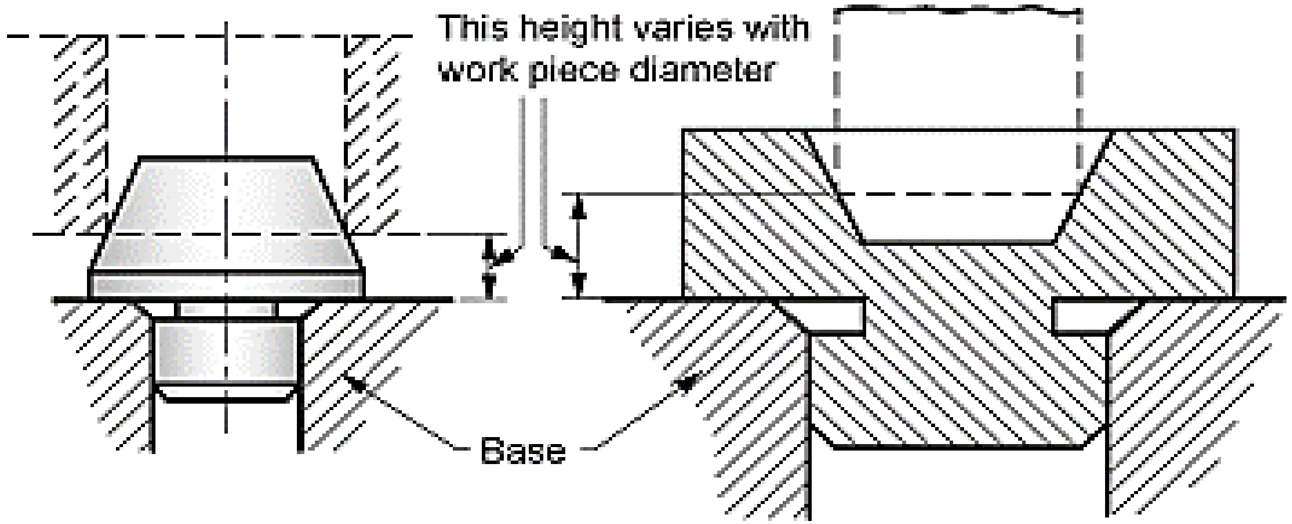
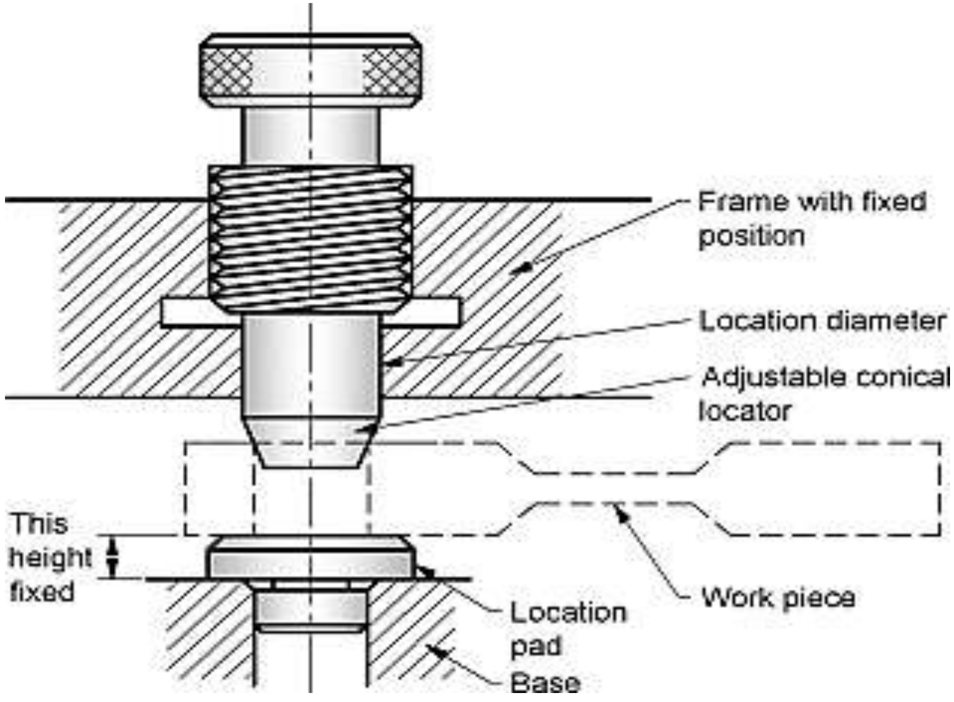


Fig. 5.3.10 : Locator retention by the use of a nut

Conical locators :





Vee locators :

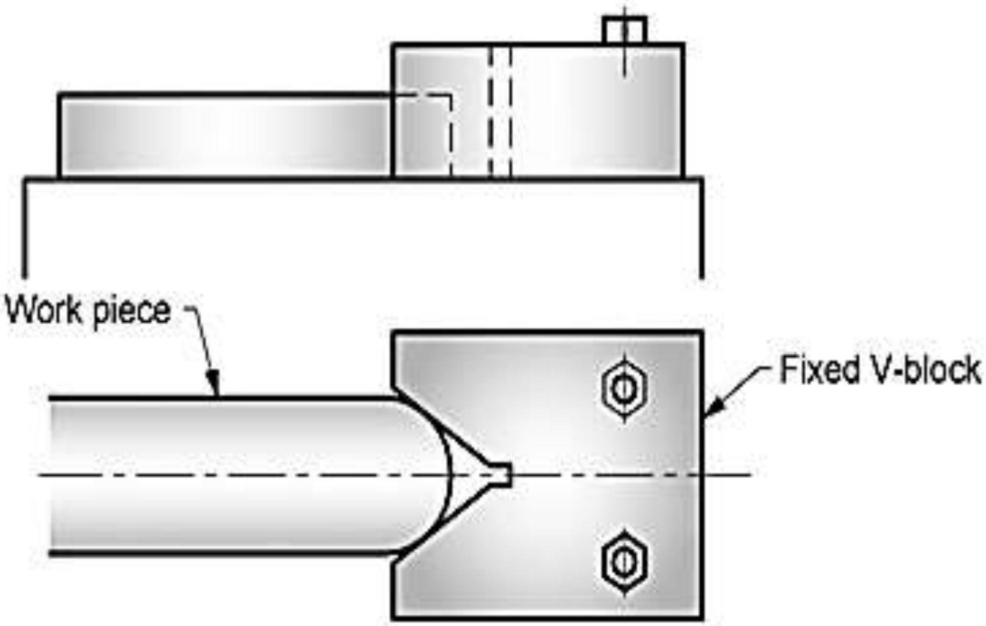


Fig. 5.3.15 : Fixed Vee locator

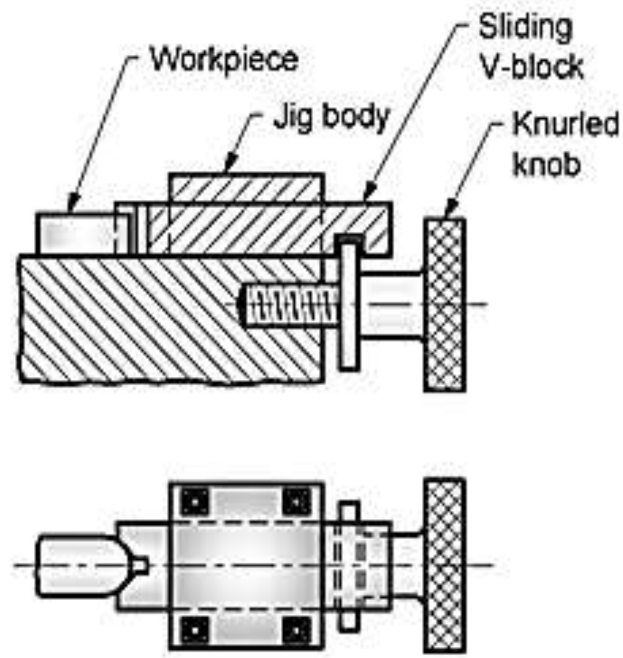


Fig. 5.3.16 : Sliding Vee locator

Clamping and Clamping Devices

Clamping :

- Aim of clamping is to establish contact between workpiece and location points or surface plus to hold the job firmly against disturbing forces.

- For to achieve this it is necessary to apply clamping force in proper direction and to maintain its pressure intensity constant.

Clamping :

- To perform this function effectively following points are considered:

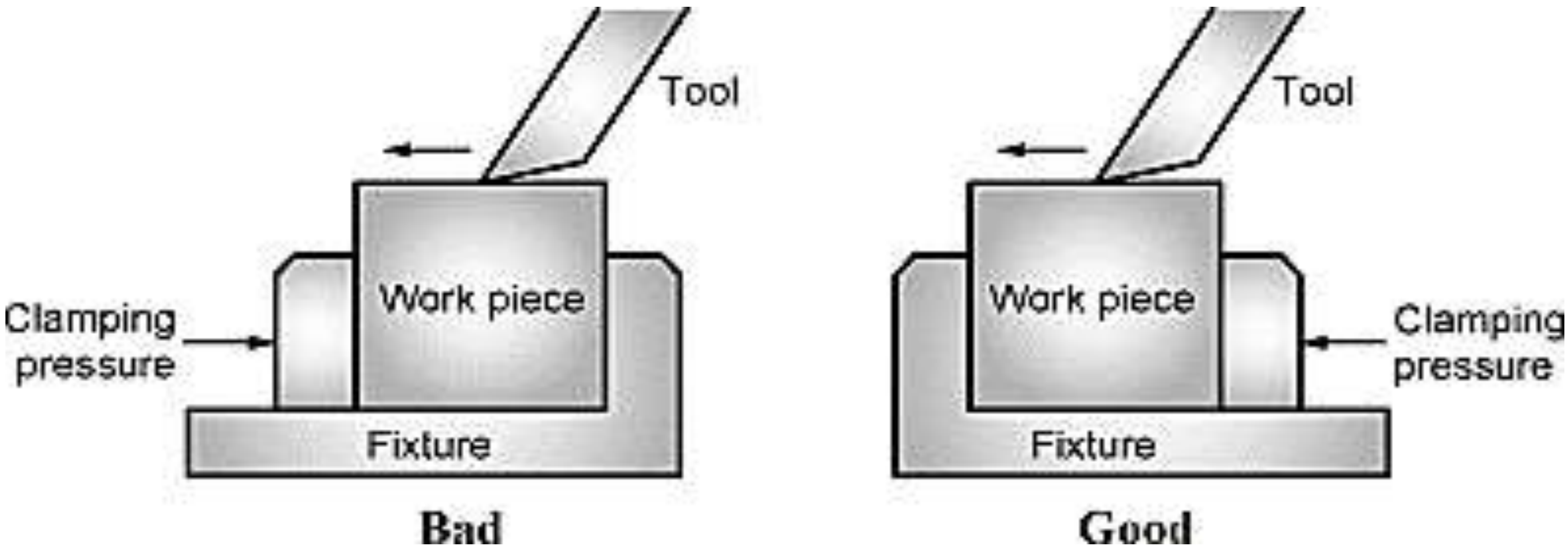
1. Clamp force required. The location and direction of clamping force.
2. Which mechanism is to be used to achieve this?
3. Whether to use simple clamp or fast clamp.
4. To decide the proportion of parts of the clamping device.

Clamping :

Following rules are to followed to achieve the objective:

- Do not provide clamping force against the cutting force.
- If possible clamping force should be kept parallel to the cutting force.
- The component should not be damaged or deformed due to clamping force.
- Clamping and cutting forces should be applied towards the locators.
- Clamping must be quick, easy and fool-proof.
- The clamping should not become loose during operation.
- Use pad when clamping is to be done on finished surfaces.

Clamping :


Tool
Work piece
Clamping pressure
Fixture
Bad
Tool
Work piece
Clamping pressure
Fixture
Good

Clamping Devices:

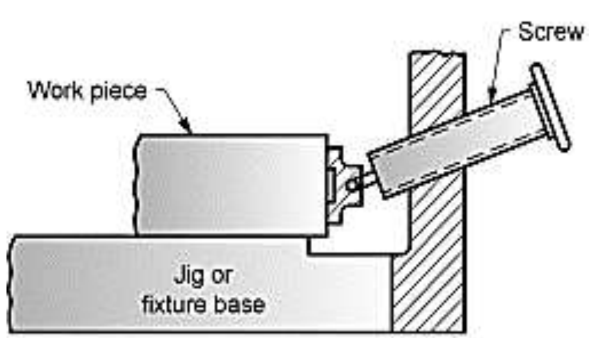
- Some of the commonly used clamping devices are discussed below.

- They can be divided into following groups :

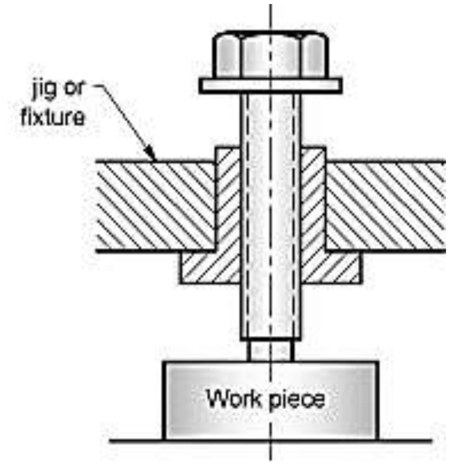
1. Screw clamps
2. Hook bolt clamps
3. Lever type clamps
4. Wedge clamps
5. Quick acting clamps.

1. Screw clamps:

- Screw clamps are simple clamps which are generally applied on the side face of the work piece thus leaving the top face free for machining.
- It carries a floating pad at the end to prevent work piece displacement and to prevent screw deflection. The pad remains stationary on the work piece while the screw rotates.
- The floating pad is attached to the screw by a pin, screw or ball.



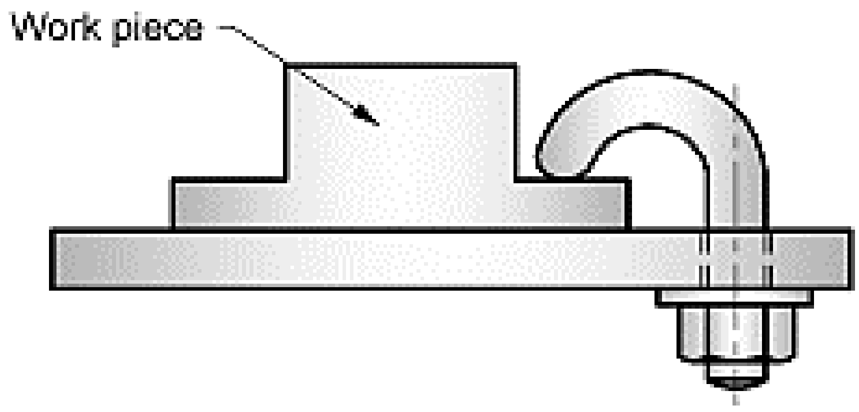
(a)



(b)

2.Hook bolt clamps :

- A hook bolt clamp shown in Fig. is a very simple device useful for light work.

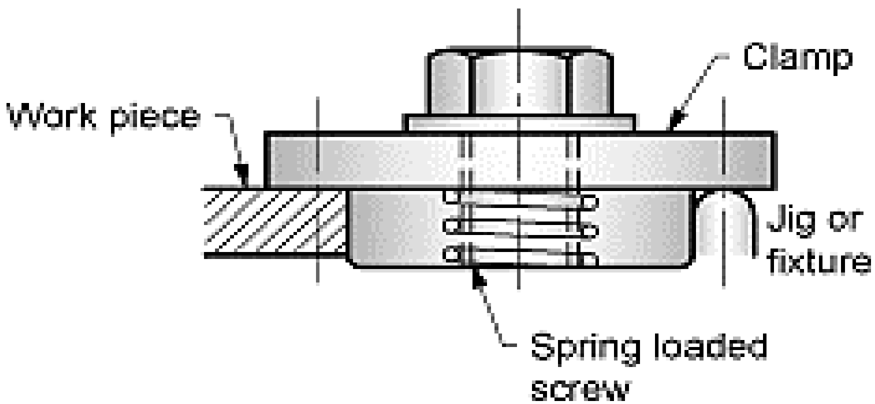


3.Lever type clamp :

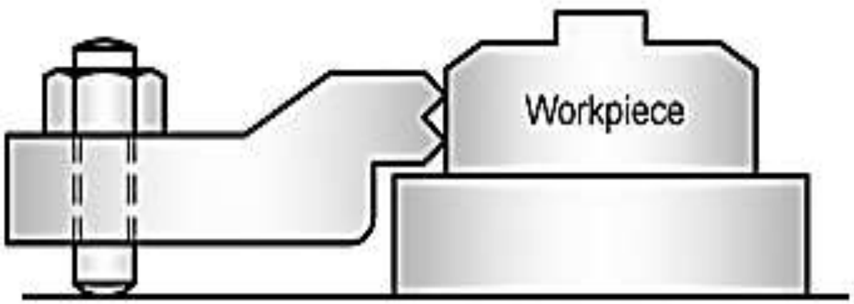
- Clamps of this type are available in number of designs. The most common of these designs are :

(i)Simple bridge clamps
(ii)Edge clamps
(iii)Heel clamps
(iv)Latch clamps
(v)Hinged clamps.

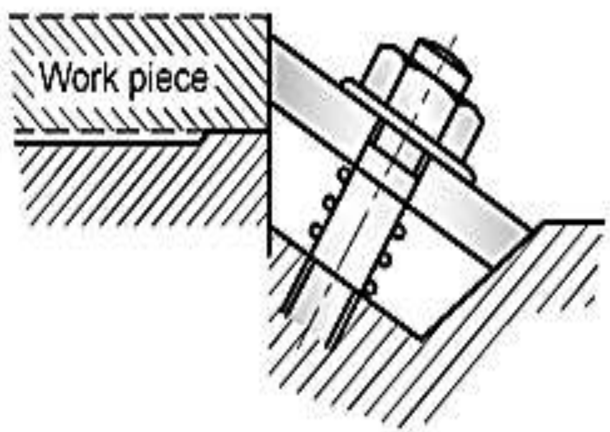
3.Lever type clamp :



Simple bridge clamp



(a)



(b)

Edge clamp

3.Lever type clamp :

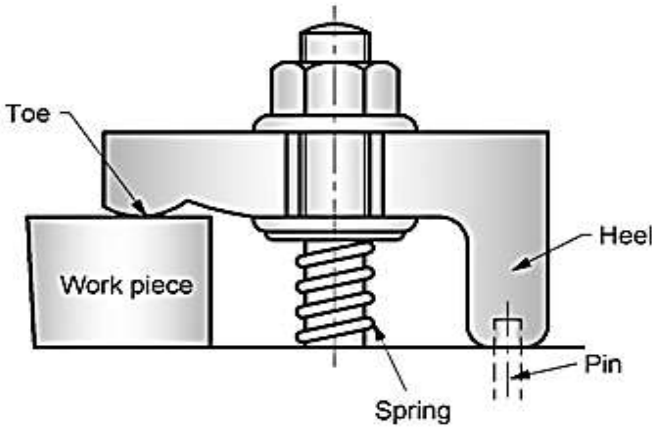


Fig. 5.4.6 : Solid heel clamp

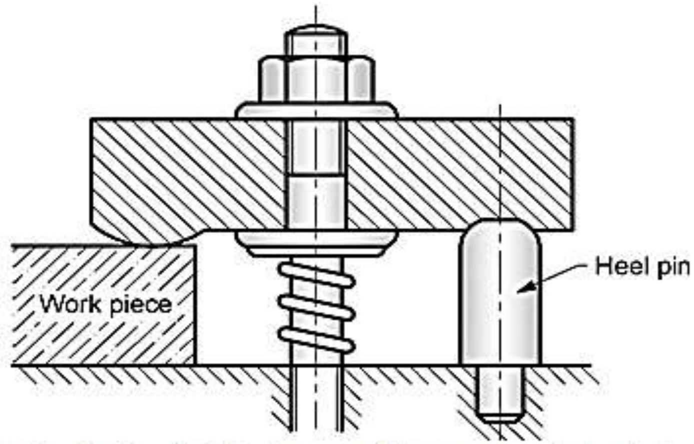
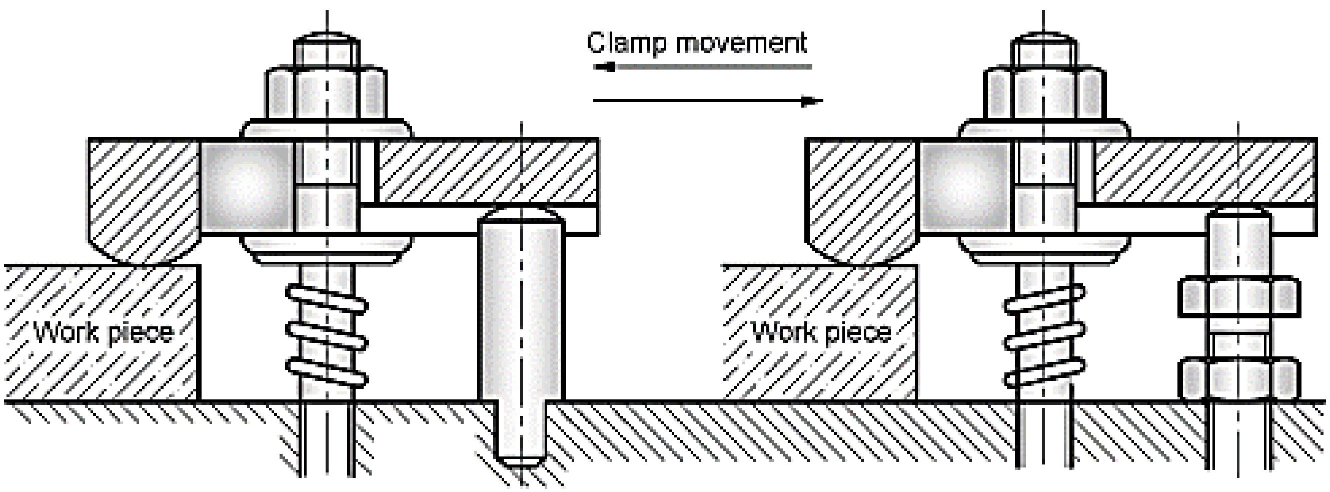


Fig. 5.4.7 : Solid clamp with a separate heel pin

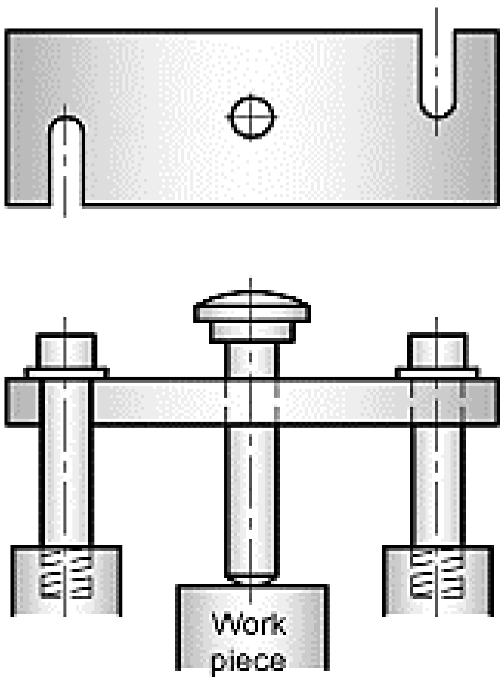


(a) Sliding clamp

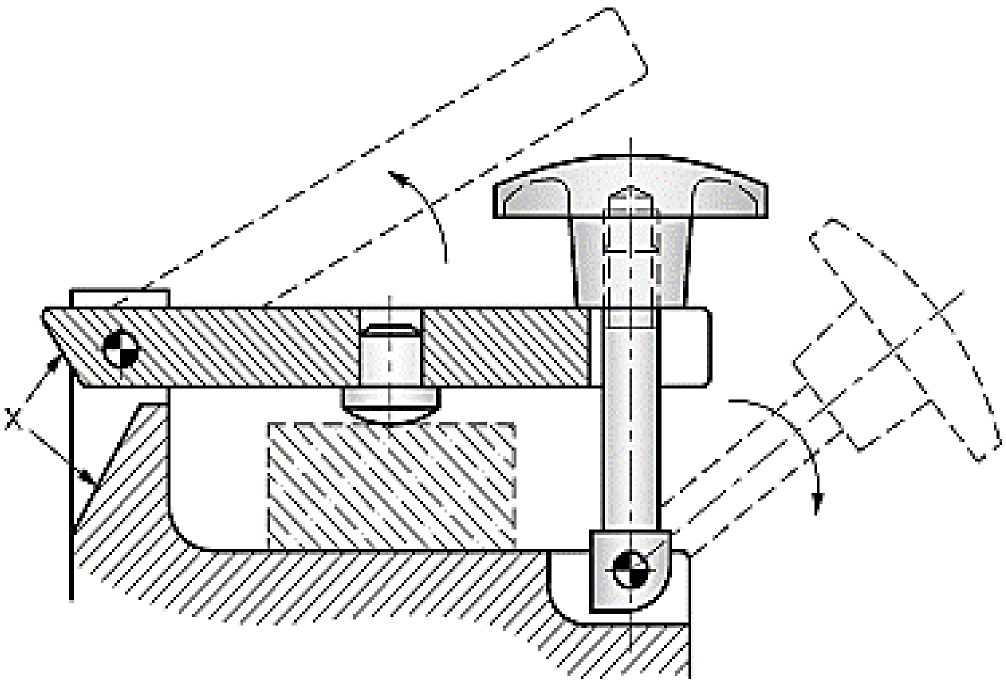
(b) Sliding clamp with adjustable heel pin

Clamps with sliding Heel plate

3.Lever type clamp :



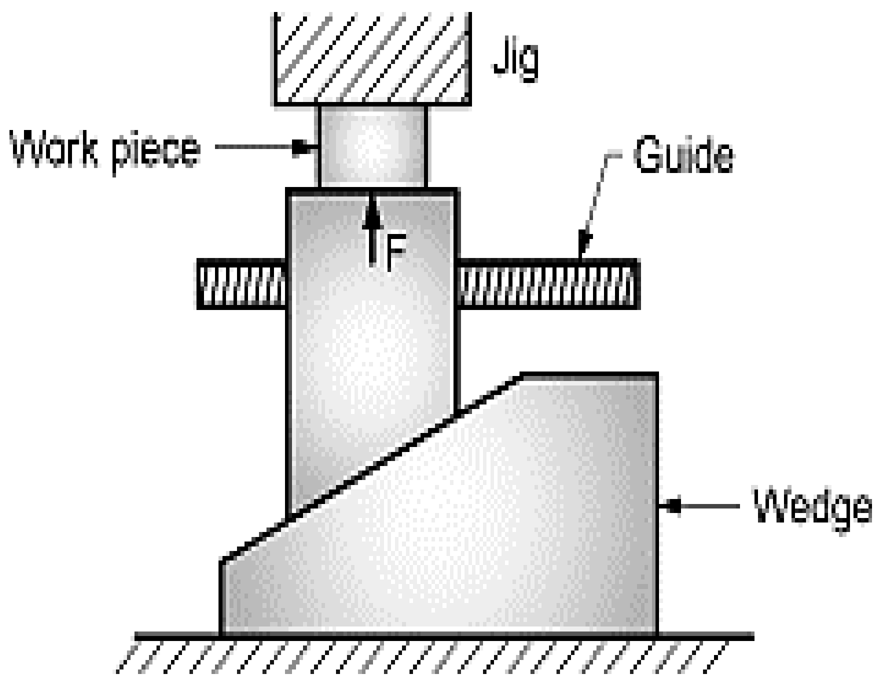
Swinging latch clamp



Hinged clamp

4.Wedge clamps :

- A wedge clamp shown in Fig. consist of a movable wedge that forces the workpiece against a fixed stop.
- The wedge has angle of 1 to 4 degree and is self holding.
- Horizontal movement of the wedge produces a vertical clamping force on the workpiece.



5.Quick Acting clamps :

- Quick acting clamps can be divided into the following groups

  (i)Swing washers and C washer clamps.
  (ii)Quick action nuts.
  (iii)Cam operated clamps.
  (iv)Toggle operated clamps.
  (v)Bayonet clamps

- These clamps are costlier than the other clamps but in the long run prove economical because of the reduced operation time.

5.Quick Acting clamps :

- Swing washer :

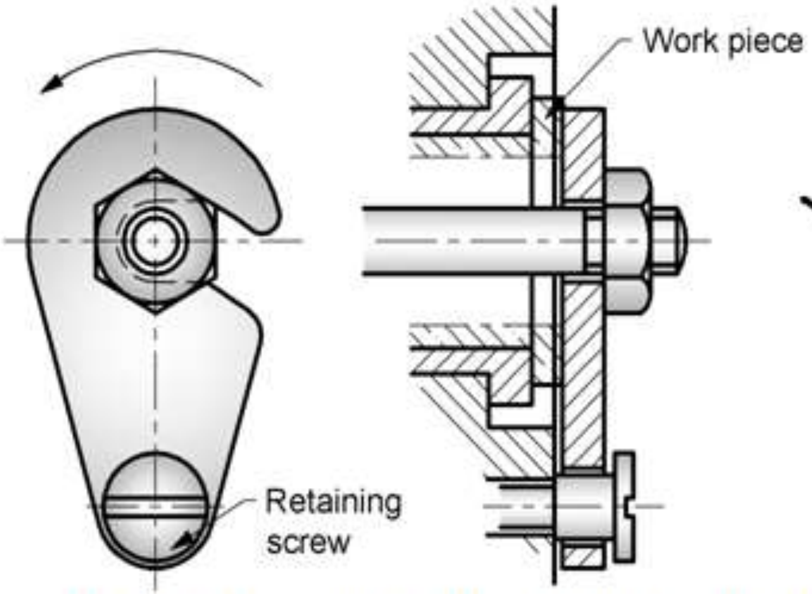


Fig. 5.4.12 : Swing washer and its application

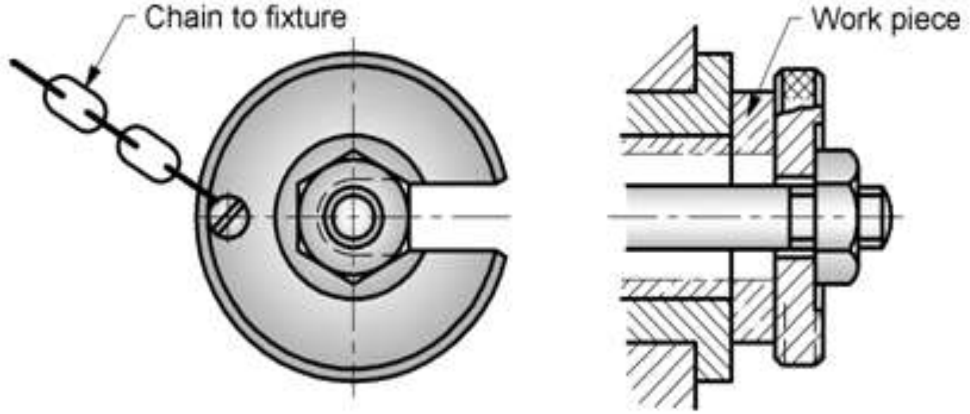
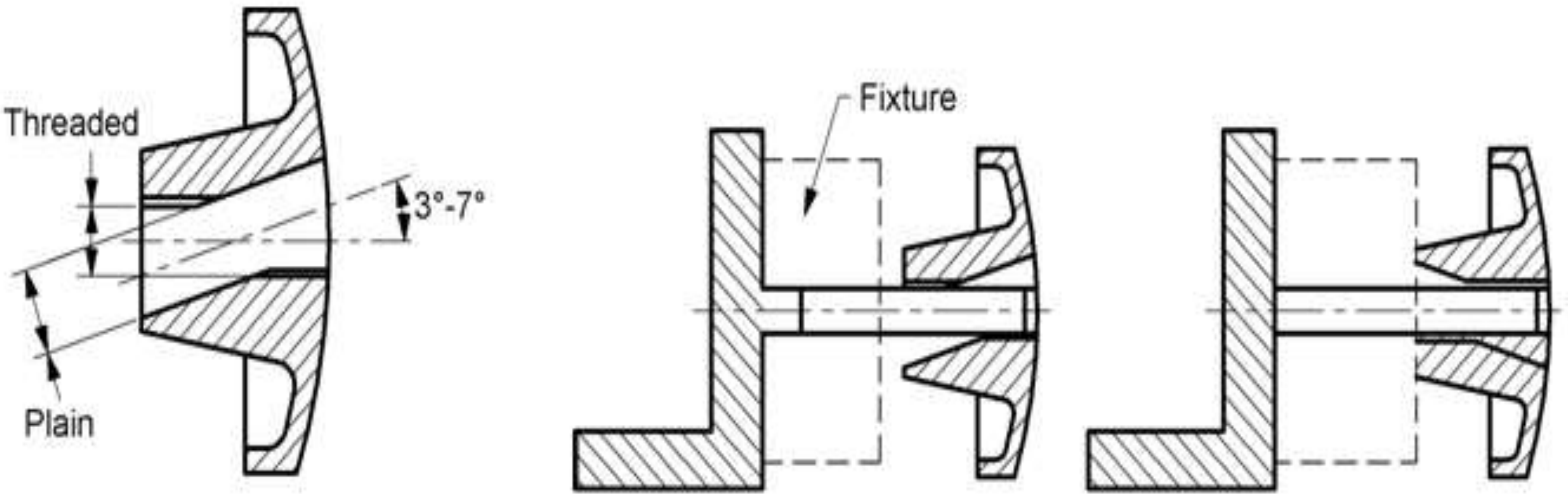


Fig. 5.4.13 : C washer

5.Quick Acting clamps :

Quick action nut :

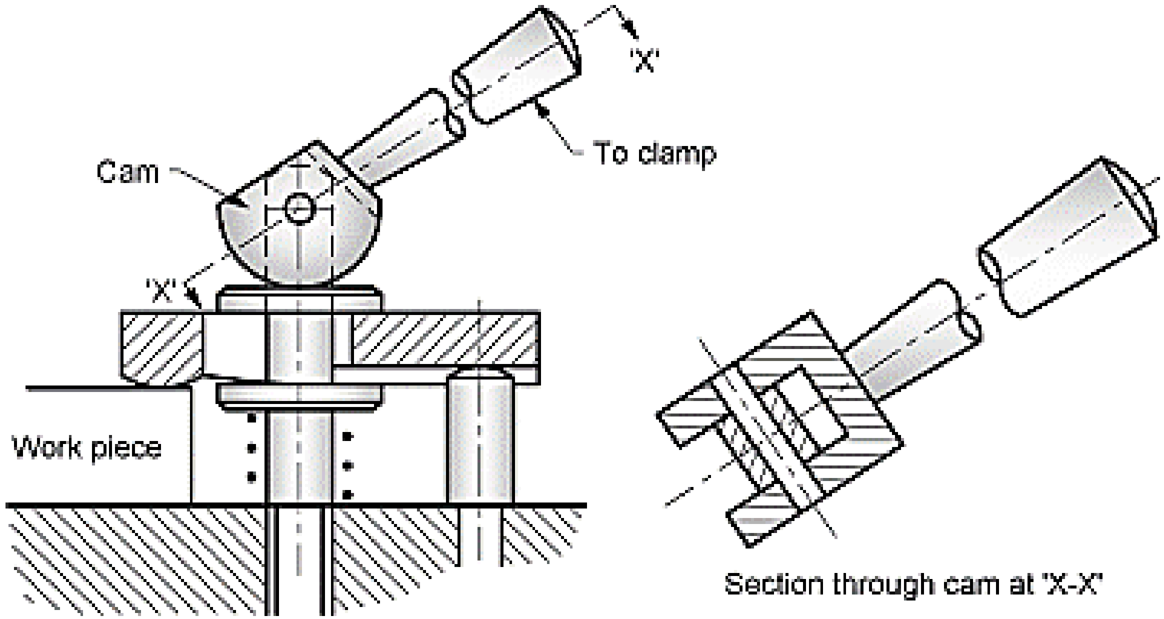


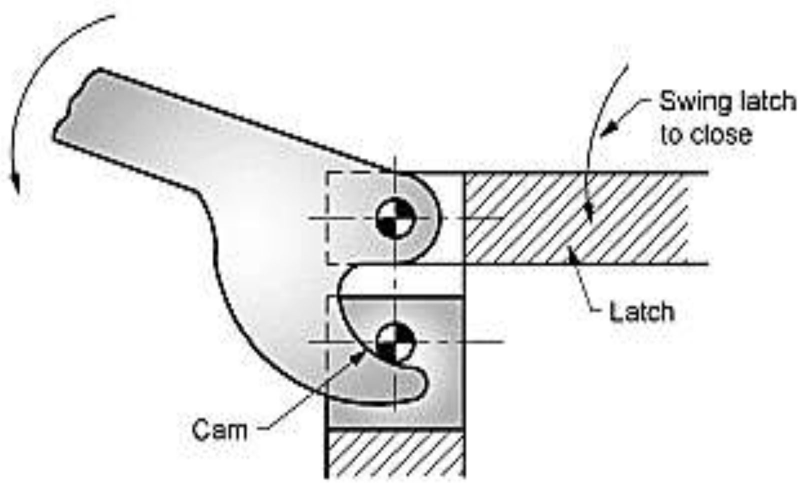
(a) Nut design

(b) Nut in action

5.Quick Acting clamps :

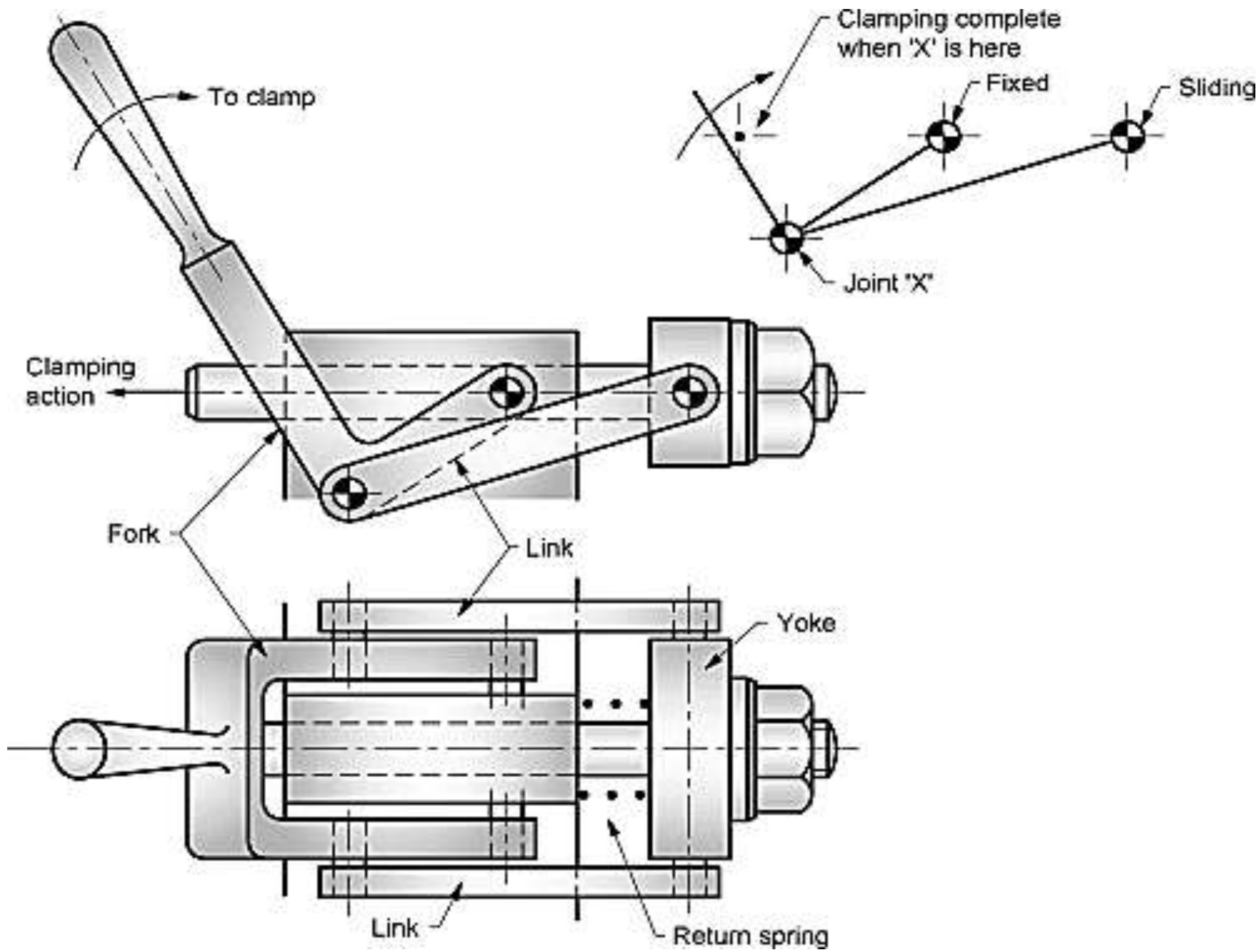
Cam operated clamps :





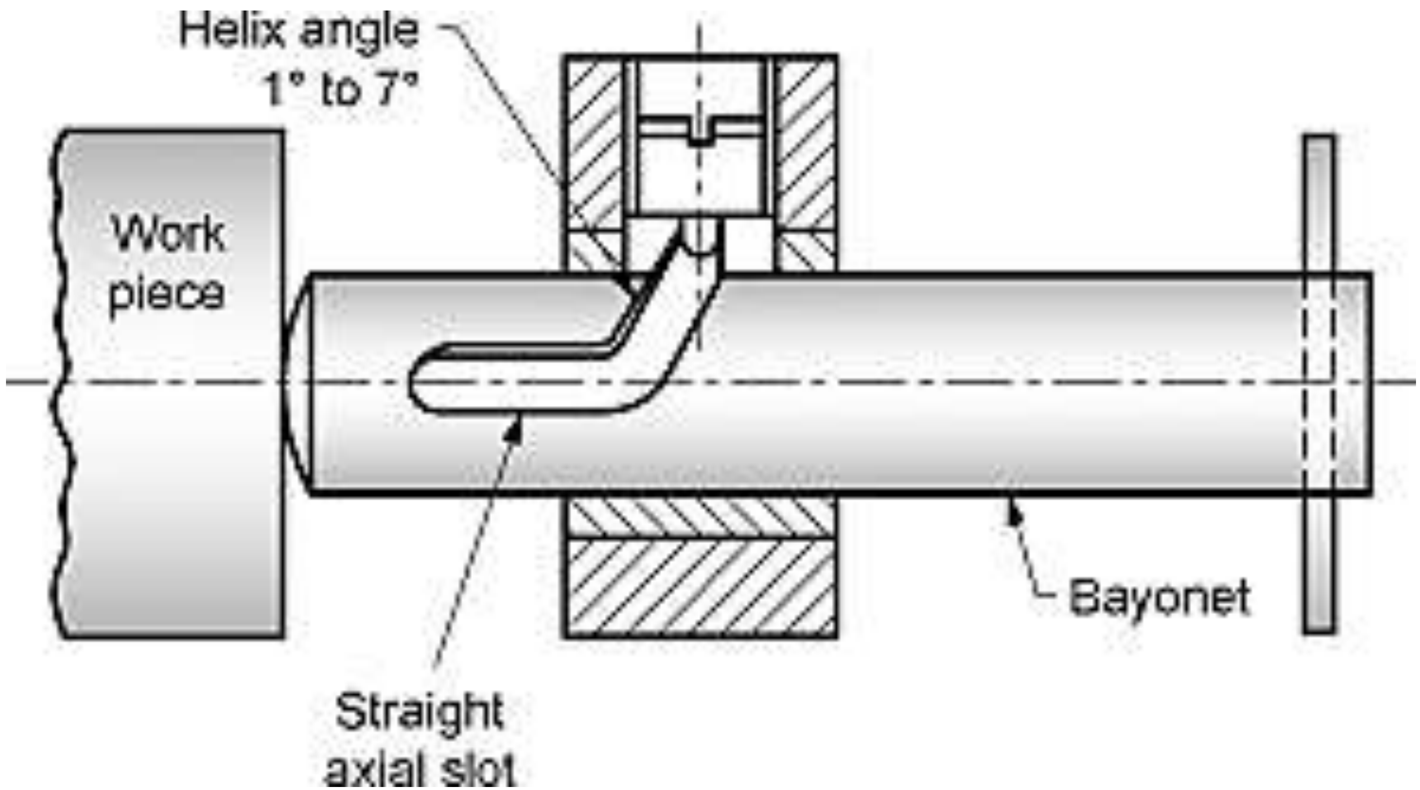
5.Quick Acting clamps :

Toggle operated clamps :



5.Quick Acting clamps :

Bayonet clamp :



Power Clamping :

- The mechanical clamping methods described so far suffer from the following disadvantages.

  (1)The clamping pressure available is limited.
  (2)The time required for clamping is long.
  (3)Clamping pressure varies from one component to another.
  (4)Operator fatigue.

- For these reasons hand clamping is employed only for small components which require lower clamping pressures.
- **Larger components use power driven clamps which are operated either by pneumatic or hydraulic power.**

Power Clamping :

Advantages :

1. The average clamping time with power clamping is about 25 percent of the time with manual clamping.

2. Pressures are uniform and the forces can be much higher than those available with mechanical clamps.

3. When several clamps are used in one fixture, arrangement can be made to operate them simultaneously.

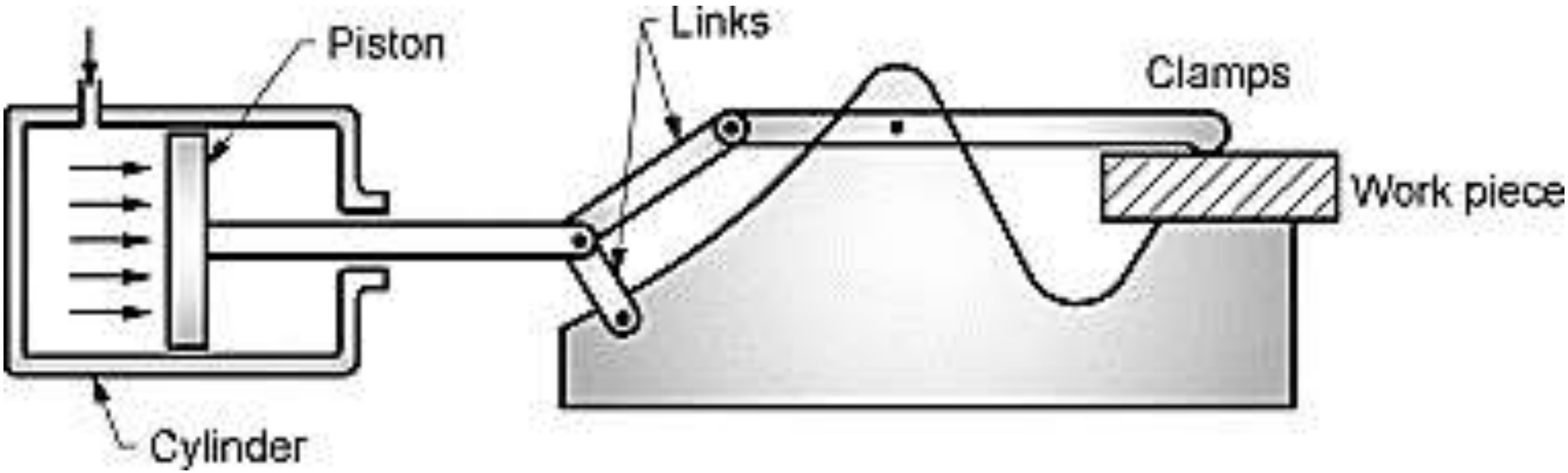
4. Operator fatigue is minimum.

5. Means can be provided for automatic release of the forces beyond safety limits eliminating any chance of damage due to carelessness or laziness on the part of operator.

6. Better safety of delicate parts against overloading.

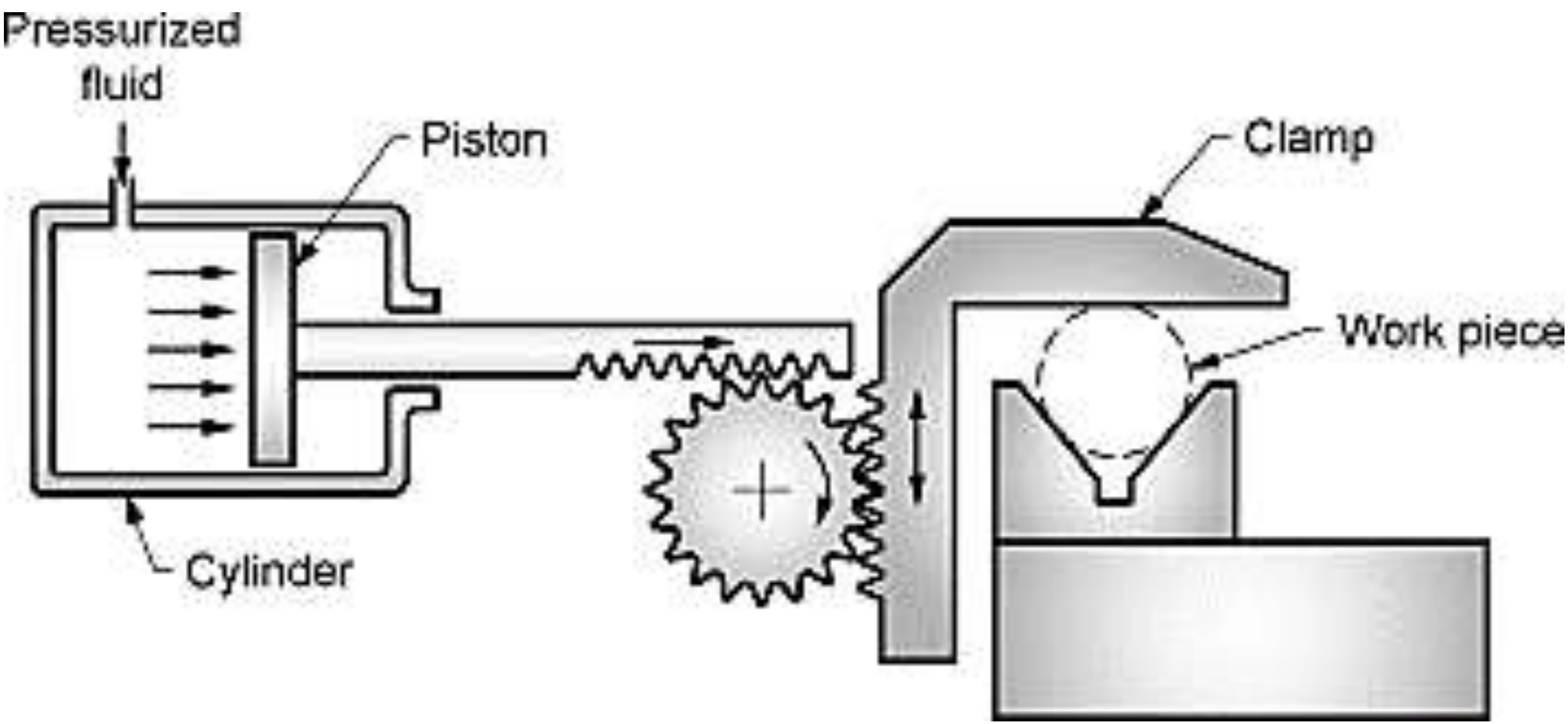
7. Power clamping has a better control of clamping pressure.

Power Clamping :



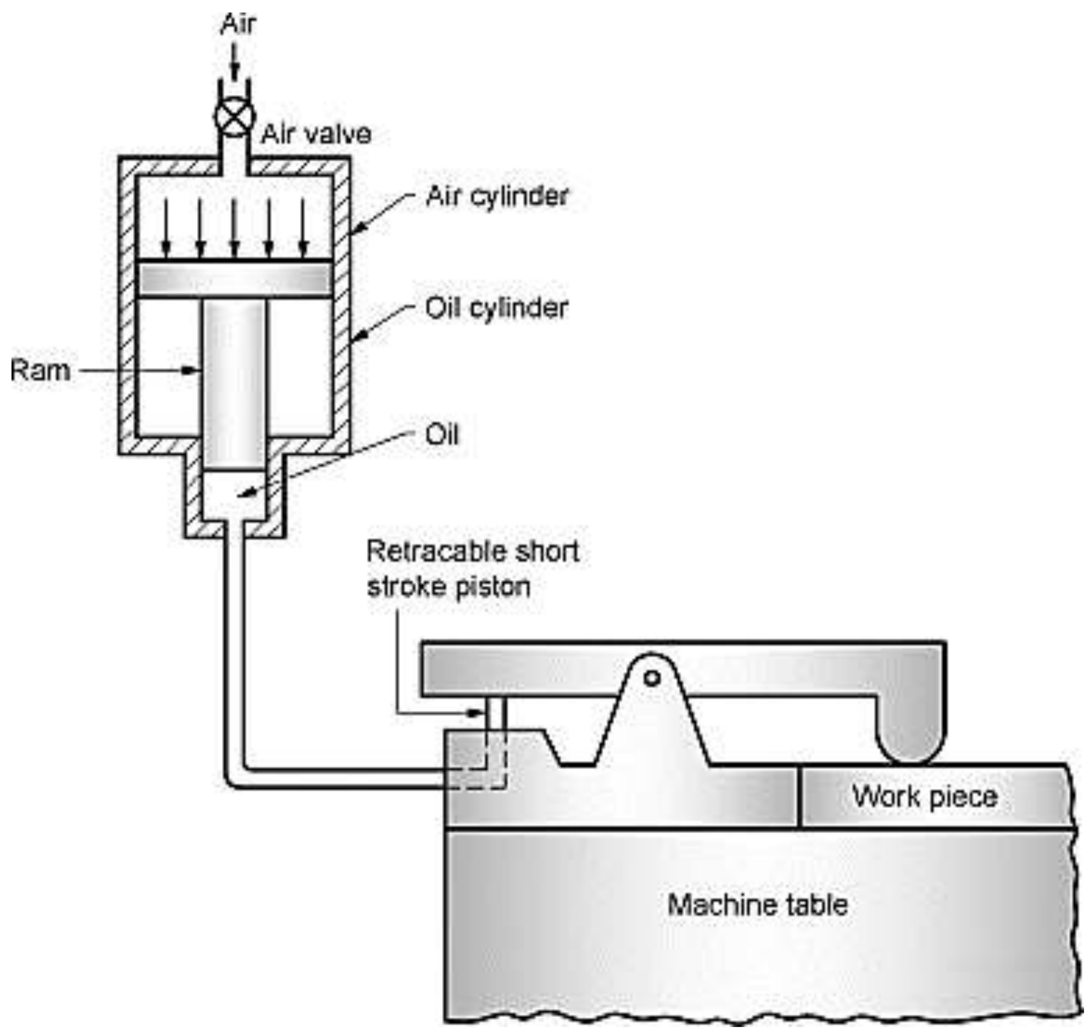
Schematic diagram of a fluid power clamp

Power Clamping :



Fluid power clamping using rack and pinion actuation

Power Clamping :



Air to hydraulic booster

Drilling Jigs

Drilling Jigs :

- Drilling jigs are used to locate and hold the work piece for drilling, reaming counter boring, counter sinking, spot facing and tapping operations.
- With the exception of taps, tools are guided during cutting and jigs should make provision for tool guiding elements in addition to location, support and clamping systems.
- A drilling jig should be of light design with enough rigidity because it has to be handled frequently.
- It should be stable since it is **not** normally clamped to the machine table.
- The feet of the jig should extend well outside the holes to be drilled to prevent rocking during operation.

Types of drilling jigs :

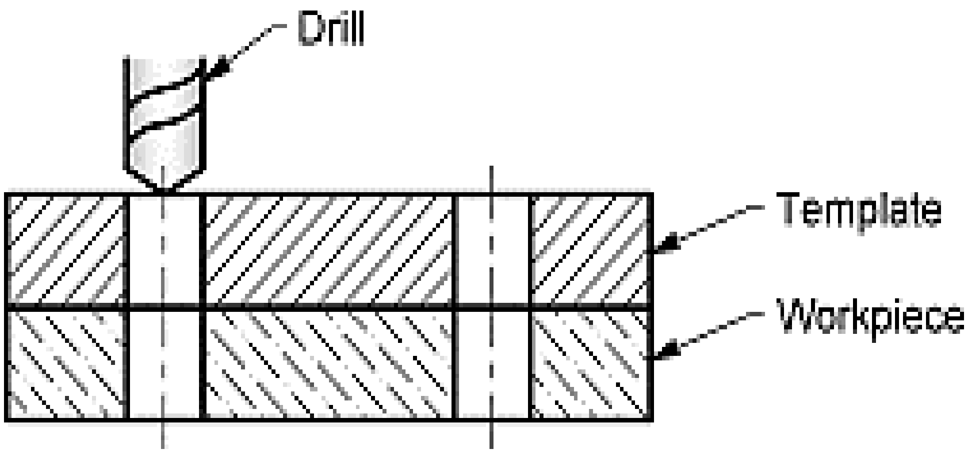
- Drilling jigs are named or classified on the basis of their shape, shape of the major locating element, method of construction and use.

- The major categories are given below:

1.Template jig
2.Plate jig
3.Channel jig
4.Diameter jig
5.Solid jig
6.Post jig
7.Angular post jig
8.Turn over jig
9.Box jig
10.Latch or head type
11.Sandwich jig
12.Indexing jig

1.Template jig :

- This is the simplest type of drilling jig. It is simply a plate made to the size and shape of the workpiece with the required number of accurately made holes.

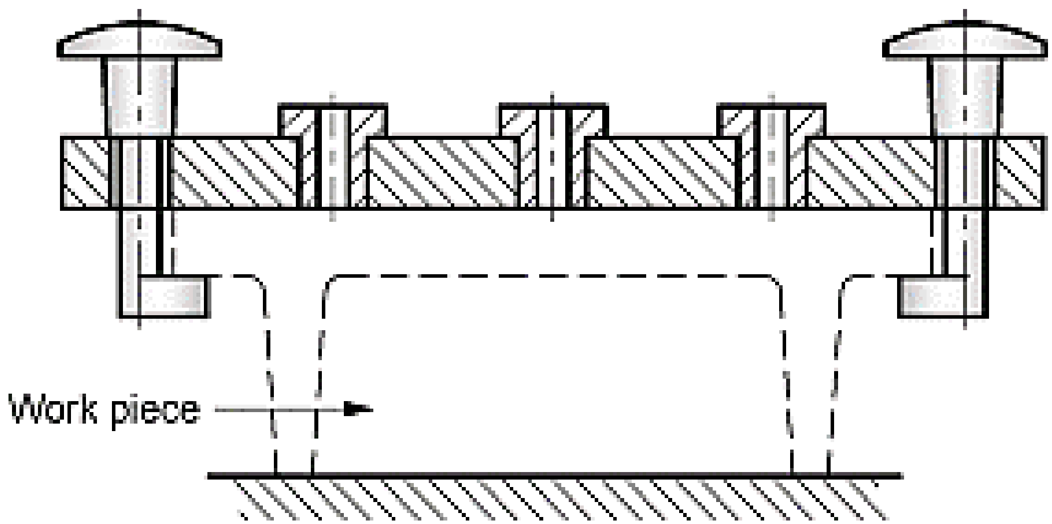


- It may or may not have bushings. When bushing is not used the whole jig plate is normally hardened.

- For use, the jig is placed on the work piece and holes drilled through the holes in the template.
- This type of jig is suitable only for a few parts.

2.Plate jig :

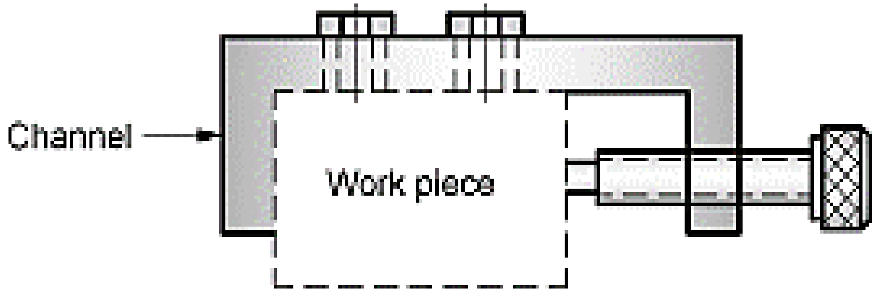
- Instead of simple holes, drill bushes are provided in this jig for accurately guiding the tool.
- The jig essentially consists of a jig plate or bush plate with a provision for clamping and location.



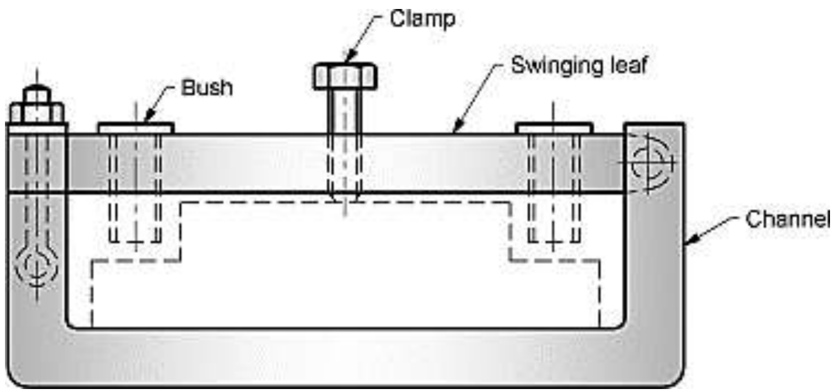
- Plate jigs are used for drilling accurately spaced holes on larger jobs.
- The jig is located and clamped to the work piece directly for use.

3.Channel jig :

- The channel type jig shown in Fig. is a slightly more elaborate jig made of a channel section.



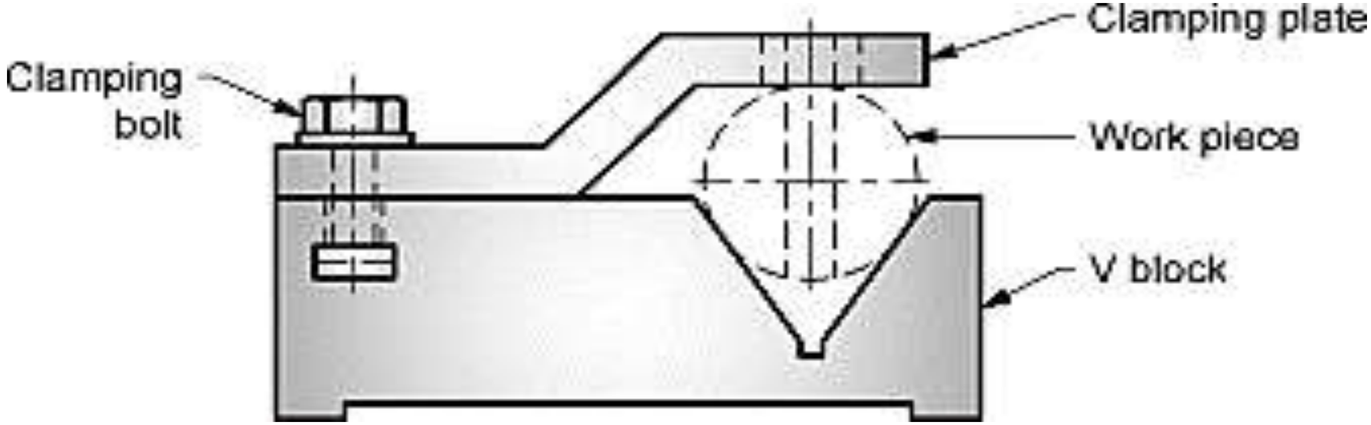
- This jig may also be provided with a swinging type leaf to form a channel and leaf type jig.



4.Diameter jig :

- Diameter jigs are used to drill radial holes on cylindrical or special work pieces.

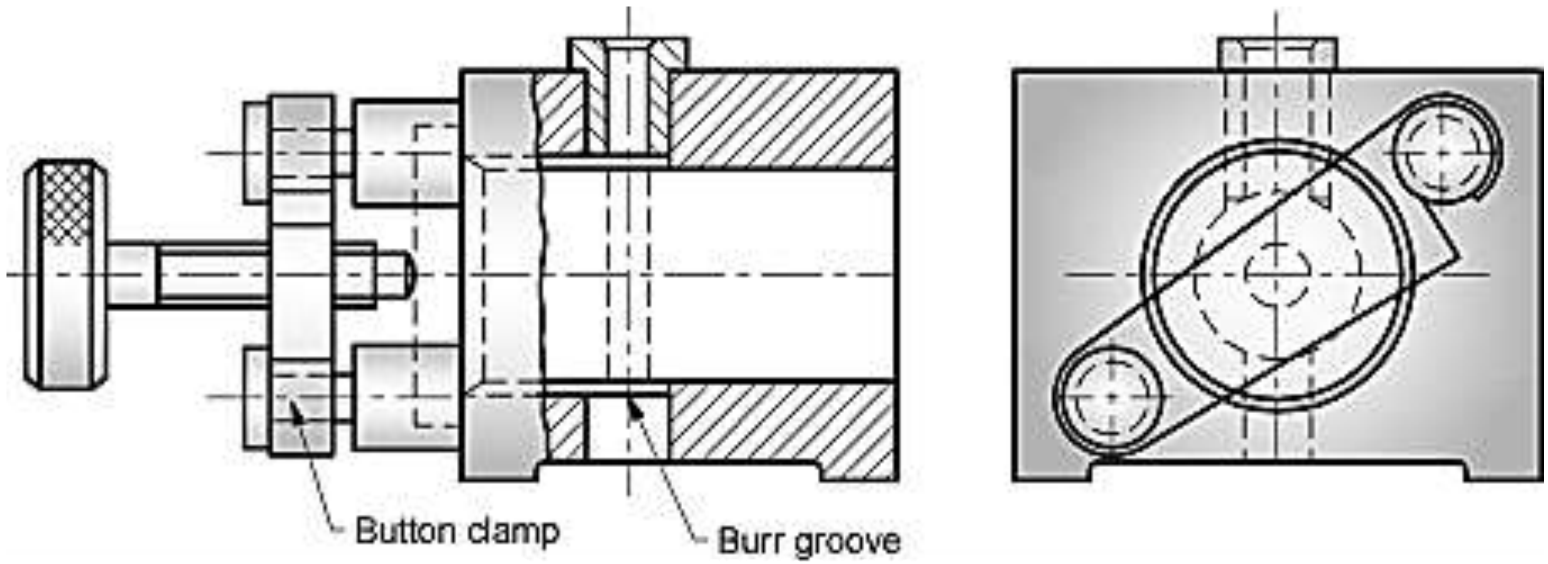
- As shown in Fig. the work is placed on a fixed V block and then clamped by the clamping plate which also locates the work.



- The guidance to the tool is provided by the drill bush shown.

5.Solid jig :

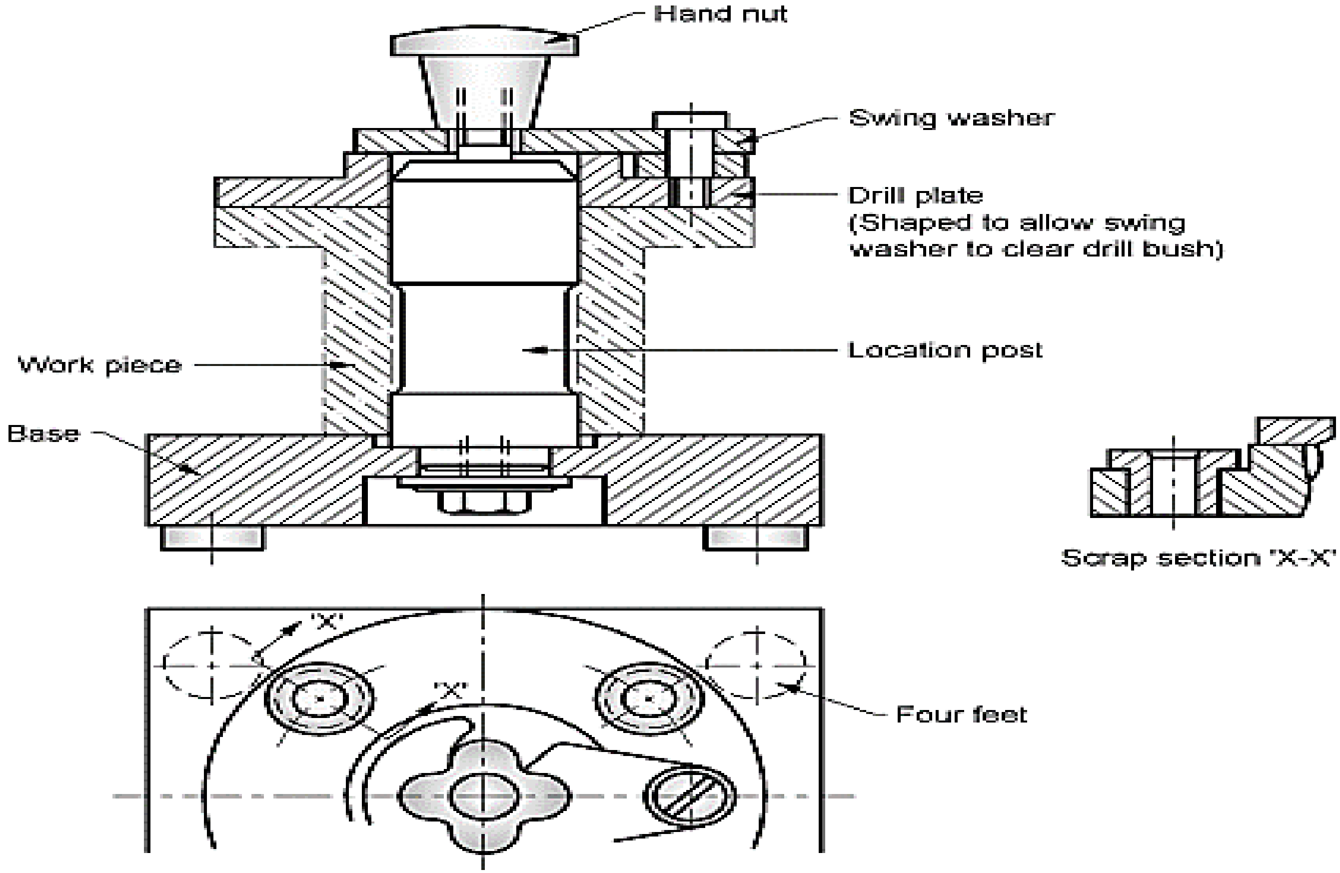
- Fig. shows a solid jig that is made from a block of steel in which the work piece is clamped down by a strap clamp or swinging clamp.



- Burr grooves are provided to remove the work piece easily.

6.Post jig :

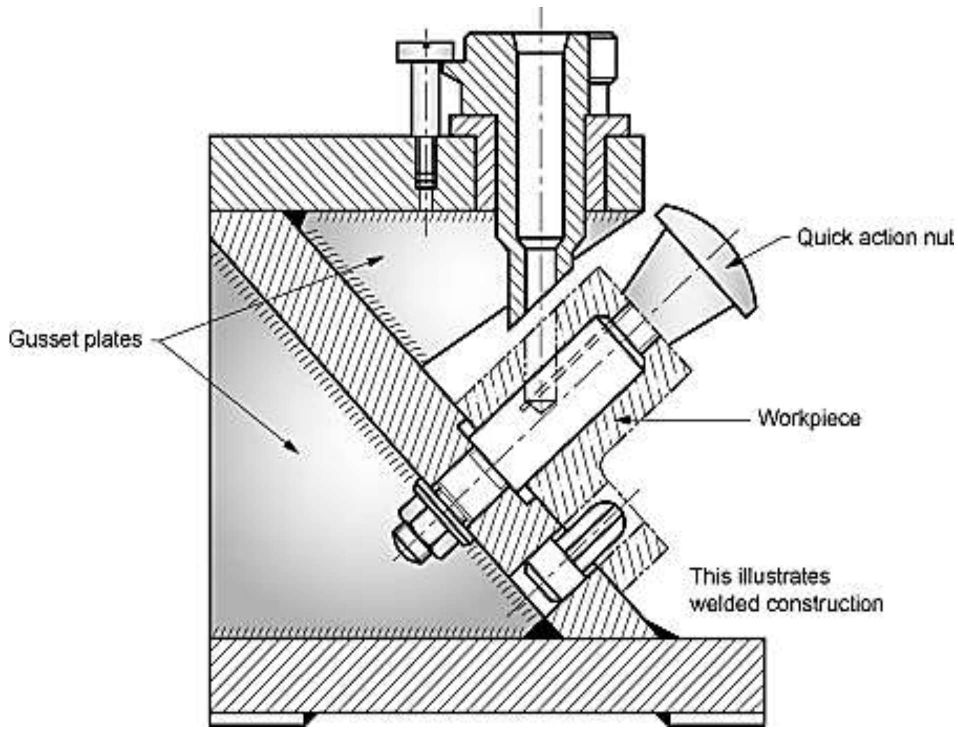
- In this jig the work piece is located on its bore on the post. The post is also used to locate the drill plate.



- The swing washer makes it possible to remove the drill plate without removing the hand nut.

7.Angular post jig :

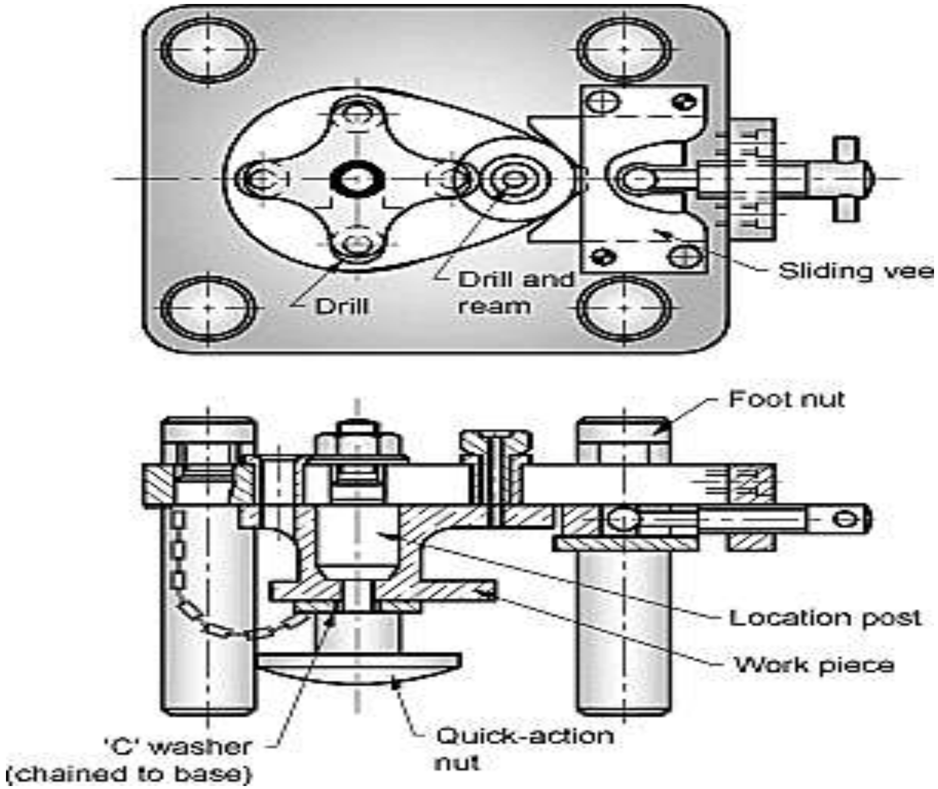
- Fig. shows an angular post jig of welded construction.
- An extended and shaped drill bush is used to prevent drill run out and yet make possible the removal of work piece.



- A quick action nut is used as the bore in the work piece is small and it requires the nut to be removed for unloading the work piece.

8.Turn over jig :

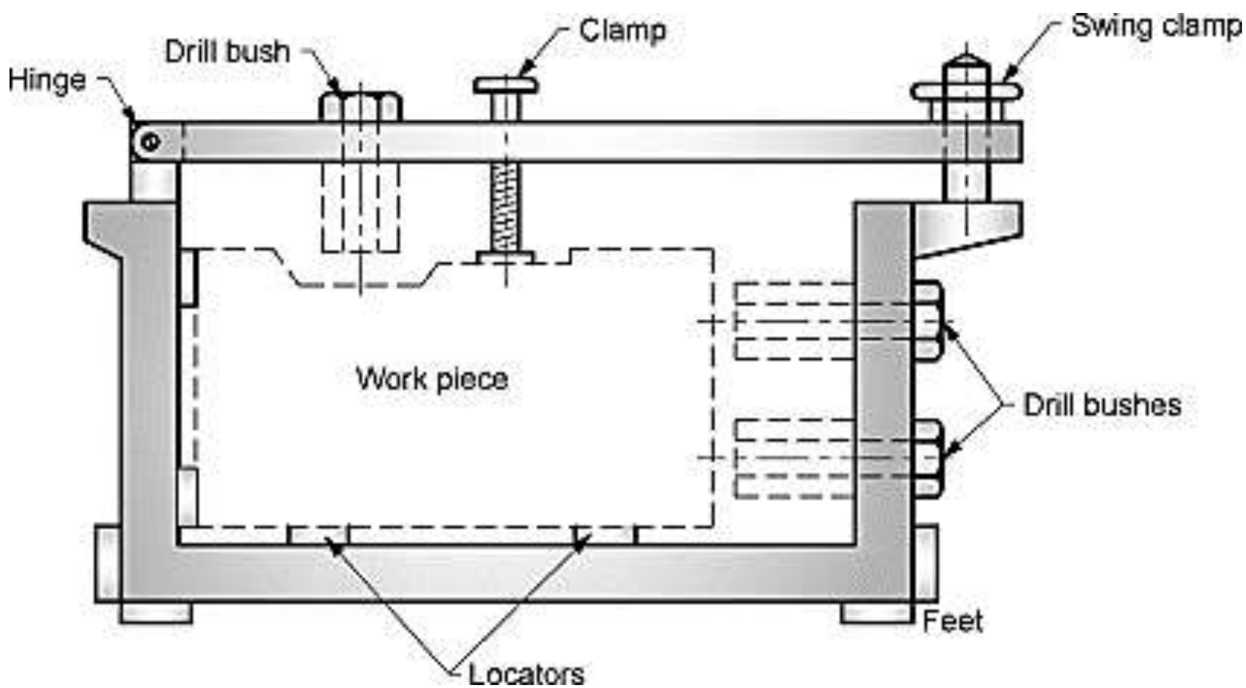
- Turn over jigs are plate jigs with jig feet. The feet provide square resting surface to the jig when drilling holes.



- The jig is seated on four foot nuts while locating and clamping the workpiece. It is then turned over to support itself on its feet in the machining position as shown.

9.Box jig :

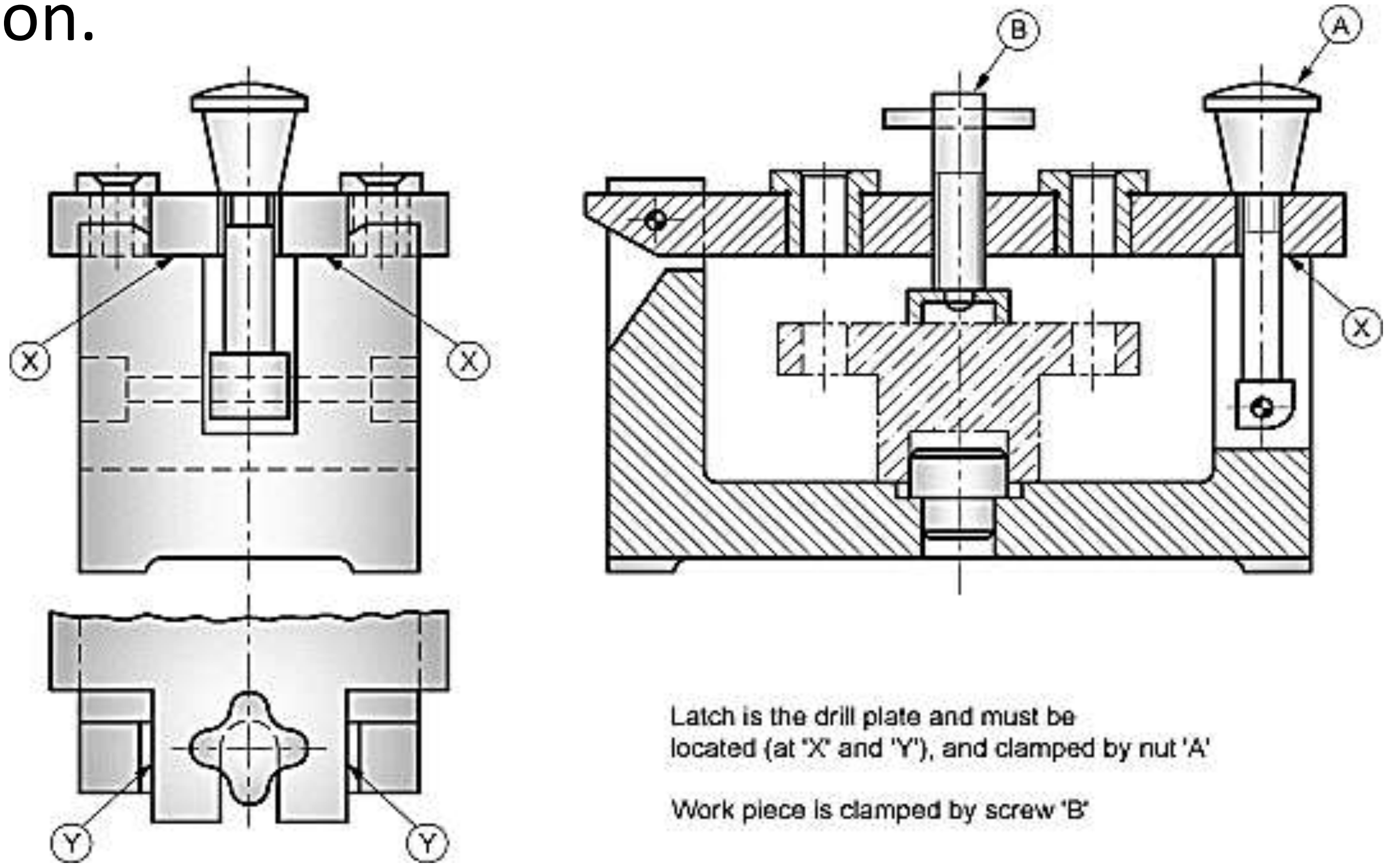
- This type of construction is **used when holes are to be machined on a number of faces on the workpiece**.
- The jig body is shaped like a box with one side open for loading and unloading the workpiece.



- The box is closed and clamped by a hinged latch with bushes and clamping screws.

10.Latch type jig :

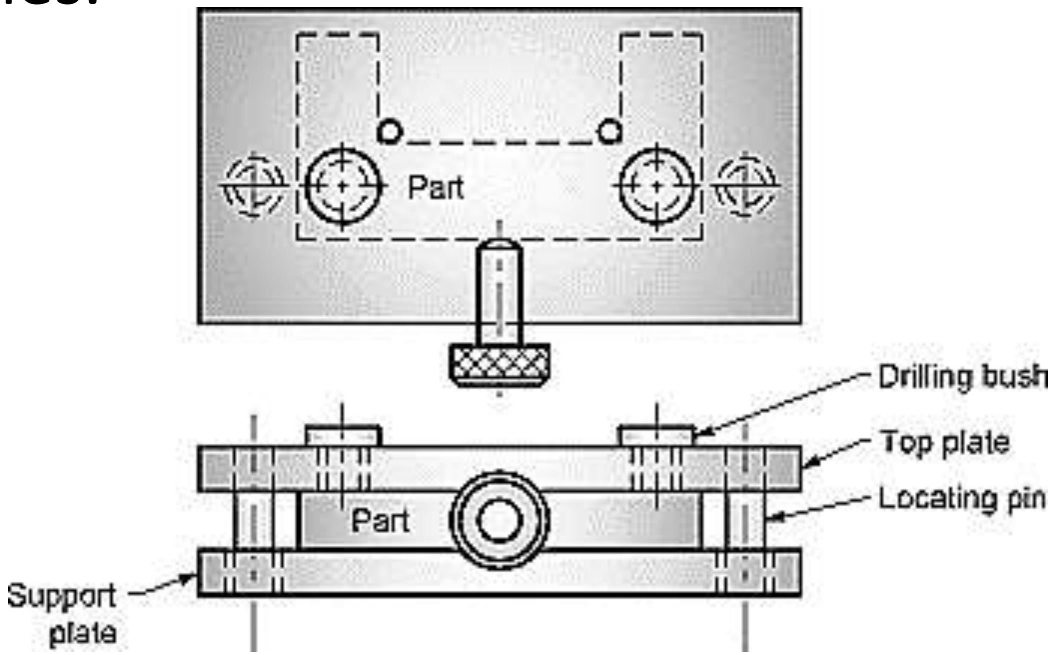
- In this type of jig the latch carries the drill bushes and should be positively located (Face X and slot Y) so that the drill bush bores vertical in spite of workpiece height variation.



- The latch is clamped by nut A and the work piece by screw B.

11.Sandwich jig :

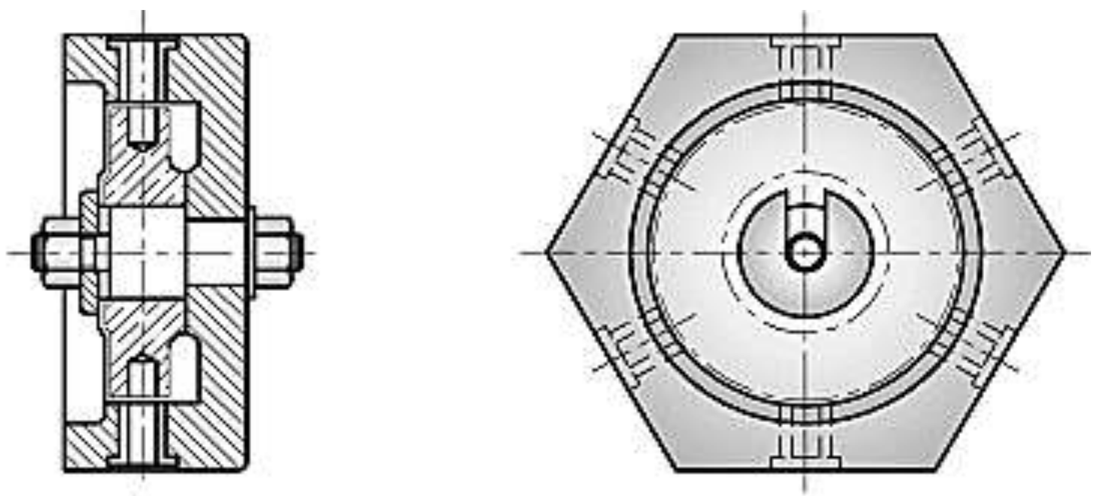
- This type of jig is used for drilling holes in thin or soft parts to avoid bending or warping.
- Support plate is provided at the bottom and the work piece is sandwiched between the plate and the top which carries the drill bushes.



- The top and bottom plates are located with the help of locating pins as shown.

12.Indexing jig :

- Used to drill a series of holes on a circle on the face of a workpiece.
- Every time the jig is indexed, it brings a hole position under the drill.



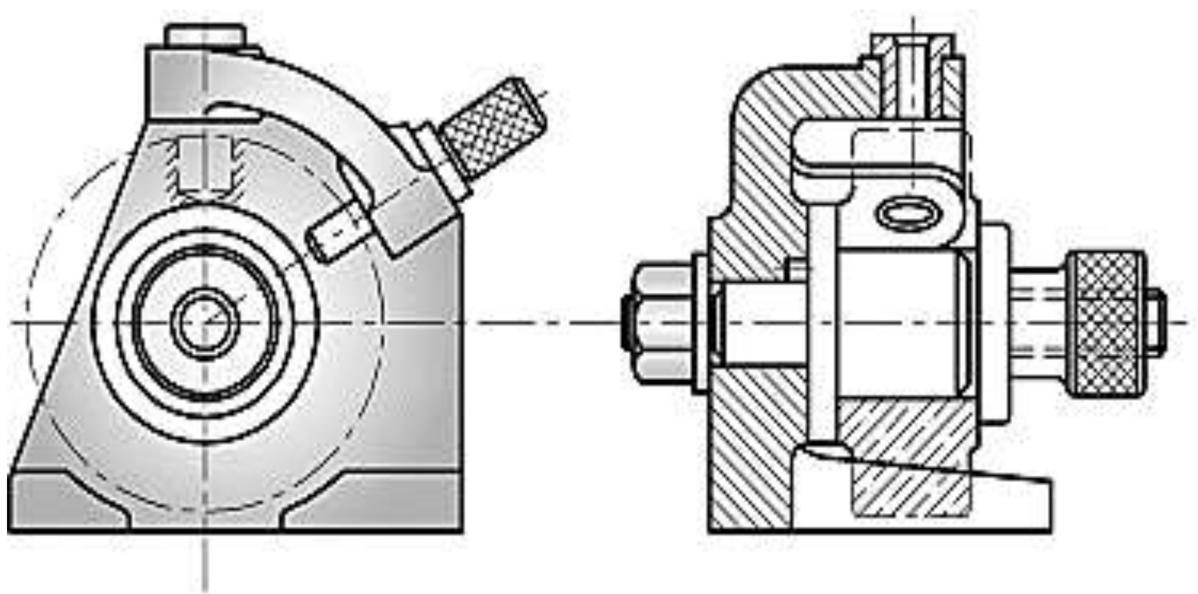
(a) Jig with six bushes

- In the design, drilling is performed by using each of the **six bushes** successively with the work piece clamped in one position.

12.Indexing jig :

contd…

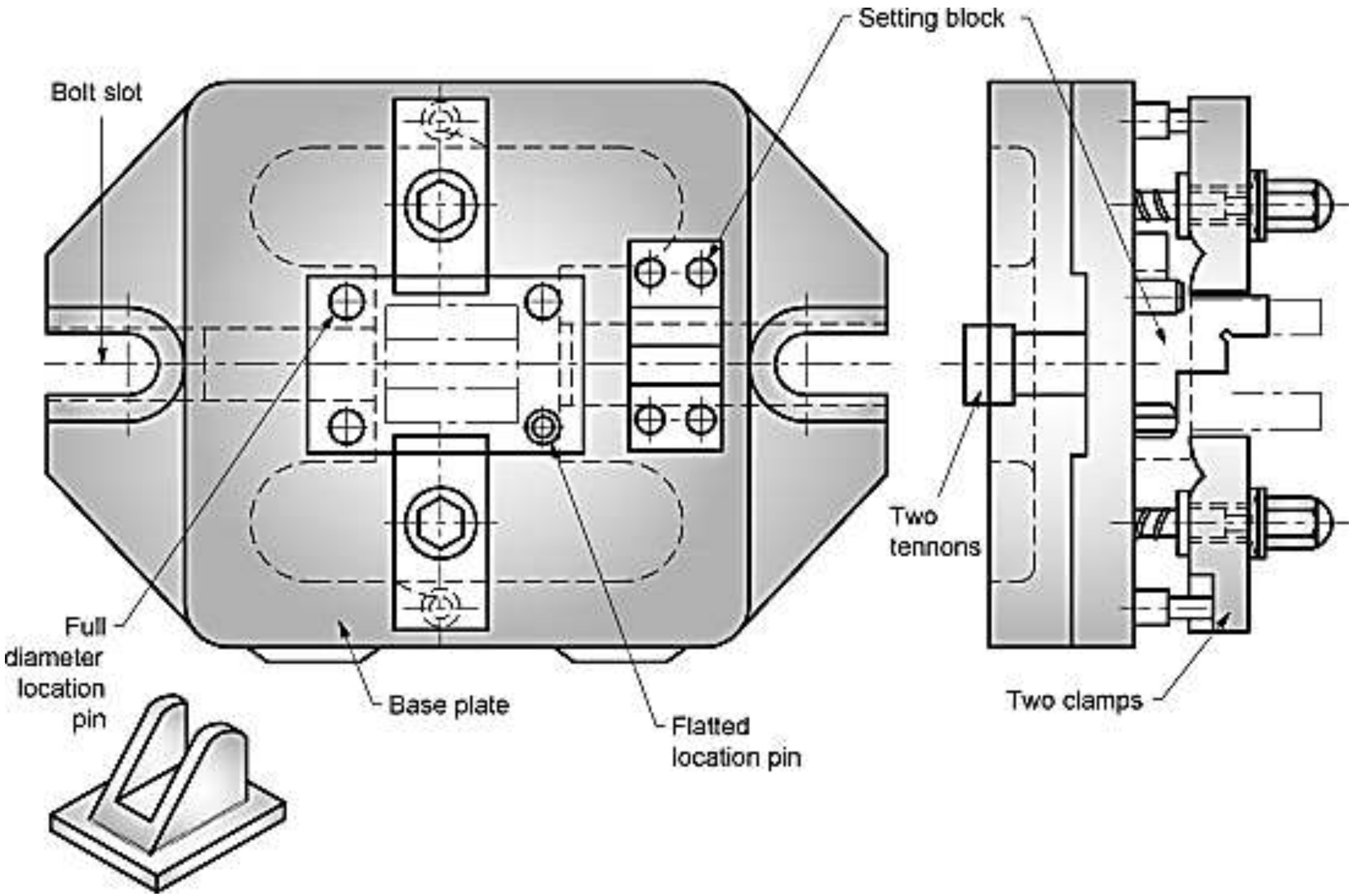
- In the design, after drilling each hole the workpiece is indexed through 60 degrees by using the previously drilled hole for location with the help of a spring loaded pi



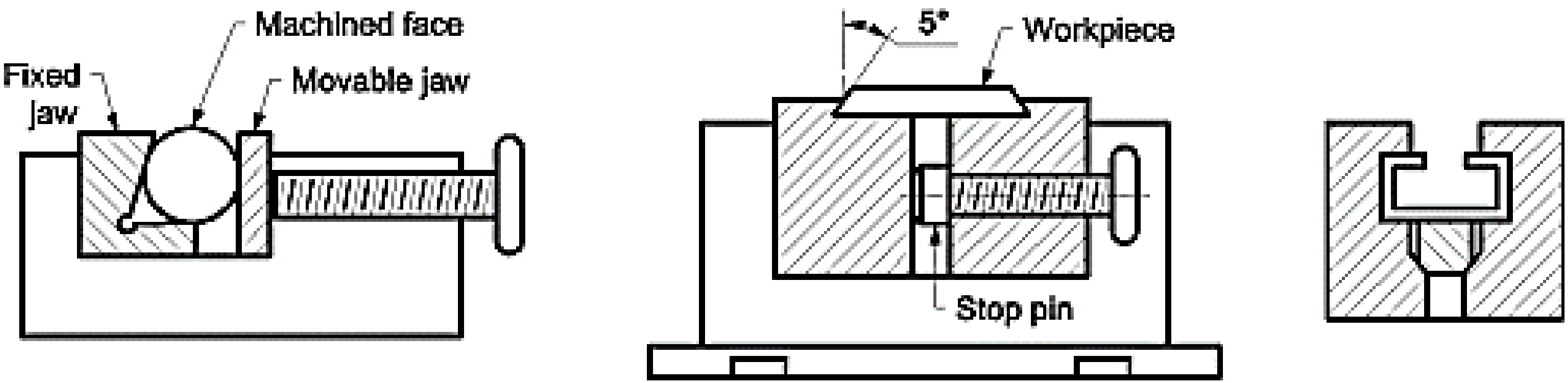
(b) Alternative design of jig for the same operation

Fixtures

Milling Fixtures :

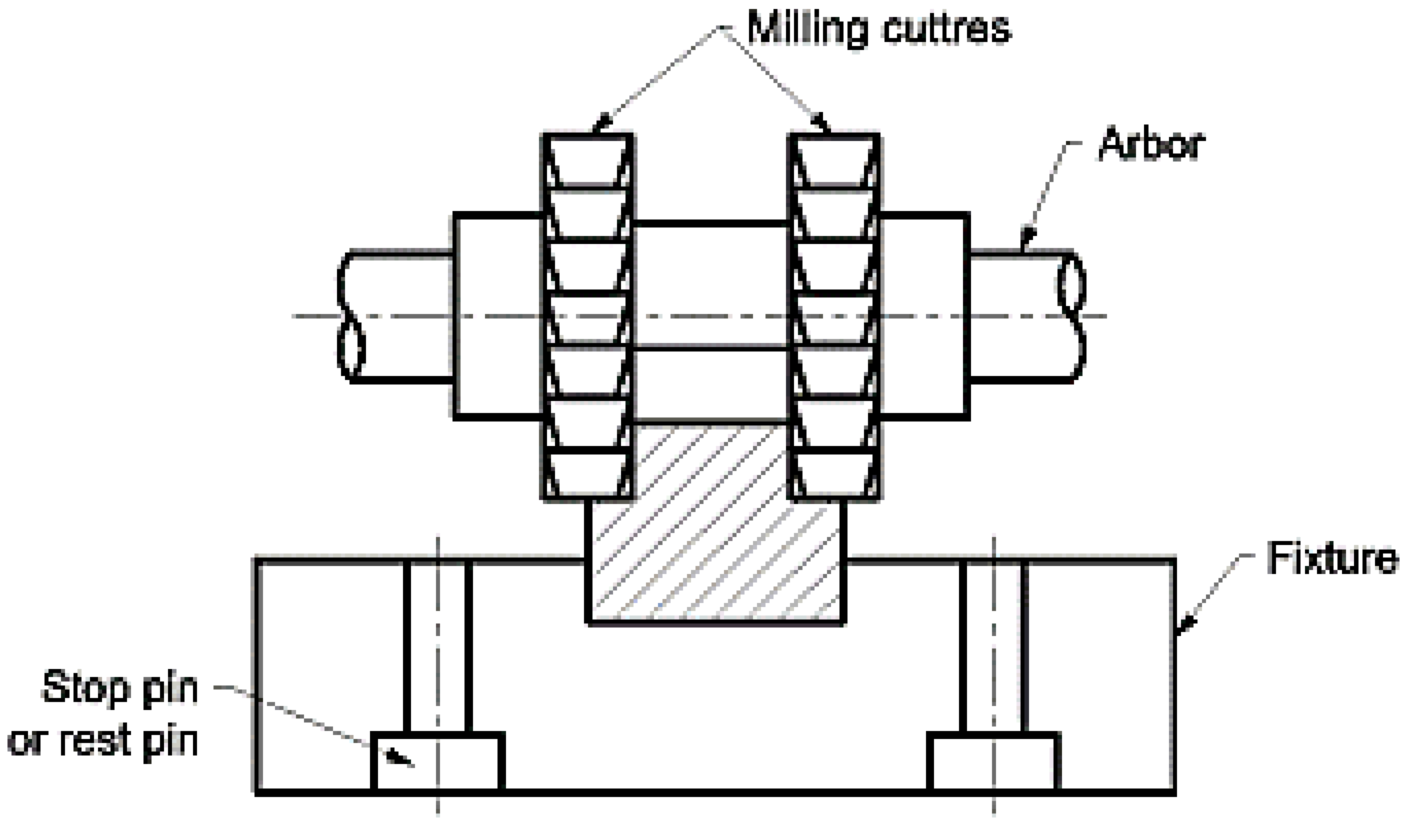


Milling machine vice fixtures:

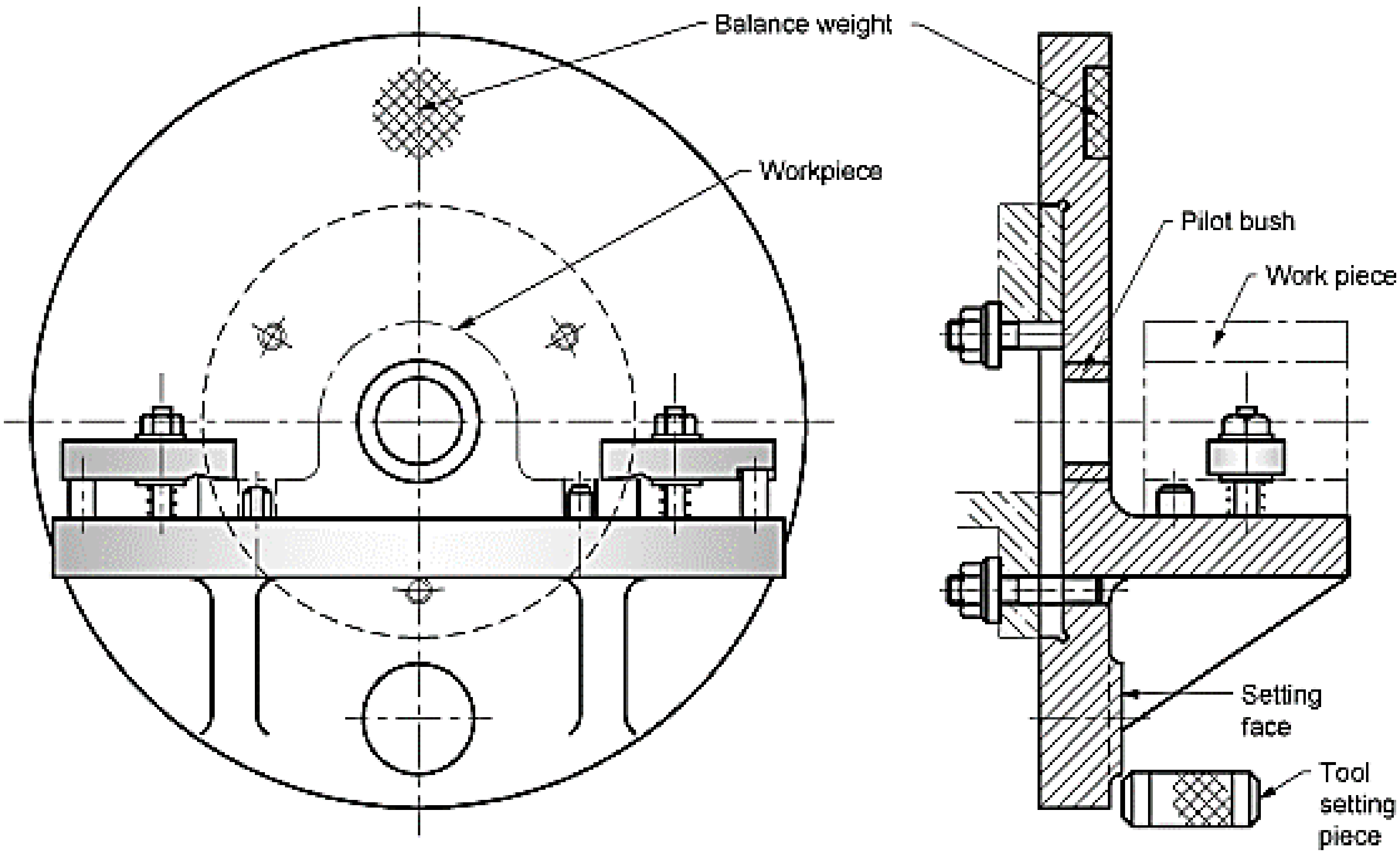


(a) (b) (c)

Straddle milling fixture:

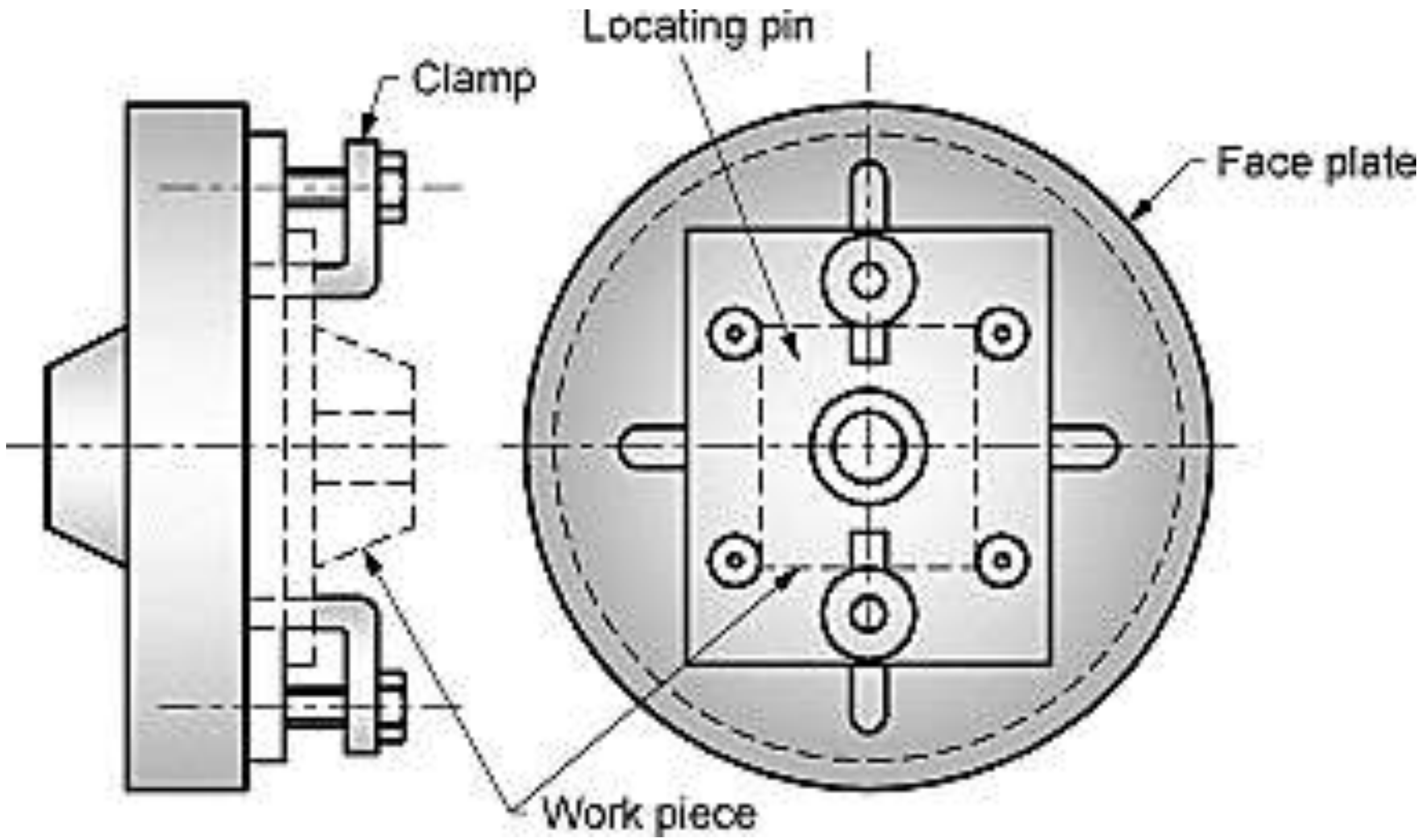


Turning fixture:



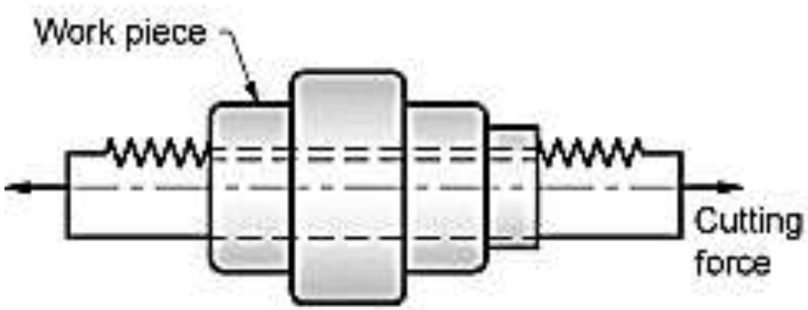
Fixture for non-symmetrical jobs

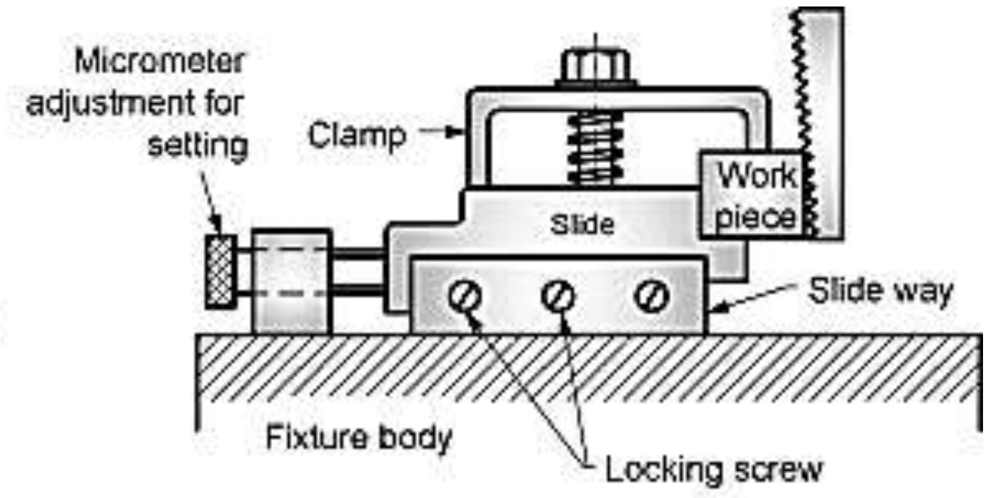
Turning fixture:



Rectangular face plate fixture for symmetrical jobs

Broaching Fixture:

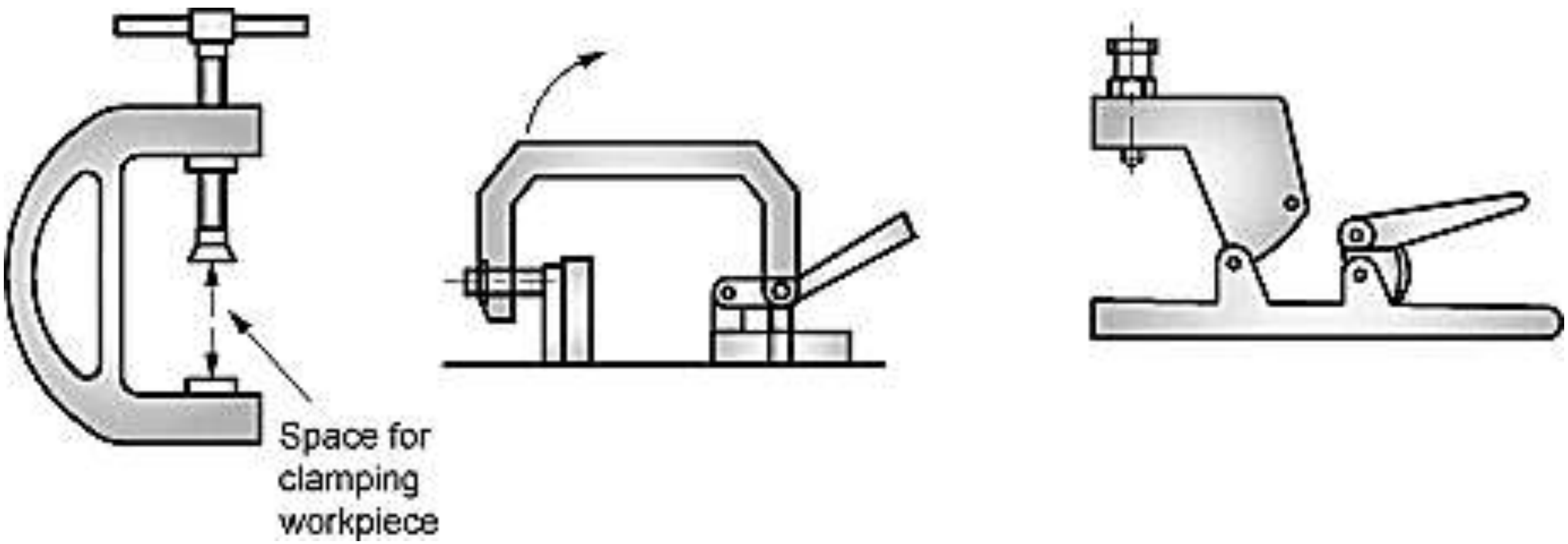




(a) Internal Broaching

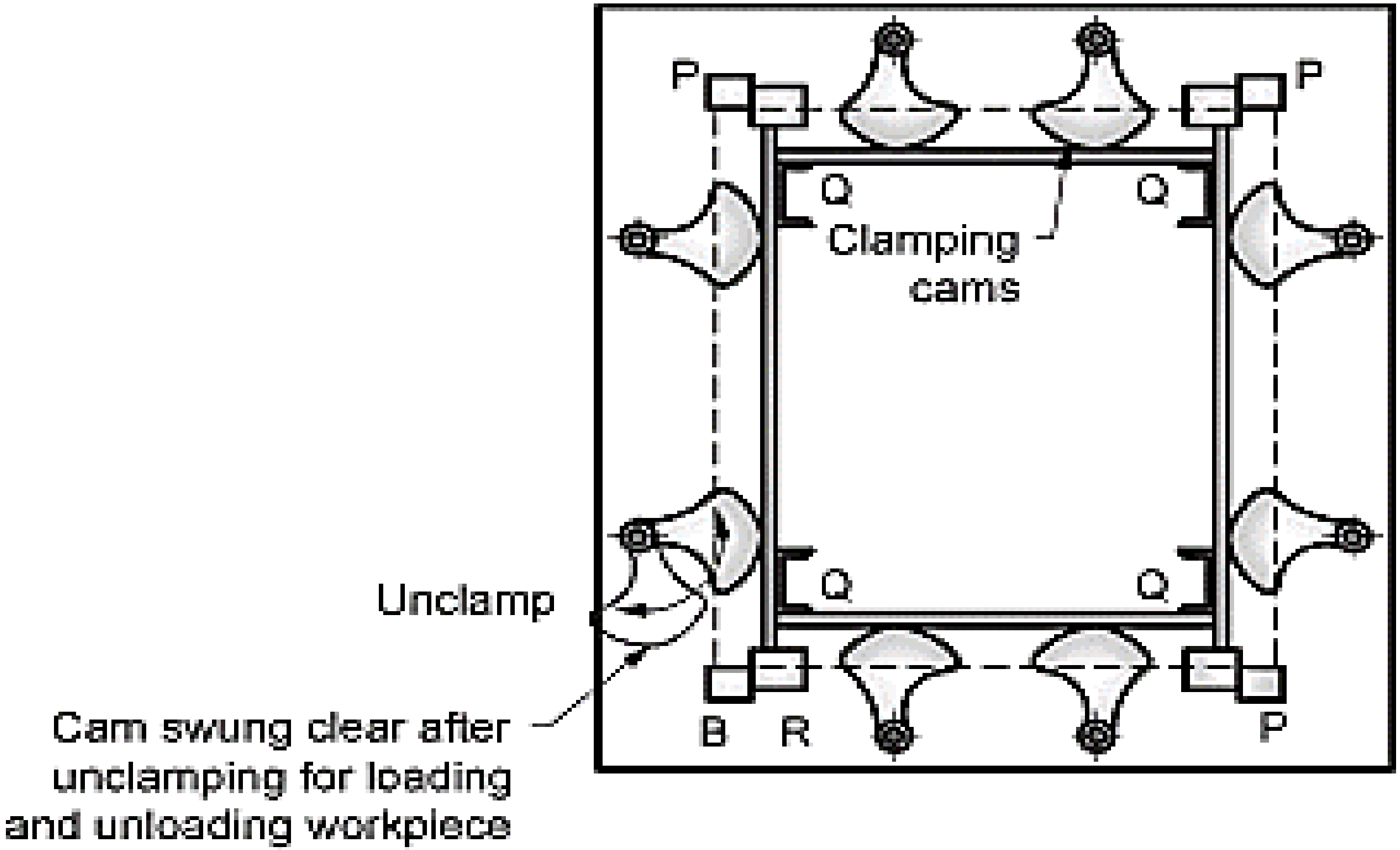
(b) External broaching

Welding Fixtures:



Clamping devices

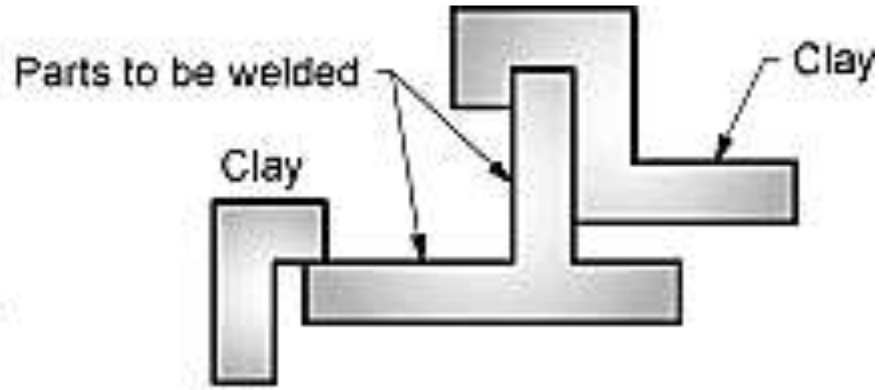
Welding Fixtures:



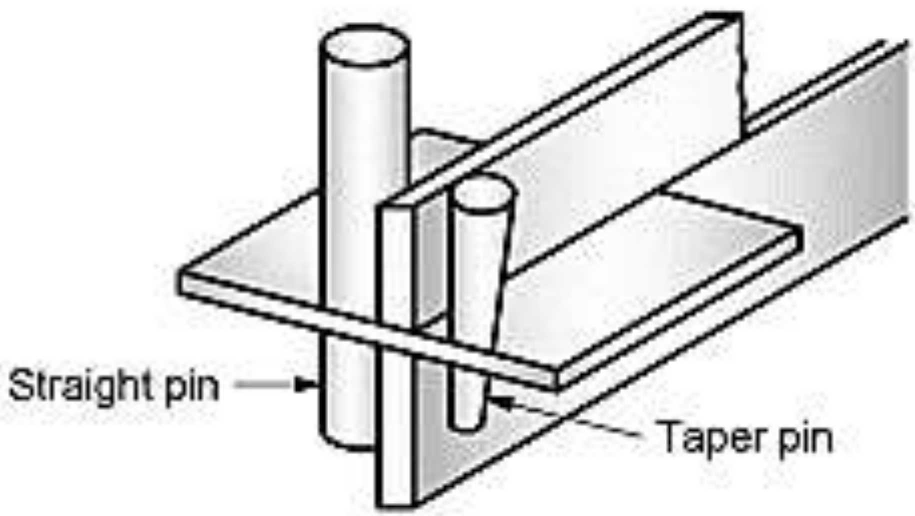
Welding fixture

Welding Fixtures:

(a)

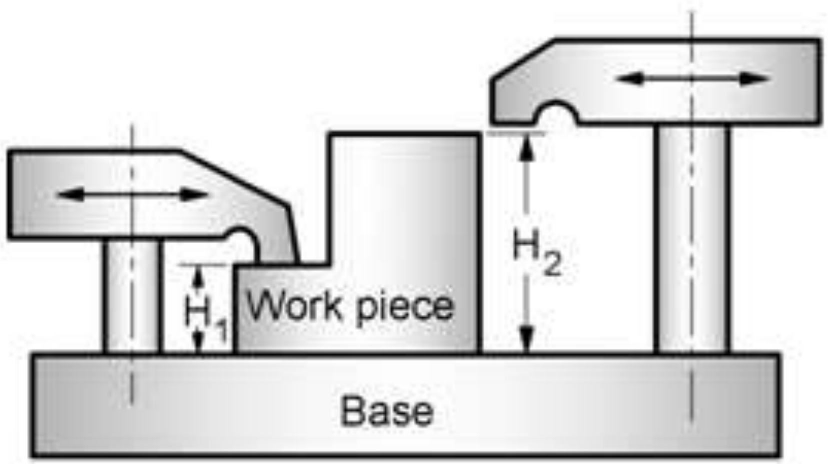


(b)

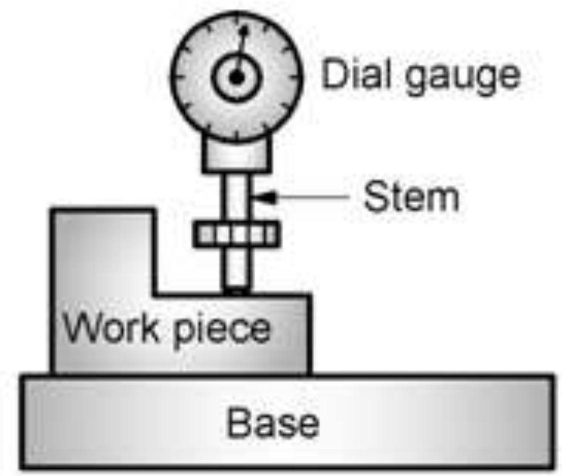


(c)

Inspection Fixtures:

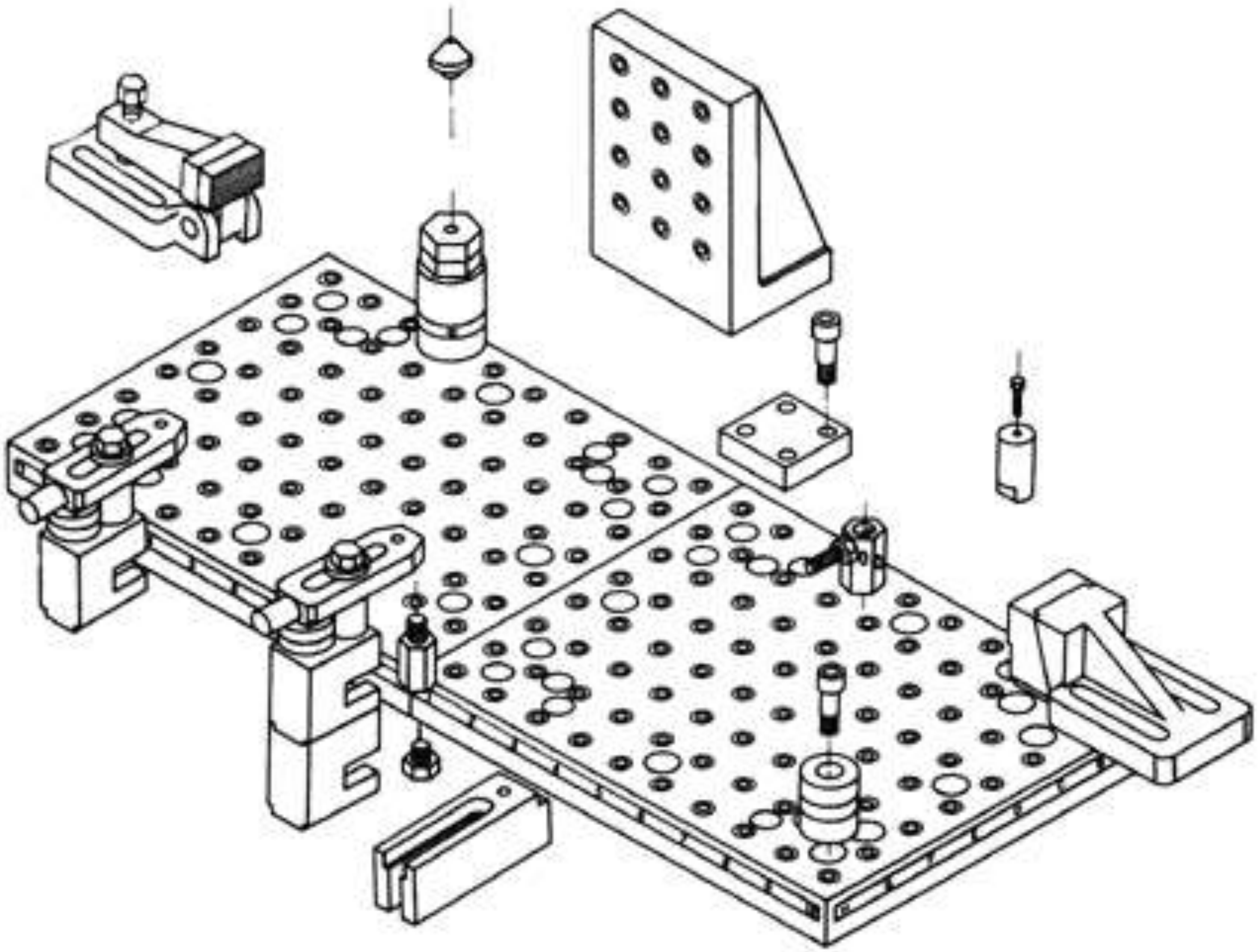


(a) Non reading type inspection fixture



(b) Dial type inspection fixture

Modular Fixtures:



Modular Fixtures:

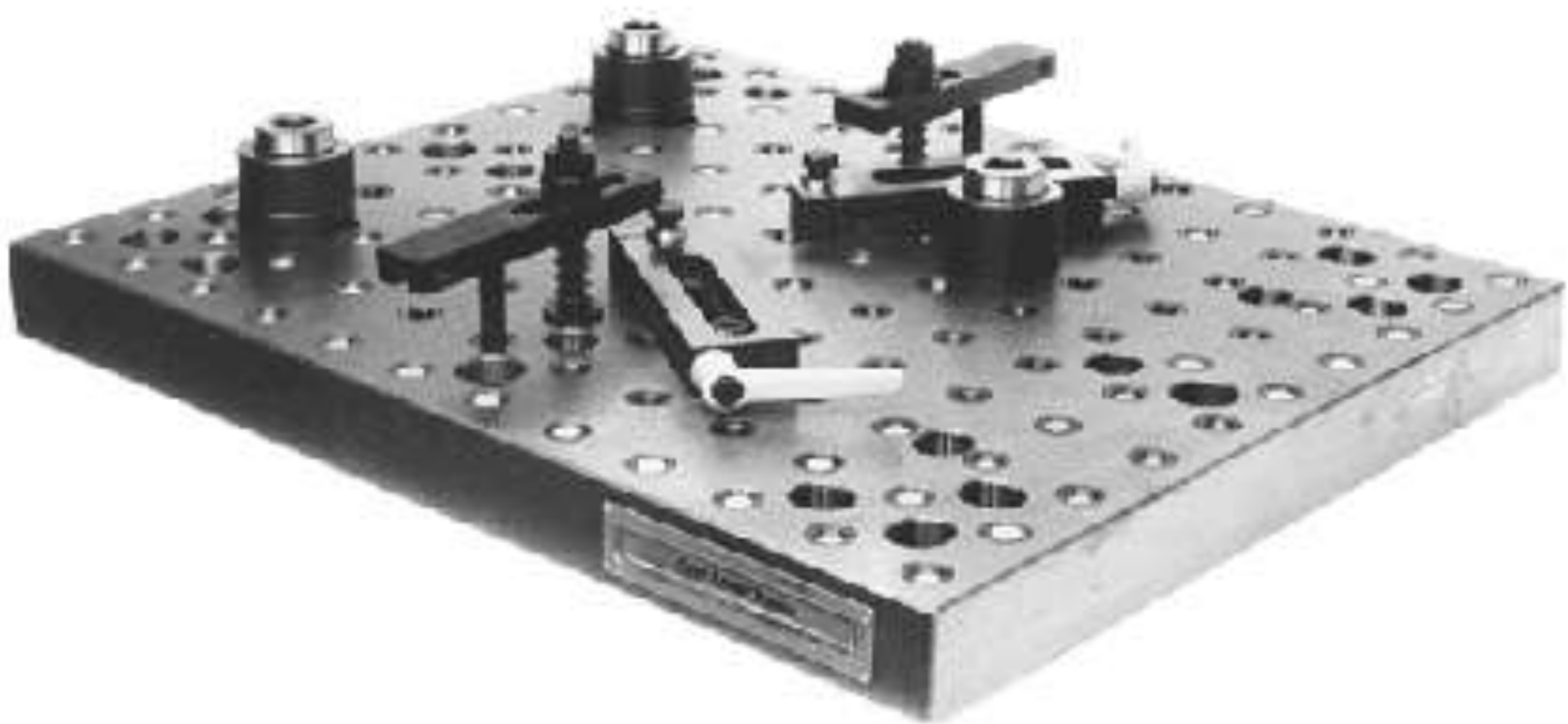
- Modular fixtures use a series of **reusable standard components** to build a wide variety of special purpose work holding devices.

- The components used to build these fixtures include a variety of matched and co-ordinated **interchangeable elements** like tooling plates, supports, locating elements, clamping devices and similar units that can be easily assembled.

- After a given production run the elements of the modular fixture **can be disassembled** and used to make a fixture for a different job.

- Modular fixtures are commonly used on **CNC** machine.

Modular Fixtures:



Modular Fixtures:

The use of modular fixtures has the following advantages:

1. Cost saving
2. Reduction in lead time
3. Reusability of components
4. Versatility
5. Suitability for pilot runs
6. Quality
7. Availability

Manufacture of Jigs and Fixtures

Manufacture of Jigs and Fixtures:

- Depending upon the **size, operation and quality requirement,** jigs and fixtures may be manufactured by one of the following methods :

    1. Casting
    2. Fabrication
    3. Welding

Manufacture of Jigs and Fixtures:

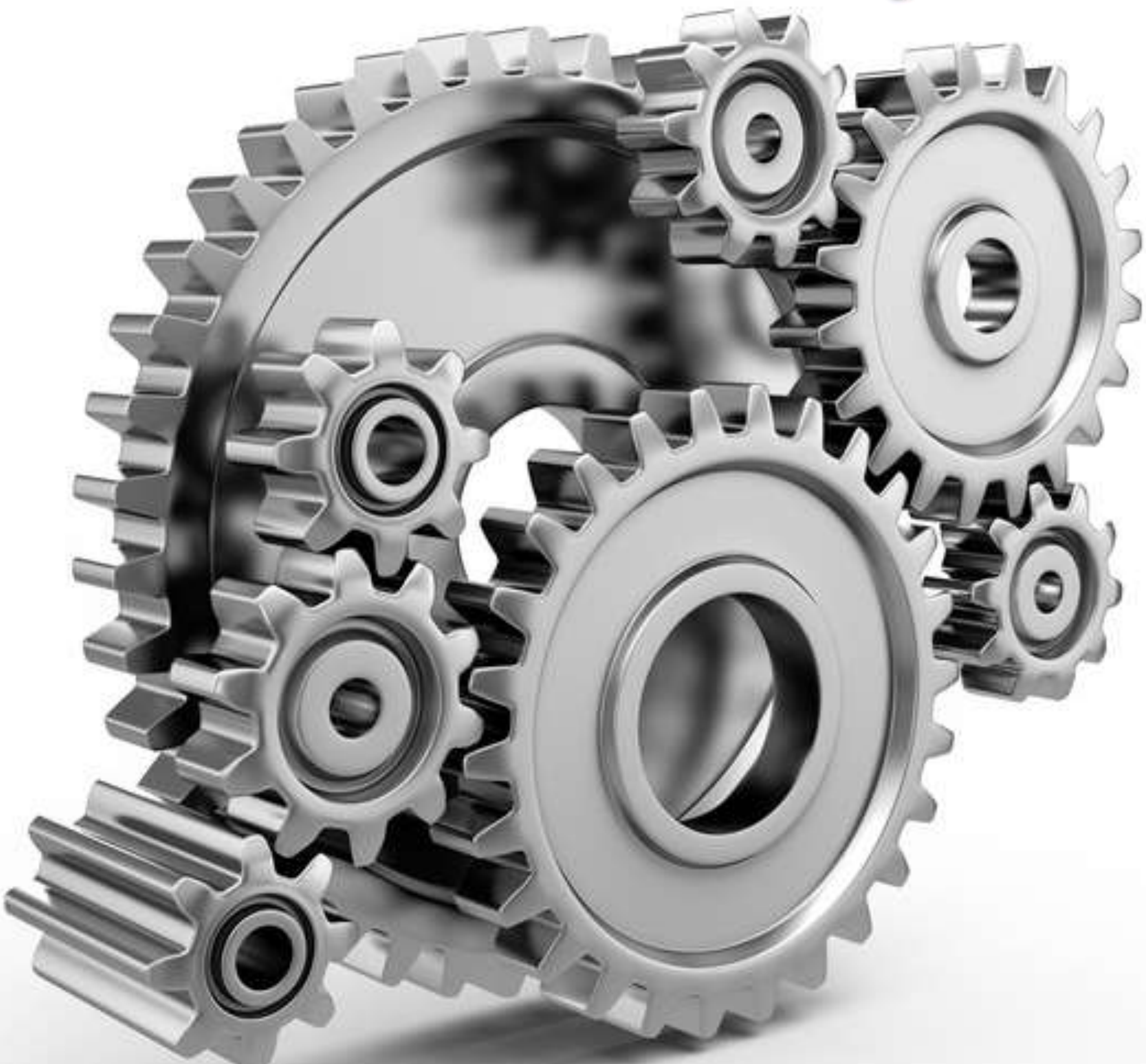
- Cast jigs and fixtures take longer time to produce and are heavier than those produced by other methods. They also are generally costlier.
- But castings have good vibration absorbing capacity, have better accuracy and may not always require a heat treatment.

- Fabricated jigs and fixtures have a medium cost, light weight and do not require heat treatment but they have low vibration resistance capacity and less accuracy.

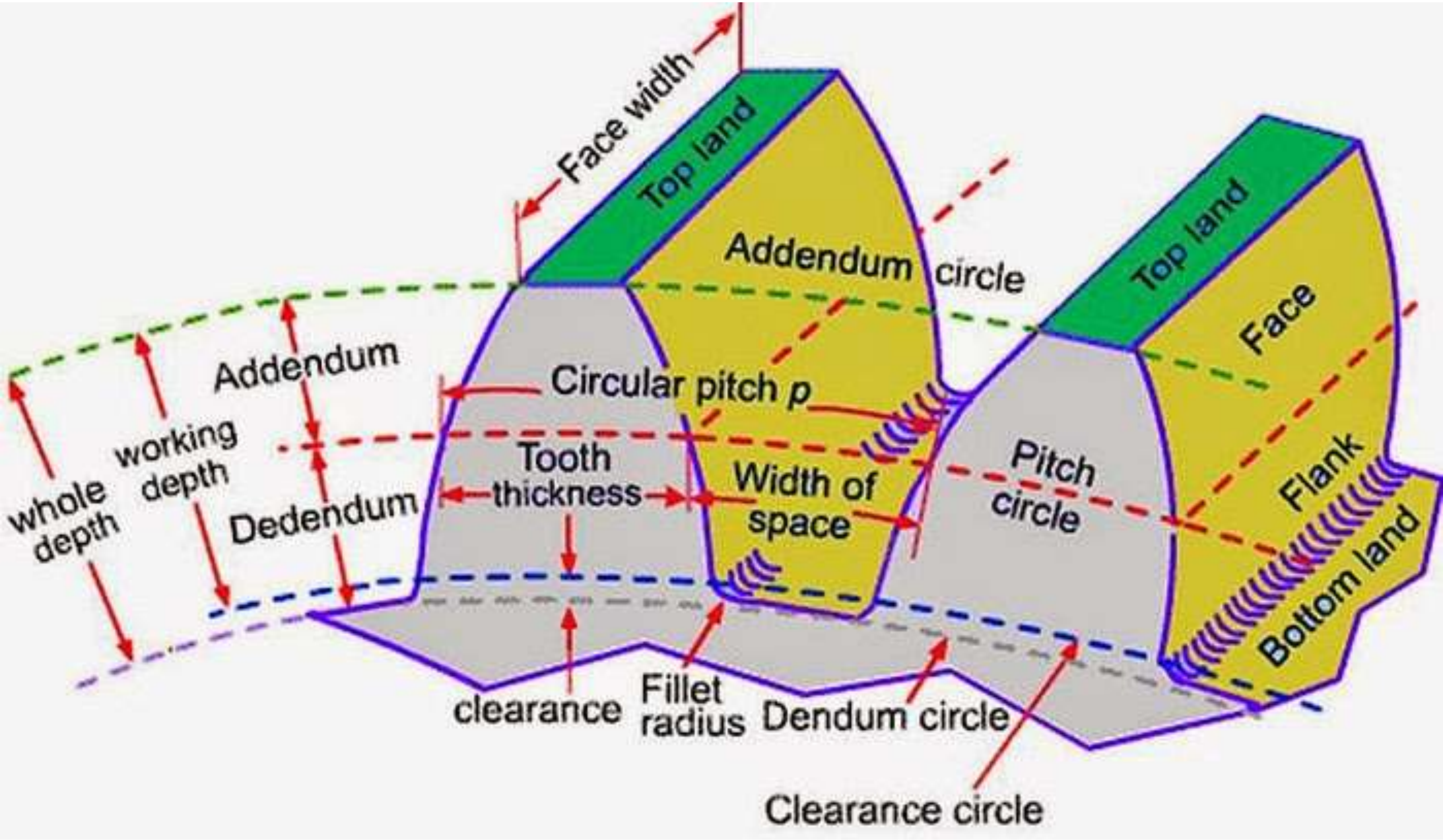
- Welded jigs and fixtures have almost similar characteristics as the fabricated ones but unlike fabricated units they cannot be separated without damage.

CHAPTER # 3

Gear and Thread Manufacturing



Gear Terminology:



Methods of manufacturing gears:

1. Casting
2. Metal Forming
3. Powder metallurgy
4. Metal removal

Casting:

- Cast in sand mould, permanent mould, shell mould, plastic mould and wax mould.

- Heavy gears of CI are generally made by sand casting.
- Poor accuracy .
- Used in slow speed drive.

- Investment casting can produce accurate gears
- Have more strength.

- Advantage of casting is low cost production.

Metal Forming:

- Roll forming
- Extrusion
- Stamping
- Coining

Metal Forming:

Roll forming :

- Gears are made by forcing a hardened master gear into a gear blank mounted on shaft.
- Master gear fed inward gradually.

- Done both hot and cold forming.
- Large defamation is possible in hot forming, finishing can be done by cold forming.
- Cold forming requires high pressure compared to hot forming.

- Method can be called chip-less method, Material saving.

Metal Forming: contd…

Extrusion:

- Metal bar is extruded through several block dies with the final die having the shape of the desired tooth element.
- Material can finally be extruded to obtain gear on surface of bar.
- Extruded gear bar is then hacksawed.
- Only spur gears are manufactured by this method.
- Gear used in watches.

Metal Forming: contd…

Stamping:

- Sheet metals gears.
- Up to 3 mm thickness.
- Used in toys, watches, domestic appliances.

Coining:

- Gears coined from blanks in a hydraulic press or forging hammer.
- Gear required light machining.

Powder metallurgy:

- Metal powder is pressed in dies confirming to the tooth shape.
- Sintering is done.
- Coined to increase density and surface finish.

- High quality gears.
- Small gears upto 25 mm diameter.
- CI, Steel, Brass and others alloys.

Metal Removal:

- Widely used method of producing gears.

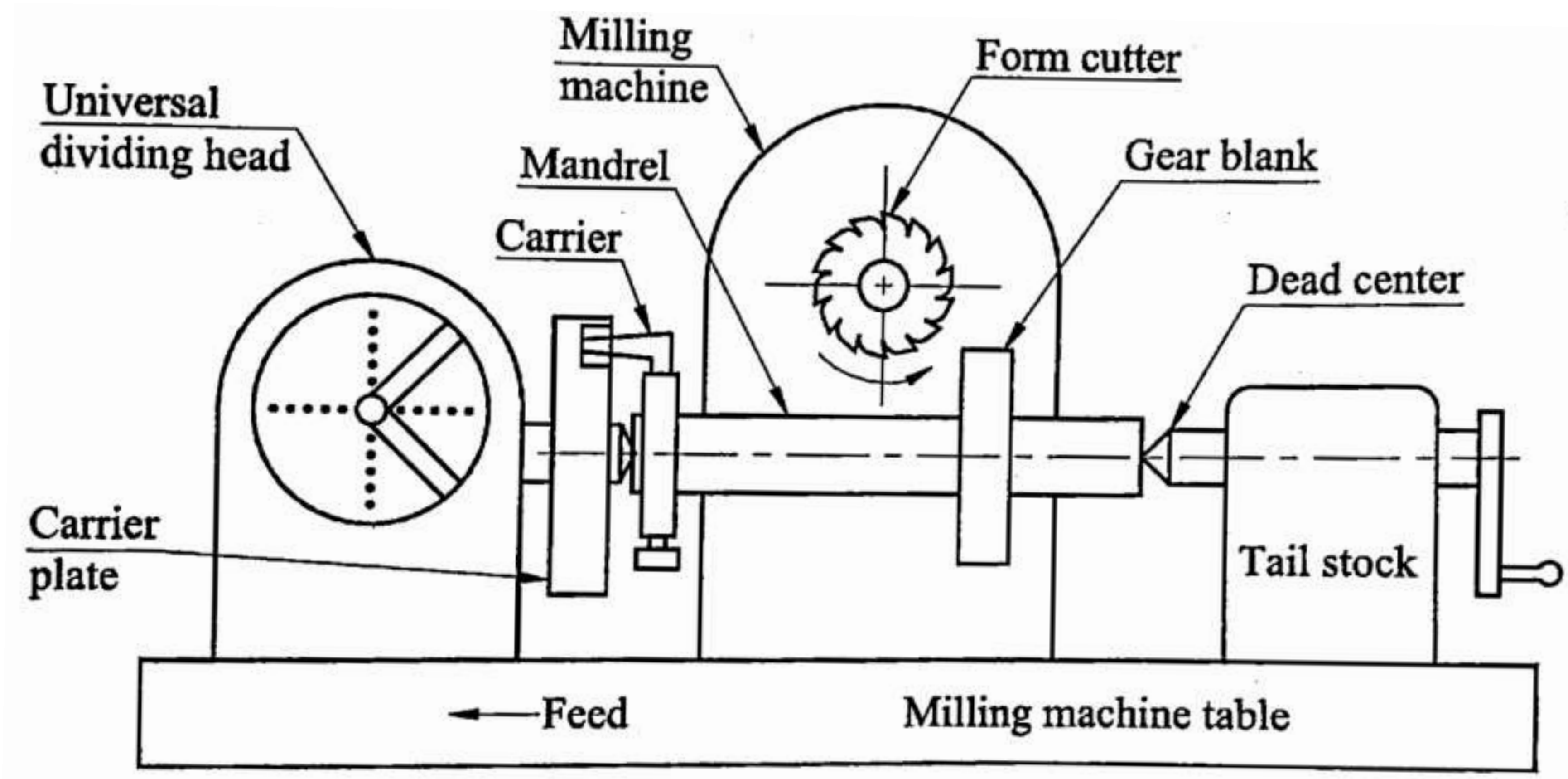
Forming or profiling

- Cutter used has the same as form as the space between the teeth to be cut.
- Requires the use of special cutter for each application.

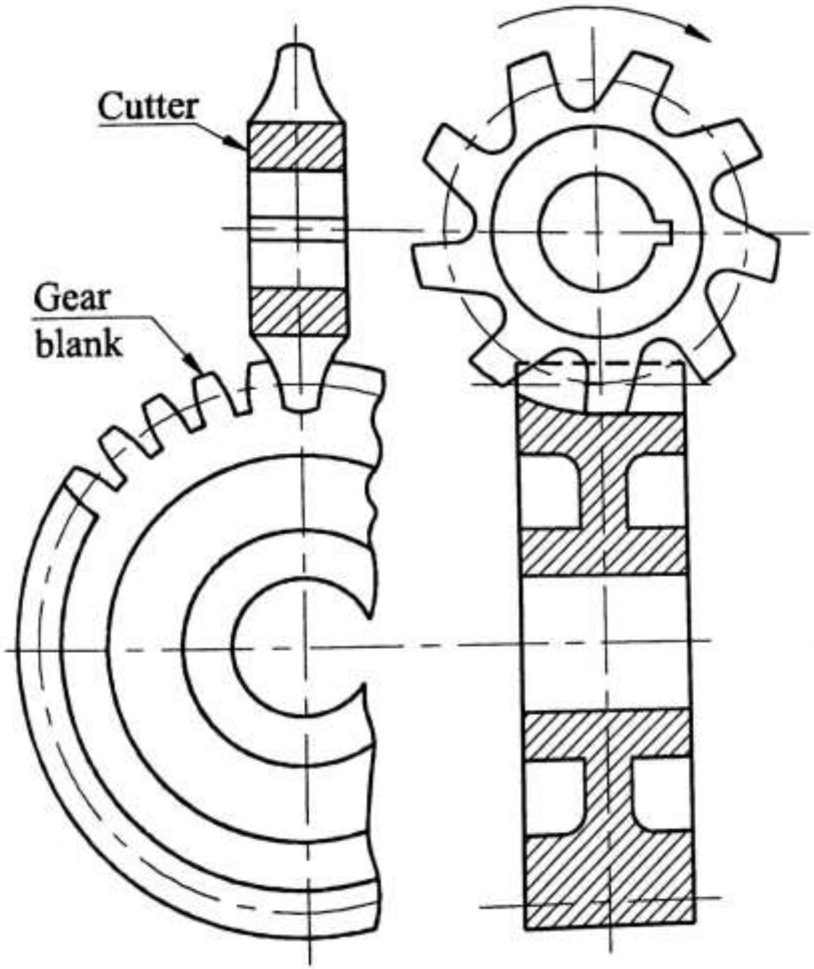
1. Gear cutting on milling machine with formed disc cutter or end-milling cutter.
2. Gear cutting on planer or shaper with single point formed tool.
3. Gear cutting with formed cutter in broaching machine.

1. Gear cutting by milling with from cutters:

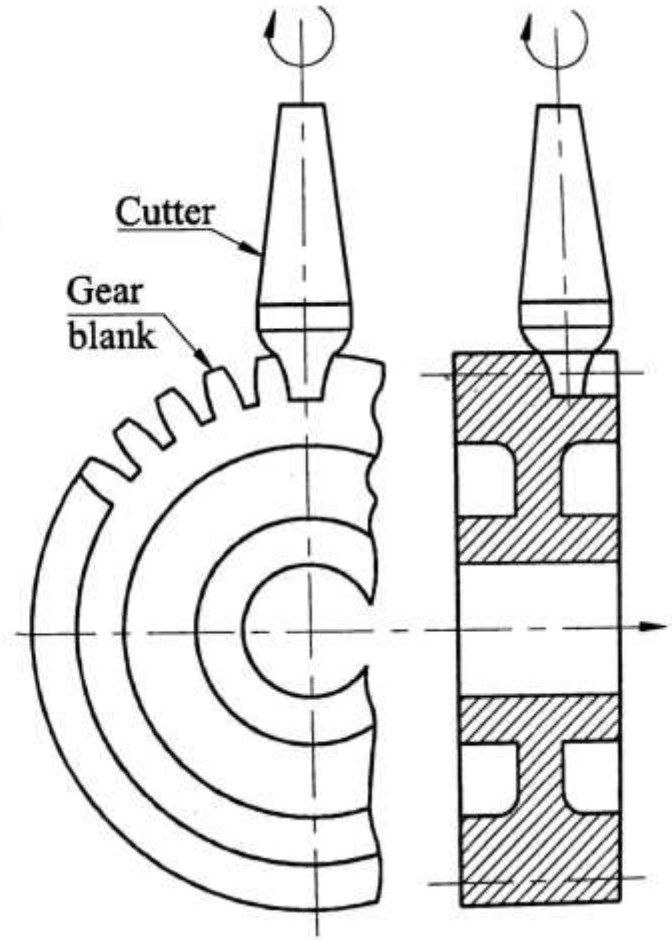
- Milling machines are capable of cutting practically every type of gear by employing an universal indexing mechanism and a form cutter.



1. Gear cutting by milling with from cutters: contd…

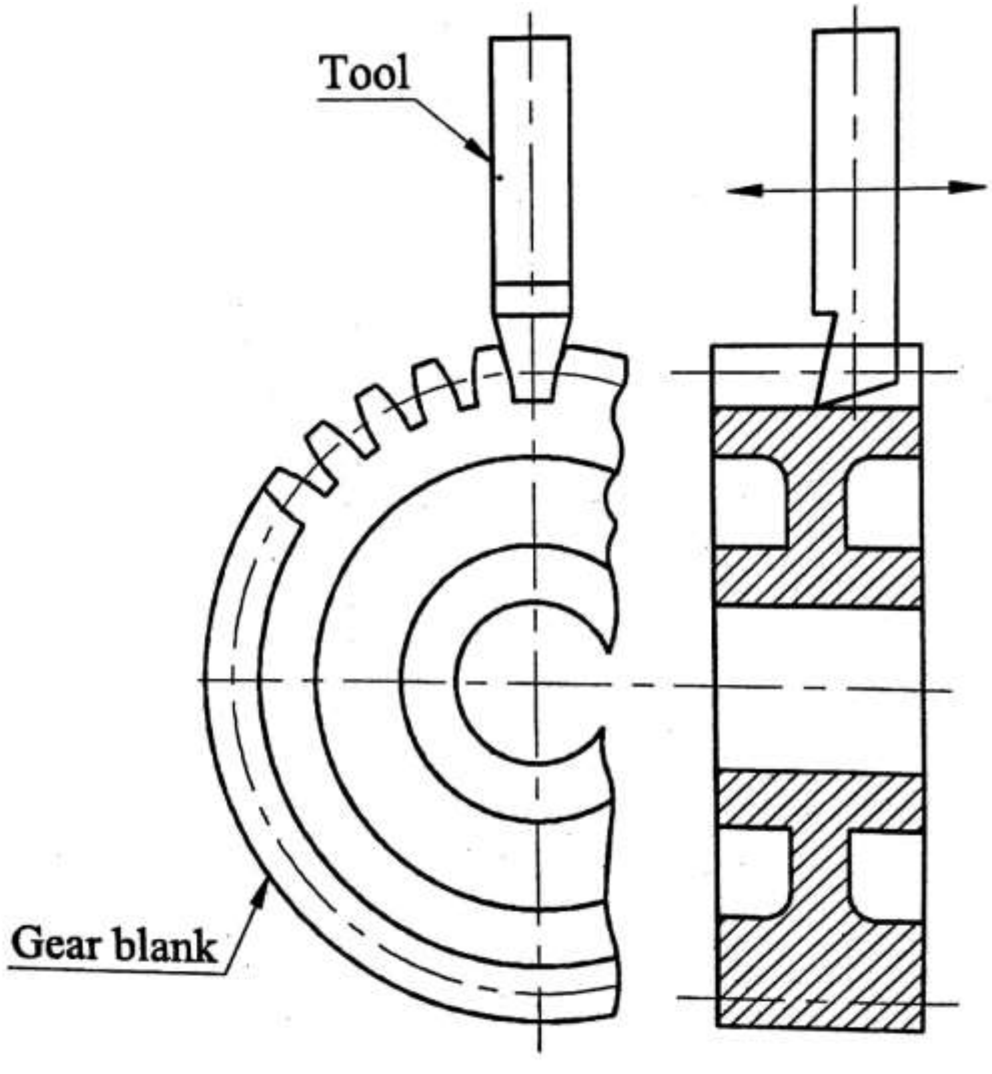


[Disc type from cutter]



[End mill cutter]

2. Gear cutting with single point formed tool on shaper/planer:



3. Broaching:

- Both internal and external gears can be manufactured using a from tool called broach.

- Broach should carry teeth which confirms in shape to the profile of the tooth space of the gear to be cut.

- Teeth cut on the gear carry superior finish.

- Favorable process for cutting internal gears.

Metal Removal: contd…

Gear generation

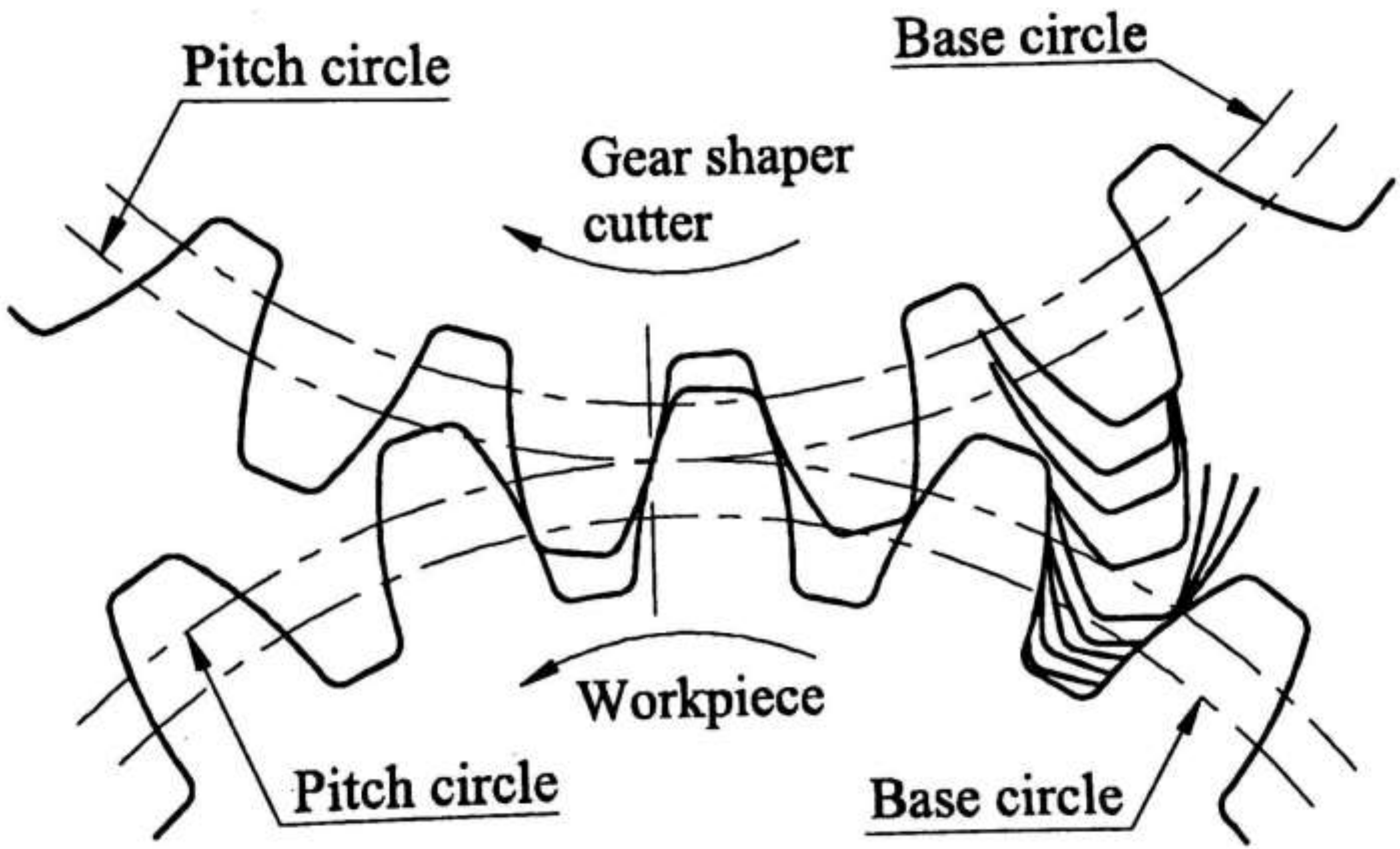
- One of the gears on the rack is made into a cutter by proper sharpening.
- This cutter gear meshes with the gear blank.
- Teeth on blank are developed or generated by relative rolling motion of the cutter and the blank.

- Same cutter of a particular module can cut gears of different number of teeth without profile deviation.

- Can be used for mass production.

1. Gear shaping:

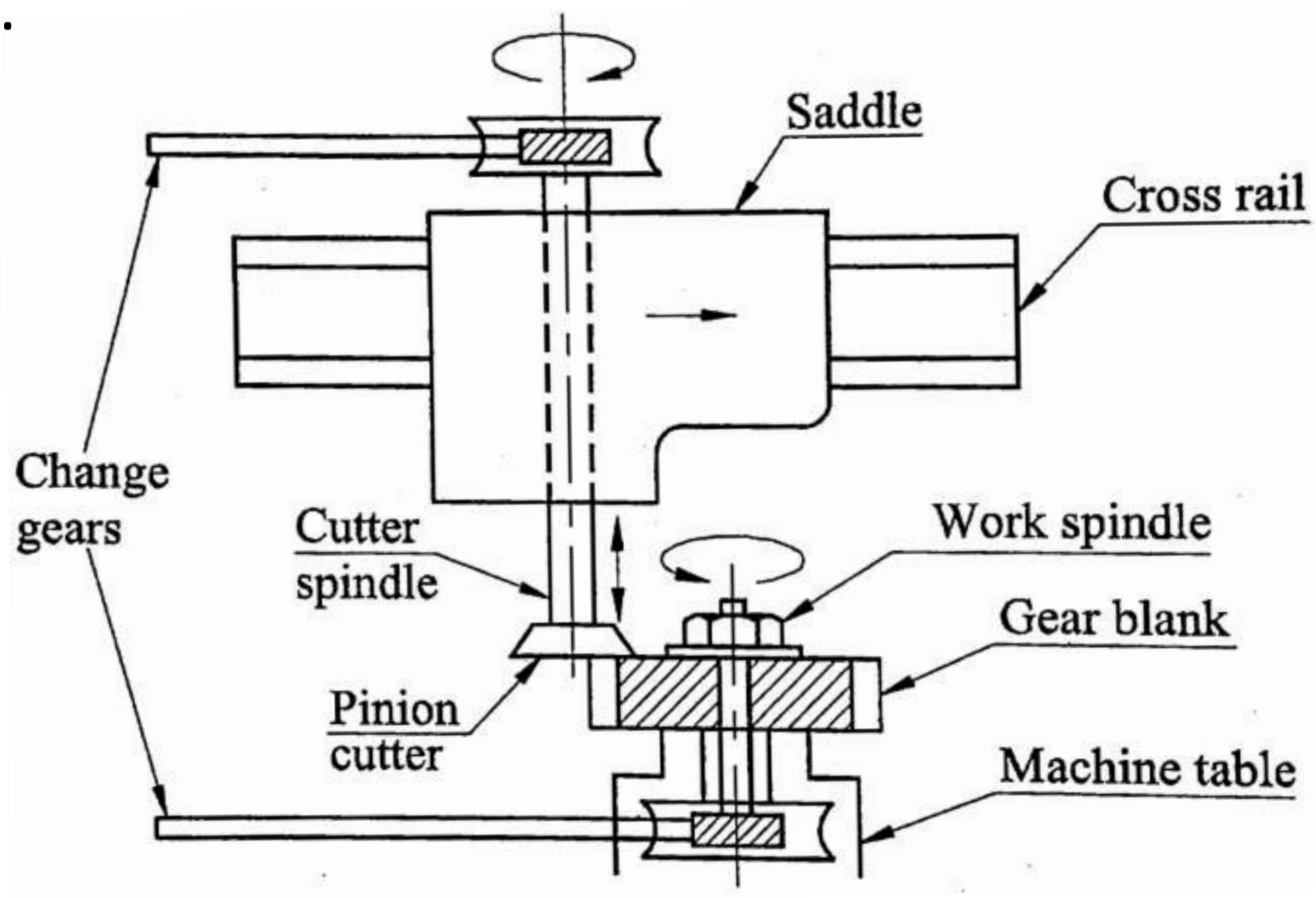
- Cutter is a gear provided with cutting edge.



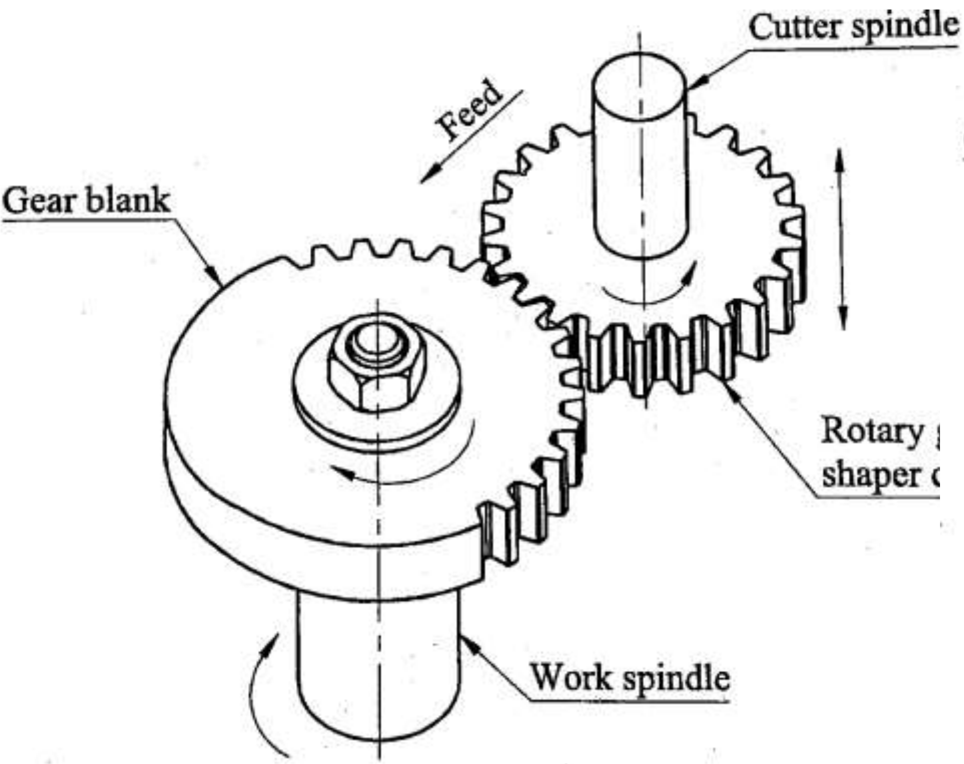
1. Gear shaping:

contd...

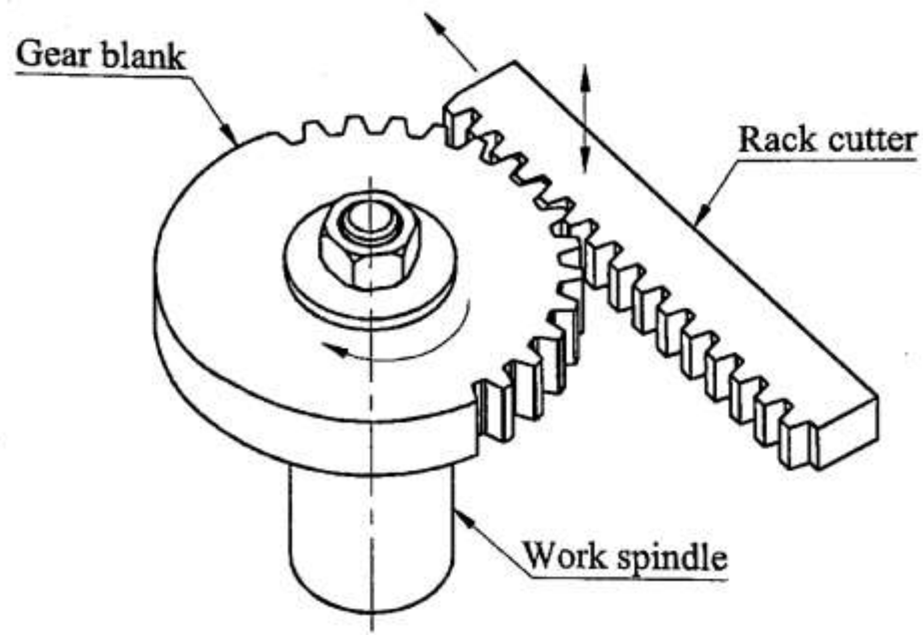
- Cutter is mounted with its axis vertical and reciprocate.
- Cutter and gear blank both rotate slowly about their own axis.



1. Gear shaping:



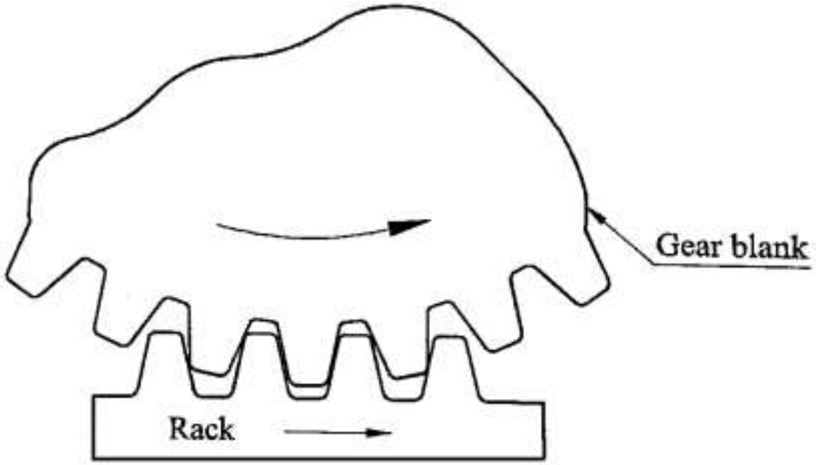
[Rotary shaper cutter]

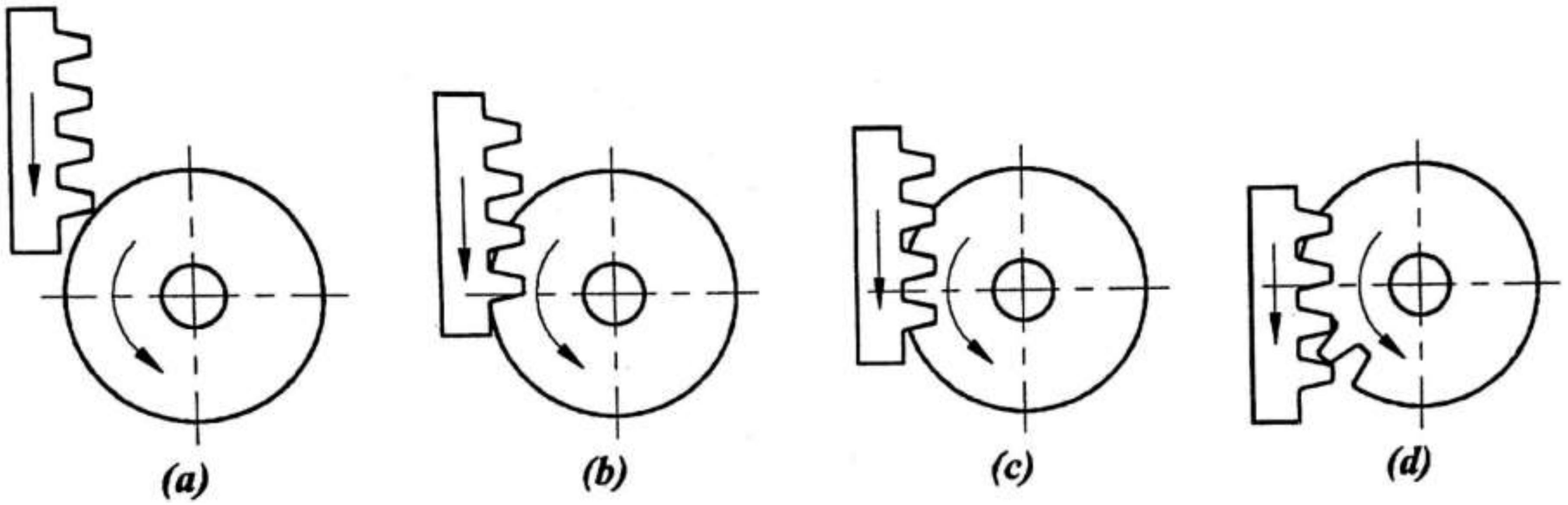


[Rack type shaper cutter]

2. Gear planing:

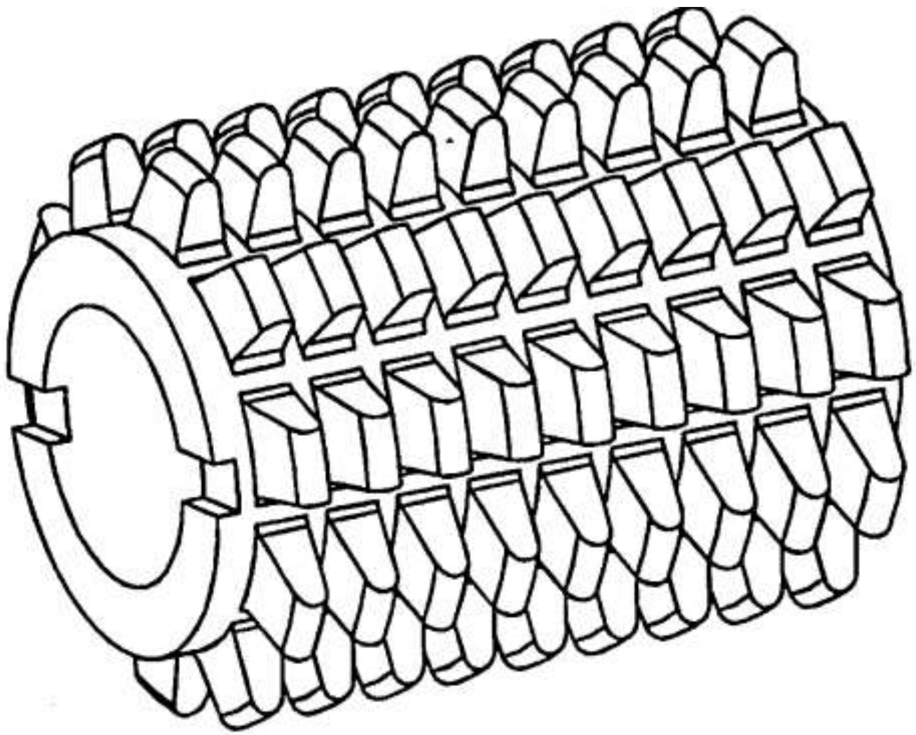
- Generating spur gear and heliacal gear with the help of rack type cutter.





3. Gear hobbing:

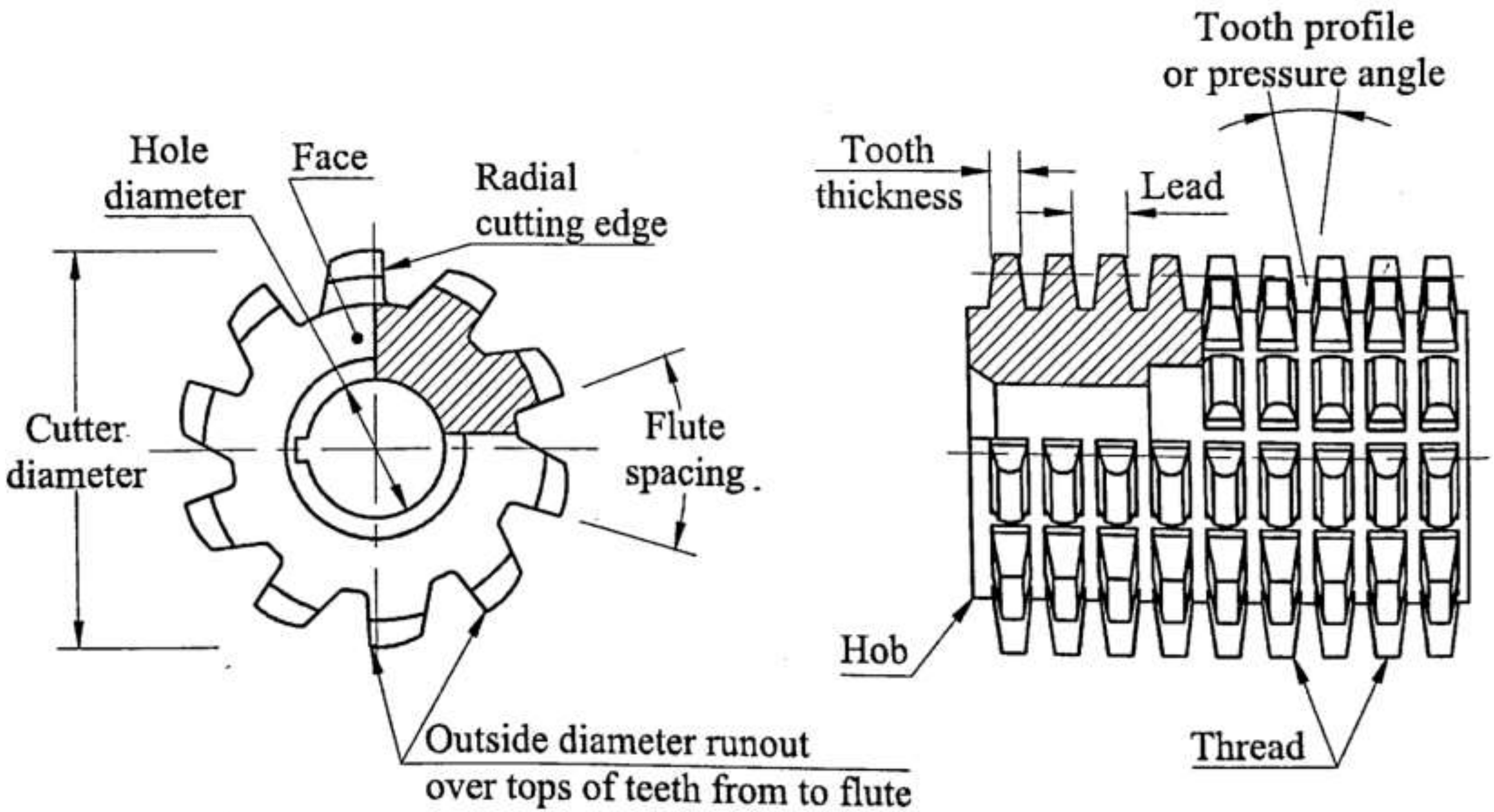
- Fastest of the gear generating processes.



(a) Hob

3. Gear hobbing:

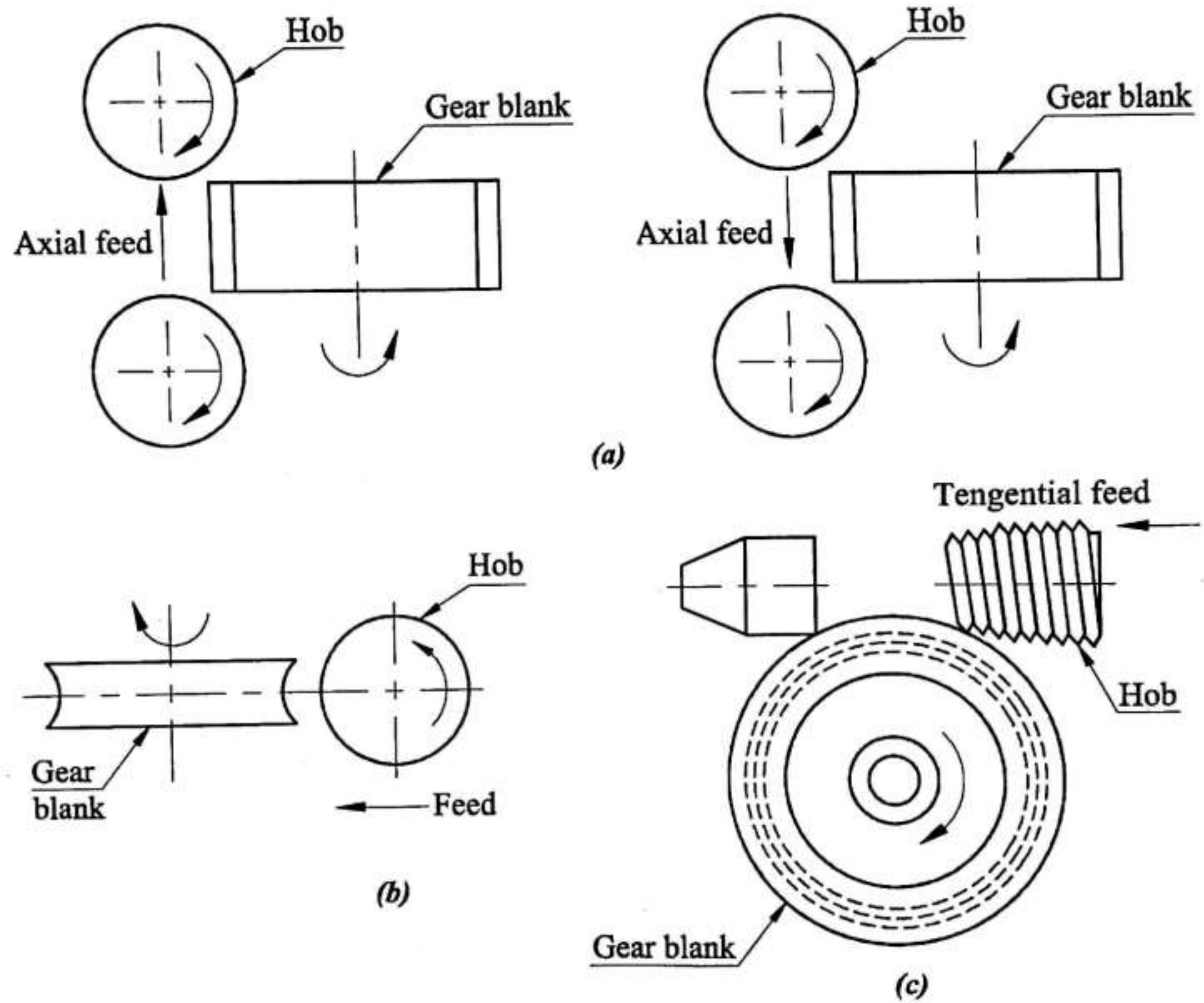
contd...



(b) Elements of hob

3. Gear hobbing:

contd…



Gear finishing process:

- The surface of gear teeth produced through forming or generation process is not very accurate and properly finished.

- Results in noise, excessive wear, backlash among meshing teeth or sometime in ultimate failure of the gear in the drive.

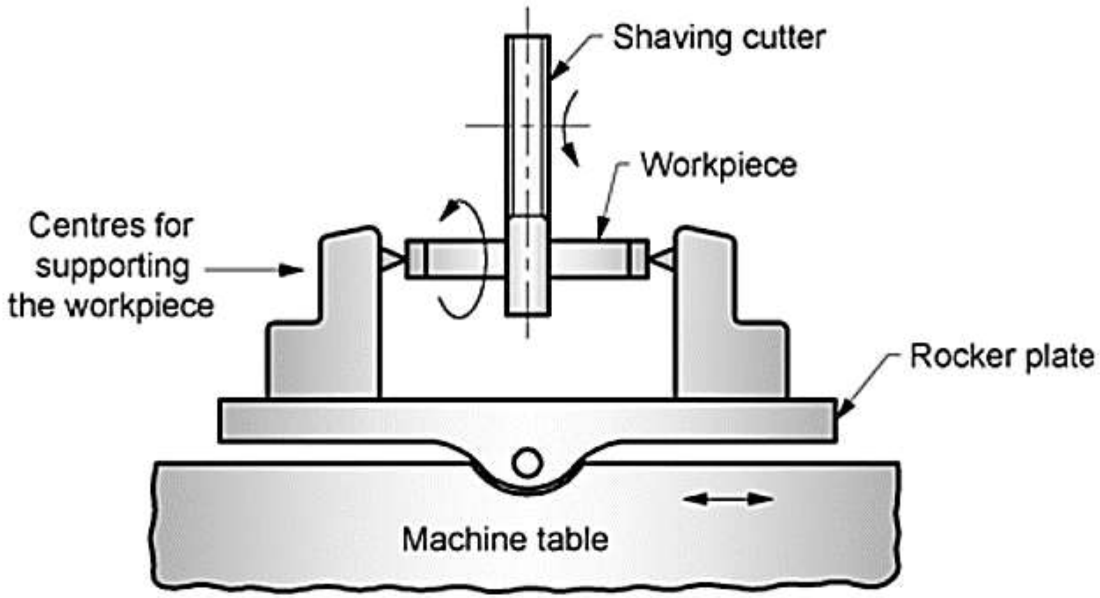
- To overcome these defects, some finishing operations become necessary after the gears are produced.

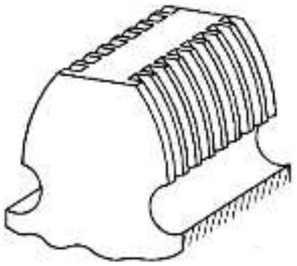
- It makes gear quite and smooth during running.

Gear finishing process: contd...

1. Gear shaving:

- Gear run at high speed in mesh and pressed against a hardened gear shaving cutter.
- Sharp edges of the shaving cutter scrape small amount of metal from the surface of the teeth removes surface irregularities.





Gear finishing process: contd…

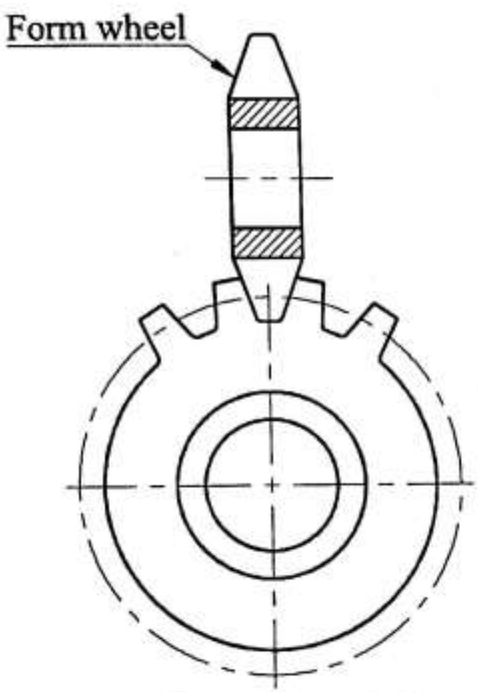
2. Gear burnishing:

- Done before hardening of gears.
- Work gear rolled under pressure, with hardened and accurately finished gear.
- Excessive martial from non-desired regions is plastically moved out by rolling action.
- Though the method provides smooth and accurate tooth profile, it increases localized residual stresses.
- Never advisable to employ the method on precision gears.

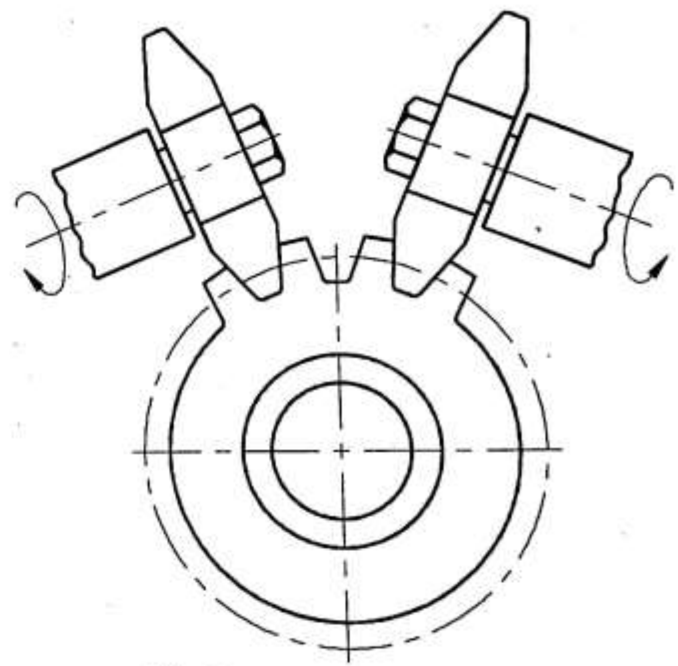
Gear finishing process: contd…

3. Gear grinding:

- Most accurate method of finishing gear teeth.
- Method is slower and more expensive but it gives highest quality gears.



(a) Form wheel grinding



(b) Generation grinding

Gear finishing process: contd…

4. Gear lapping:

- Lapping is often done on hardened gears (Hardness, > 45RC) to remove burrs, scales, abrasions, nicks and irregularities from the surface and to remove small errors caused by heat treatment.

- It is carried out by running the work gear in mesh with a mating gear or one or more small cast iron toothed laps under a flow of fine abrasives in oil.

- During lapping the work is turned first in one direction and then in the other to finish both sides of the tooth.

- Very small amount of material is removed during lapping.

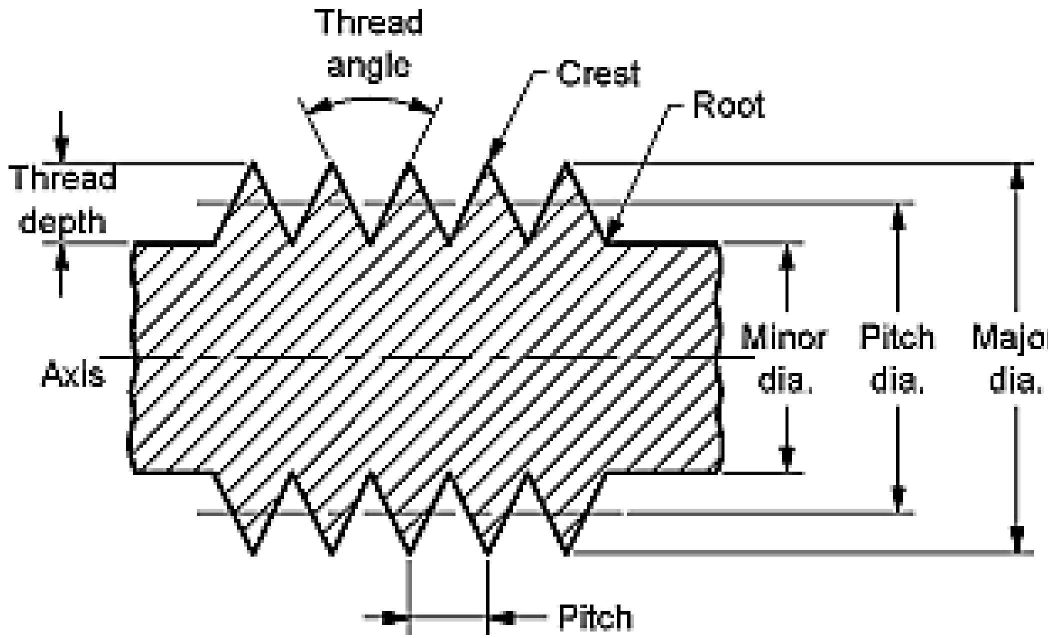
5. Gear honing:

- Like lapping, honing is also suitable for finishing heat treated gears.
- It is carried out with the help of steel tools having abrasive or cemented carbide particles embedded in their surface.
- The honing tool is pushed with constant force along the tooth space.
- The honing tools are costlier than lapping tools but the process is much faster.

Thread Manufacturing

Thread :

- A screw thread is a ridge of uniform cross section in the form of a helix provided on the outside or inside of a cylindrical or conical surface.



- External threads are provided on bolts, screws and studs while internal threads are necessary on the corresponding nuts or machine members into which these units are to be screwed.

Applications of Thread :

- Functionally threads serve many purposes. Bolts, studs, screws and other fasteners are threaded for holding components securely yet permitting them to be separated whenever desired.

- Screw jacks and presses are provided with threaded components for transmitting power.

- Lead screws in machine tools facilitate controlled accurate movements.

- Accurately cut screws in dividing machines, micrometers and other measuring devices are used to control and measure fine dimensions.

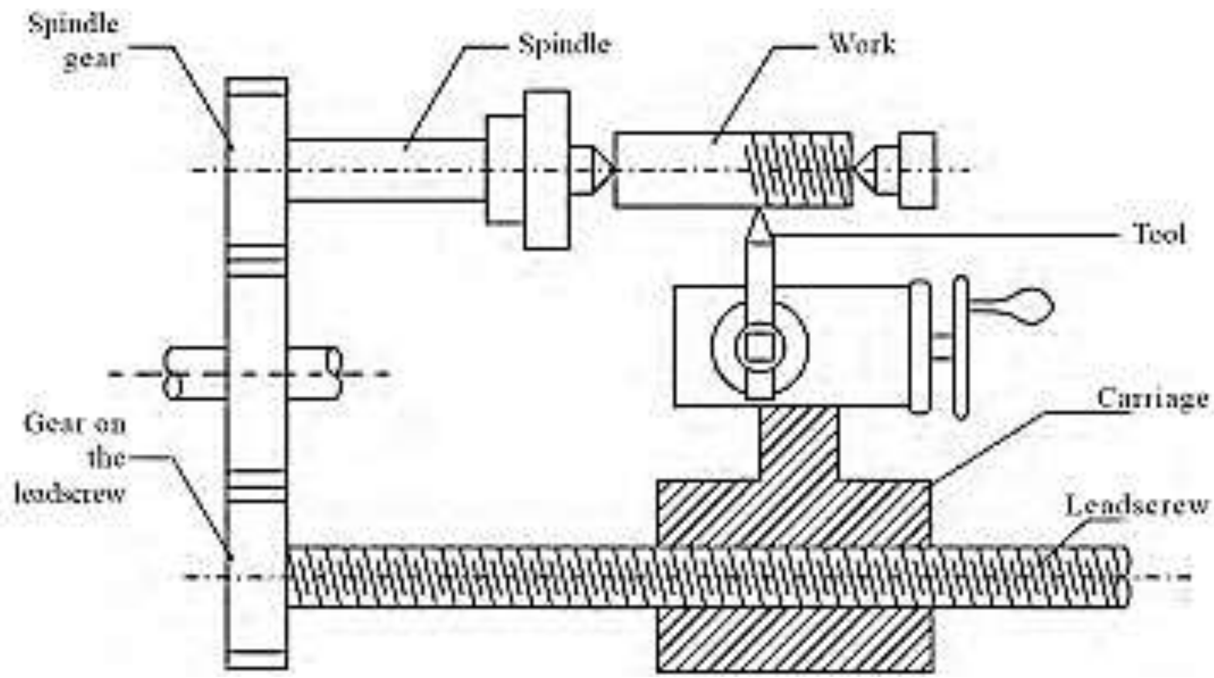
Thread Manufacturing Methods:

Screw threads may be manufactured by any one of the following methods :

1. Thread cutting on a lathe
2. Thread chasing
3. Die threading
4. Tapping
5. Thread milling
6. Thread rolling
7. Thread grinding
8. Thread casting
9. Thread whirling

Thread Cutting on a Lathe :

- Using a single point form tool.
- Lead screw of the machine to control the form and lead of the thread respectively.
- Both internal and external threads can be cut.
- The full depth of the thread is produced by a number of successive passes each with a small depth of cut.



Thread Cutting on a Lathe : contd…

- The method is extremely slow and cannot be made automatic.

- The process of engaging and disengaging of the carriage half-nut using a chasing dial requires considerable skill and attention of the operator.

- Screw cutting with a single point tool is still an economical method for one piece or small quantity production.

Thread chasing:

- A chaser is a multi-point threading tool having the same form and pitch as that of the thread to be chased.

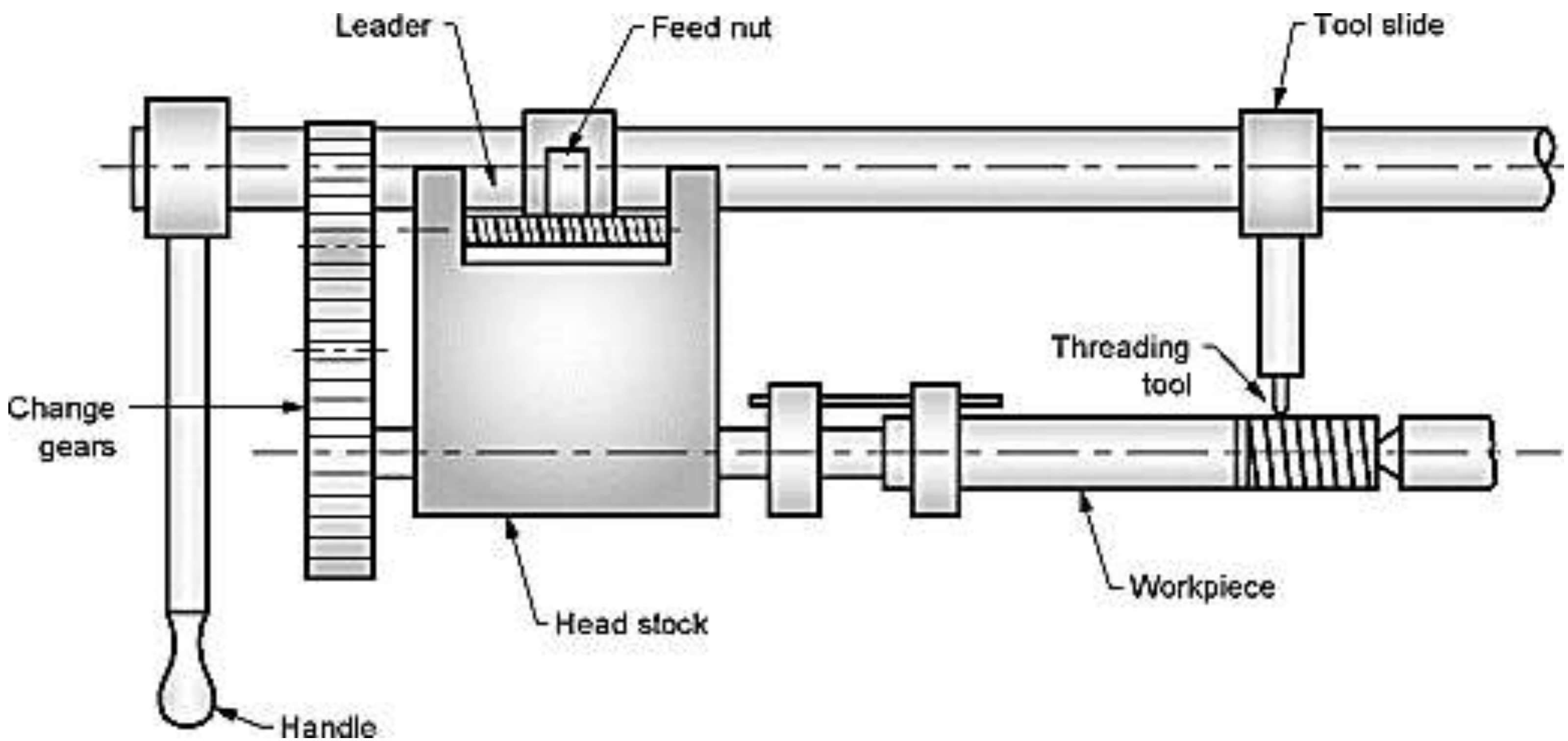
- The device may be in the form of an attachment used on the lathe or may be built into a special purpose machine.

- In this device power from the headstock of the machine is given to a short lead screw known as the leader by means of change gears.

Thread chasing:

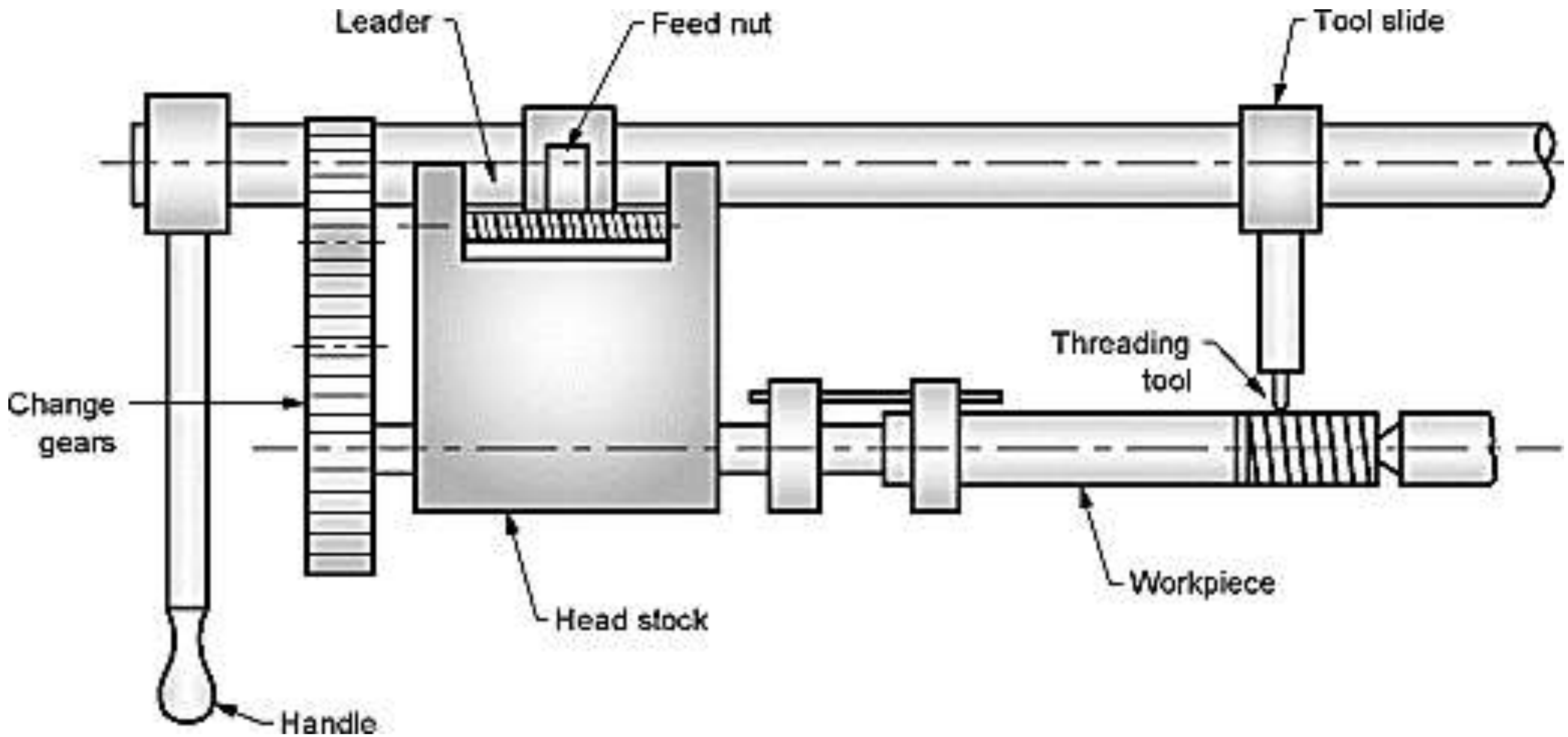
contd...

- Power from headstock is given to a short lead screw known as the leader by means of change gears.
- The feed nut and the tool slide are carried on a shaft which can be engaged or disengaged to the leader with the help of the handle shown.



Thread chasing:

- The feed nut can be engaged to the leader at any position of the work rotation.
- The operation is carried out at about 50 percent of the speed for turning .
- Allows considerably higher cutting speeds to be used.



Thread cutting dies:

- The dies used in die threading may be solid or self opening type. Solid dies are made of high speed steel and are mainly used for hand threading but can be used on turret and lathes with suitable holders.

- Some **adjustable dies** are available with provision for size compensation of wear on dies.

- **Solid dies** are made of carbon steel or H.S.S and are generally used for threading by hand.

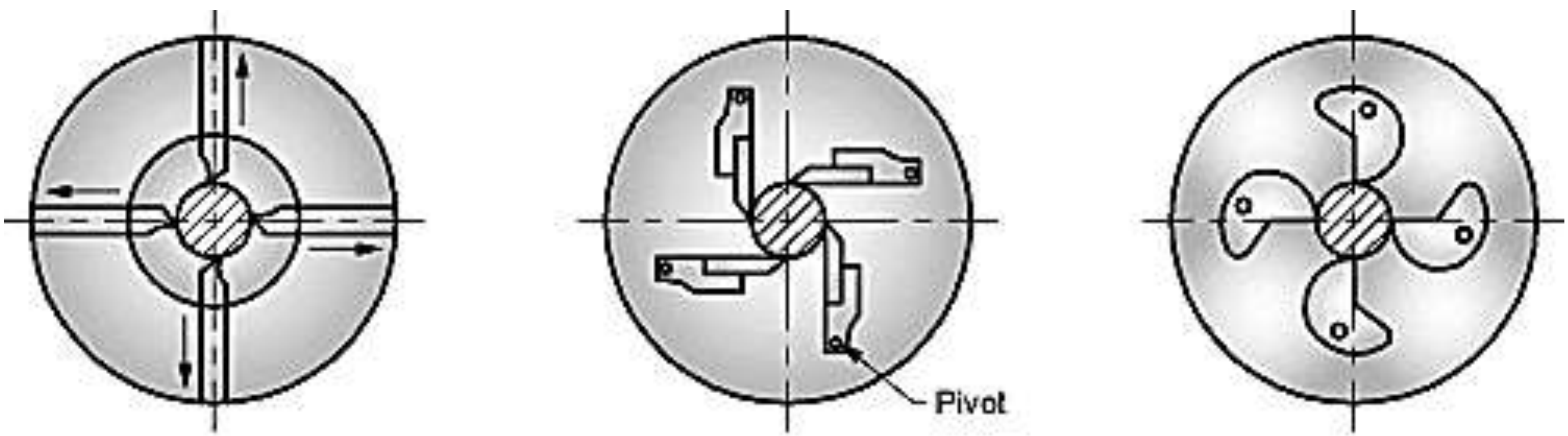
- The main drawback of these dies is that after be the thread has been completely cut, the die has to be withdrawn by reversing the spindle.

Thread cutting dies: contd…

- The **self-opening dies** use H.S.S. chasers mounted in die heads.
- The die heads are provided with arrangement for opening and closing of the thread chasers within the die head.
- After the thread has been completed the chasers are withdrawn radially outwards in the body due to the action of a cam or scroll.
- This clears the chasers from the threads. The die head can be withdrawn without reversing the spindle.

Thread cutting dies:

- Depending upon the type of chasers, **self opening die heads** can be classified into three main types :
  - (1)Radial
  - (2)Tangential
  - (3)Circular



(a) Radial (b) Tangential (c) Circular die

Tapping:

- Tapping is a thread cutting process for producing internal threads.

- Like die threading tapping also uses multipoint cutting tools called taps and may be done manually or on machines.

- The use of tapping tools with machines essentially follows the same procedure as manual tapping.

Tapping :

contd...

- Feed being automatic with the machine, the threads produced are more accurate and uniform.

- Machining rate can be considerably increased by providing the machine features like...

  - fast retraction of the tool,
  - continuous or automatic loading and unloading of parts and
  - use of multiple spindles.

Thread milling :

- The most common method of thread milling is with a multi-tooth cutter called **hob** on a thread milling machine.

- The hob is carried in a cutter head mounted on the carriage that slides between the head stock and the tail stock.

- The cutter and job axis lie in parallel planes with the cutter set at an angle equal to the lead angle of the thread.

- The cutter rotates at the milling speed while the job is revolved at a slow feeding speed.

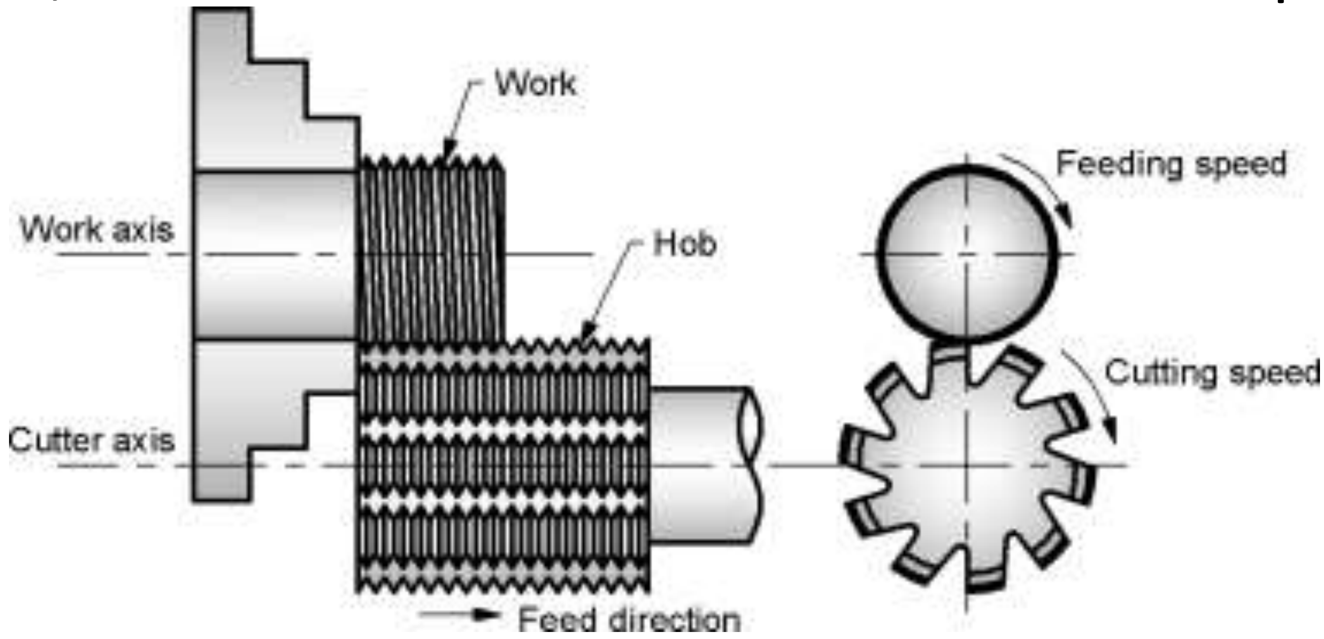
Thread milling :

contd…

- During operation the revolving cutter is first fed to the full depth into the work.

- Then fed lengthwise along the slowly revolving workpiece.

- So that by the time the thread being cut encircles the job diameter, each thread would have advanced one pitch.



Thread rolling:

- Produces external threads by a cold forging operation rather than a cutting operation.

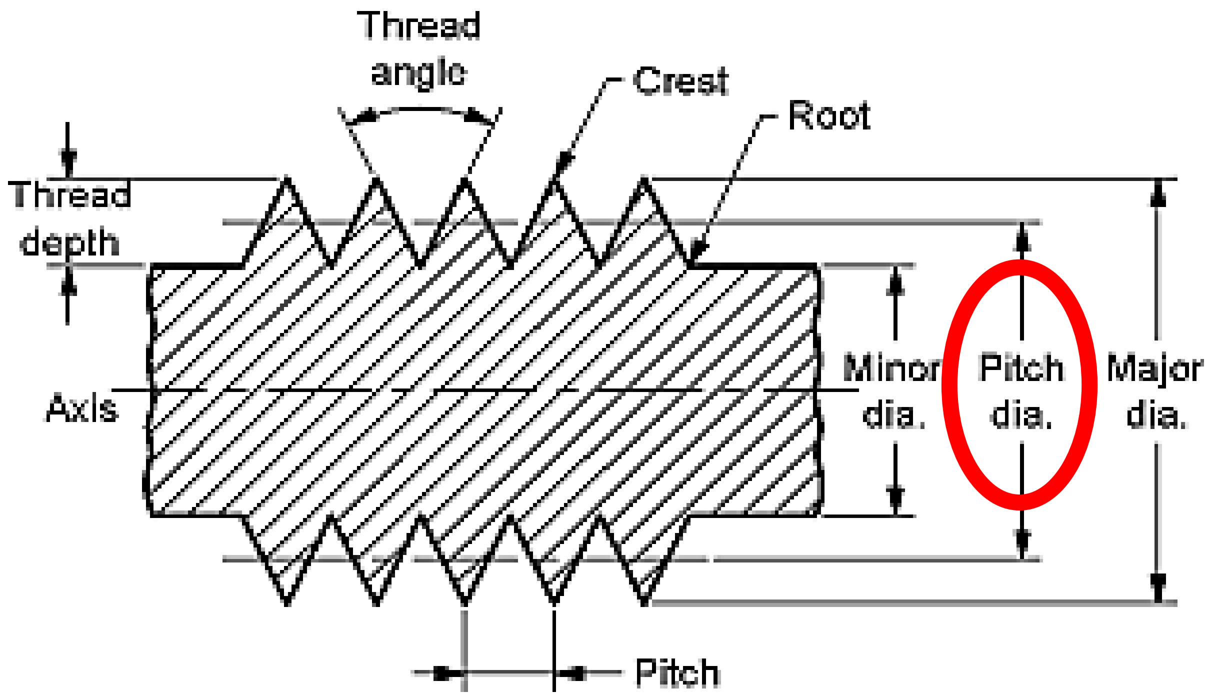
- This is achieved by subjecting a thread blank to pressure between two hardened steel dies.

- The surfaces of the dies carry reverse form of the thread to be cut.

- Application of pressure causes plastic flow of the material.

Thread rolling:

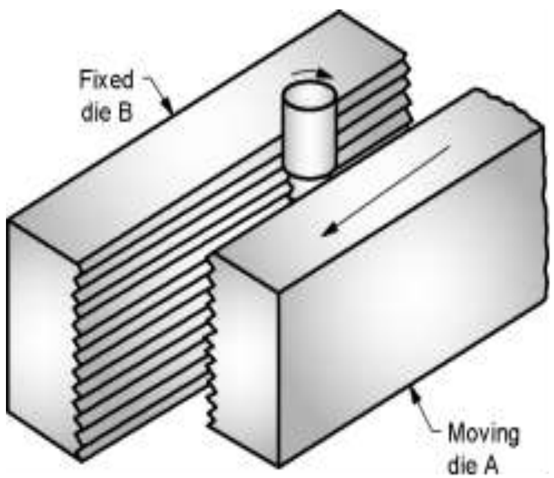
- The diameter of the blank is approximately equal to the pitch diameter of the required thread.

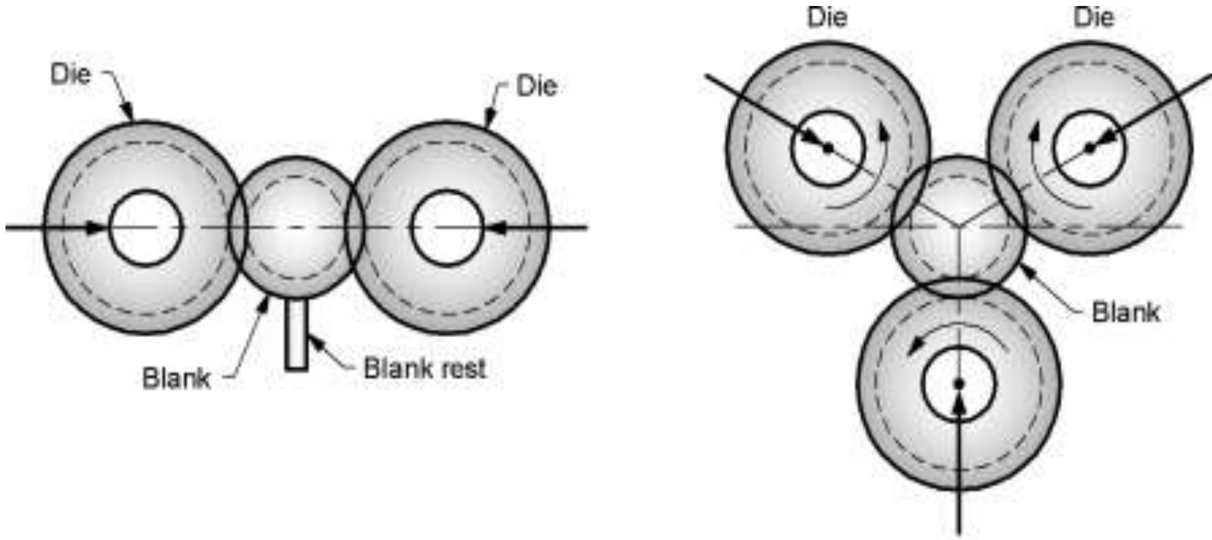


- The die thread penetrates to form the depression or roots of the thread while the displaced material forms the crests and flanks.

Thread rolling:

- Dies may be in form of grooved blocks or threaded rolls.
- Thread rolling can be carried out on any material that can withstand the forging pressure.
- Two types of dies are in common use for thread rolling.
    - Flat dies
    - Cylindrical dies



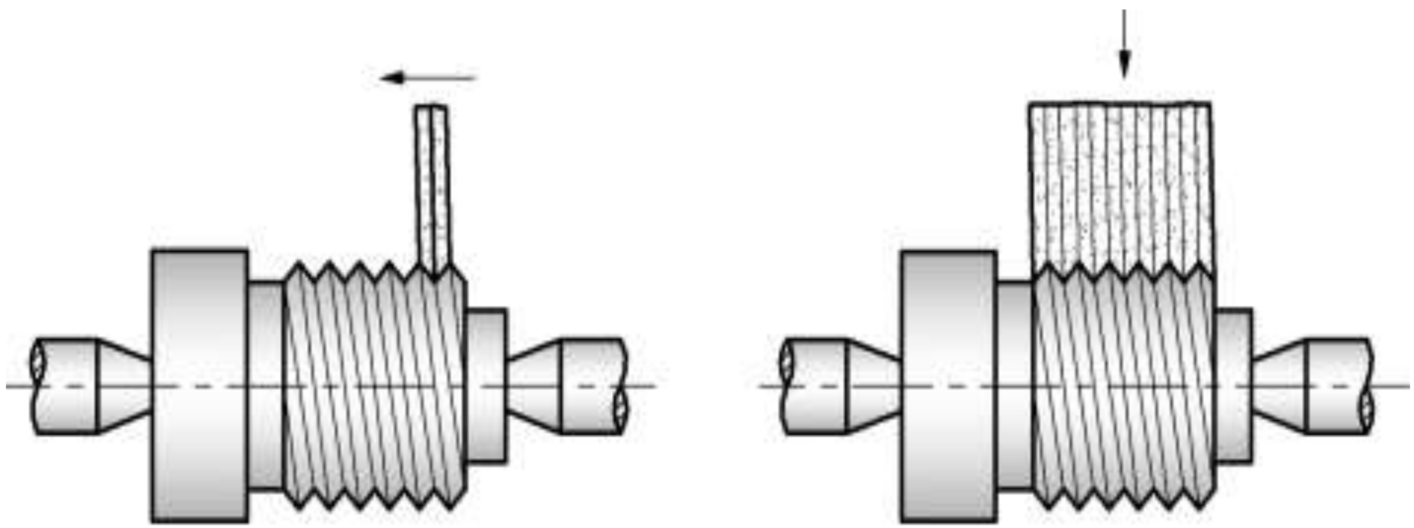


(a) Two die method

(b) Three die method

Thread grinding :

- Thread grinding is used as a forming or finishing operation.
- Done on threads which are required to have a very high degree of finish and accuracy.
- Materials which are very hard or very soft and for threads which have been heat treated.



(a) Single wheel grinding (b) Plunge cut grinding

- A lot of cutting fluid must be used to get the best results.

Thread casting:

- The accuracy and finish of threads produced by casting depends on the casting process used.
- Threads made by sand casting are rough and are not used much except in some vices and rough working machinery.
- Threads made by die casting and permanent mould casting are quite accurate and of high finish.
- These methods can be used to produce external and internal threads in complex jobs but the methods are suitable for low melting temperature metals.

Thread whirling :

- The process can be carried out on special thread whirling machines or on standard engine lathes equipped with thread whirling attachment.

- The thread whirling equipment essentially consists of a tool holding ring which carries four carbide tipped tools, mounted at 90 dgree to each other.

- The ring is set eccentric to the work axis and is run at speeds of 1000-3000 rpm by an independent motor.

- The carrier unit can be swivelled to set the tool path along the axis of the helix angle of the thread and is provided with a setting microscope for setting the tools.

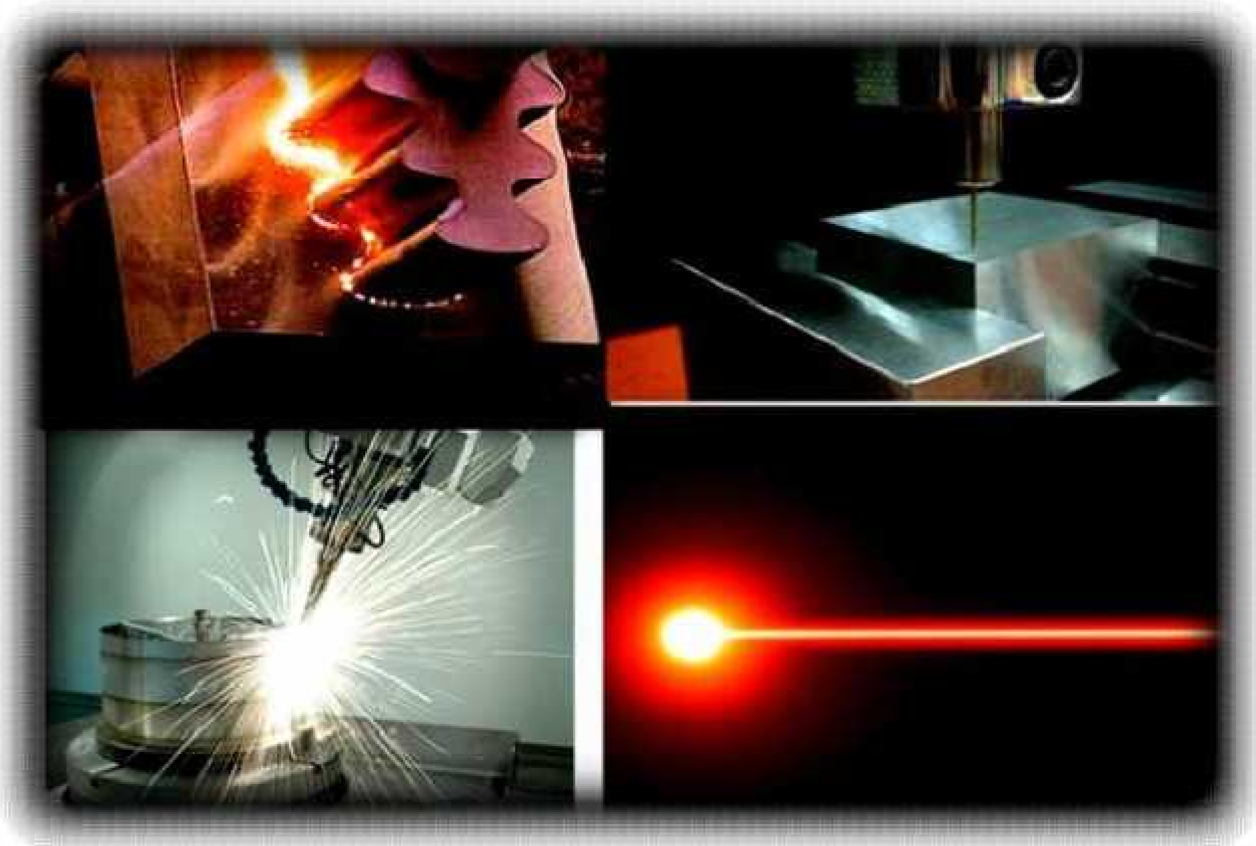
Thread whirling :

Thread whirling :

contd…

- The whole unit is mounted on the carriage of the machine and is provided linear motion corresponding to the pitch of the screw being cut by gearing it to the machine lead screw.
- The work piece, mounted horizontally is provided a slow rotational motion of 3-30 rpm from the headstock through a reducer.
- Two of the whirling tools cut along the flanks of the thread, the third cuts at the root while the fourth one which has the full tooth form finishes the thread.

Non Conventional Machining



Comparison between Conventional and Non-conventional machining :

Sr. No	Conventional	Non-Conventional
1	Direct contact of tool and workpiece.	Tools are non-conventional technique like Laser beam, electric arc etc.
2	Cutting tool is always harder than w/p.	Tool may not be harder and it may not be physical presence.
3	Tool life is less due to high wear.	Tool life is more.
4	Generally Macroscopic chip formation.	Material removal occur with or without chip formation .
5	Material removal takes place due to application of cutting force.	It uses different energy like electrical, Thermo-Chemical etc. to provide machining.
6	Suitable for all material	Not suitable for all material.
7	It cannot be used to make prototype parts very effectively.	It can be used to produce prototype parts very effectively.

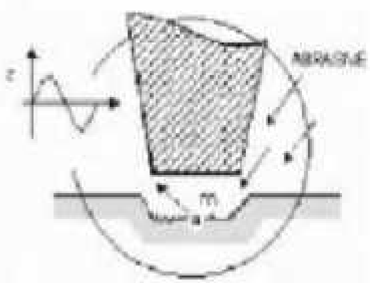
NON CONVENTIONAL MACHINING PROCESSES

Form of Energy Used

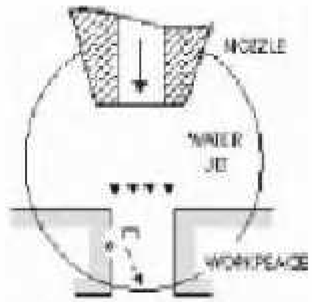
Mechanical	Electrochemical	Chemical	Thermo-Electric
MATERIAL	**REMOVAL**	**DUE**	**TO**
Erosion	Ion Displacement	Ablative Reaction	Vaporizations

EXAMPLES:

Mechanical	Electrochemical	Chemical	Thermo-Electric
Abrasive jet M/c Ultrasonic M/c	Electrochemical M/c Electrochemical Grinding	Chemical M/c	ElectroDischargeM/c Electron beam M/c Laser beam M/c Ion beam M/c Plasma Arc m/c

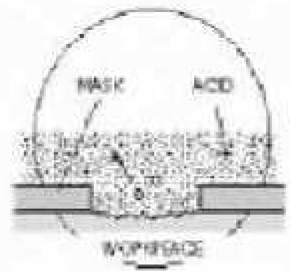


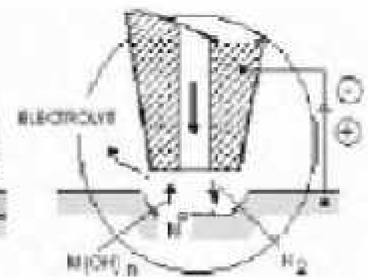
ULTRA SONIC MACHINING
(USM)



WATER JET MACHINING
(WJM)

ABRASIVE JET MACHINING
(AJM)





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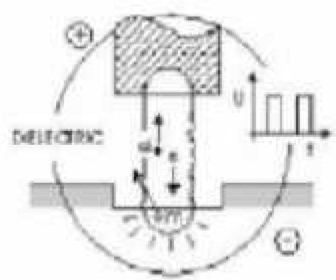
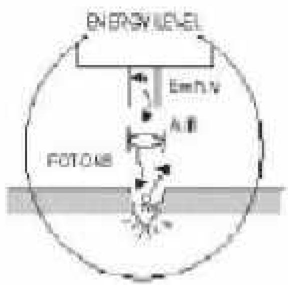
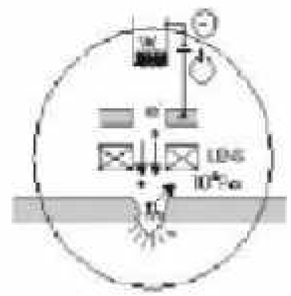
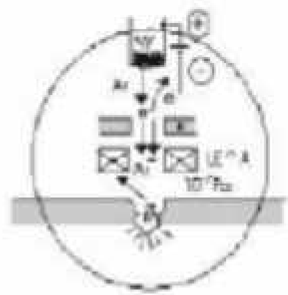
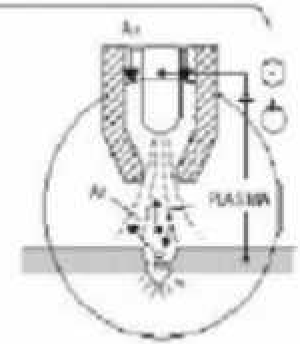








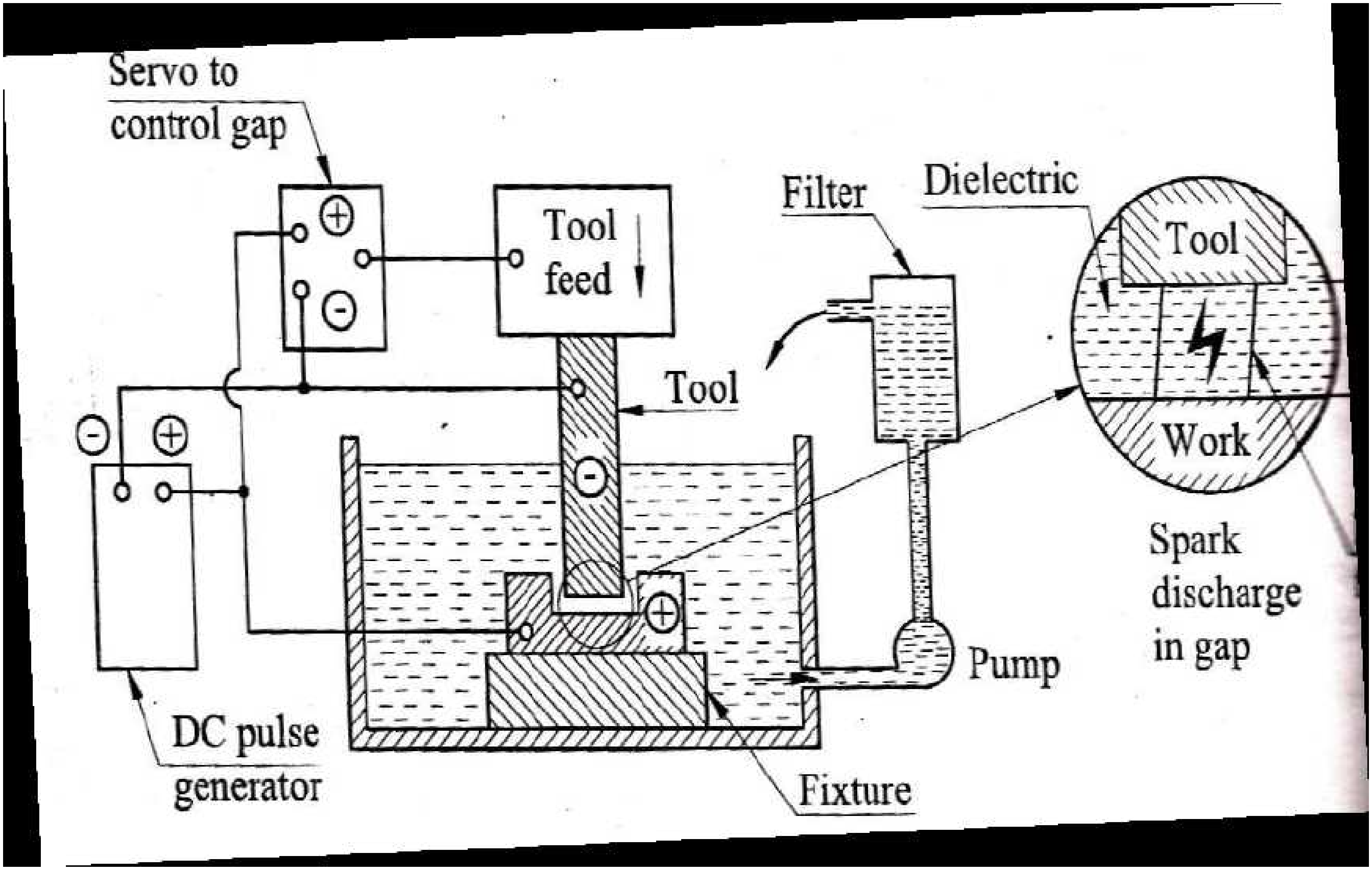
ION BEAM MACHINING
(IBM)



PLASMA ARC CUTING
(PAC)

Electric Discharge Machining/Spark Erosion/ Spark Machining / Thermal Erosion /Electro Erosion Process

Principle of EDM:



- The main attraction of EDM over conventional machining is that this technique use thermoelectric process to erode undesired material from the w/p.

Construction :

- System consist of Shaped tool, Power supply source, Dielectric fluid and its circulation line, Servo controlled tool feed mechanism and work.
- Tool ⟹ Cathode (Negative terminal)
- Work ⟹ Anode (Positive terminal)
- Terminals are connected to DC power supply to create potential difference between work and tool.
- Distance between work and tool is known as Spark gap and it is filled by dielectric fluid.

Working:

- High voltage is applied between terminals and it induce electrical field in spark gap.
- Free electrons on tool are subjected to electrostatic force and hence they are emitted from tool and accelerate towards work. There would be collision between electrons and molecules in dielectric. It cause further generation of electrons because of ionization of dielectric molecules.
- This cyclic process increase concentration of electrons in spark gap and when potential difference is sufficiently high dielectric break down and large no. of electrons will flow from tool to job and ions from job to tool.
- This movement of electrons visually seen as Spark and electrical energy is dissipated as thermal energy of spark.
- With a very short duration of spark , temperature of electrodes raised locally to more than their normal boiling point and this heat of spark melt a tiny bit of metal from work.
- The melted metals cools and solidifies as tiny particles in dielectric .
- The metal is carried away due to circulation of dielectric by means of pump and the process continues.

Process Parameter:

Voltage: 40 to 300 V

Current: 0.5 to 400 A

Spark gap: 0.0125 to0.125 mm

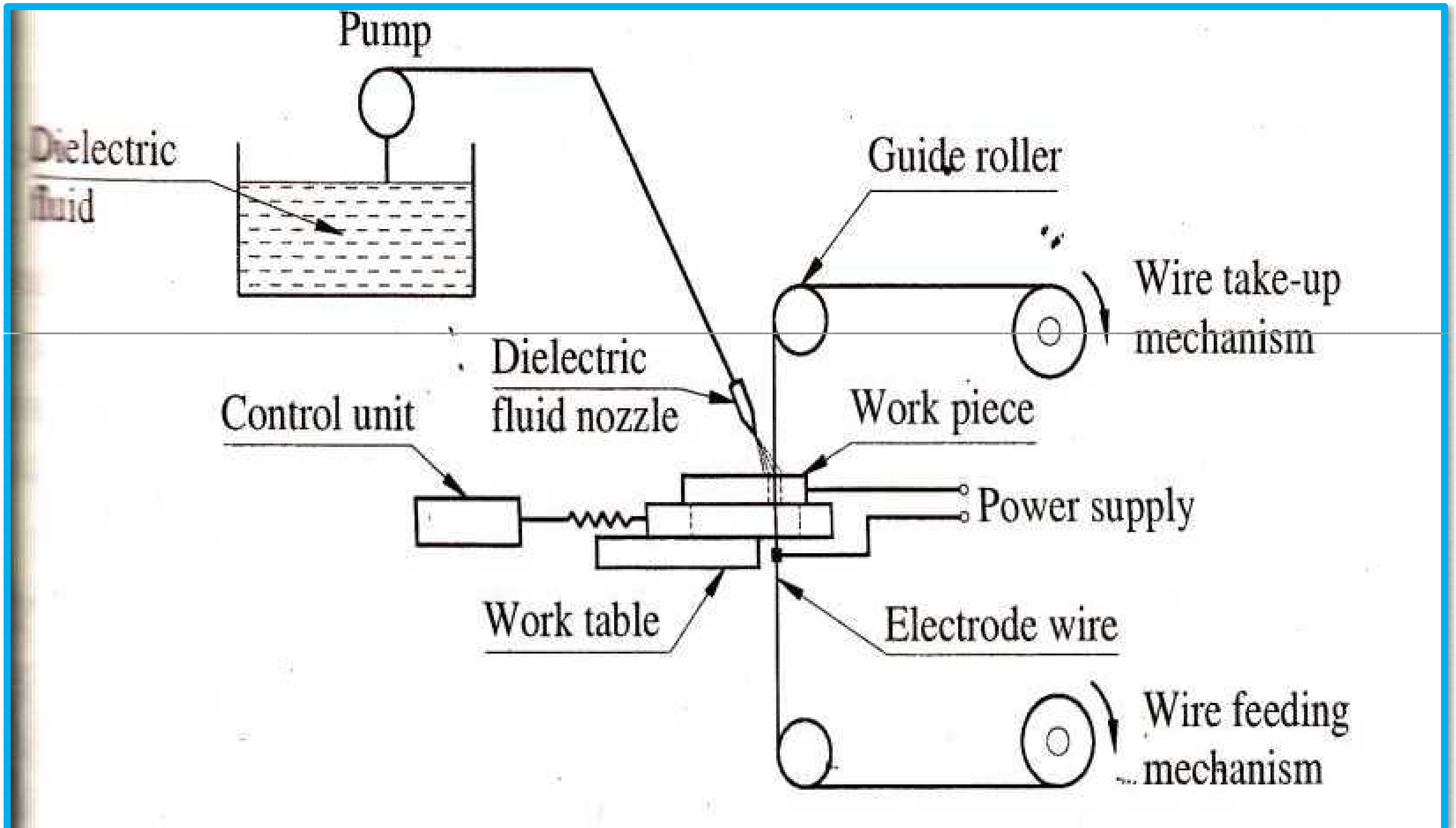
Pulse duration: 2 to 2000 microsecond

MRR: 800 mm^3 – 5000 mm^3

Application of EDM:

- EDM Drilling to drill very small holes and EDM milling to machine complex shapes.
- EDM can be used to make parts with irregular shape with precision for forging press tool, extrusion dies, cutting tool dies etc.

Wire Cut EDM


Pump
Dielectric fluid
Guide roller
Wire take-up mechanism
Dielectric fluid nozzle
Control unit
Work piece
Power supply
Work table
Electrode wire
Wire feeding mechanism

- Wire EDM use Electro thermal mechanism to cut electrically conductive materials.

Construction:

- EDM consist NC unit to control counter movement of work, wire feeding mechanism to move wire at constant tension, power supply and dielectric fluid supply.
- Wire of 0.02 to 0.3 mm diameter
- Tool ⟹ Cathode (Negative terminal)
- Work ⟹ Anode (Positive terminal)
- Dielectric is de-ionized water applied as localized steam rather than submerging the whole work.
- Wire for EDM is made of Brass, copper, tungsten, and Zinc or brass coated wire. The wire should have high tensile strength and good electrical conductivity.

Working:

- During operation wire moves along prescribed path and remove material from work.
- Same as EDM process material is removed due to series of discrete discharge between Anode and Cathode in presence of dielectric fluid.
- The place of discharge heated to extremely high temperature and that surface is melted and material removed.
- Removed particles flushed away by flowing dielectric fluids.

Advantage of Wire cut EDM:

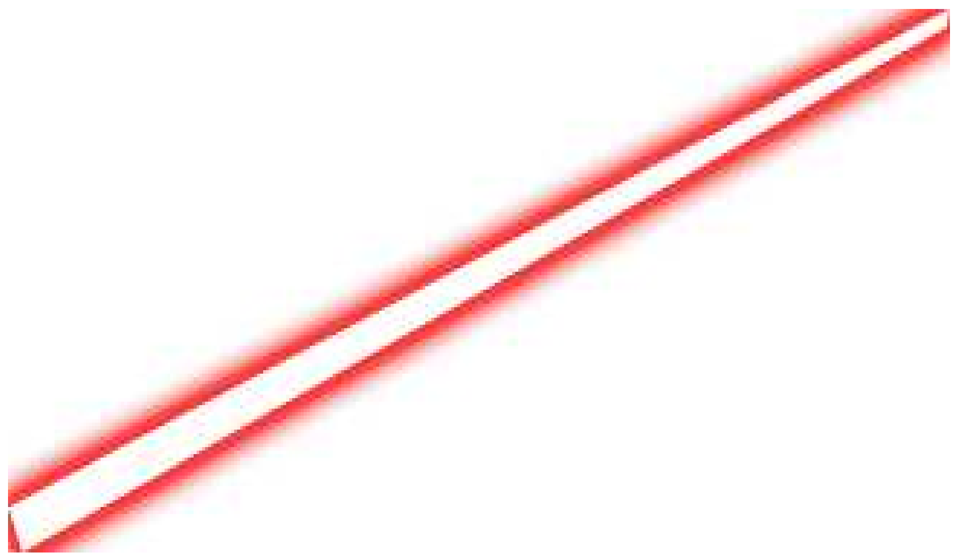
- Smooth machine surface and polishing not required.
- Forming electrode to product shape is not required.
- Wear of electrode is negligible.
- Production rate is high machine can be easily operated for long time.

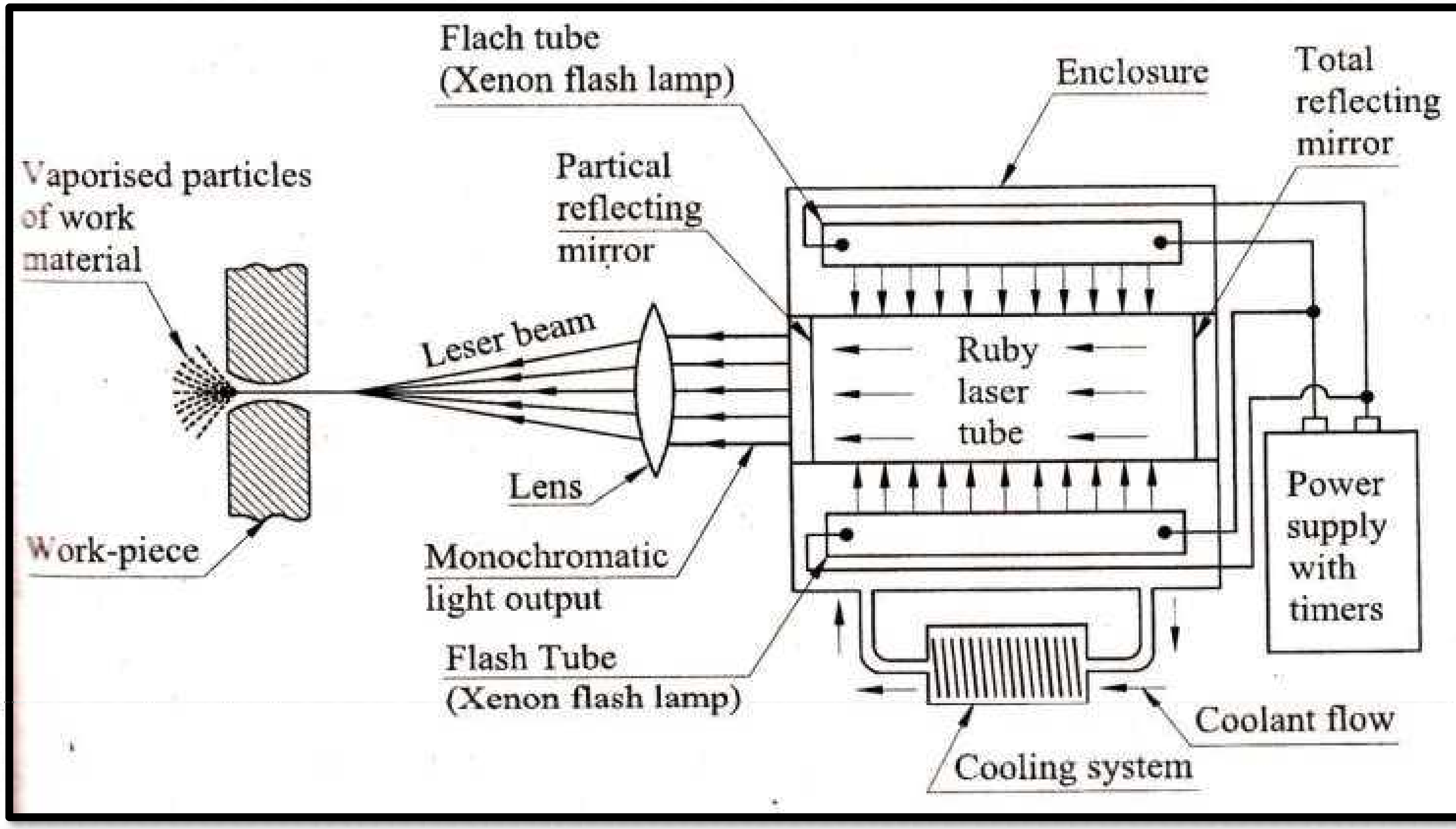
Application of Wire cut EDM:

- Intricate components for electrical and Aerospace industries.
- Machining of sheet metal die, extrusion dies and prototype parts.
- Cylindrical objects are cut with high precision.

Laser beam machining (LBM)

It is thermal metal removal process which uses LASER beam to melt and vaporize particles on the surface of metallic and non-metallic work-pieces.





Construction:

- It consist cylindrical crystal ruby tube, flash tube, focusing lens, power supply source, total and partial reflecting mirror and cooling system.
- Ruby is Aluminum oxide with 0.05% Cr dispersed and it's one end is blocked with total reflective mirror while other end having partially reflected mirror.
- Flash tube is placed outside ruby crystal.

Working:

- Capacitor bank is charged by high voltage energy supplied which energize flash tube by trigging system.
- Flash tube flashes white light and Cr atoms in ruby crystal absorb this energy and get excited.
- This atoms pumped to high energy level and drop back to original state. When atoms jump from one to another level it emits photons (Red fluorescent light). This phenomenon is known as lasing action or stimulation effect.
- Due to reflection this effect is enhanced and finally photons will come out from partially reflected mirror with great intensity called LASER.
- Laser beam is focused with the help of lens and work is placed near focal point of lens. Due to high temperature work material will melt and vaporize.
- Ruby rod becomes high efficient at low temperature. Thus it is continuous cooled with water or liquid Nitrogen.

LBM Process parameters:

- Voltage: 4500 V
- Pulse duration: 100 microsecond
- MRR: 0.1 mm^3/min
- Surface Finish: 0.5-1.2 μm (CLA)

APPLICATION of LBM:

- LASER drilling
- LASER metal cutting
- LASER welding

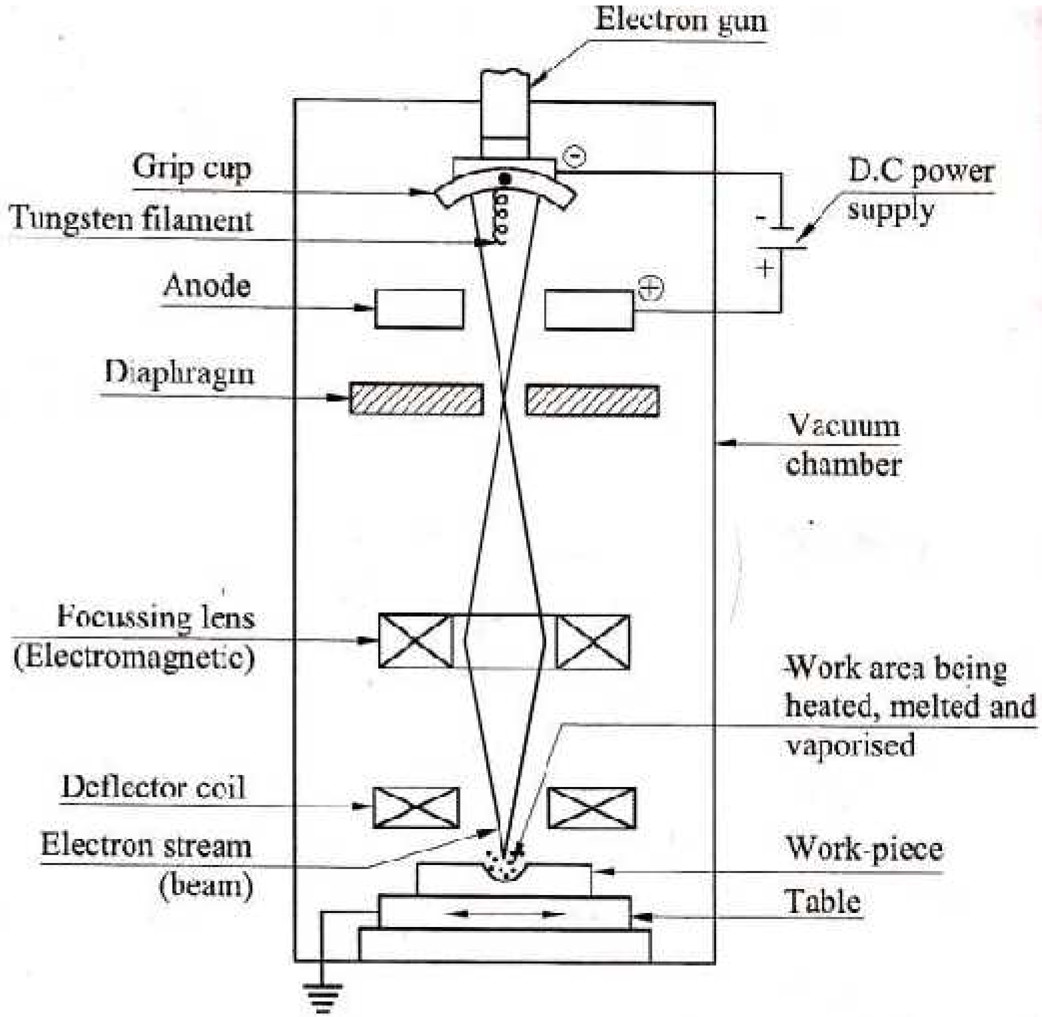
ADVANTAGE of LBM:

- Small, complex and micro sized holes.
- No direct contact between tool and work.
- Accuracy is high and doesn’t require filler material.
- Dissimilar material can easily welded.
- Automated easily.

DISADVANTAGE:

- It can’t be used to drill deep holes.
- Highly reflective material can’t be effectively machined.
- Initial investment is high.
- Safety must be followed strictly and skilled operator required.

Electron Beam Machining(EBM) Process thermo Electrical process in it MRR By high velocity electron beam emitted from tungsten filament. Kinetic energy of beam transferred to work, producing heat and melt or vaporize material locally.



Construction:

- It consist of vacuum chamber, electron gun, magnetic lens to focus beam, deflecting coil, and work table for holding.
- Electron gun consist of grid cup, tungsten filament(cathode), Anode. The filament and anode are connected with DC power supply.

Working:

- The tungsten filament is heated about 2500-3000 °C by high voltage DC supply in order to emit electrons. Grid cup direct electrons to travel towards the work.
- Electrons are attracted by the Anode ,and passed through already placed hole without colliding with it.
- Due to high potential difference electrons accelerated and it's velocity reaches near 2/3 of light velocity.
- Electron beam is refocused by electromagnetic lens system so that beam is directed with control(typically 0.25 mm diameter) towards work.
- For controlling path of cut deflector coil is used to deflect electron beam.
- Kinetic energy of high velocity beam is transmitted into heat and temperature of work increased above boiling point.

EBM process parameter:

- Voltage: 1,50,000 V
- Vacuum requirement: 133 x 10-6 N/m2
- MRR: 1.6 mm^3/min
- Surface Finish: 0.4-2.5 μm (CLA)

Application:

To drill holes in pressure differential device and to machine low thermal conductive and high melting point materials.

Advantage:

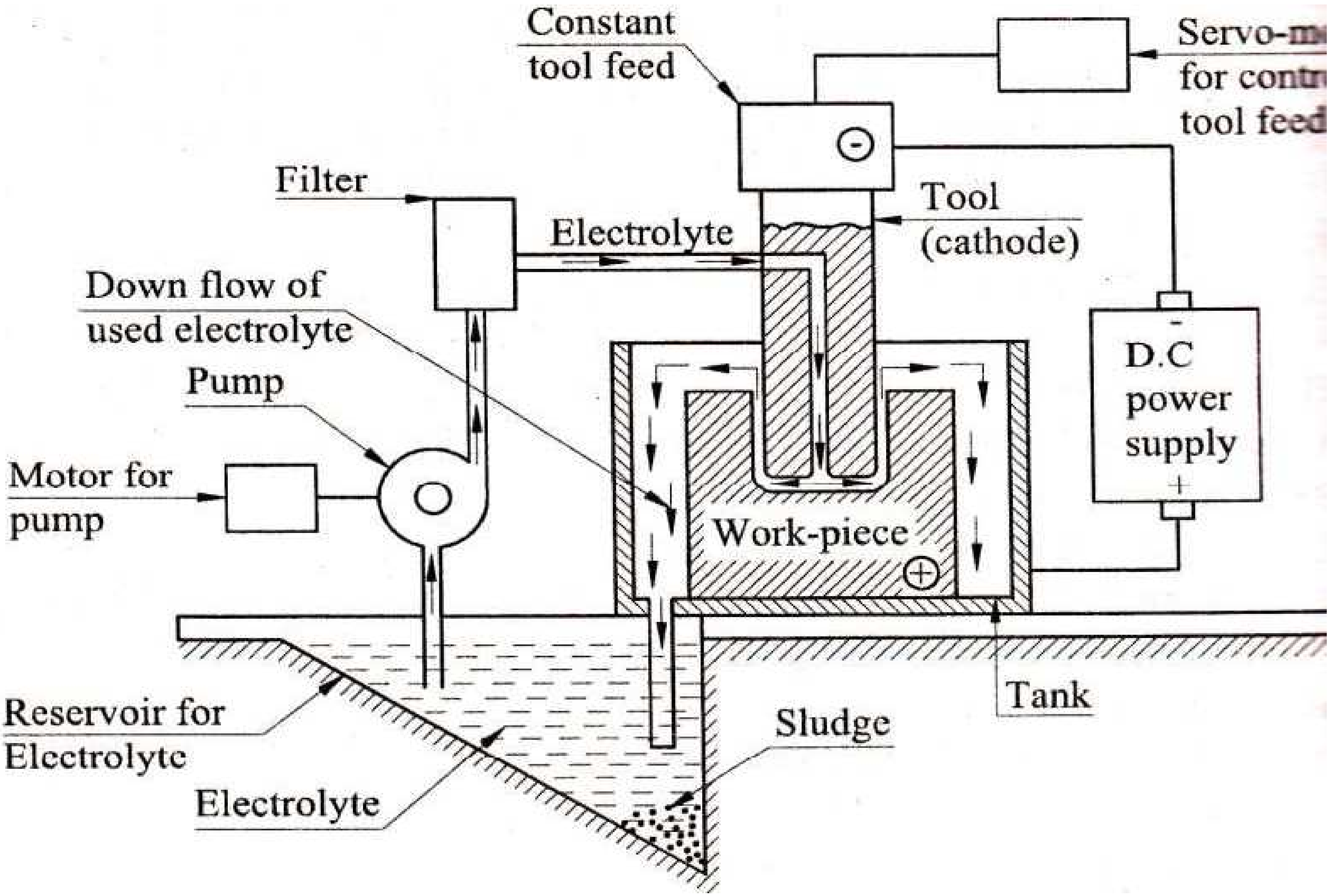
- Drill very small hole with high accuracy.
- Brittle material can be easily machined.
- Set up can be automated easily.

Disadvantage:

- Vacuum chamber is essential
- Equipment cost is high.
- Low MRR and skilled operator required.

Electrochemical Machining (ECM)

ECM is metal removal process based on principle of reverse electroplating.



Construction:

- It consist cathode(tool), Anode(work), Servomotor to control tool feed, Electrolyte tank and it's circulation arrangement, DC power supply.
- Servomotor controlled the feed of tool.
- Pump is placed for providing strong stream of electrolyte.

Working:

- DC power supply provides current 50 to 40000 A at 5 to 30 V for across the gap of 0.05 to 0.07 mm between tool and work. Electrolyte flows through this gap at velocity 30 to 60 m/s.
- Current started flowing through electrolyte with positively charged ions attracted towards the tool and negatively charged ions attracted towards work.
- Due to this flow electrochemical reaction takes place and metal removes in form sludge.
- This sludge is taken away from gap by strong stream of electrolyte.

- Following reactions takes place while machining of pure iron through ECM using NaCl+H_2O as electrolyte.

$$NaCl \rightarrow Na^{+} + Cl^{-}$$

$$H_2O \rightarrow H^{+} + OH^{-}$$

$$2H^{+} + 2e \rightarrow H_2$$

Material Removal:

$$2Na^{+} + 2OH^{-} \rightarrow 2NaOH$$

$$Fe^{2+} + 2Cl^{-} \rightarrow FeCl_2$$

$$2NaOH + FeCl_2 \rightarrow 2NaCl + Fe(OH)_2$$

ECM Process Parameter:

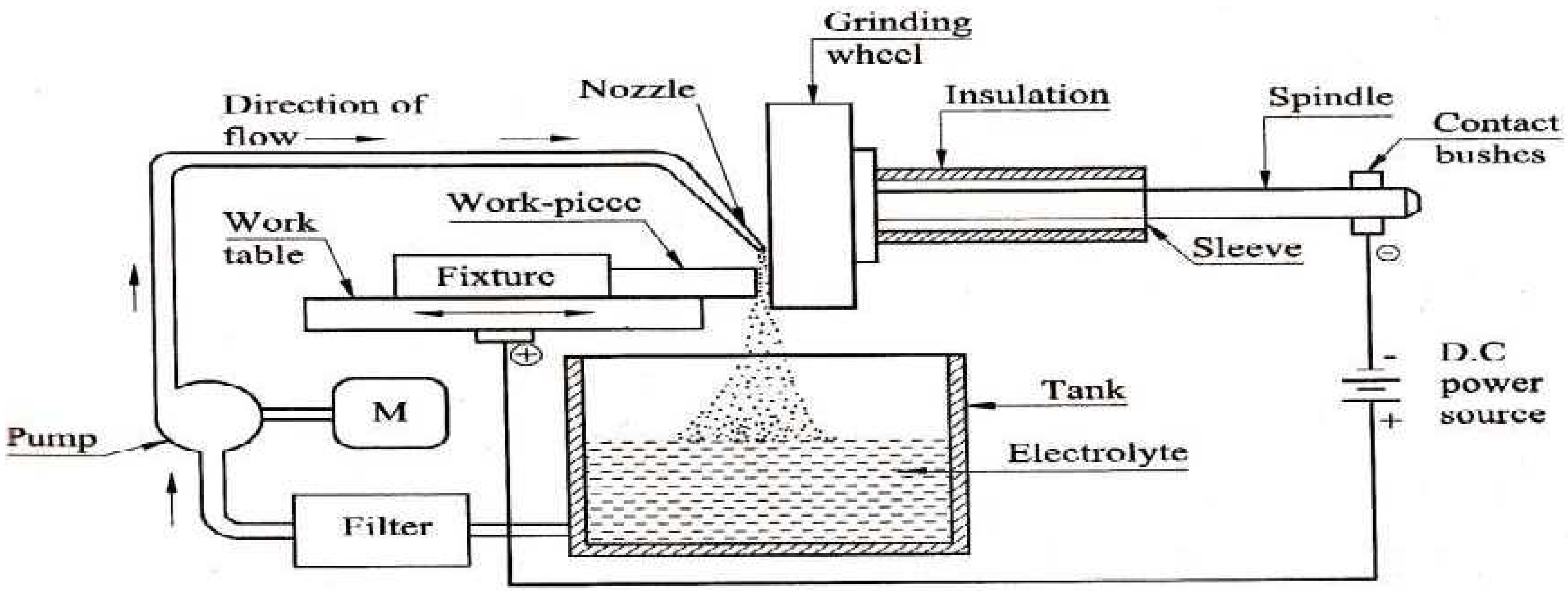
- Voltage: 4 to 30 V
- Current: 50 to 40000 A
- MRR: 1600 mm^3/min
- Surface Finish: 0.1-2.5 μm (CLA)
- Gap: 0.025 to 0.75 mm

Properties of Electrolyte:

Electrolyte provides several functions like complete the circuit, Remove material from cutting region by pressure, Carry away heat to be generated.

- High thermal and Electrical Conductivity
- Low viscosity
- Cheaper and Available
- Non corrosive and Non toxic
- Chemically Stable at process temperature.

Electrochemical Grinding (ECG) / Electrolytic Grinding / Anodic Machining



- It is combination of conventional mechanical grinding and electrochemical machining in which material removed by electrolytic activity. In this process mostly material removed by electrochemical decomposition and remaining material is removed by abrasion of metal.
- ECG is widely used because it gives burrs free surface without producing heat and after ECG, any secondary machining operation not required.

Construction:

- It consist of metallic grinding wheel as cathode, Work-piece as anode, Electrolyte tank and circulation system.
- Grinding wheel is maid such that diamond or aluminum oxide particles embedded in it and it slightly projecting out from the surface so that they touch work surface with a very little pressure. This abrasive particles preventing direct contact between wheel and work piece.
- As Electrolyte, non corrosive salt solution is used with water. It works as both Electrolyte and coolant.

Working:

- DC power is supplied between electrodes and Grinding wheel start rotating by means of motor.
- Pump circulating electrolyte From reservoir tank to machining place. When electrolyte entrapped in small cavities between work and abrasive particles it forms electrolyte cell.
- Current started flowing grinding wheel (Cathode) to work (Anode)
- Oxide film forms on surface of work due to electro chemical oxidation and this film is removed by projecting abrasive particles, which results in accurate surface finish.

Application:

- For grinding Carbide tools, refractory metals and Cobalt based alloy ECG is used.

Advantage:

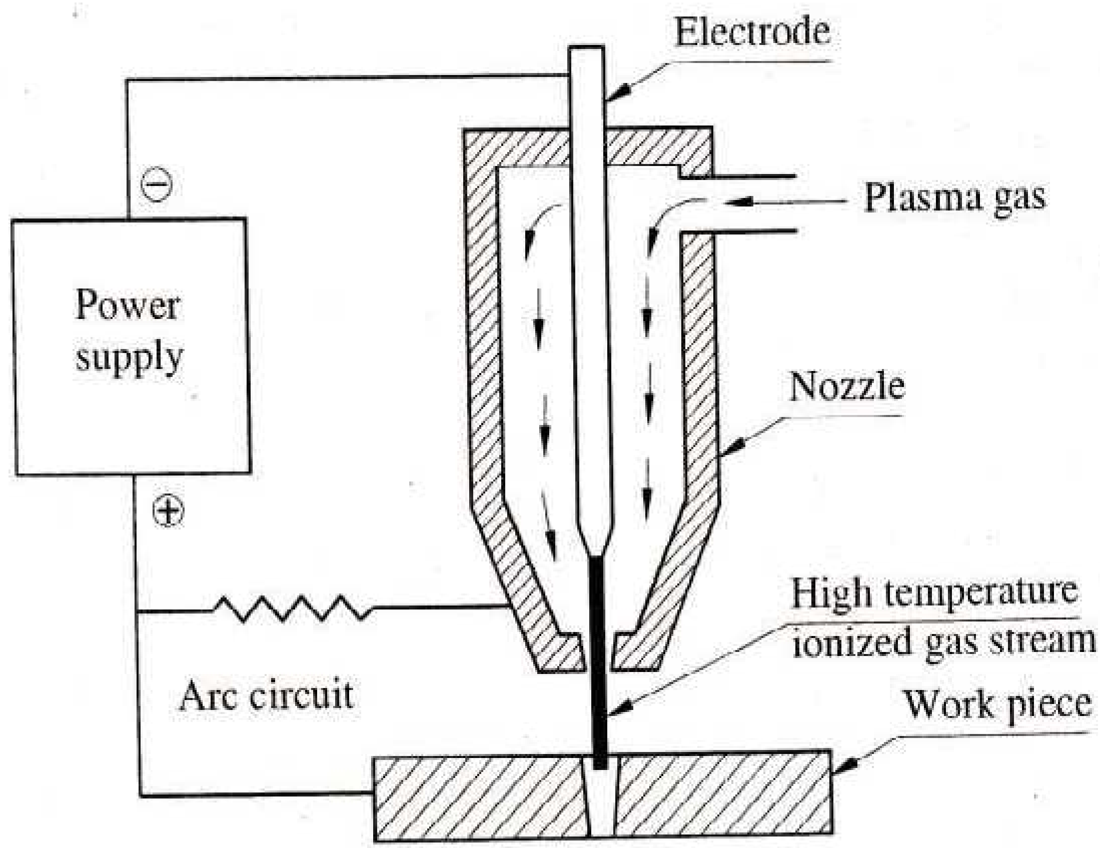
- Process is independent of material hardness and strength.
- Not completely depends on abrasive process.
- Work is not subjected to any mechanical distortion and no heat generation.
- High surface finish and tool wear is negligible.
- Rapid MRR.

Disadvantage:

- Power consumption is more and High Capital cost.
- Not applicable for non-conductive work-piece.
- It is not suitable for soft materials.

Plasma Arc Machining (PAM)

- It is method of metal cutting with arc of plasma(jet of high velocity ionized gas) that removes material from work-piece.
- At very higher temperature atoms of gas become ionized and this stage of gas is known as Plasma.



Construction:

- Plasma torch makes plasma and direct it for cutting.
- Plasma torch consist gas chamber, Nozzle as Anode and Tungsten electrode as Cathode and power supply.
- Argon, nitrogen, hydrogen, or compressed air introduced around cathode.

Working Principle:

- In gas chamber high velocity arc is generated between Anode and Cathode. Gas molecules are collide with high velocity electrons of arc and due to this gas gets ionized and large amount of heat energy librated.
- This high velocity stream of hot ionized gas (Plasma) is directed on the work-piece to melt the material.

PAM Process Parameter:

- Voltage: 30-250 V
- Current: Up to 600 A
- Power: 2-200 KW
- Velocity of plasma jet: 500 m/s
- MRR: 1,50,000 mm^3/min

Advantages:

- Any electrically conductive material machined regardless it's hardness.
- Doesn't require any surface preparation.
- It has high cutting rate.

Disadvantage:

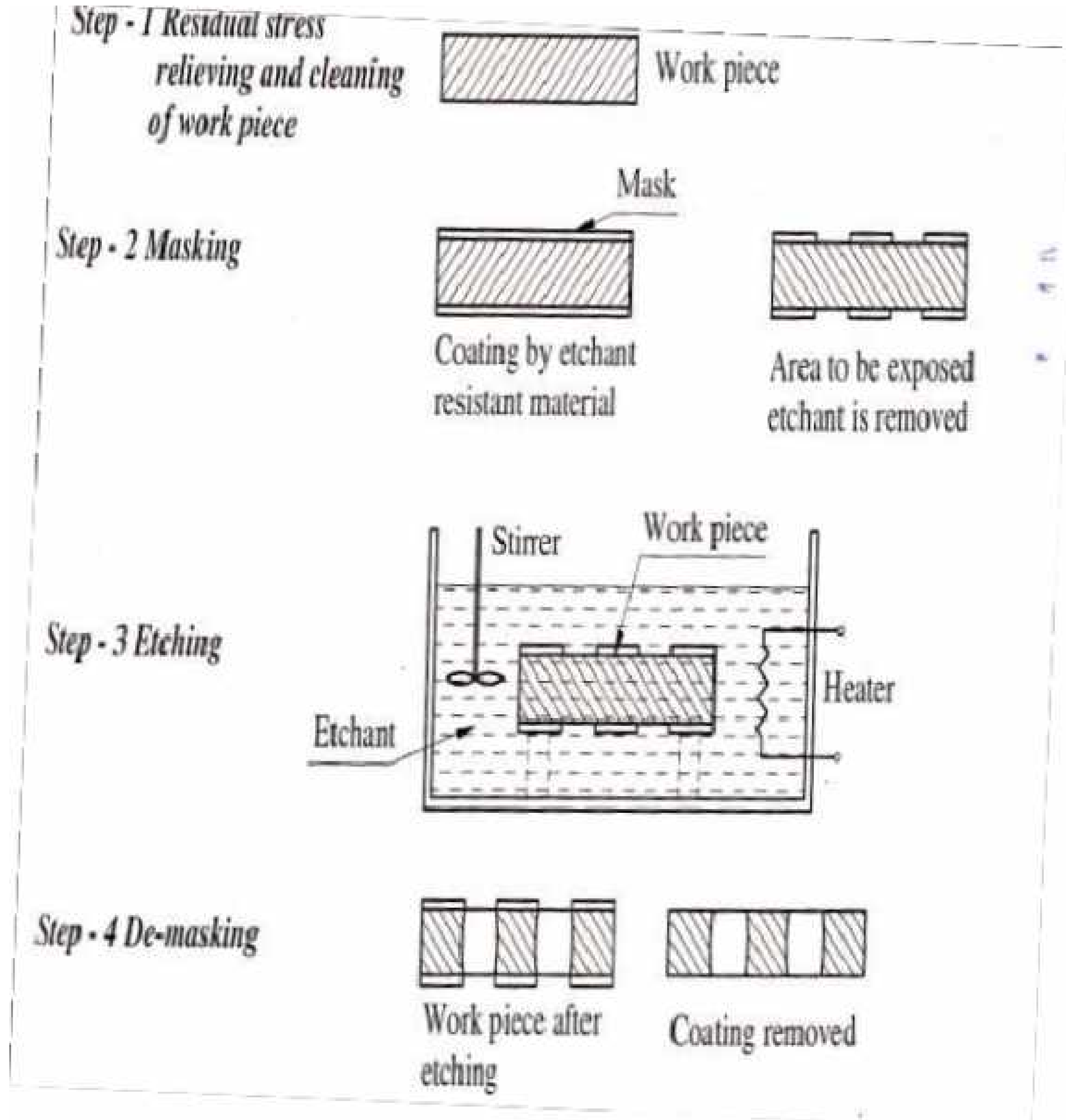
- Power consumption is very high.
- High equipment cost.
- It produced tapered surface.
- Noise protection is required.

Chemical Machining (CM)

- In Chemical Machining process material is removed by chemical dissolution using chemical reagents or etchants (Acids or Alkaline solutions).
- Chemical reaction takes place between work surface and etchants resulting into removal of material from surface.
- The surface which etched away, exposing the lower layers and process is continued till the desired amount of material removed.
- Classification of Chemical Machining:
  - Chemical blanking
  - Chemical Milling
  - Chemical engraving

Steps for CM:

1) Residual stress relieving
2) Cleaning the work piece
3) Masking
4) Etching
5) De-masking



Application of CM:

- CM is used as chemical blanking for burr free etching of printed chemical printed circuit boards, decorative panels.
- Chemical milling is commonly used in aerospace industry to remove shallow layers of material from large aircraft components like missile skin panels and airframe parts.

Advantage:

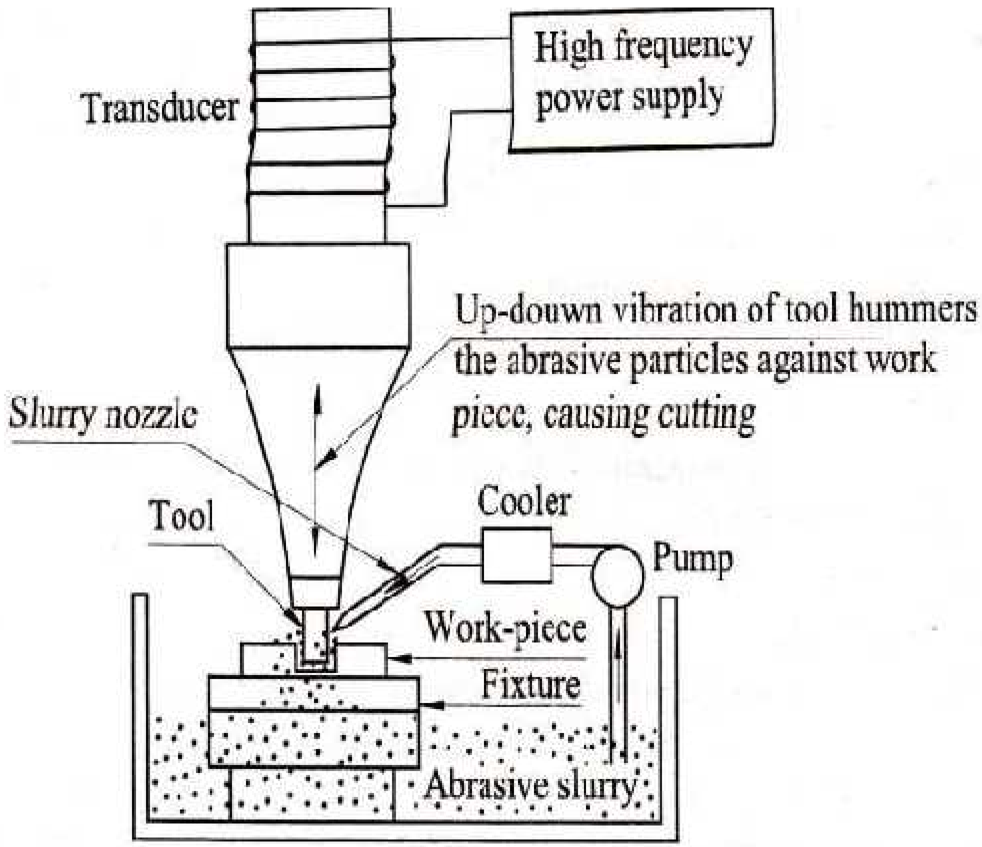
- It doesn't distort the work and all the faces of work machined simultaneously.
- Low setup, maintenance and tooling cost.
- It can be used to machine complex profiles of delicate and intricate design parts.
- Improves productivity.

Disadvantage:

- Large tank and large floor area required.
- High operation cost.
- Chemicals used in process may be dangerous to health.

Ultrasonic Grinding / Ultrasonic Machining(USM) / Ultrasonic impact Grinding

It is mechanical material removal process in which material is removed by repetitive impact of abrasive slurry on work surface, by using high frequency oscillation of shaped tool.



Construction:

- It consist of Ultrasonic generator and transducer, Concentrator, tool, Abrasive slurry and it's feed mechanism, and tool feed mechanism.
- Concentrator is tool cone which made from titanium or SS.
- Tool is attached to base of concentrator by mean of silver brazing or screws. Tool is shaped as approximate mirror image of cavity desired.
- The gap between tool and work is about 0.02 to 0.1 mm.
- Abrasive slurry is mixture of abrasive grains and carrier fluid which is provided between tool and work-piece. Generally water is used as carrier fluid.

Working:

- The ultrasonic transducer converts electrical energy into ultrasonic waves or vibrations using magnetostrictive effects.
- Tool vibrates longitudinally at 20 to 30 kHz with amplitude 0.02 mm pressed on the work surface with light force.
- Concentrator increase the amplitude of vibration in order to give required force amplitude ratio.

- The abrasive particle in form of abrasive slurry is continuous circulate between tool and work. The tool performs hampering action on abrasive particles.
- The vibration of tool tip accelerates the abrasive particles at high rate and it imparts the necessary force for cutting action.
- The tool is gradually moves down by means of tool feed mechanism to maintain constant gap.

USM Process Parameter:

- Vibration frequency: 15 to 30 kHz
- Vibration amplitude: 25 to 100 μm
- Gap: 0.02 to 0.1 mm
- Surface finish: 0.2 to 0.8 μm (CLA)
- MRR: 300 mm^3/min

Application of USM:

- It is used for machining of hard and brittle material like ceramics, boron carbide, titanium carbide.
- USM enables a dentist to drill a hole of any shape on teeth painlessly.

Advantage of USM:

- Non-conductive materials can also machined.
- There is no any change in microstructures, physical or chemical properties.
- Better surface finish and higher structure integrity.
- Noiseless operation.
- Work piece harder than 60 HRC like carbide, Ceramics machined by USM.

Disadvantage of USM:

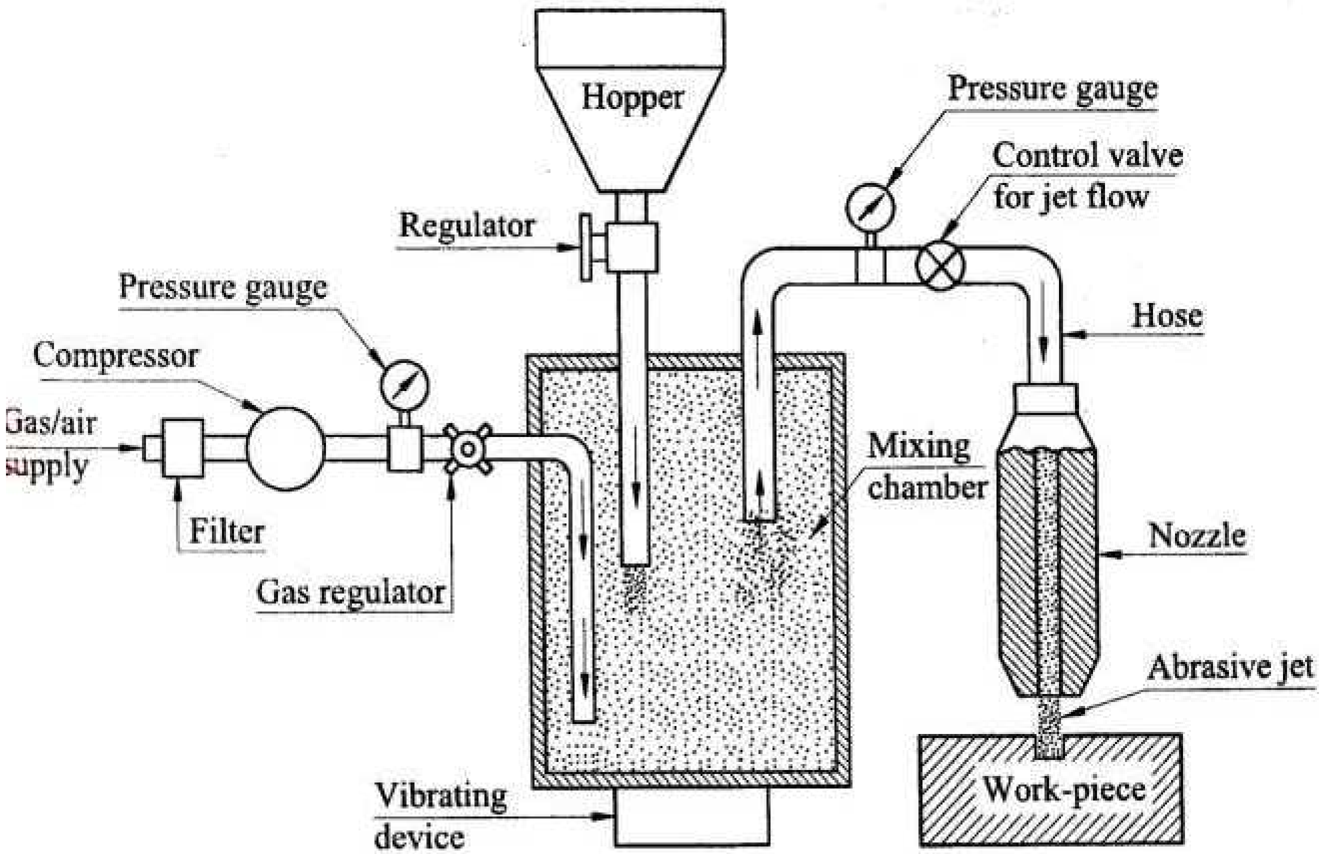
- Low MRR.
- High power consumption.
- High tooling cost and it wears rapidly.
- Not suitable for soft materials

Factors affecting MRR and surface finish in USM:

- Tool amplitude and frequency.
- Tool shape. Abrasive
- grain size. Abrasive
- concentration.
- Work hardness-tool hardness ratio.
- Feed force.

Abrasive jet machining / Micro-abrasive Blasting

Abrasive jet machining is mechanical energy based unconventional machining process used to remove unwanted material from a given workpiece.



Construction:

- It consist of Compressor (To pressurize the gas), Filter, mixing chamber, Hopper, Vibrator, Nozzle, Pressure gauge and flow regulator.
- The nozzle is made of a hard material like tungsten carbide.
- Abrasive used are aluminum oxide, Silicon carbide, or Sodium bicarbonate.
- The gases commonly used are air, N_2, CO_2.
- Hopper is placed above mixing chamber for feeding purpose.
- Vibrating device placed below mixing chamber to vibrate mixture of abrasive and gas.

Working:

- First dry air or gas is filtered and then it compressed by compressor.
- A pressure gauge and flow regulator controls the pressure and regulate the flow of the compressed air.
- Compressed air entered into the mixing chamber where it mixed with abrasive particles.

- Then mixture passes through nozzle where high velocity fine abrasive jet is produced. The nozzle increases velocity about 200 to 400 m/s at the expense of it’s pressure.
- As a result of repeated impact material removed from work due to erosion. Again new surface exposing and so on material removed by erosion.

AJM Process Parameter:

- Abrasive size: 25 μm
- Nozzle diameter: 0.13 to 1.2 mm
- MRR: 0.8 mm^3/min
- Surface Finish: 0.5-1.2 μm (CLA)

Application:

- Drilling, Cleaning, and polishing of hard surface.
- To machine intricate shapes which is difficult to machine.
- Aircraft fuel system, Medical appliances and Hydraulic valves.

Advantage of Abrasive Jet Machining:

- No heat is generated in work. So it is suitable for heat sensitive materials.
- No physical contact between tool and work.
- Thin and fragile materials also machined.
- Low investment.
- Smooth surface finish.

Disadvantage:

- Low MRR.
- Abrasive powder cannot be reused.
- Nozzle life is less and maintenance of nozzle required.

Factors affecting performance of AJM:

- Abrasive grain size and It's mass flow rate
- Mixing ratio.
- Velocity of abrasive particles.
- Gas pressure.
- Nozzle tip distance.

WATER JET MACHINING (WJT)

Water jet acts like a saw and cuts a narrow groove in the material.

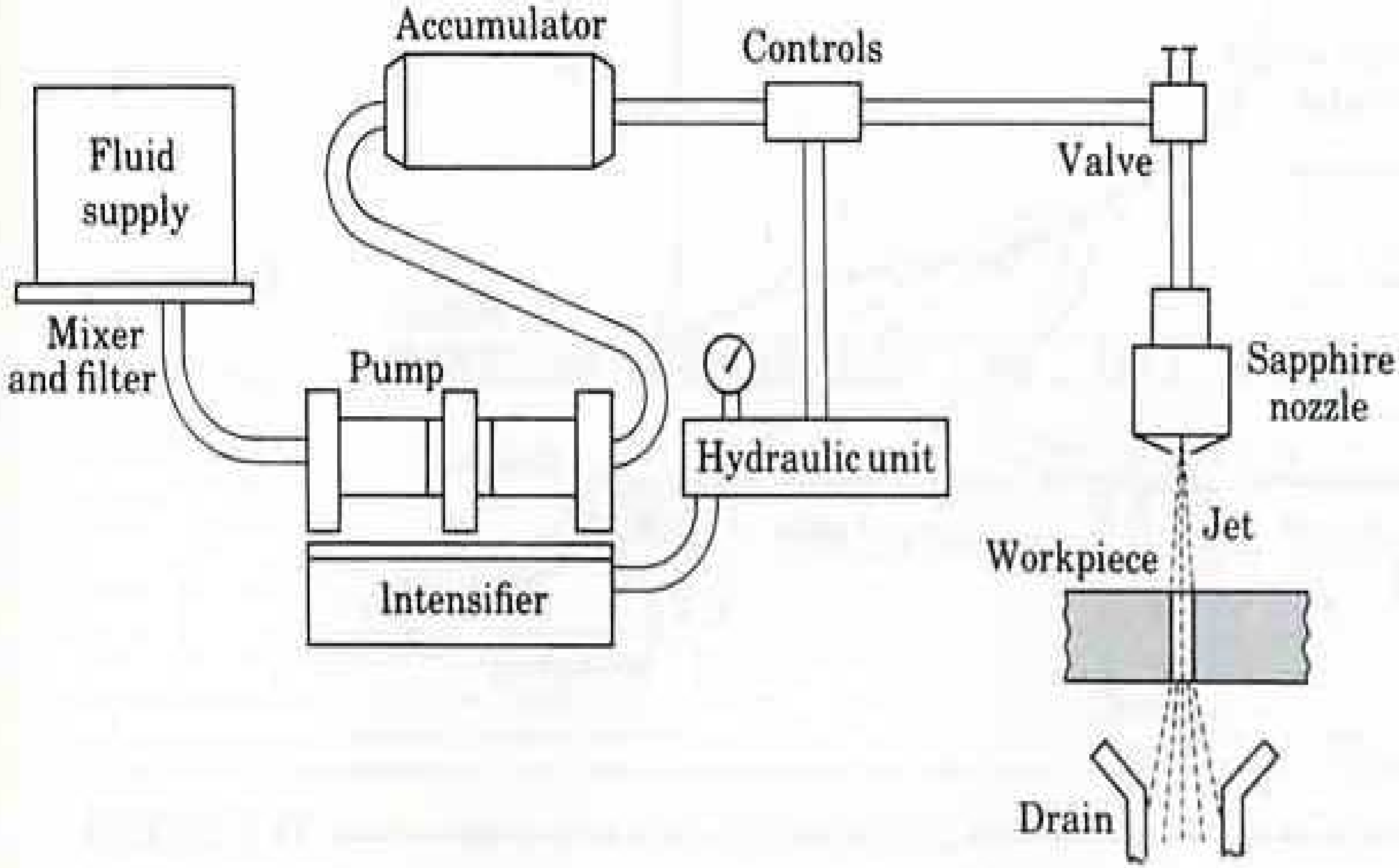
Pressure level of the jet is about 400MPa.

Advantages

- No heat produced
- Cut can be started anywhere without the need for predrilled holes
- Burr produced is minimum
- Environmentally safe and friendly manufacturing

Application

Used for cutting composites, plastics, fabrics, rubber, wood products etc. Also used in food processing industry.


Accumulator
Controls
Fluid
supply
Valve
Mixer
and filter
Pump
Sapphire
nozzle
Hydraulic unit
Jet
Workpiece
Intensifier
Drain

Comparison between various Non-conventional Machining Process

Process	Medium	Surface finish m (CLA)	MRR	Power consumption	Tooling Cost	Investment cost	Efficiency
EDM	Liquid dielectric	0.2-1.2	800	Low	High	Medium	High
ECM	Electrolyte	0.1-2.5	1500	Medium	Medium	Very high	Low
CM	Liquid chemical	0.5-2.5	15	High (Chemical cost)	low	Medium	Medium
LBM	Air	0.5-1.2	0.1	Very low	Low	Low	Very high
EBM	Vacuum	0.5-2.5	1.6	Low	Low	High	Very high
PAM	Argon	Rough	75000	Very low	Low	Very low	Very low
USM	Abrasive in water	0.2-0.5	300	Low	Low	Low	High
AJM	Abrasive in gas	0.5-1.2	0.8	low	low	Very low	High

UNIT 3 PRESS AND PRESS TOOLS

Structure

3.1 INTRODUCTION

Metal forming is one of the manufacturing processes which are almost chipless. These operations are mainly carried out by the help of presses and press tools. These operations include deformation of metal work pieces to the desired size and size by applying pressure or force. Presses and press tools facilitate mass production work. These are considered fastest and most efficient way to form a sheet metal into finished products.

Objectives

After studying this unit, you should be able to understand

- introduction of press tool,
- major components of press working system,
- different criteria of classification of presses,
- different types of presses,
- description of important parts of a press,
- specifications of a press,
- other press working tools, like punch and die,
- components of press working system,
- different types of die sets, and
- design considerations for die set design.

3.2 PRESS

A press is a sheet metal working tool with a stationary bed and a powered ram can be driven towards the bed or away from the bed to apply force or required pressure for various metal forming operations. A line diagram of a typical pres is explained in the Figure 2.1 hydraulic system. The relative positions of bed and ram in the press are decided by the structure of its frame. The punch is generally gripped into the punch holder and punch holder is attached to ram. A balster steel plate is attached to the bed of the press and die is mounted on the balster steel plate.

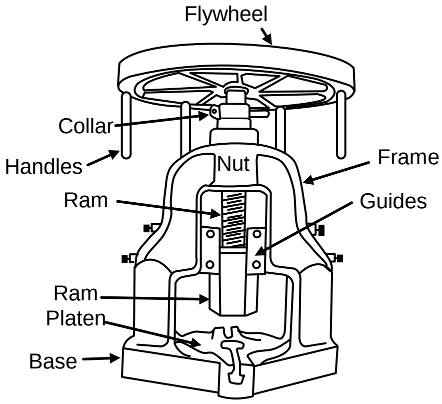


Figure 3.1 : Line Diagram of a Typical Press

Presses are available in a variety of capacities, power systems and frame type. Meaning of capacity of press is its capability to apply the required force to complete the operation.

Power and Drive System

Power systems on presses are either hydraulic presses use a large piston and cylinder to drive the ram. This system is capable to provide longer ram strokes than mechanical dries. It gives a consistent applied load. Its working is comparatively slower. These presses can be single action or double action or so on. Number of actions depends on the number of slides operating independently.

Mechanical presses are used several types of drive mechanisms. These drives includes eccentric, crankshaft, knuckle joint, etc. These drives are used to convert rotational motion given by a motor into linear motion of the ram. A fly wheel is generally used as reservoir of energy for forging operations. These presses are recommended for blanking and punching operations as the involved drives are capable to achieve very high forces at the end of their strokes.

Press working is used in large number of industries like automobile industry, aircraft industry, telecommunication electrical appliance, utensils making industry are major examples.

3.3 TYPES OF PRESSES

There are different criteria of classification of presses into different categories. These criteria, related classifications and their descriptions are discussed below.

According to the Power Source

These power source are categorized as :

Manually Operated or Power Driven

These presses are used to process thin sheet metal working operations where less pressure or force is required. These are operated by manual power. Most of manually operated presses are hand press, ball press or fly press.

Power Presses

Power presses are normally driven by mechanical mechanism or hydraulic system. Power source of these presses may be electric motor or engine.

According to the Type and Design of Frame

The type and design of frame depending on the design of frame these are classified as inclinable, straight side, adjustable bed, gap frame, horning and open end.

Inclinable Frame Press

Its frame is called inclinable due to its capability to tilt back upto some angle. It can be locked into nay of its inclined position as shown in Figure 3.2. Its back is open to exit the scrap so it is also called open back inclinable press.

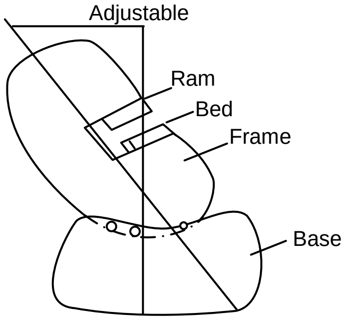


Figure 3.2 : Inclinable Frame Press

Gap Frame Press

These presses have larger frame openings, that means a wide gap between its base and ram to accommodate larger workpieces. It also has longer beds, as shown in Figure 3.3.

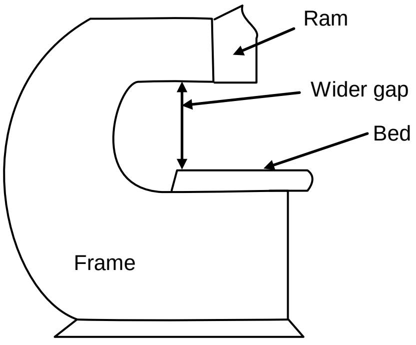


Figure 3.3 : Line Diagram of a Gap Frame Press

Straight Side Press

These presses have straight side type frame which is preferred for presses having larger bed area and high tonnage. This offers greater rigidity and capable of longer strokes. The frame consists of vertical and straight sides so it is called straight side press.

Adjustable Bed Type Press

It is also called column and knee type press because it has a knee type bed supported on its column shaped frame. Its bed (knee) can be adjusted at any desirable height by moving it vertically up or down with the help of power screws. In this structure there is slight lack of rigidity as compared to other structures. It is shown in Figure 3.4.

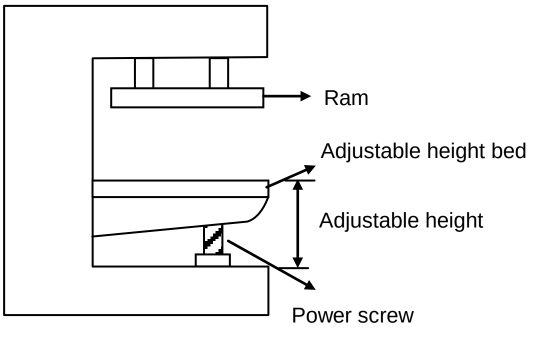


Figure 3.4 : Adjustable Bed Type Press

Open End Press

It has a solid type of vertical frame with all sides open. Driving mechanism is housed at the back and ram controlling mechanism at the front. It is easily to accommodate workpiece and dies in this type of structure. Its is identified as light duty machine.

Horning Press

It consist of a vertical frame, top of which over hangs towards the front. The over hanging portion serves for housing for driving mechanism and ram control. The frame consists of a front face as a work table called horn.

According to the Position of Frame

Presses can also be categorized by the position of frame as described below.

Inclinable Frame

Already described.

Vertical Frame

Vertical frame type of press is already been discussed, it cannot be adjusted like inclinable frame. Gap, adjustable bed, straight side, open end and honing presses are the example of vertical frames.

Horizontal Frame

It has a fixed frame in horizontal position. It provides the facility of auto ejection of produced part and scrap due to gravity.

Inclined Frame

Like inclinable frame, inclined frame press has an inclined frame but fixed, it cannot be adjusted to any other angle.

According to the Actions

According to the number of actions it can be categorized as single action, double action or triple action press. Here number of actions is same as the number of rams on the press.

According to Mechanism Used to Transmit Power to Ram

Crank Press

It consists of crankshaft driven by a flywheel, rotary motion of the crankshaft is converted into reciprocating motion with the help of a connecting rod connected to ram.

Cam Driven Press

In this press, a cam is used to press the ram down words and suitably located springs restore the original position of ram when pressure applied is removed. This mechanism has a limitation of size of the press.

Eccentric Press

In this press, the driving shaft carries an eccentric integral with it. One end of the connecting rod carried an attachment of revolving eccentric and its other end is connected to ram. As the eccentric shaft revolves, the offset between the eccentric centre and the centre of rotation of the shaft provides the required movement.

Knuckle Press

This press is driven with the help of knuckle joint mechanism. The main advantage of this press is partial back thrust is transferred to crankshaft, its major portion is transferred to back crown which is capable to hear. This enables the application of this press for heavier jobs with high intensity of blows. These presses are recommended for coining, squeezing, extruding and embossing. They have a limitation of shorter stroke lengths.

Toggle Press

These presses work on toggle mechanism and used for double and triple action presses for driving the outer rams. However, crankshaft drive is used for the inner ram. These are used for large draw dies, in which this mechanism actuates the blank holder whereas the punch is operated by the crank driven inner ram.

Screw Press

This is known as power screw or percussion press. There is a vertical are like frame, its job forms a nut. There is a flywheel at the top of and engages the ram at its bottom. The flywheel is driven by a friction disc and the rotating screw lowers and raises the ram. The flywheel is accelerated by friction drive. Its total energy is expanded in striking the work, bringing it to a halt. The intensity of blow can be regulated by adjusting the height of the die. Higher the position of the die, lesser the speed of the flywheel and hence lower the intensity of blow. These presses have a limitation that the ram movement is slow so these are recommended for sheet metal work only.

Hydraulic Press

These presses have a piller type construction or carry the hydraulic cylinder at the top of the crown. These presses provide longer stroke than mechanical presses with adjustable intensity of blow. Their stroke length can also be adjusted with full tonnage. These are recommended for deep drawing, extruding and plastic moulding.

Rack and Pinion Press

Rack and pinion driven presses are called rack and pinion presses meant for long strokes. Major advantage is faster operation of this press due to involvement of quick return motion. There are some limitations of this press. Load bearing capability of rack and pinion mechanism is very low so these are light duty machines. Ram movement is slightly slower. These presses have very limited use now-a-days.

According to Number of Drive Gears

Number of drive gears means number of gears attached at the ends of crankshaft, used to drive it. Smaller presses have single drive and larger presses may be double drive crankshafts. Very large presses with longer beds, carry long crankshafts. They have risk of twisting. These crankshafts are provided with one driving gear at each ends, these presses are named as twine drive presses. If a press carries two crankshafts each having a twin drive, such presses are called quadruple drive presses.

According to Number of Crankshaft in a Press

According to the number of crankshafts used in a press, these are directly classified as single crank (having one crankshaft) double crank (having two crankshafts).

Method of transmission of power from Motor to Crankshaft

The method used for transmission of power from motor to crankshaft categorized presses into following categories :

Direct Drive Press

In this case, power is directly transferred through gears pair. Smaller gear is mounted on the motor shaft, called pinion, its mating gear which is larger, mounted on the crankshaft. The larger gear also acts as flywheel. The flywheel is attached to the crankshaft through clutch and equipped with the facility of disengaging it as per the need. Such presses have shorter strokes and these are light duty presses.

Flywheel Driven Presses

These presses consists no gears so also called "No geared presses". For the transmission of power motor pulley is connected to flywheel driven crankshaft by Vee belt and pulley system. A clutch is used to engage or disengage the flywheel with the crankshaft. These presses are light duty presses providing shorter and quicker strokes.

Single Geared Drive Presses

This press consists of a counter shaft between motor shaft and crankshaft. Flywheel is mounted on the countershaft. Power is transferred from motor to flywheel (countershaft) through 'Vee' belt drive and then from counter shaft to crankshaft through pinion and gear. Clutch is mounted between pinion and flywheel to disengaged the power transmission as per the requirements. In these presses there are two steps for rpm reduction and torque enhancement so these are heavy duty mechanics with longer strokes.

Double Geared Drive Presses

In these type of presses an additional shaft named as intermediate shaft is introduced between the countershaft mounted flywheel and the crankshaft of a single geared drive. Twin drive is possible in this case by having similar gear train on other sides of two shafts. This provides slow stroke with larger power.

According to the Purpose of Use

Some of the operations require low stroke strength and some lager stroke strength. In the same way requirements of stroke length is different for different operations. So depending on power and stroke length presses are classified as given below depending on their suitability of performing different operations.

(a) Shearing press

(b) Seaming press

(c) Straightening press

(d) Punching press

(e) Extruding press

(f) Caining press

(g) Forging press

(h) Rolling press

(i) Bending press.

3.4 MAIN PARTS OF A TYPICAL POWER PRESS

Different types of presses have almost common types of main parts. These parts are described below.

Base

The all machine tool, base is the one of the parts of a press. It is main supporting member for workpiece holding dies and different controlling mechanisms of press. Size of the table limits the size of workpiece that can be processed on a press. In case of some special presses the base carries mechanism for tilting the frame in any desirable inclined position too.

Frame

Frame constitute main body of the press located at one edge of its base. It houses support for ram, driving mechanism and control mechanisms. Some of the press have column shaped frame.

Ram

This is main operating part of the press which works directly during processing of a workpiece. Ram reciprocates to and fro within its guideways with prescribed stroke length and power. The stroke length and power transferred can be adjusted as per the requirements. Ram at its bottom end carries punch to process the workpiece.

Pitman

It is the part which connects the ram and crankshaft or ram eccentric.

Driving Mechanism

Different types of driving mechanisms are used in different types of presses like cylinder and piston arrangement in hydraulic press, crankshaft and eccentric mechanisms in mechanical press, etc. these mechanisms are used to drive ram by transferring power from motor to ram.

Controlling Mechanisms

Controlling mechanisms are used to operate a press under predetermined controlled conditions. Normally two parameters are adjusted by controlling mechanisms length of stroke of ram and power of stroke. Transfer of power can be disengaged with the help of clutch provided with driving mechanisms as per need. In most of the presses controlling mechanisms is in built with the driving mechanisms. Now-a-days compute controlled presses are being used in which controlling is guided by microprocessor. These presses provides reliable and accurate control with automation.

Flywheel

In most of the presses driven gear or driven pulley is made of the shape of flywheel, which is used for storing the energy reserve wire of energy) for maintaining constant speed of ram when punch is pressed against the workpiece. Flywheel is placed in the driving mechanism just before the clutch is sequence of power transmission.

Brakes

Brakes are very urgent in any mobile system. Generally two types of brakes are used normal brake, which can bring the driven shaft to rest quickly after disengaging it from flywheel. Other is emergency brakes which are provided as foot brake to any machine. These brakes include power off switch along with normal stronger braking to bring all motions to rest quickly.

Balster Plate

It is a thick plate attached to the bed or base of the press. It is used to clamp the die assembly rigidly to support the workpiece. The die used in press working may have more than one part that is why the phrase die assembly is being used at the place of die.

3.5 SPECIFICATIONS OF A PRESS

Expressing size of a machine (press) includes expressing each of the parameters pertaining to it quantitatively in appropriate units. Expressing size in the above mentioned way is the specifications of press. The following parameters are expressed as specifications of a press.

(a) **Maximum Force :** Maximum force that its ram can exert on the workpiece, this is expressed in tones and called tonnage. It varies from 5 to 4000 tonnes for mechanical press. It may be up to 50,000 tonnes by hydraulic press.

(b) **Maximum Stroke Length :** Maximum distance traveled by the ram from its top most position to extreme down position. It is expressed in mm. the stroke length is adjustable so different values that can be obtained between minimum and maximum of stroke length, these are also the part of specifications.

(c) **Die Space :** Total (maximum) surface area, along with ($b \times d$), of bed, base, ram base. This the area in which die can be maintained.

(d) **Shut Height :** Total opening between the ram and base when ram is at its extreme down position. This is the minimum height of the processed workpiece.

(e) **Press Adjustments :** Different stroke lengths (already covered in point number 2). Different tonnage that can be set as per the requirement.

(f) **Ram Speed :** It is expressed as number of strokes per minute. Generally it can be 5 to 5000 strokes per minute.

3.6 PRESS TOOL

Commonly used tools which are major components of press working are punches and dies. Punch is an important part of the system which is fastened to the ram and forced into the die where workpiece to be processed is supported. Die is a work holding device, designed specifically for a particular design of a product. Die is rigidly held on the base of the press. Die carries an opening which ϕ is perfectly aligned with the punch and its movement. Both die and punch work together as a unit and this is called a die set. Punch and die both are made of high speed steel. Die is the part where strength and wear resistant both properties are required. So normally working surface of the die is made of satellite or cemented carbide. Details of the die set are described below.

Punch

Lower end of the ram holds punch holder which is equipped with the punch plate. Punch plate is generally made of stainless steel or HSS. The punch plate holds the punch rigidly and accurately. Different ways of holding the punch are described below :

(a) Punch can be fastened by forcing it to punch plate, top end of the punch is flattened to fit in the countersunk recess as shown in Figure 3.5.

(b) Punch can be clamped to the punch plate by a set screw. The correct position of the punch is located by cutting a slot into the punch plate as shown in Figure 3.5.

(c) Shank of the punch is forced into the punch plate top end of the punch is made flat to fit into the countersunk recess as shown in Figure 3.5.

(d) Punch can be tightly secured to the punch plate with the help of grubs screws as shown in Figure 3.5.

(e) Set screws are used to fastened the punch to the punch plate as shown in Figure 3.5.

(f) Fastening of punch with the help of a set screw and it is located during fastening with the help of two dowel pins shown in Figure 3.5.

(g) Flange end of the punch is secured to the punch plate by set screws from the punch end as shown in Figure 3.5.

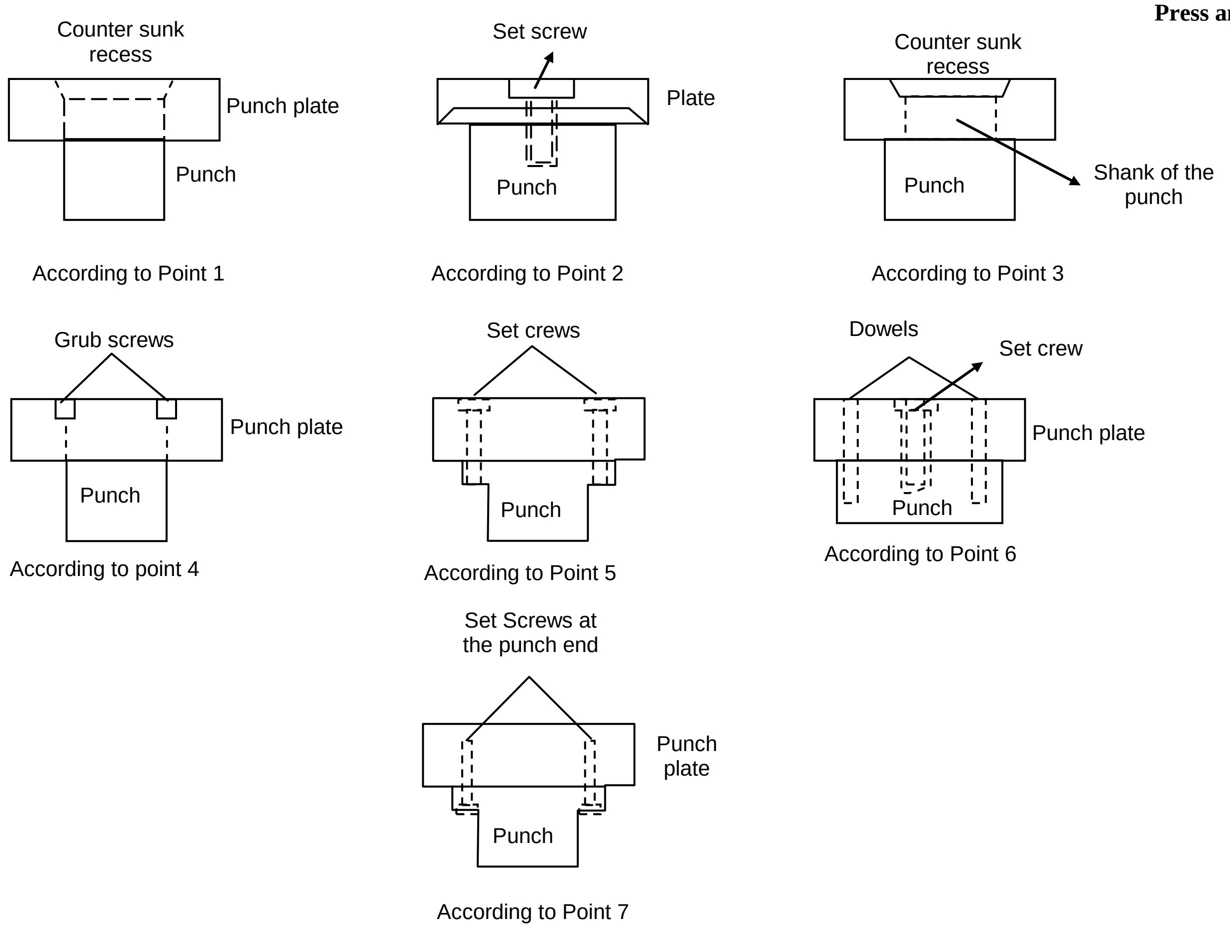


Figure 3.5 : Different Ways of Holding a Punch

3.7 DIE SET AND ITS DETAILS

The complete die set consists of a punch, die and some other accessories which are described in this section later. Perfect alignment of punch and die is most important for satisfactory working of punch. Accessories of die set provides the require alignment and rigidity to the system and improves accuracy of the system performance. These accessories are the finished parts, removal of waste. The die accessories are shown in Figure 3.6. These are described as below.

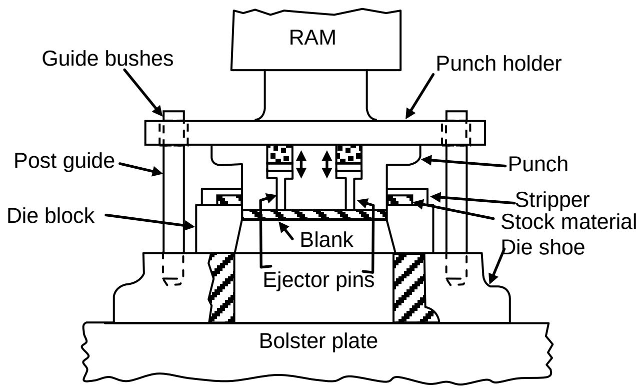


Figure 3.6 : Die Accessories

Punch Holder

It is also known by its other name upper shoe of die set. Punch holder is clamped to the ram of press. It holds the punch below it.

Punch

It is the main tool of die assembly which directly comes in contact of workpiece during its processing, its detail have already been described.

Die Holder

It is also called die shoe. Its work as a support for the die block and it is rigidly fastened to the balster plate of the press.

Stops

Stops are used for maintaining correct spacing of the sheet metal when it is fed below the punch to maintain the quality of output. These restrict the feed of stock (workpiece) to a pre-determined length each time without doing any precise measurements. Normally two types of stops are used bottom stop and lever stop as described below.

Bottom Top

Bottom stop is a tape of mechanical mechanism. This mechanism stops the movement of punch after end of each cut. A button is located in such a manner when fresh stock is fed to die, the button is pressed due to the impact of the fed stock, indicating feeding of true length of the stock. This way the mechanism also acts as a fixture. Pressing of button enables the system ready for next cutting action. The button stop is used in hand presses and in slow acting power presses.

Lever Stop

This mechanism operates with the help of a lever. After the completion of one cut, the stop mechanism stops the downwards movement of punch for next cut when fresh stock is fed it is stopped by a lever after feeding it up to certain length. The lever also enables the punch to move for cut.

Pilots

Pilot is used for correct location of blank when it is fed by mechanical means. The pilot enters into the previously pierced hole and moves the blank to the correct position to be finally spaced by the stops. Normally pilots are fitted to the punch holders.

Strippers

Stripper is used to discard the workpiece out side the press after the completion of cutting or forming operation. After the cutting when punch follows upward stroke the blank is stripped off from the punch cutting edge and prevents it from being lifted along with the punch. This action of prevention is performed by the stripper.

Knockouts

Knockout is also a type of stripper which is used generally in case of invarted dies. After the completion of cutting action, the blank is ejected by the knockout plate out of cutting edge.

Pressure Pads

Pressure pads are plates which grip the workpiece very tightly at the ends when it plastically flows between the punch and the die. This tight griping eliminates the chances of wrinkling in the process of metal forming. A spring loaded plunger acting on the bottom of workpiece plate also serve the same function. The pressure pads do a type of ironing on the sheet metal workpiece.

Guide Posts

Accurate alignment between die opening and punch movement is very important. Guide posts are used for correct alignment of punch and die shoe.

Punch Plate

Punch plate is also known as punch retainer. This is fixed to the punch holder. Punch plate serves as a guide way to hold the punch in right position and properly aligned. This makes the replacement of punch quick and correct.

Backing Plate

Backing plate is used to distribute pressure uniformly over the whole area (maintains uniform stress), it prevents the stress concentration on any portion of punch holder. This is generally made of hardened steel inserted between the punch and punch holder.

Die Retainer

The purpose of die retainer is same that is of punch plate and punch holder. Die retainer is fixed to the bed (base) of the press to hold the die block in correct alignment with the movement of punch. In some specific cases die shoe itself works as a die retainer.

3.8 METHODS OF DIE SUPPORTING

Die is normally held in die holder which is clamped to the balster plate mounted on the table or base of the press. Three different methods of securing die blocks to the die holder are discussed here.

Method 1

The die block is secured to the die holder by four set screws shown in Figure 3.7. Here only one screw is shown. The position of the die is correctly located by dowel pin.

Method 2

The die block is secured by the set screws at the bottom of the die holders shown in Figure 3.7.

Method 3

Die block is secured by an wedge which is clamped to the die holder by set screws, shown in Figure 3.7.

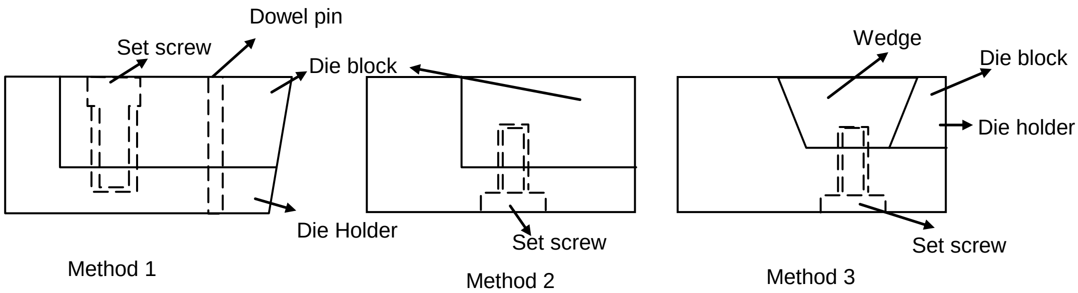


Figure 3.7 : Different Methods of Die Supporting

3.9 CLASSIFICATION OF DIES

There is a broader classification of single operation dies and multi-operation dies.

(a) Single operation dies are designed to perform only a single operation in each stroke of ram.

(b) Multi operation dies are designed to perform more than one operation in each stroke of ram.

Single operation dies are further classified as described below.

Cutting Dies

These dies are meant to cut sheet metal into blanks. The operation performed so is named as blanking operation. These dies and concerned punches are given specific angles to their edges. These are used for operation based on cutting of metal by shearing action.

Forming Dies

These dies are used to change two shape of workpiece material by deforming action. No cutting takes place in these dies. These dies are used to change the shape and size related configuration of metal blanks.

As there is a classification of single operation dies, multi-operation dies are can also be classified (further) as described below.

Compound Dies

In these dies two or more cutting actions (operations) can be executed in a single stroke of the ram.

Combination Dies

As indicated by their names these dies are meant to do combination of two or more operations simultaneously. This may be cutting action followed by forming operation. All the operations are done in a single action of ram.

Progressing Dies

These dies are able to do progressive actions (operations) on the workpiece like one operation followed by another operation and so on. An operation is performed at one point and then workpiece is shifted to another working point in each stroke of ram.

Another classification of dies is also possible on the basis of specific operations that can be performed on them. This classification is described below.

Shearing Operations

These belong to the category of cutting dies. These are used for operations involving shearing action on the workpiece material like blanking, punching, perforating, notch making, slitting, etc.

Drawing Operations

All dies designed for flanging, embossing, bulging and cupping operations fall in the category of drawing operation dies.

Bending Operations

Some of the dies designed for angle bending, curling, forming, folding, plunging, etc. operations fall in the category of dies based on bending operations.

Squeezing Operations

Another category of dies based on squeezing operations are capable to do operations like flattening, planishing, swaging, coining, sizing, extruding and pressing operations.

On the basis of construction, dies can be classified in the following ways :

Cut-off Die

The die designed for cutting off operation is called cut-off die. It provides a vertical surface along which punch slides to cut-off the workpiece by shearing action.

Drop through Die

As indicated by their names, these dies are made hollow where blank fall down after being cut-off.

Return Type Die

In these dies a knockout plate is incorporated, by which the cut blank returns back to the position at which it was cut before it ejected.

Simple and Compound Dies

These are two different dies, simple dies are those dies, used for single exclusive operation in each stroke of ram. These dies have already been discussed in earlier section. In compound dies two or more operations can be done at a single working point. Initial cost of such dies is more due their complicated design and difficult manufacturing. Their low operating cost makes these very economical as a single compound die is equivalent to two or three simple dies.

There is also reduction of cost of using of two or three presses because multiple operations are accomplished in a single press by a single operator.

Continental Dies

These are similar to other dies but the conceptual difference is, these are meant to do research and development work. These cannot do mass production as they may not be very robust.

Sub-press Die

These are designed by incorporating two punch shoe in the die which is actuated by springs to its starting position.

Follow Die

This is designed to do two operations, one followed by other operation. It is like a progressive die which have already been discussed earlier in this unit.

Transfer Die

It is also like a progressive die having more then one working points. It is different form progressive die as it has feeding fingers in the die which transfer the workpiece from one work station to other. In some cases feeding fingers are attached to press, then the press is called transfer press.

Shuttle Die

This is also a type of progressive die having bars in the die just below the workpiece position at each workstation. After the completion of one operation, lift to bear shifts the workpiece from one station to another.

3.10 IMPORTANT CONSIDERATION FOR DESIGN OF A DIE SET

Important points should be considered while designing a die set are listed below :

(a) Cost of manufacturing depends on the life of die set, so selection of material should be done carefully keeping strength and wear resistant properties in mind.

(b) Die is normally hardened by heat treatment so design should accommodate all precautions and allowances to overcome the ill effects of heat treatment.

(c) Accuracy of production done by a die set directly depends on the accuracy of die set components. Design should be focused on maintaining accurate dimensions and tight tolerances.

(d) Long narrow sections should be replaced by block shaped sections to avoid warpage.

(e) Standardized components should be used as much as possible.

(f) Reinforcing grips should be used as per the requirements of the sections.

(g) Easy maintenance should be considered. Replacement of parts should be easy.

(h) The process should be shock proof, if it is unavoidable, shock resistant properties should also be consider while selecting the material of components of die set.

Along with the important design consideration one should also know about the proper material selection for components of a die set various types of tool steels with their suitability for components of die set.

Material or selected tool steel should be very hard to resist wear and strong to hear load to the same time die set components may have very complicated shape, design and need very accurate sizing. Most of them are manufactured by machining and then finishing operations. Their manufacturing involves processing of tool steel to make these components, then these are hardened by different hardening methods like water hardening, oil hardening, air hardening and hard coatings while selecting a die set component material following factors should be taken in care :

(a) Life of the die set component as required.

(b) Their mobility to be manufactured and accuracy level.

(c) Ability to bear wear, shock and load (type of process subjected).

(d) Their costs, both initial cost and operating costs.

3.11 SUMMARY

Metal forming is one of the chip less manufacturing processes. These operations are performed by the press and press tools. Presses can be classified into different categories depending upon their capacity, capabilities and mechanisms used for their operations. Presses can also be categorized depending upon their construction and frame as straight side, adjustable bed type, open end honing press. Method of transmission of power from the place of its generation to the place of its utilization also serve an important criteria for the classification of presses. In general, a press is described by its main parts like base, frame, ram, pitman, driving mechanism, controlling mechanism, flywheel, brakes, balster plate all these parts along with their functions are described here.

Die and punch are the integral part of a pres tool system. Die and punch are normally fitted to a press tool system. Punch and die can be fitted to a press by different methods as described in the unit. Different types of dies are also described in the unit, which are used for different types of workpieces and operations. Accuracy of the operation largely depends on the accuracy of die and punch. So die and punch should be designed and manufactured very carefully. The important considerations for designing die set and punch for pres tool system are described in details.

3.12 ANSWERS TO SAQs

Refer the preceding text for all the Answers to SAQs.

MANUFACTURING TECHNOLOGY

UNIT – III

SHEET METAL FORMING PROCESSES

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Department of Mechanical Engineering

ANUCET

Sheet Metal

Introduction

- Sheet metal is a metal formed into thin and flat pieces. It is one of the fundamental forms used in metalworking, and can be cut and bent into a variety of different shapes.
- Countless everyday objects are constructed by this material. Thicknesses can vary significantly, although extremely thin sheets are considered as foil or leaf, and sheets thicker than 6 mm (0.25 in) are considered as plate.

Sheet Metal Processing

- The raw material for sheet metal manufacturing processes is the output of the rolling process.
- Typically, sheets of metal are sold as flat, rectangular sheets of standard size.
- If the sheets are thin and very long, they may be in the form of rolls. Therefore the first step in any sheet metal process is to cut the correct shape and sized blank from larger sheet.

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Sheet Metal Working

- Performing Cutting and forming operations on relatively thin sheets of metal
- Thickness of sheet metal = 0.4 mm to 6 mm
- Thickness of plate stock > 6 mm
- Operations usually performed as cold working

Manufacturing Technology

Sheet Metal operations

Introduction

- Sheet metal forming is a grouping of many complementary processes that are used to form sheet metal parts.
- One or more of these processes is used to take a flat sheet of ductile metal, and mechanically apply deformation forces that alter the shape of the material. Before deciding on the processes, one should determine whether a particular sheet metal can be formed into the desired shape without failure.
- The sheet metal operations done on a press may be grouped into two categories, cutting (shearing) operations and forming operations.

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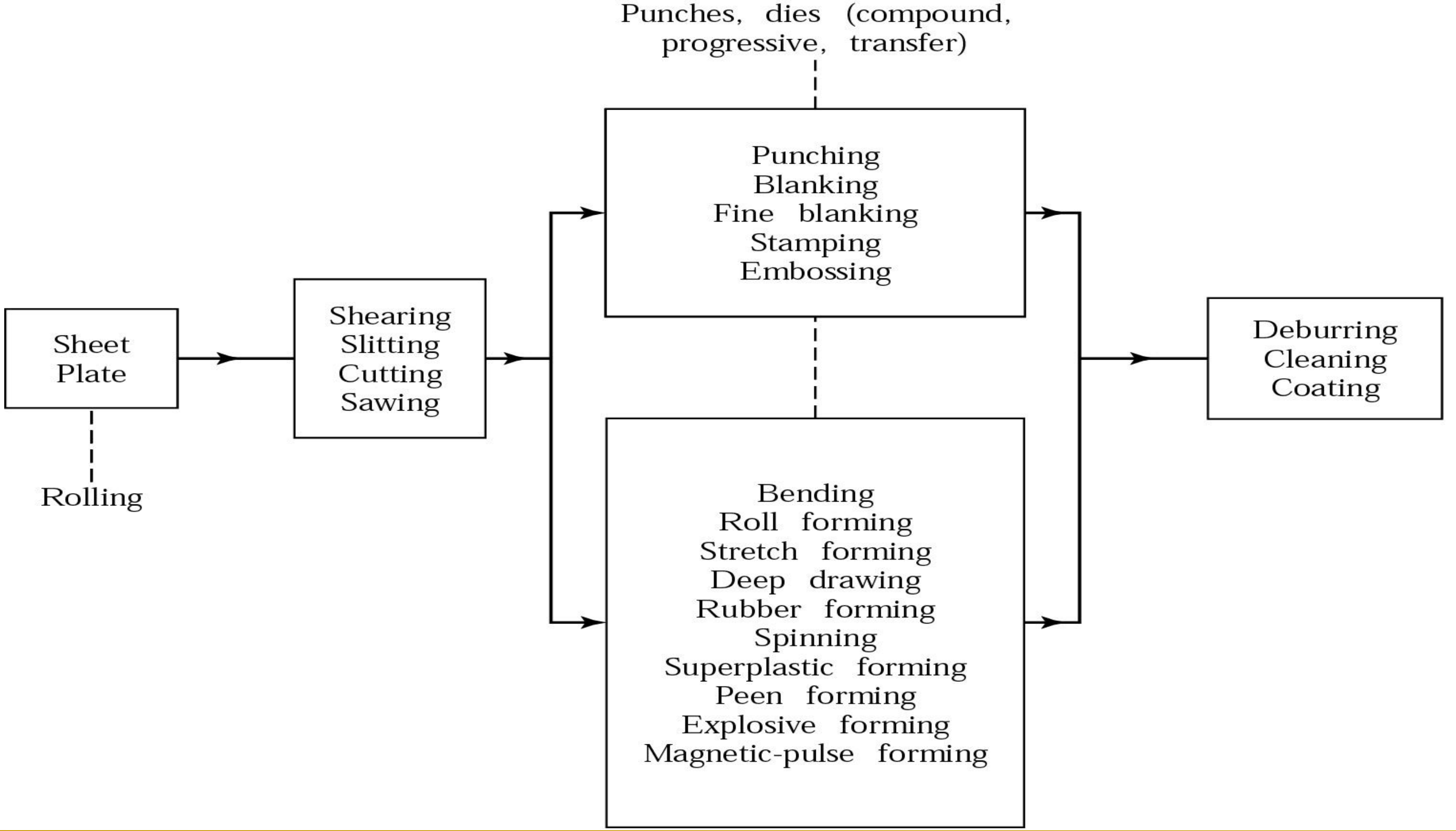
Sheet Metal operations



Sheet Metal operations

- The art of sheet metal lies in the making of different shapes by adopting different operations. The major types of operations are given below
  - Shearing (Cutting)
  - Bending
  - Drawing
  - Squeezing

Manufacturing Technology

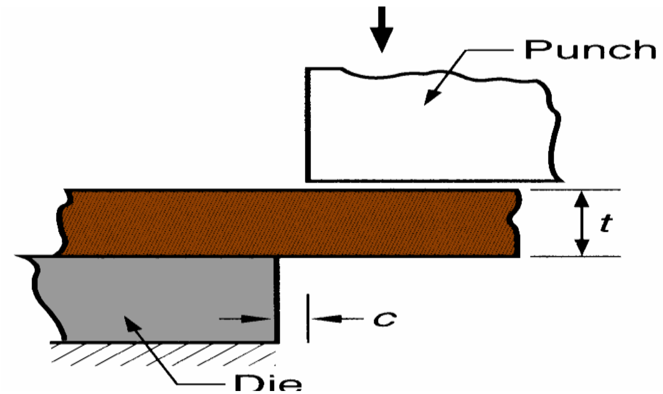
Sheet Metal operations

- Shearing
  - Cutting to separate large sheets; or cut part perimeters or make holes in sheets
- Bending
  - Straining sheet around a straight axis
- Drawing
  - Forming of sheet into convex or concave shapes
- Squeezing
  - Forming of sheet by gripping and pressing firmly – Coining & Embossing

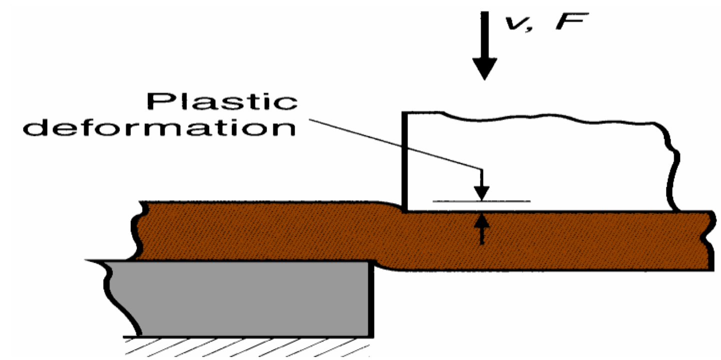
Manufacturing Technology

Shearing (Cutting)

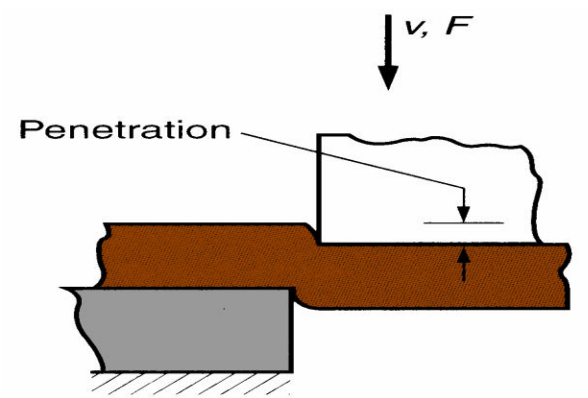
- Shearing of sheet metal between two sharp cutting edges



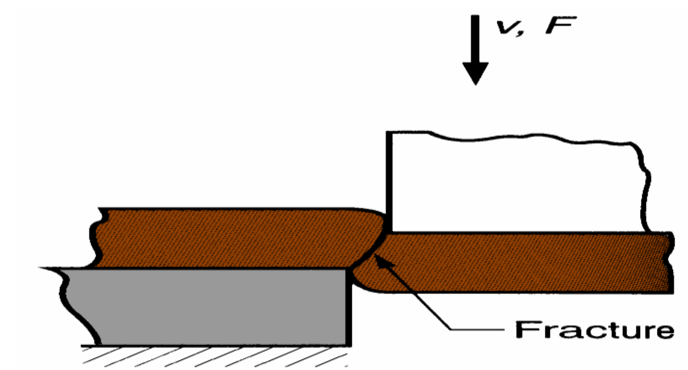
A. **Just before the punch contacts work**



B. **Punch begins to push into work, causing plastic deformation**



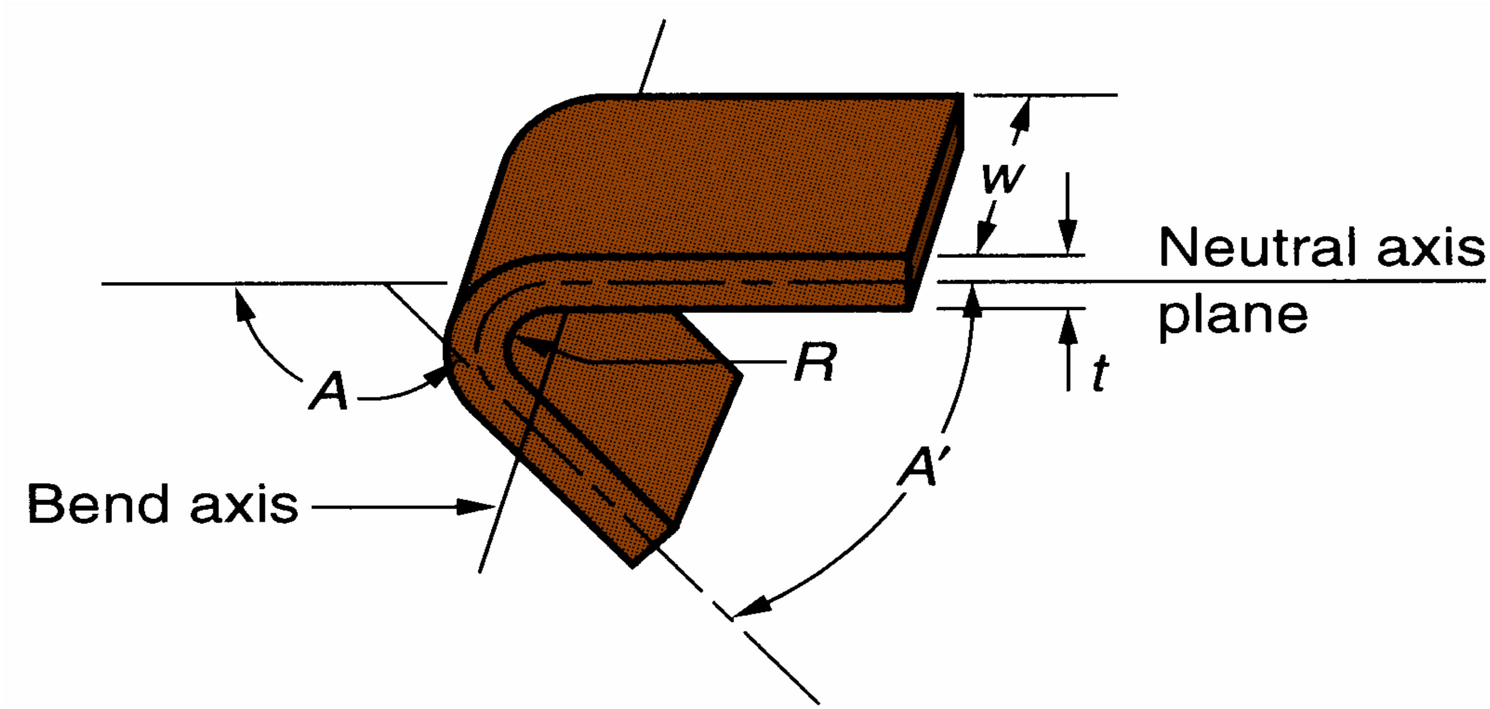
C. **Punch compresses and penetrates into work causing a smooth cut surface**



D. **Fracture is initiated at the opposing cutting edges which separates the sheet**

Bending

- Straining sheet metal around a straight axis to take a permanent bend



Bending of sheet metal

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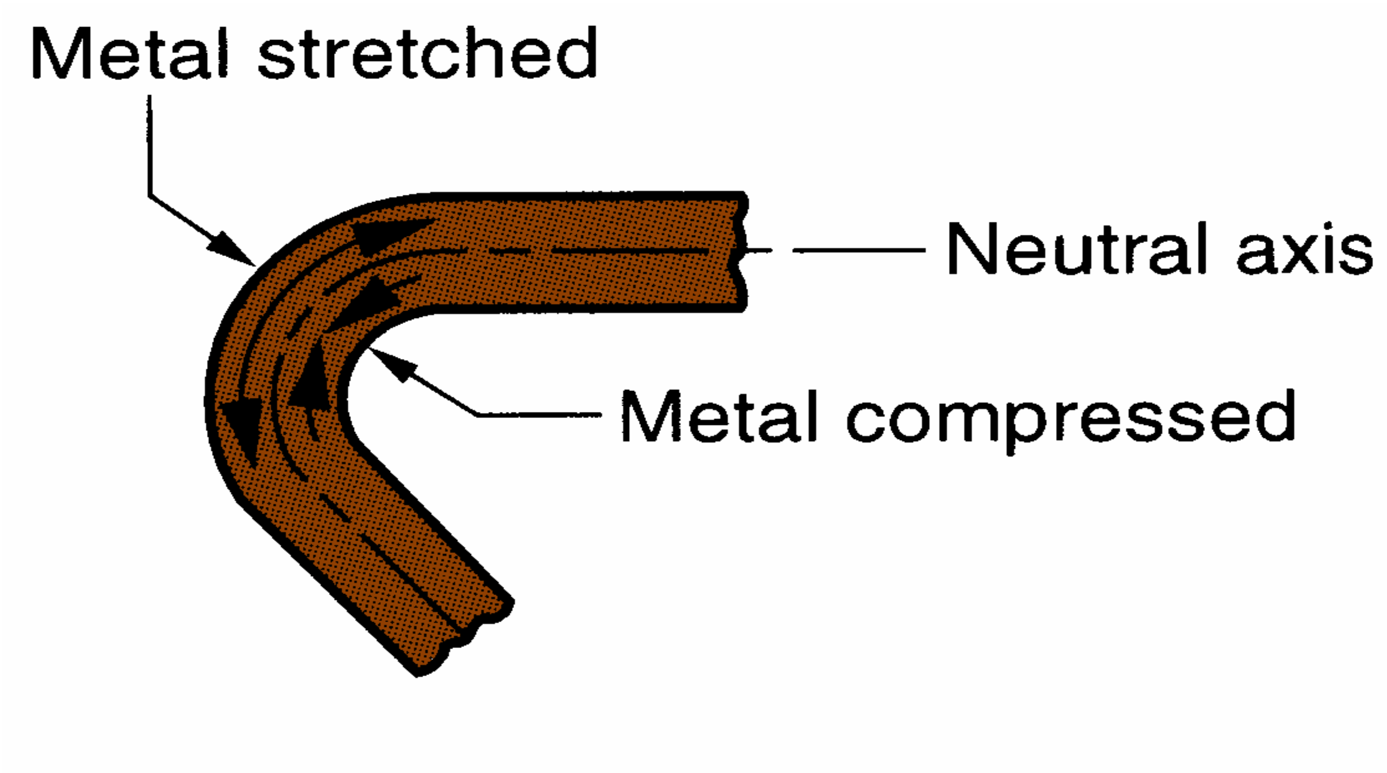
- Metal on inside of neutral plane is compressed, while metal on outside of neutral plane is stretched



Both compression and tensile elongation of the metal occur in bending

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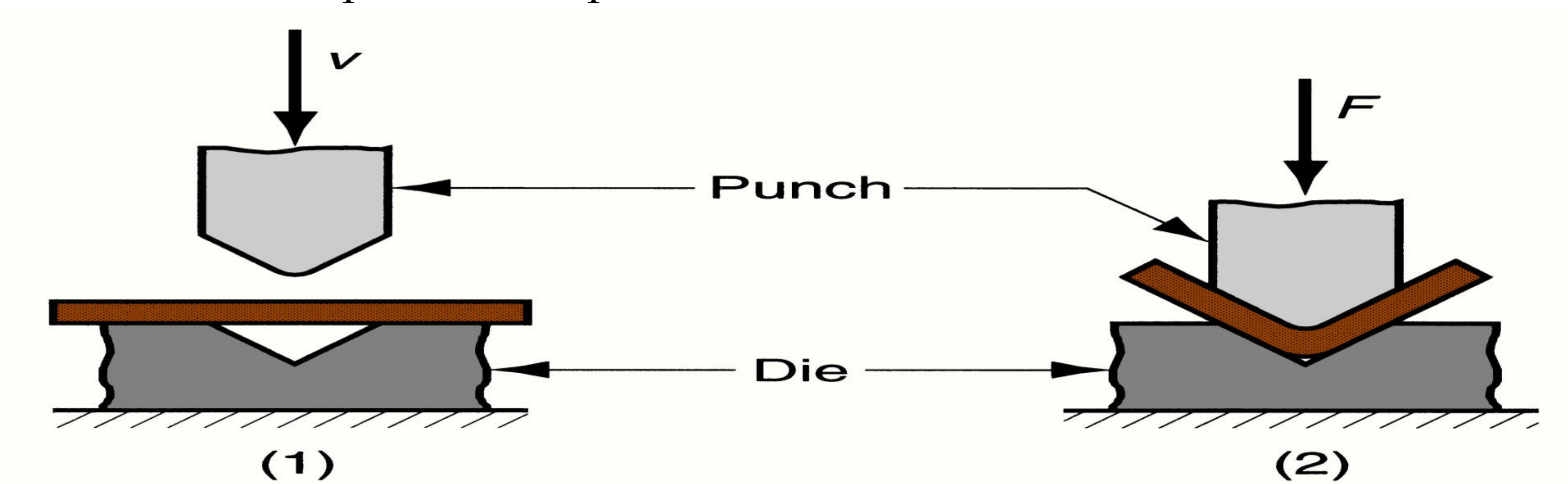
Types of Sheet metal Bending

- V-bending- performed with a V - shaped die
- Edge bending - performed with a wiping Die

V-Bending

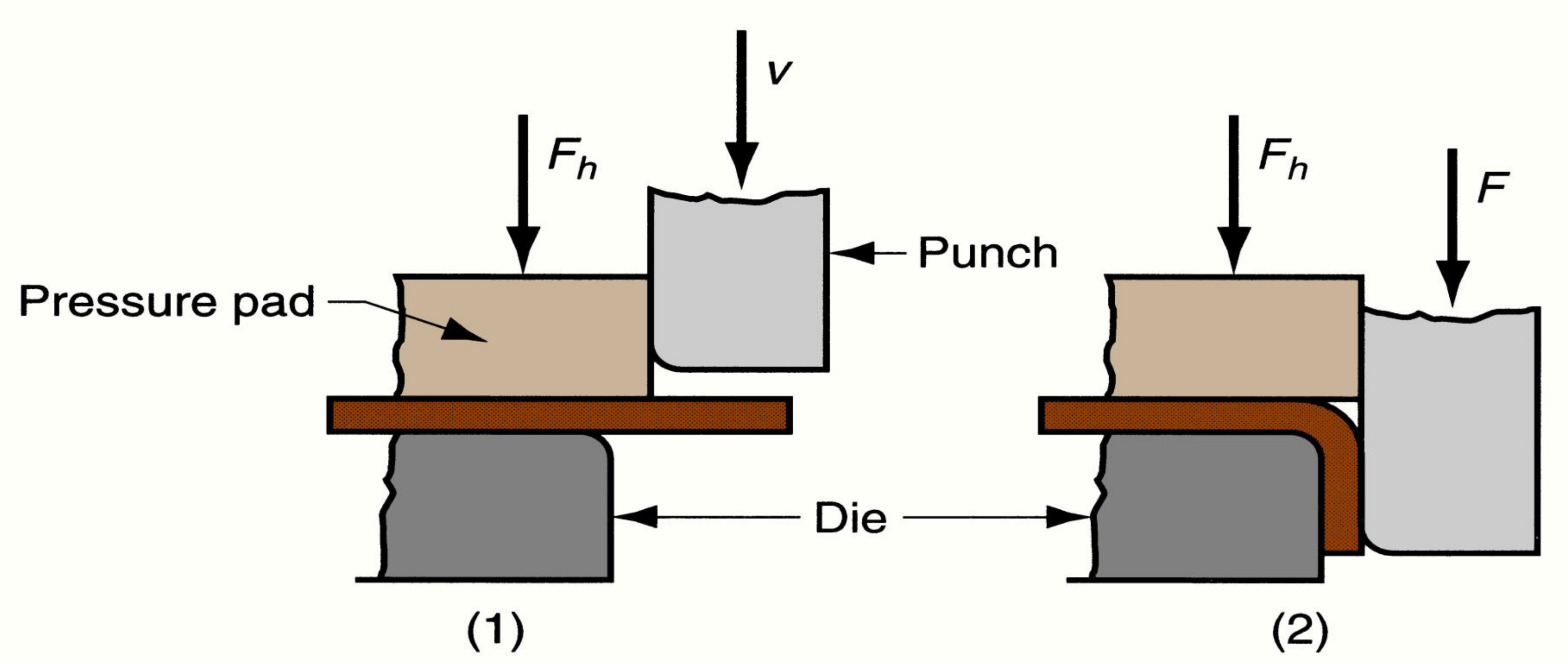
- For low production
- Performed on a press brake
- V-dies are simple and inexpensive



V-bending

Edge Bending

- For high production
- Pressure pad required
- Dies are more complicated and costly



Edge bending

Stretching during Bending

- If bend radius is small relative to stock thickness, metal tends to stretch during bending, so that estimation of amount of stretching (final part length) is important.

Bending Allowance

$$BA = 2\pi \frac{A}{360}(R + KT)$$

Where

- BA = Bend allowance;
- A = Bend angle;
- R= Bend radius;
- T = Stock thickness and K is factor to estimate stretching
- If R < 2T, K = 0.33
- If R = 2T, K = 0.50

Manufacturing Technology

Bending Force

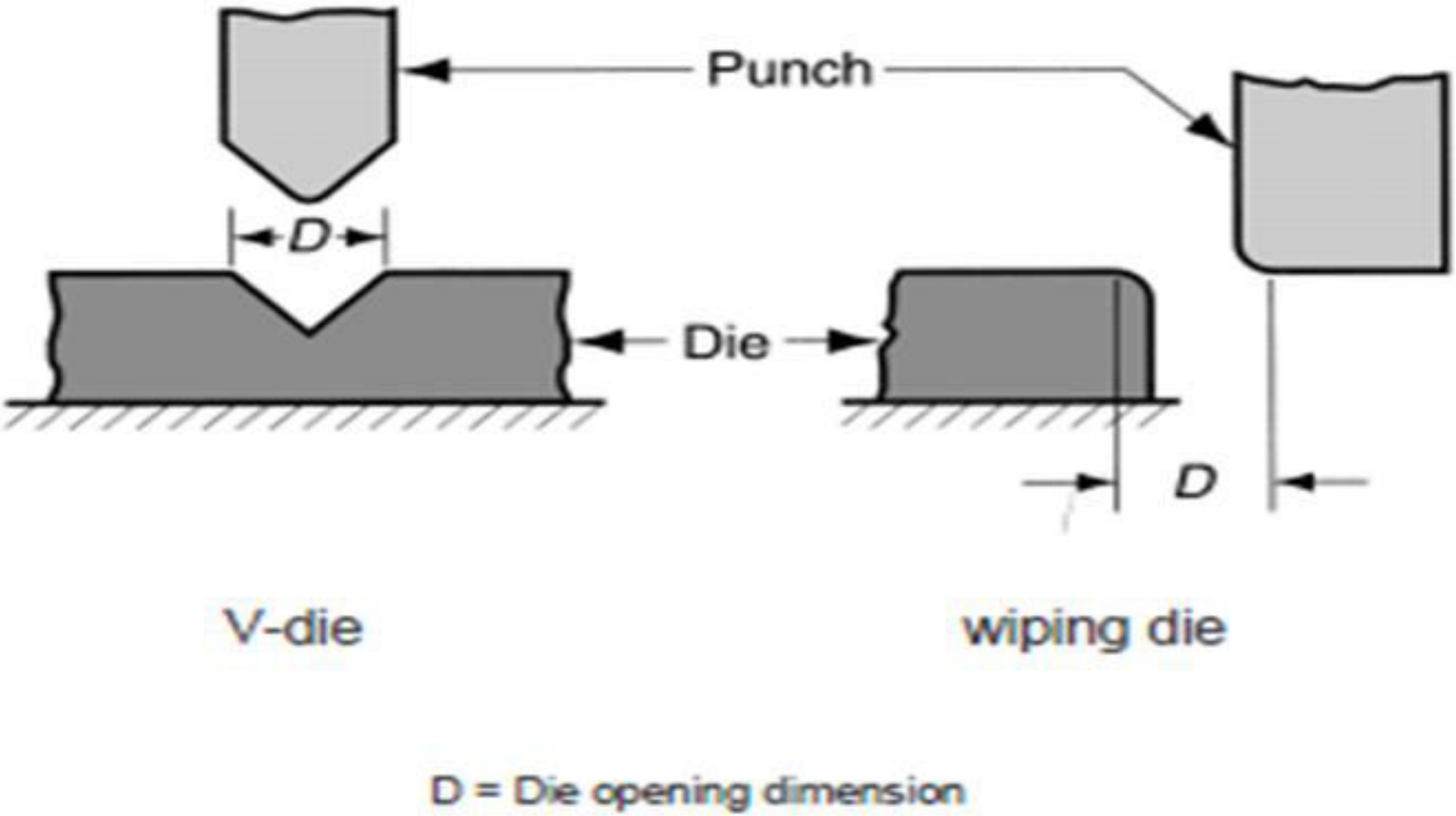
Maximum bending force estimated as follows

$$F = \frac{K_{bf} T_S W T^2}{D}$$

Where

- F = Bending Force
- T_S = Tensile strength of sheet metal
- W= Part width in direction of bend axis
- D = Die opening dimension
- T = Stock thickness and K is factor estimates bend force
- For V-Bending- K_{bf} = 1.33
- For Edge-Bending - K_{bf} = 0.33 or 0.50

Die opening dimension - D



Bending Force Calculation

Example -1

- A sheet-metal part 3mm thick and 20mm long is bent to an included angle of 60^o and a bend radius of 7.5mm in a V-die. The die opening is 15mm. The metal has tensile strength of 340 MPa. Compute the required force to bend the part.

Solution

Bending force Required

$$F = \frac{K_{bf}\, TS\, w\, t^2}{D}$$

$$F = \frac{1.33 \times 340 \times 20 \times 3^2}{15} = 5426.4$$

The bending force required to bend the part is 5426.4 N

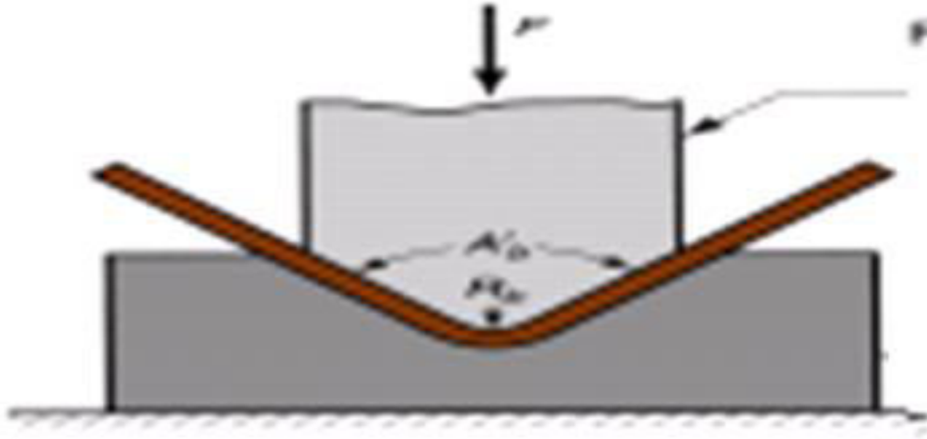
Manufacturing Technology

Spring back in Bending

- Spring back = increase in included angle of bent part relative to included angle of forming tool after tool is removed

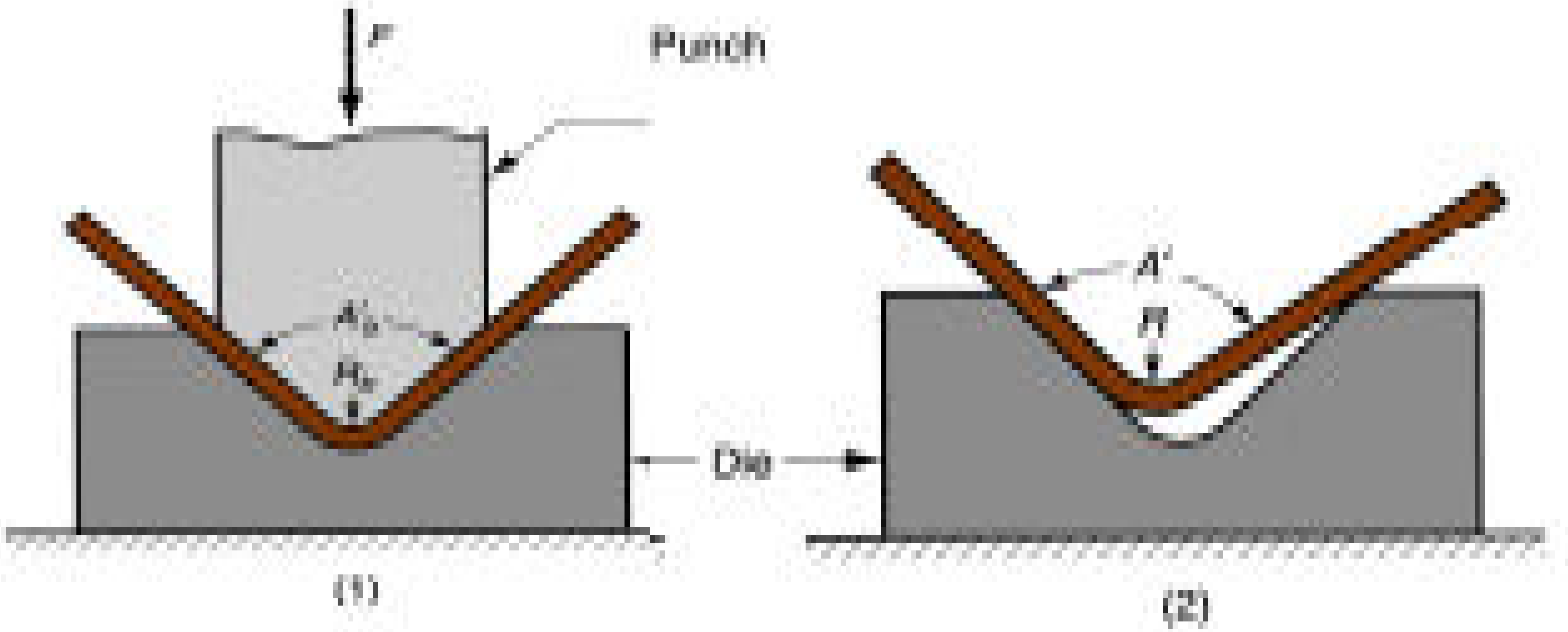
Reason for spring back

- When bending pressure is removed, elastic energy remains in bent part, causing it to recover partially toward its original shape
- Spring back in bending shows itself as a decrease in bend angle and an increase in bend radius



Manufacturing Technology

Spring back



1. During bending the work is forced t take the radius R_b and include angle A_b of the bending tool (punch in v-bending)
2. After punch is removed the work springs back to radius R and angle A

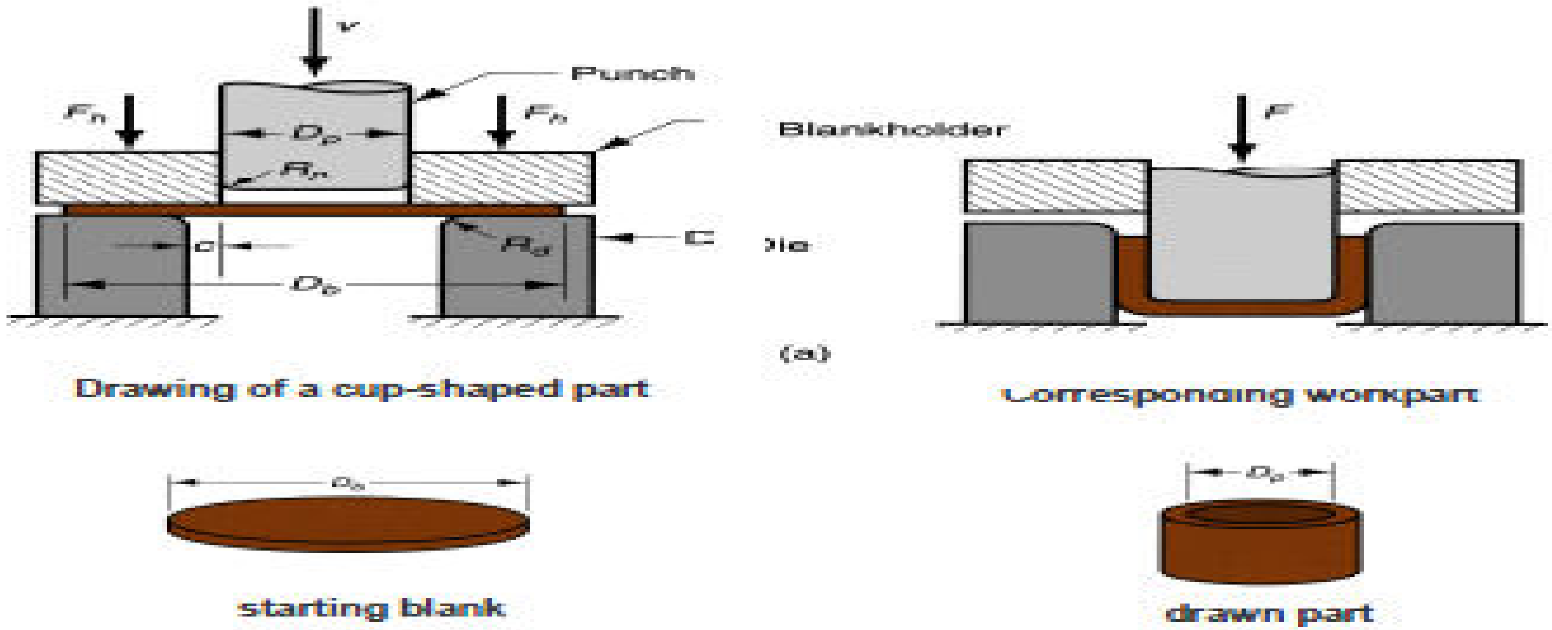
Spring back

- When a plate is bent, using a bending tool, the plate initially assumes the angle of the tool **θ′.** As the plate is removed from the tool, it springs back to an angle **θ'_b** less than the tool angle .
- The spring back, **S_b** defined as follows

$$S_b = \frac{(\theta' - \theta'_b)}{\theta'_b}$$

Manufacturing Technology

- Drawing
  - Forming of sheet into convex or concave shapes
  - Sheet metal blank is positioned over die cavity and than punch pushed metal in to opening
  - Products – Beverage cans, automobile body parts and ammunition shells



Manufacturing Technology

- Drawing Clearance
  - In drawing sides of punch and die separated by a clearance c is given by
    - C = 1.1 T
    - Where T – Stock thickness
- Drawing Ratio
  - The ratio between diameter of blank (D_b) to diameter of Punch (D_b)
  - $$DR = \frac{Db}{Dp} \leq 2$$
- Drawing Reduction Ratio
  - $$R = \frac{D_b - D_p}{D_p} \leq 0.5$$

Manufacturing Technology

- Drawing Thickness to Diameter Ratio
  - $D_{T/D} = T / D_b \geq 1\%$
- Drawing Force
  - The force required for the drawing operation, F_d is given as
  - $$D_F = \pi D_P T_S T (D_R - 0.7)$$
  - Where

    D_R = Drawing Ratio
    T_S = Tensile strength of sheet metal
    Dp = Diameter of punch
    T = Stock thickness

Manufacturing Technology

- Holding force of the Blank

$$F_h = 0.015 S_y \pi [D_p{}^2 - (D_p + 2.2t + 2r_p)^2]$$

- Where
  - S_y is the Yield Tensile strength of the blank
  - r_p - Punch Radius or Die radius

Example-2

- A cup drawing operation is performed in which the inside diameter is 80mm and the height is 50mm. The stock thickness is 3mm, and the starting diameter is 150mm. Punch and die radii = 4mm. The tensile strength of the material is 400Mpa and the yield strength is 180Mpa. Determine:
  - (i) Drawing ratio
  - (ii) Reduction
  - (iii) Drawing force
  - (iv) Blank holder force

Solution

(i) $DR = D_b / D_p = 150/80 = 1.875$

(ii) $R = \dfrac{D_b - D_p}{D_b} = 1 - \dfrac{1}{DR} = 1 - \dfrac{1}{1.875} = 0.4667$

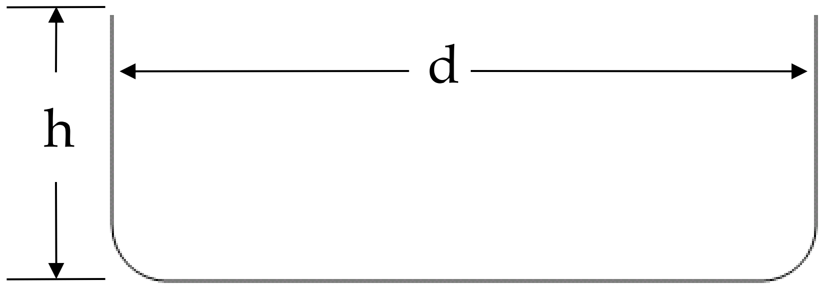
(iii) $D_f = \pi D_p T_s T(DR - 0.7) = \pi 0.08 * 0.003 * 400x10^6 (1.875 - 0.7) = 354{,}371.6N$

(iv) $F_h = 0.015 S_y \pi [D_p{}^2 - (D_p + 2.2t + 2r_p)^2]$

$F_h = 0.015 * 189x10^6 * \pi[0.15^2 - (0.08 + 2.2 * 0.003 + 2 * 0.004)^2] = 114{,}942.29N$

Blank Size Calculation

- For final dimensions of drawn shape to be correct, starting blank diameter Db must be correct.
- Solve Db by setting starting sheet metal blank volume = final product volume
- To facilitate calculation, assume negligible thinning of part wall with diameter d height h



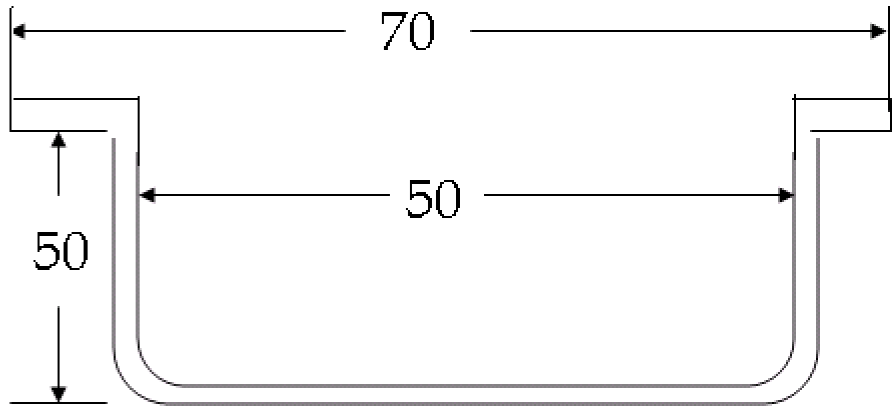
The Size or Diameter of the blank is given by

- Blank volume = Final product volume
- $\pi D^2/4 = \pi d_1^2/4 + \pi d_2 h$
- $D^2 = d_1^2 + 4 d_2 h$
- The Size or Diameter of the blank is

$$D = \sqrt{d_1^2 + 4 d_2 h}$$

Example-3

- Calculate the blank size of the given shell as shown in fig



$$D = \sqrt{d_1^2 + 4 d_2 h}$$

$$D = \sqrt{70^2 + 4 \times 50 \times 50}$$

Blank size D = 122mm

Manufacturing Technology

Sheet metal Process in detail

- Cutting (Shearing) Operations
- In this operation, the work piece is stressed beyond its ultimate strength. The stresses caused in the metal by the applied forces will be shearing stresses. The cutting operations include
  - Punching (Piercing)
  - Blanking
  - Trimming
  - Notching
  - Perforating
  - Slitting
  - Lancing
  - Parting
  - Shaving
  - Fine blanking

Shearing Operations

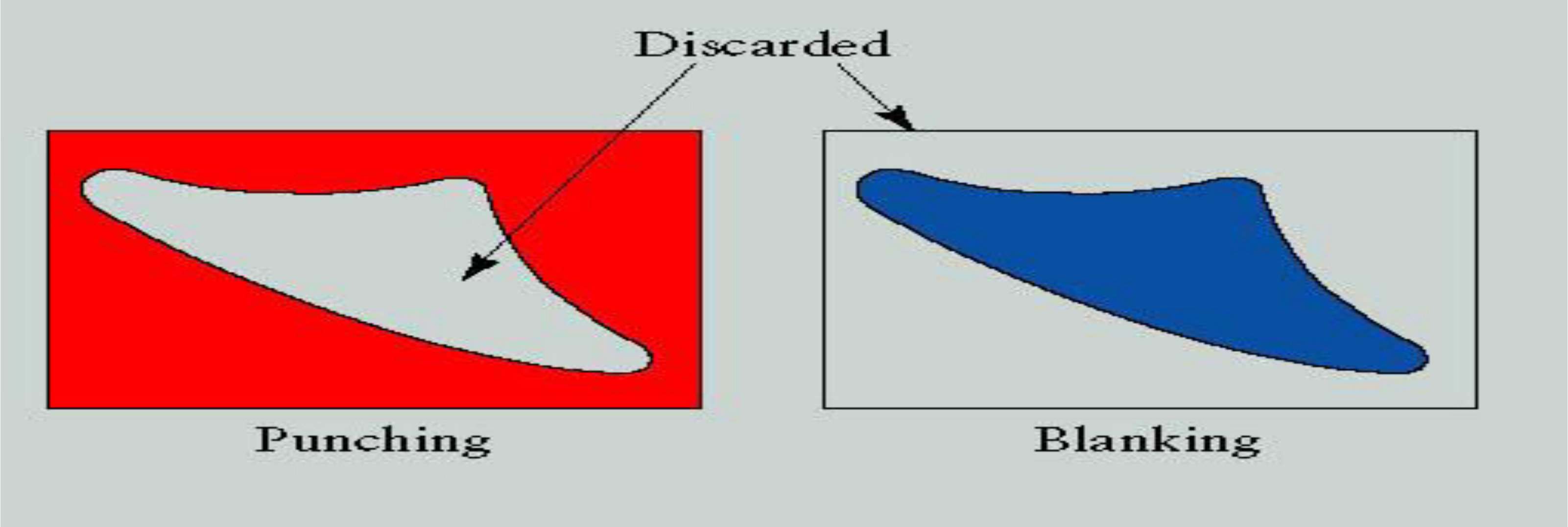
- **Punching (Piercing)** It is a cutting operation by which various shaped holes are made in sheet metal. Punching is similar to blanking except that in punching, the hole is the desired product, the material punched out to form the hole being waste.
- **Blanking**: Blanking is the operation of cutting a flat shape sheet metal. The article punched out is called the blank and is the required product of the operation. The hole and metal left behind is discarded as waste.
- **Notching**: This is cutting operation by which metal pieces are cut from the edge of a sheet, strip or blank.

- **Perforating**: This is a process by which multiple holes which are very small and close together are cut in flat work material.
- **Slitting**: It refers to the operation of making incomplete holes in a work piece.
- **Lancing**: This is a cutting operation in which a hole is partially cut and then one side is bent down to form a sort of tab. Since no metal is actually removed, there will be no scrap.
- **Parting**: Parting involves cutting a sheet metal strip by a punch with two cutting edges that match the opposite sides of the blank.

- **Shaving**: The edge of blanked parts is generally rough, uneven and un-square. Accurate dimensions of the part are obtained by removing a thin strip of metal along the edges.
- **Fine blanking**: Fine blanking is a operation used to blank sheet metal parts with close tolerances and smooth, straight edges in one step.
- **Trimming**: This operation consists of cutting unwanted excess material from the periphery of previously formed components.

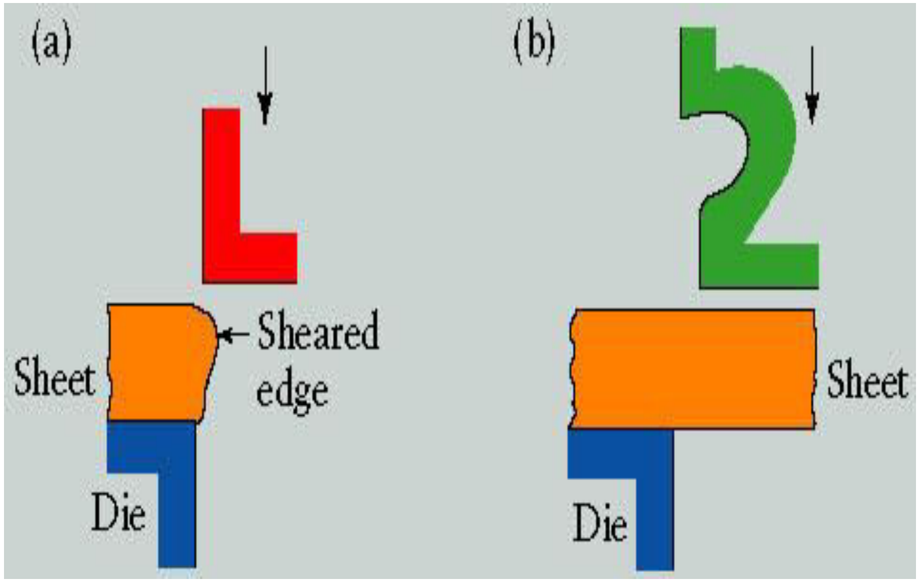
Manufacturing Technology

Shearing Operations

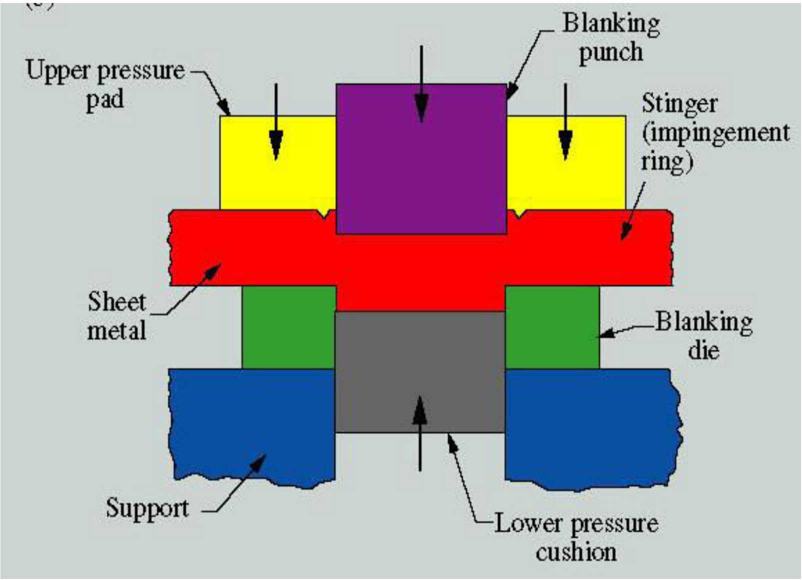


Manufacturing Technology

Shearing Operations



Schematic illustrations of shaving on a sheared edge. (a) Shaving a sheared edge. (b) Shearing and shaving, combined in one stroke.



Fine blanking

Shaving

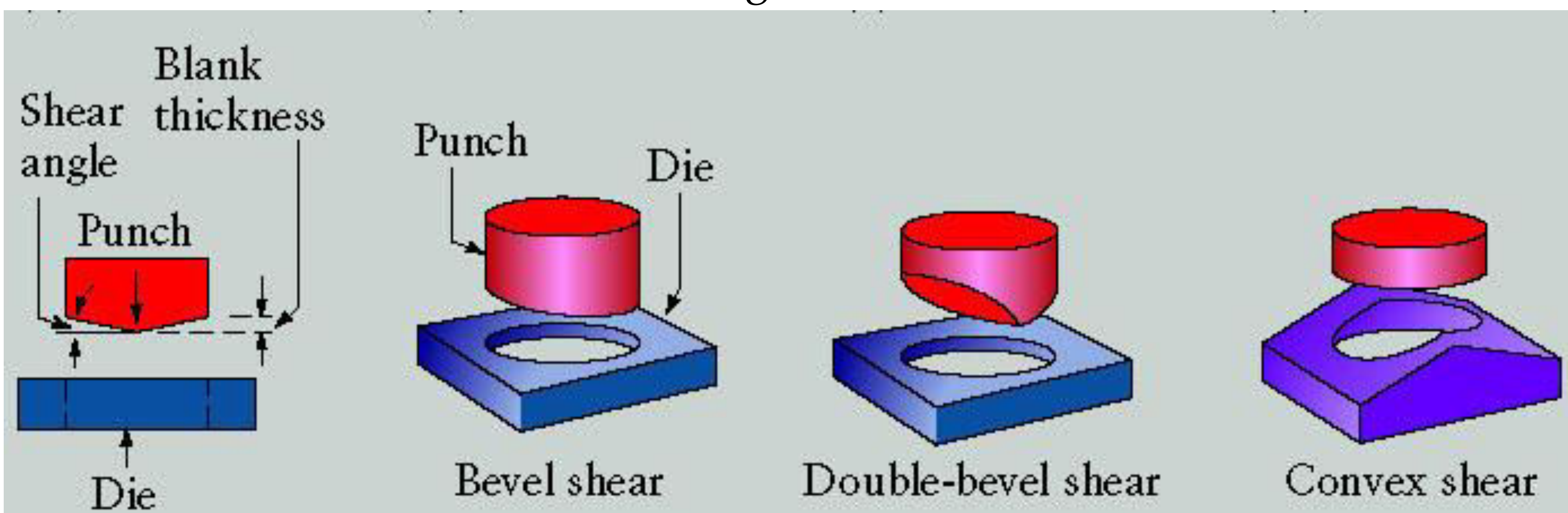
Trimming

Shearing Dies

- Because the formability of a sheared part can be influenced by the quality of its sheared edges, clearance control is important.
- In practice, clearances usually range between 2% and 8% of the sheet's thickness; generally, the thicker the sheet, the larger is the clearance (as much as 10%). However, the smaller the clearance, the better is the quality of the edge.

Punch and Die Shapes

- As the surfaces of the punch and die are flat; thus, the punch force builds up rapidly during shearing, because the entire thickness of the sheet is sheared at the same time. However, the area being sheared at any moment can be controlled by beveling the punch and die surfaces, as shown in the following Figure. This geometry is particularly suitable for shearing thick blanks, because it reduces the total shearing force.

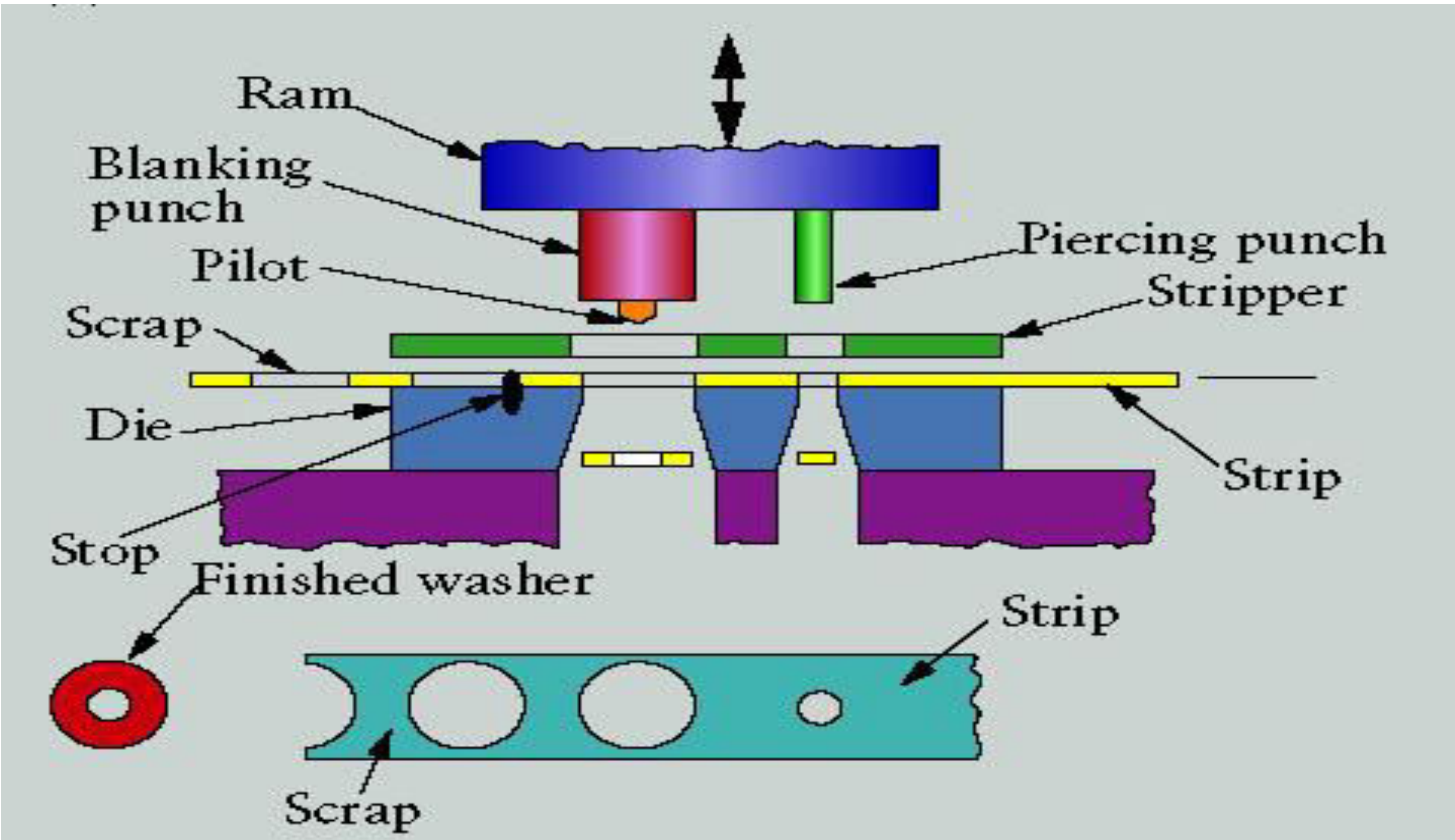


Examples of the use of shear angles on punches and dies

Types of Shearing Dies

- **Progressive Dies**: Parts requiring multiple operations, such as punching, blanking and notching are made at high production rates in progressive dies. The sheet metal is fed through a coil strip and a different operation is performed at the same station with each stroke of a series of punches.
- **Compound Dies**: Several operations on the same strip may be performed in one stroke with a compound die in one station. These operations are usually limited to relatively simple shearing because they are somewhat slow and the dies are more expensive than those for individual shearing operations.
- **Transfer Dies (Combination Dies)**: In a transfer die setup, the sheet metal undergoes different operations at different stations, which are arranged along a straight line or a circular path. After each operation, the part is transfer to the next operation for additional operations.

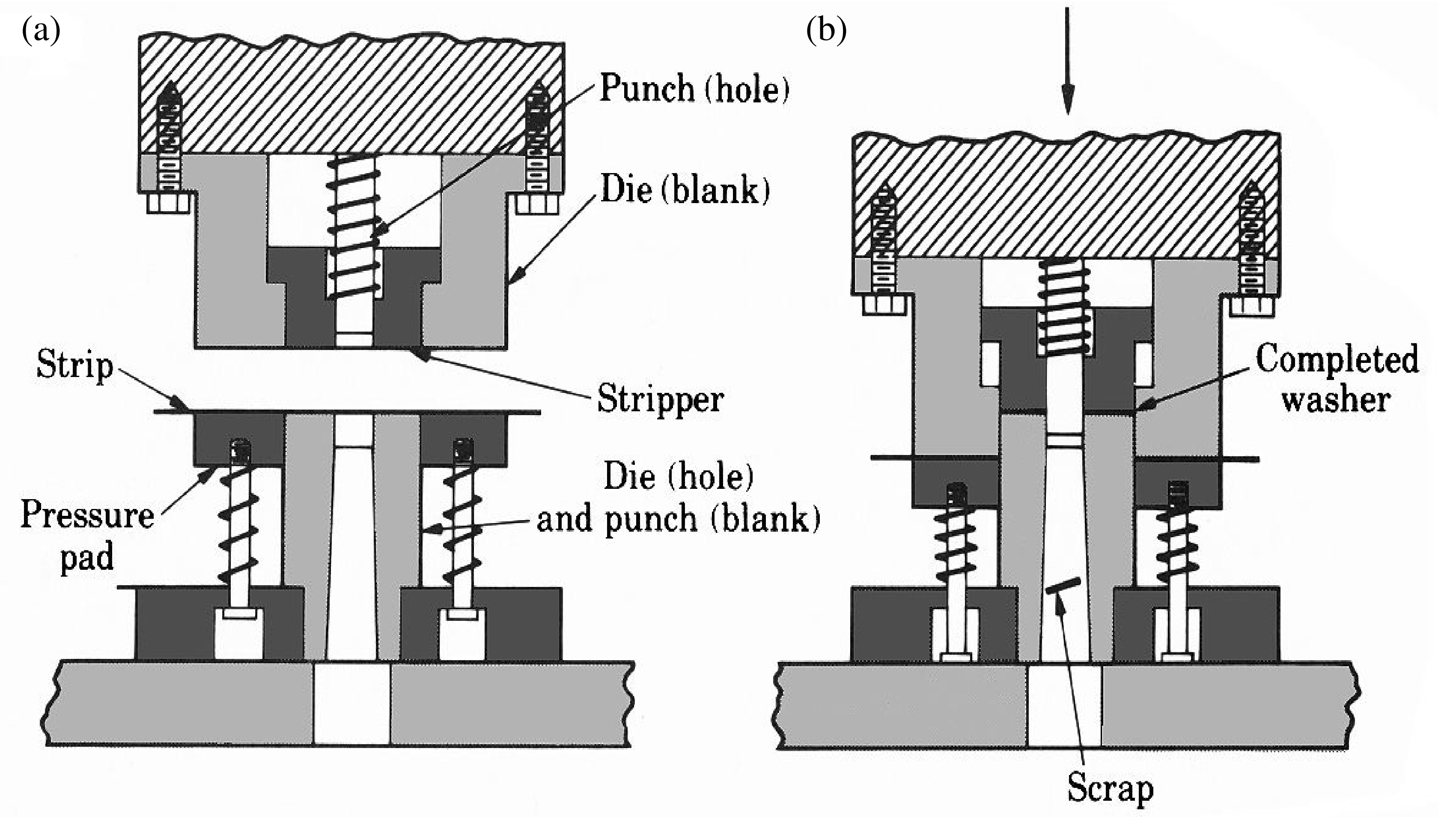
- **Progressive Die**



(a) Schematic illustration of making a washer in a progressive die.
(b) Forming of the top piece of an aerosol spray can in a progressive die.

Manufacturing Technology

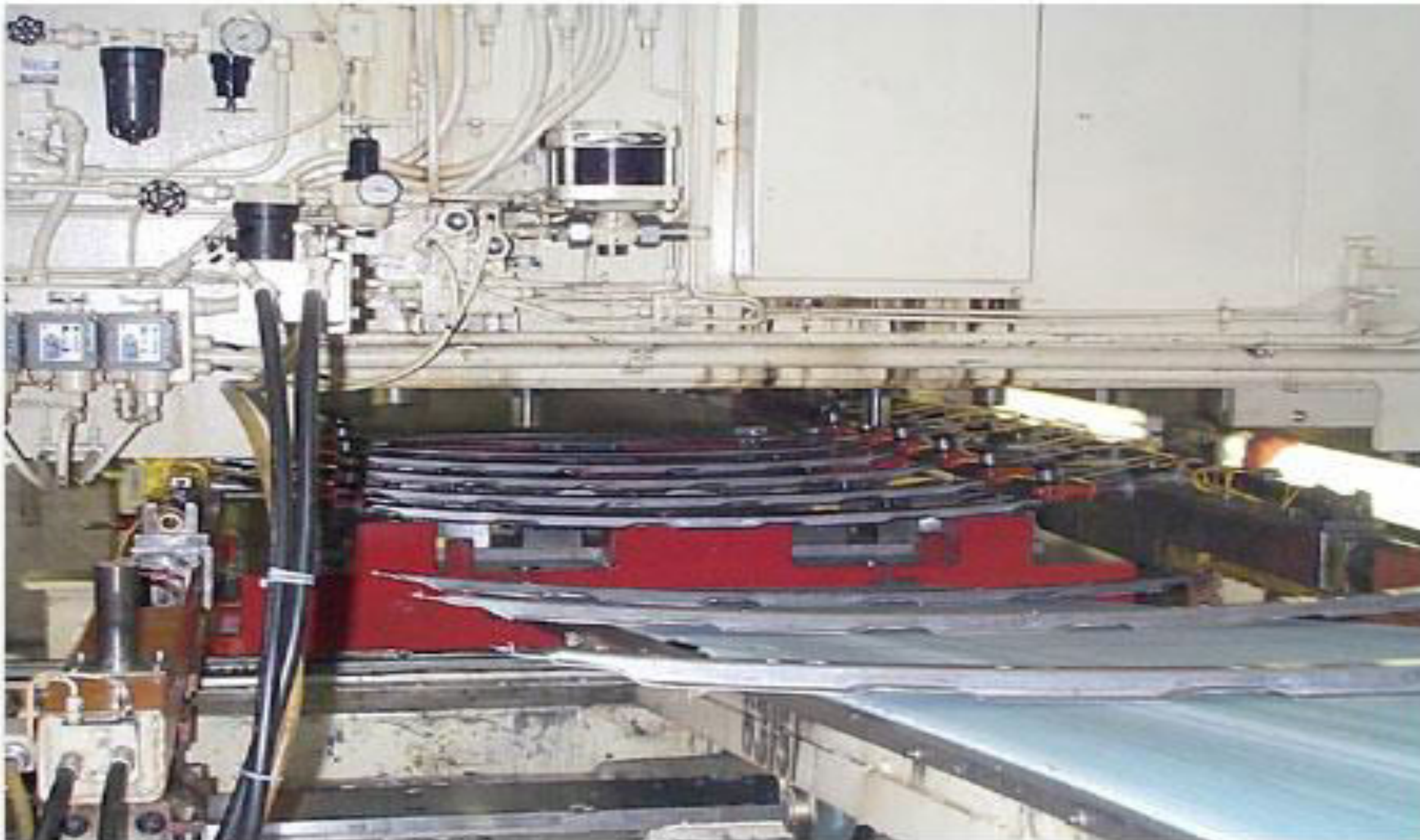
- **Compound Die**



Schematic illustrations: (a) before and (b) after blanking a common washer in a compound die.
Note the separate movements of the die (for blanking) and the punch (for punching the hole in the washer).

Manufacturing Technology

- **Transfer Dies**



Forming Operations

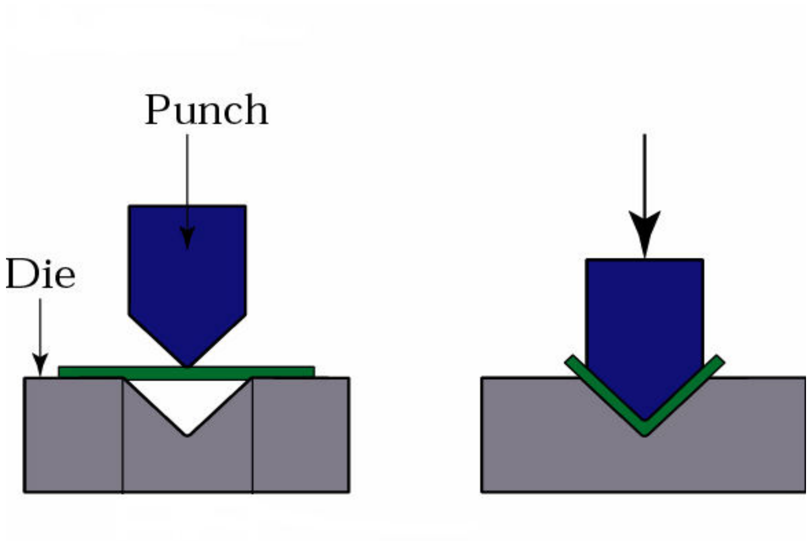
- In this operation, the stresses are below the ultimate strength of the metal. In this operation, there is no cutting of the metal but only the contour of the work piece is changed to get the desired product. The forming operations include
  - **Bending**
  - **Drawing**
  - **Squeezing**

- **Bending**: In this operation, the material in the form of flat sheet or strip, is uniformly strained around a linear axis which lies in the neutral plane and perpendicular to the lengthwise direction of the sheet or metal
- **Drawing** : This is a process of a forming a flat work piece into a hollow shape by means of a punch, which causes the blank to flow into die cavity.
- **Squeezing**: Under this operation, the metal is caused to flow to all portions of a die cavity under the action of compressive forces.

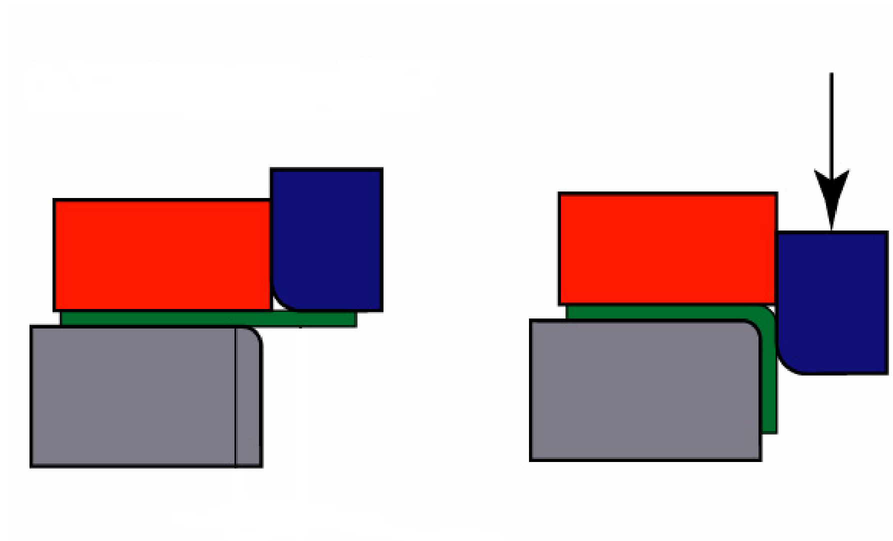
Types of Bending operations

- V-bending
- Edge bending
- Roll bending
- Air bending
- Flanging
- Dimpling
- Tube forming
- Stretch forming
- Press break forming
- Beading
- Roll forming
- Bulging

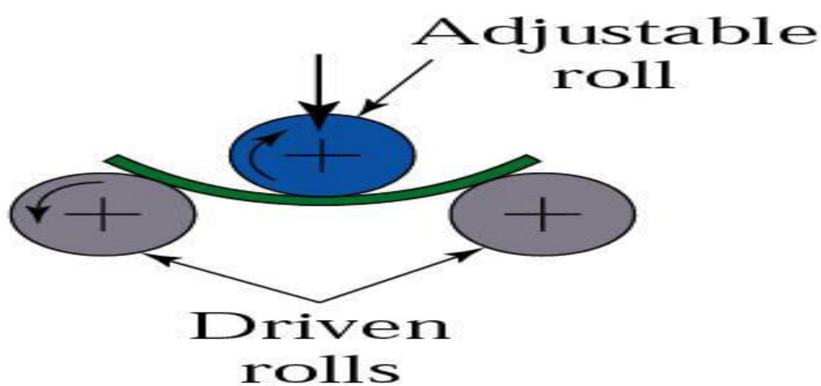
Bending operations



V-bending



Edge bending



Roll bending

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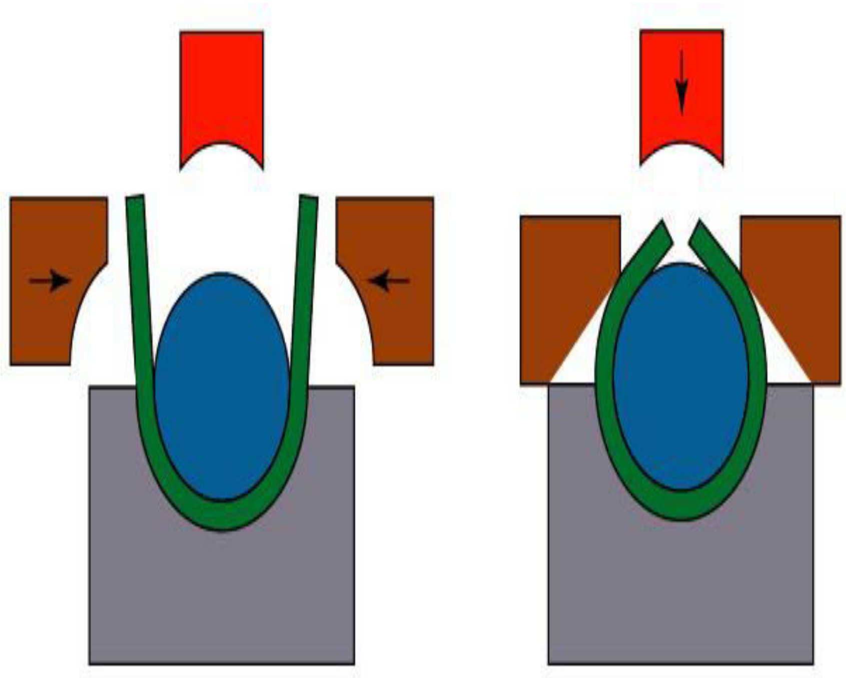
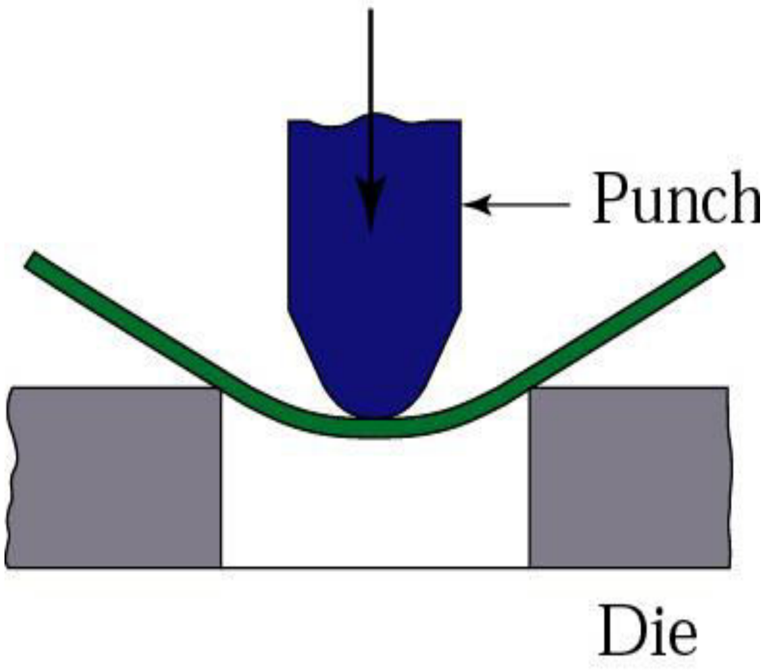
Bending operations



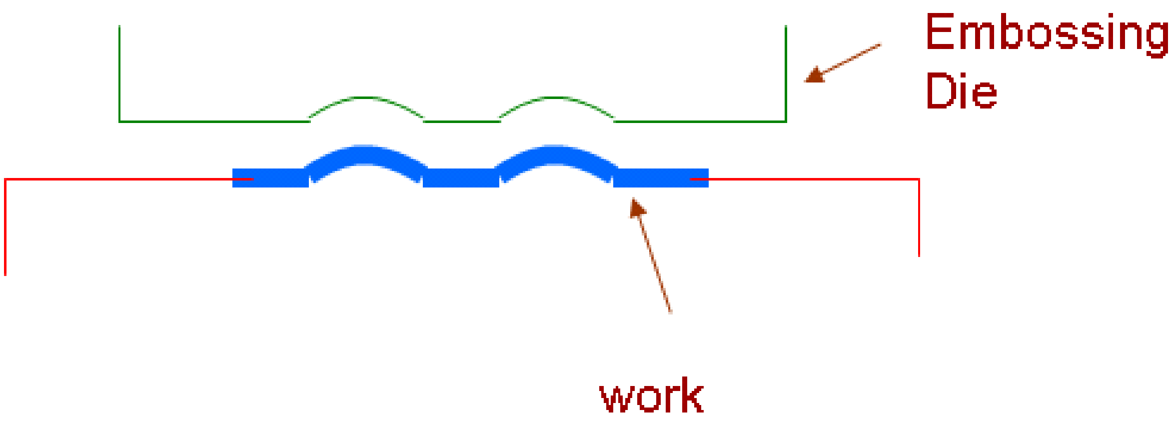
Bending in 4-slide machine



Air bending

Embossing

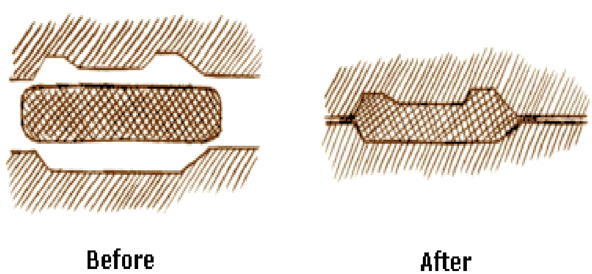
- This is the process of making raised or projected design on the surface of the metal with its corresponding relief on the other side. This operation includes drawing and bending. It uses a die set which consists of die and punch with desired shape. This operation requires less force compared with coining process. It is very useful for producing nameplates tags and designs on the metal.



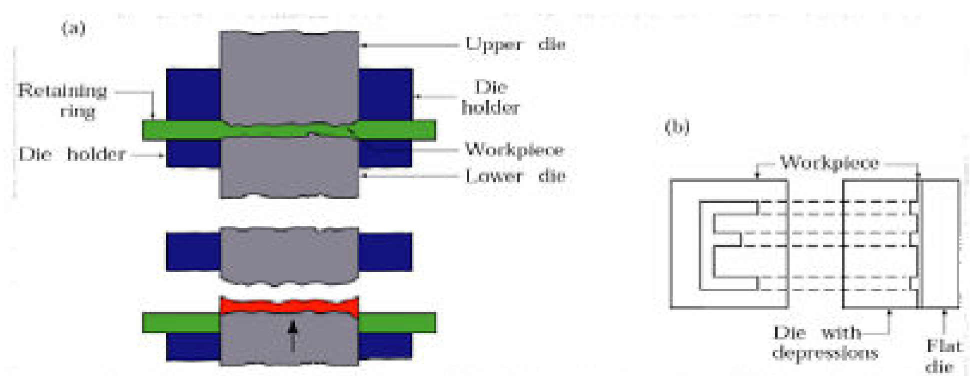
Manufacturing Technology

Coining

- It is a cold working sizing operation. It is used for the production of metals coins. The coining processes consists of die and punch. By using the punch and die, the impression and images are created on the metal. The pressure involved in coining process is about 1600Mpa. The metal flows plastically and squeezed to the shape between the punch and die. The metal is caused to flow in the direction of perpendicular force. The type of impression is formed by compressive force. The type of impression obtained on both sides will be different

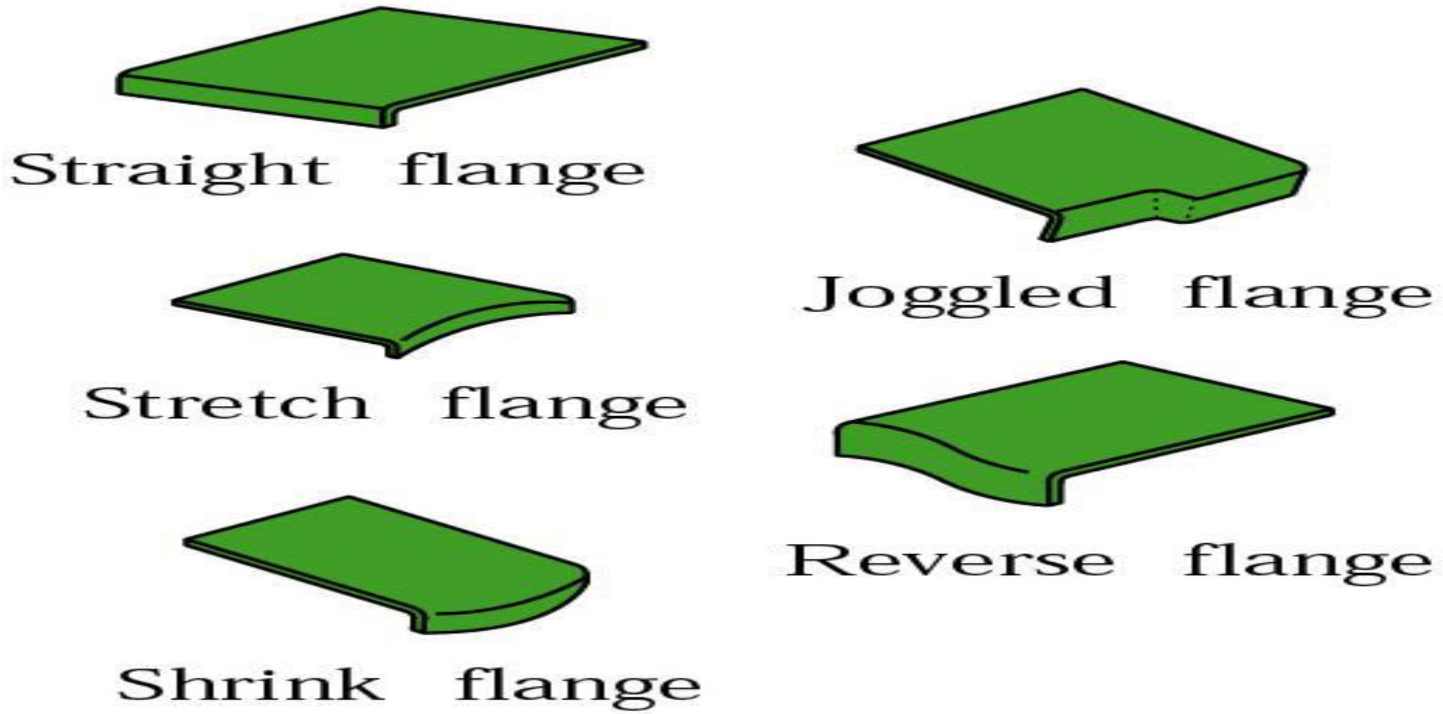


COINING

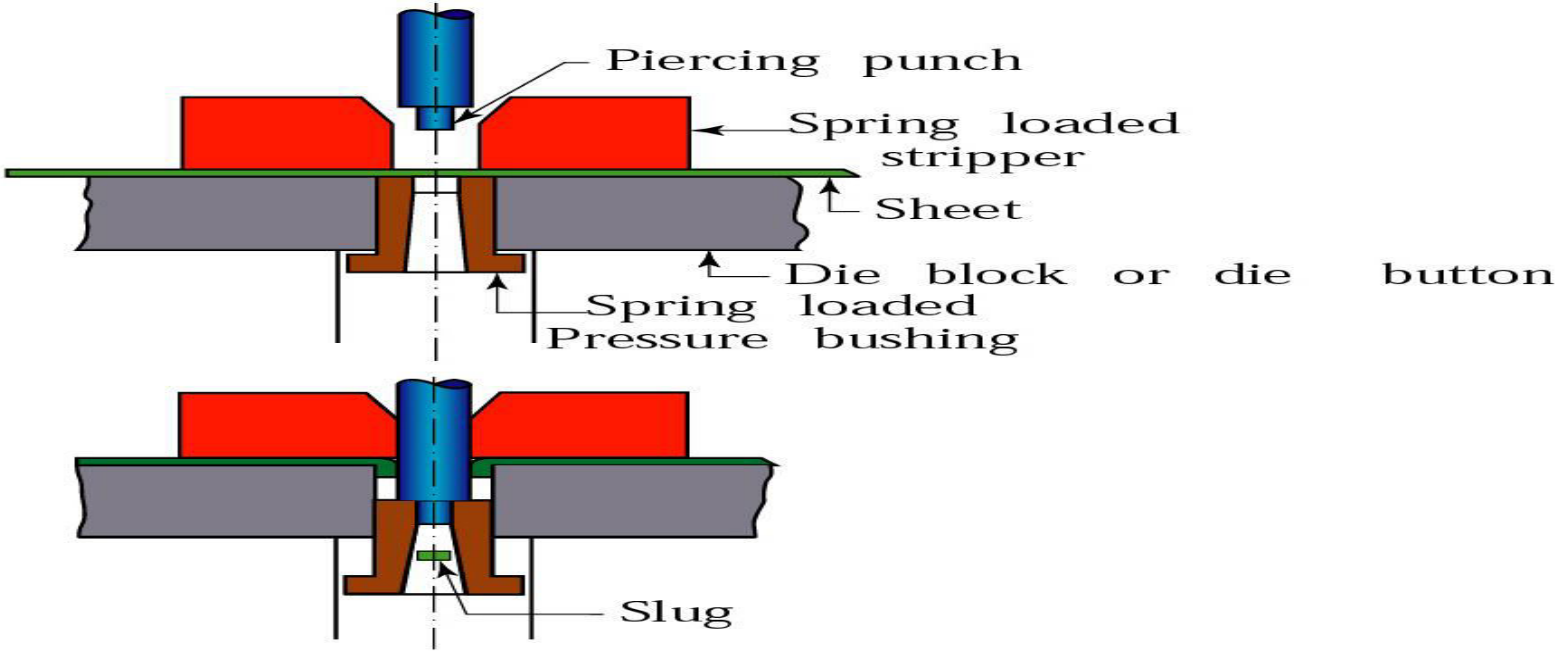


Manufacturing Technology

- **Flanging**
  - Flanging is a process of bending the edges of sheet metals to 90^o
    - Shrink flanging – subjected to compressive hoop stress.
    - Stretch flanging –subjected to tensile stresses



- **Dimpling**:
  - First hole is punched and expanded into a flange
  - Flanges can be produced by piercing with shaped punch
  - When bend angle < 90 degrees as in fitting conical ends its called flanging

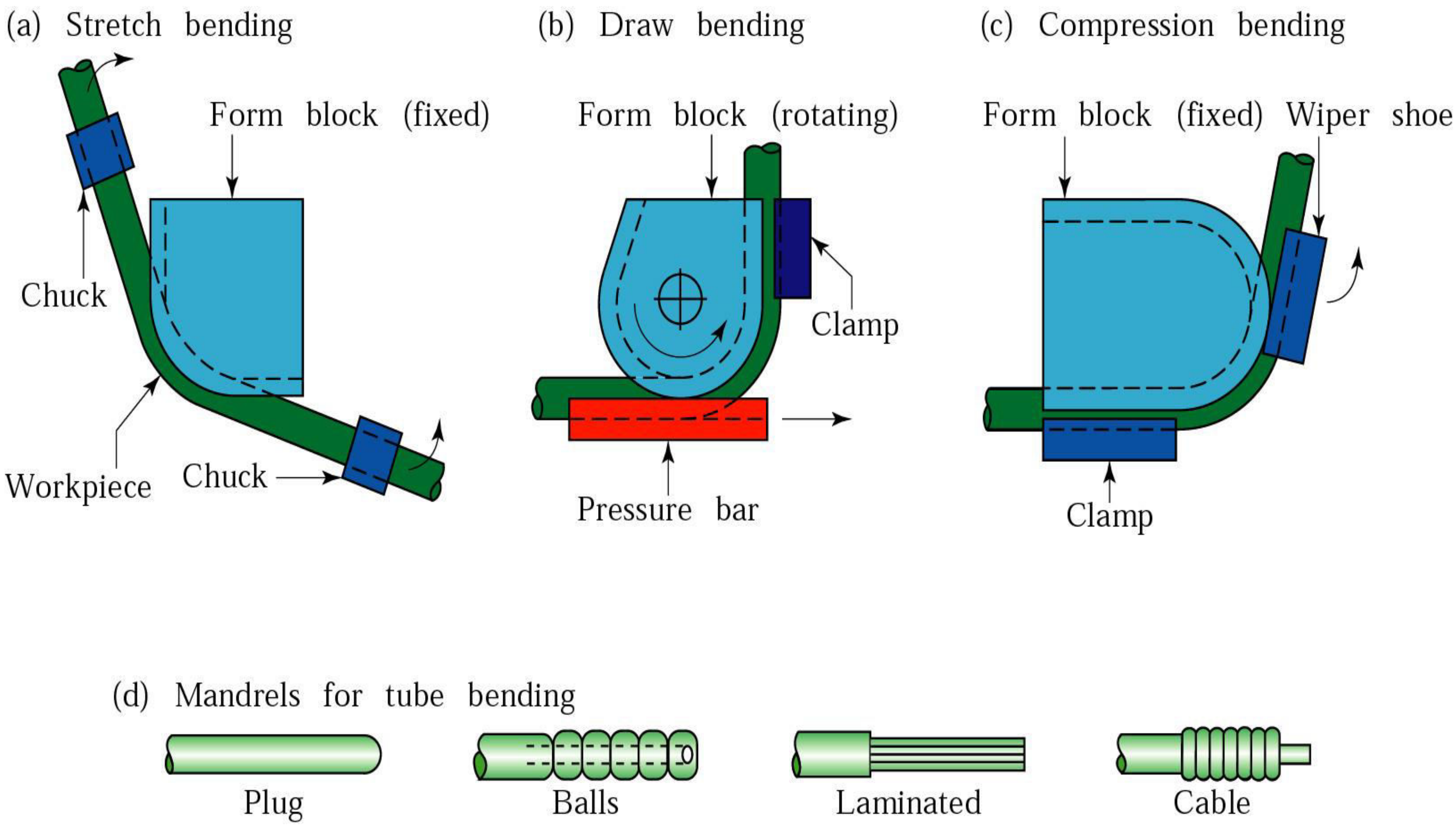


Tube Forming or Bending

- Bending and forming tubes and other hollow sections require special tooling to avoid buckling and folding. The oldest method of bending a tube or pipe is to pack the inside with loose particles, commonly used sand and bend the part in a suitable fixture.
- This technique prevents the tube from buckling. After the tube has been bent, the sand is shaken out. Tubes can also be plugged with various flexible internal mandrels.

Manufacturing Technology

Tube Forming



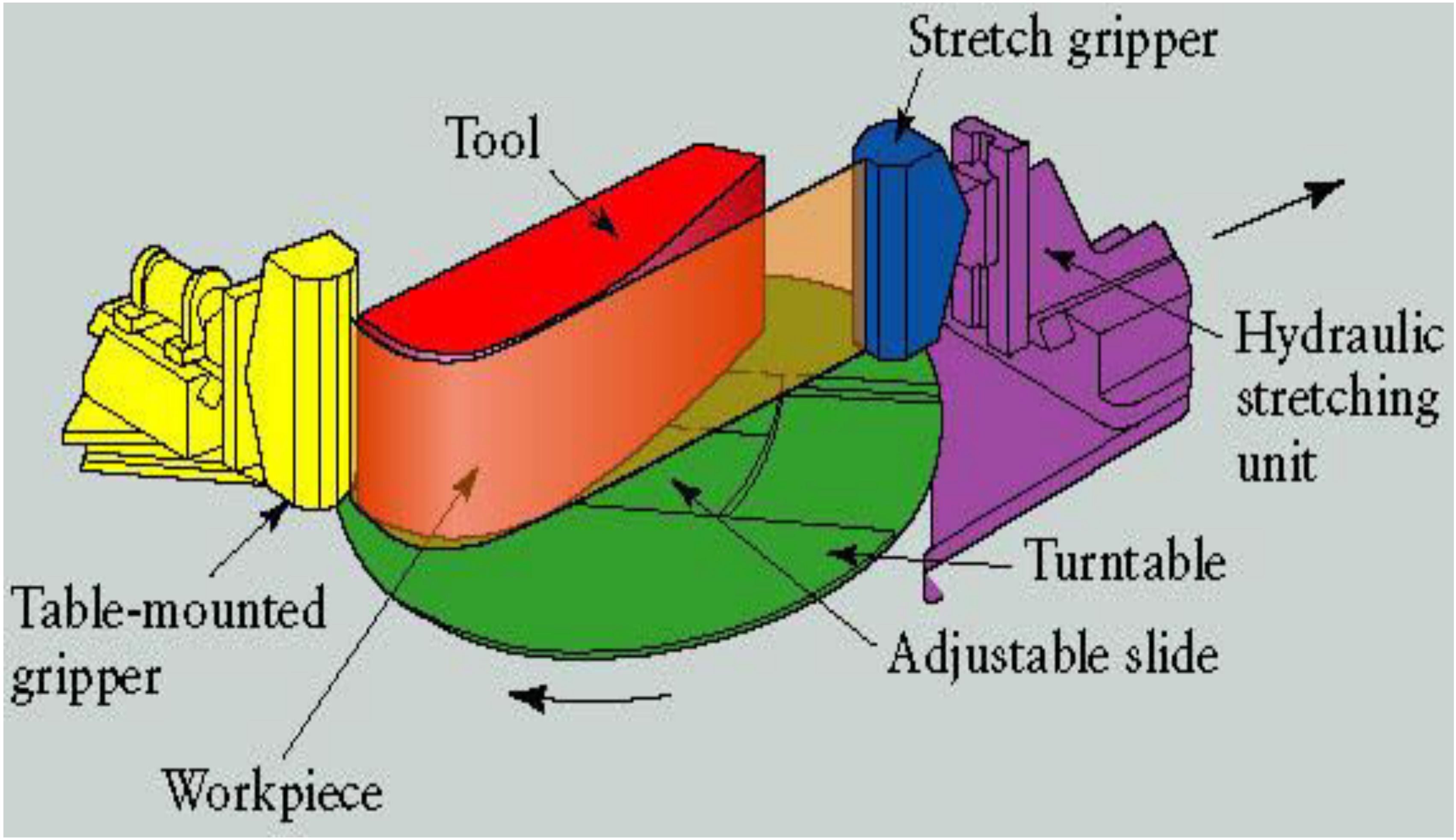
Methods of bending tubes. Internal mandrels, or the filling of tubes with particulate materials such as sand are often necessary to prevent collapse of the tubes during bending .Solid rods and structural shapes can also be bent by these techniques

Stretch Forming

- In stretch forming, the sheet metal is clamped around its edges and stretched over a die or form block, which moves upward, downward or sideways, depending on the particular machine. Stretch forming is used primarily to make aircraft-wing skin panel, automobile door panels and window frames.

Manufacturing Technology

Stretch Forming

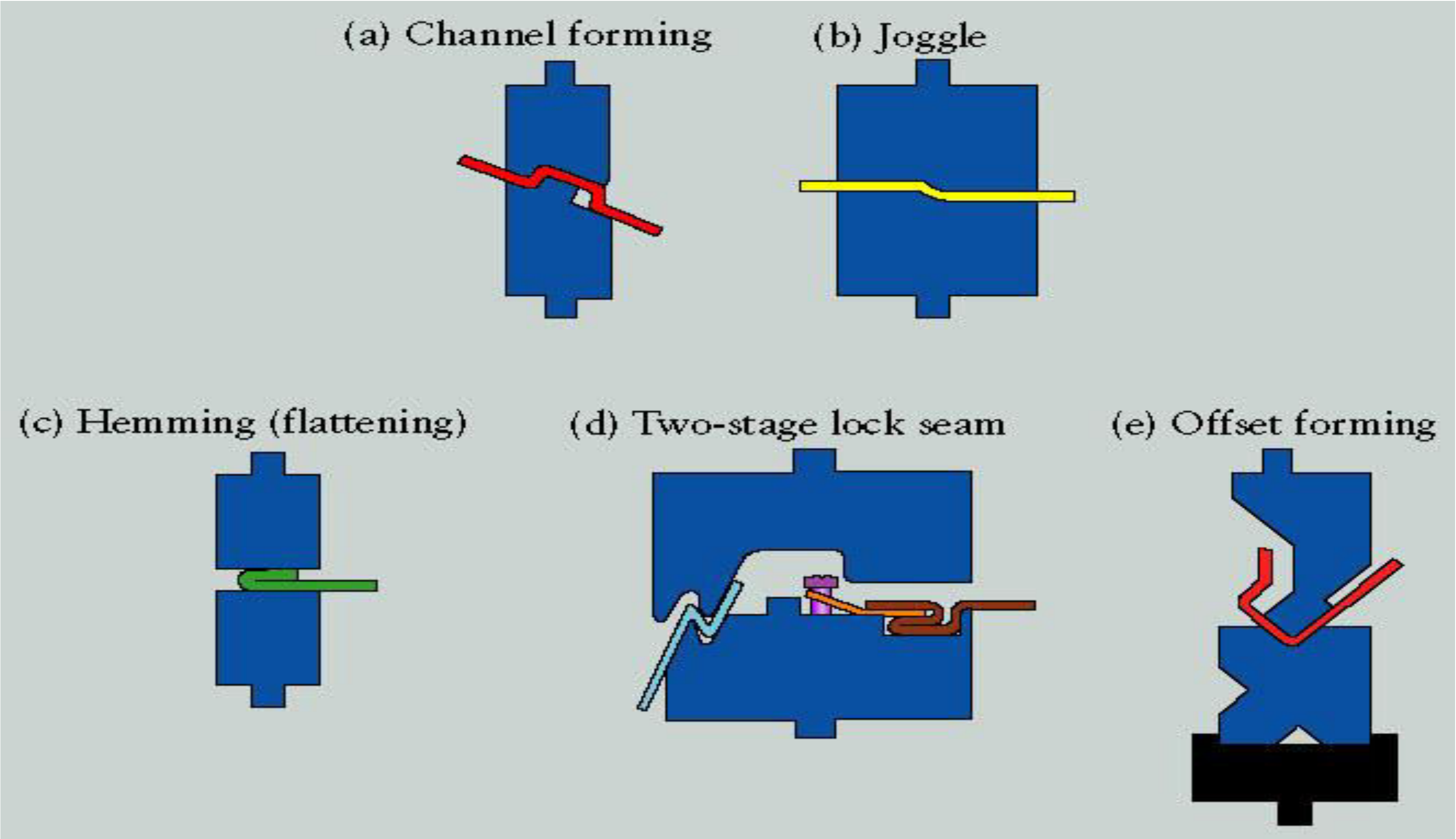


Schematic illustration of a stretch-forming process. Aluminum skins for aircraft can be made by this process.

Press break forming

- Sheet metal or plate can be bent easily with simple fixtures using a press. Long and relatively narrow pieces are usually bent in a press break. This machine utilizes long dies in a mechanical or hydraulic press and is suitable for small production runs. The tooling is simple and adaptable to a wide variety of shapes

Press break forming

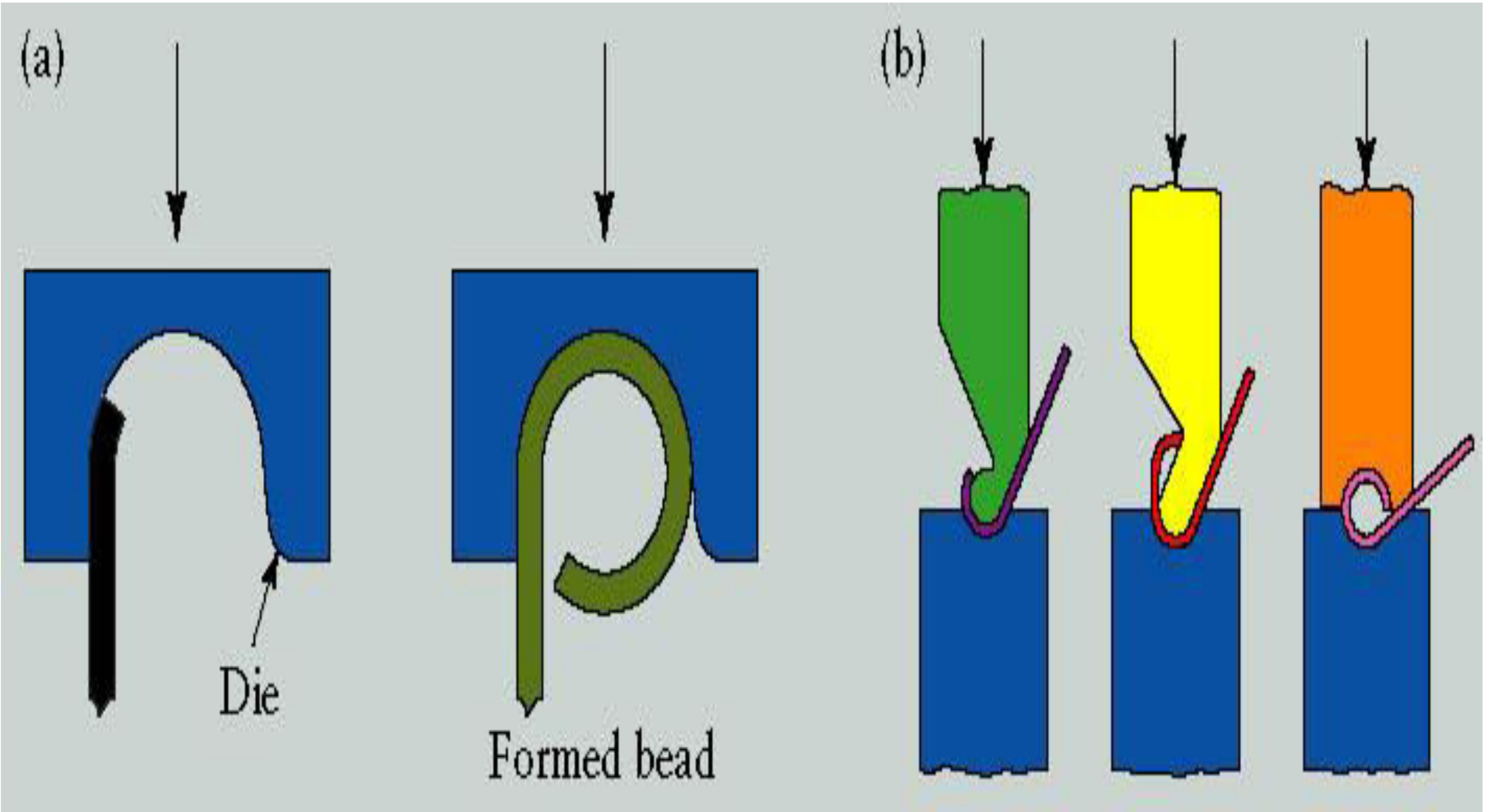


Schematic illustrations of various bending operations in a press brake

Beading

- In beading the edge of the sheet metal is bent into the cavity of a die. The bead gives stiffness to the part by increasing the moment on inertia of the edges. Also, it improves the appearance of the part and eliminates exposed sharp edges

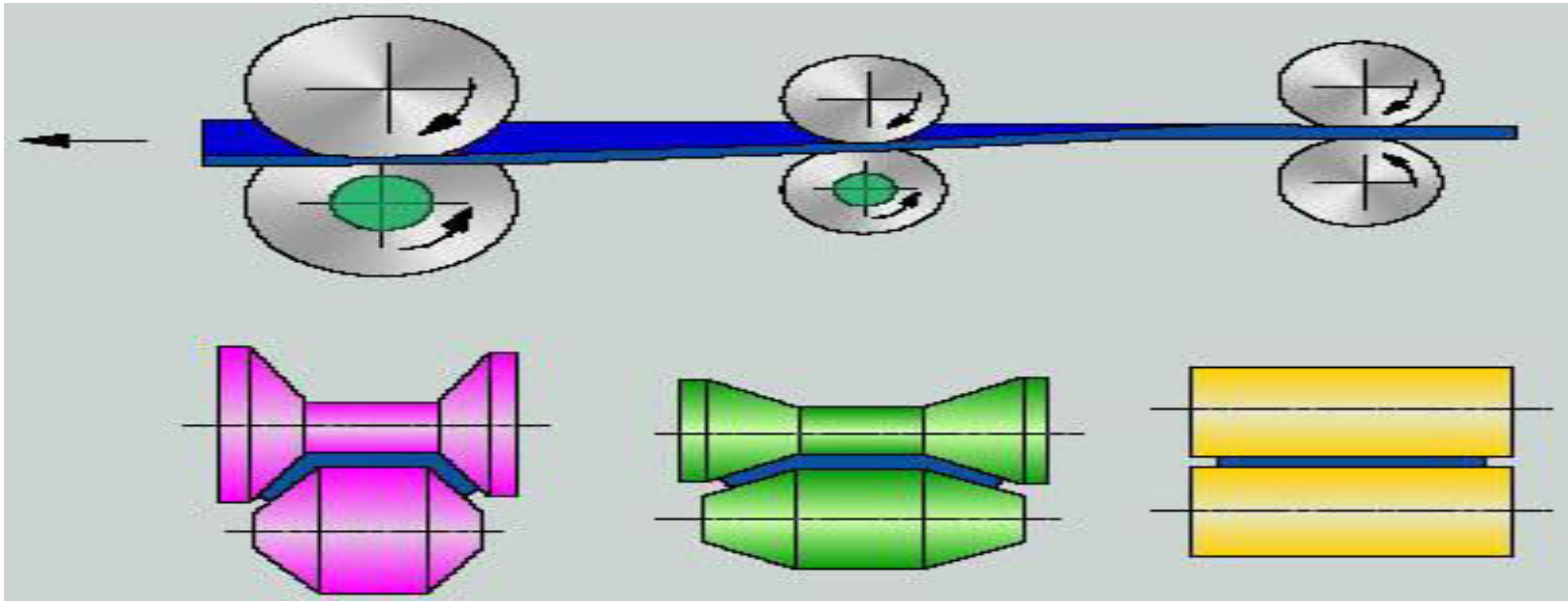
Beading



(a) Bead forming with a single die. (b) Bead forming with two dies, in a press brake.

Roll forming

- For bending continuous lengths of sheet metal and for large production runs, roll forming is used. The metal strip is bent in stages by passing it through a series of rolls.



Roll-forming process

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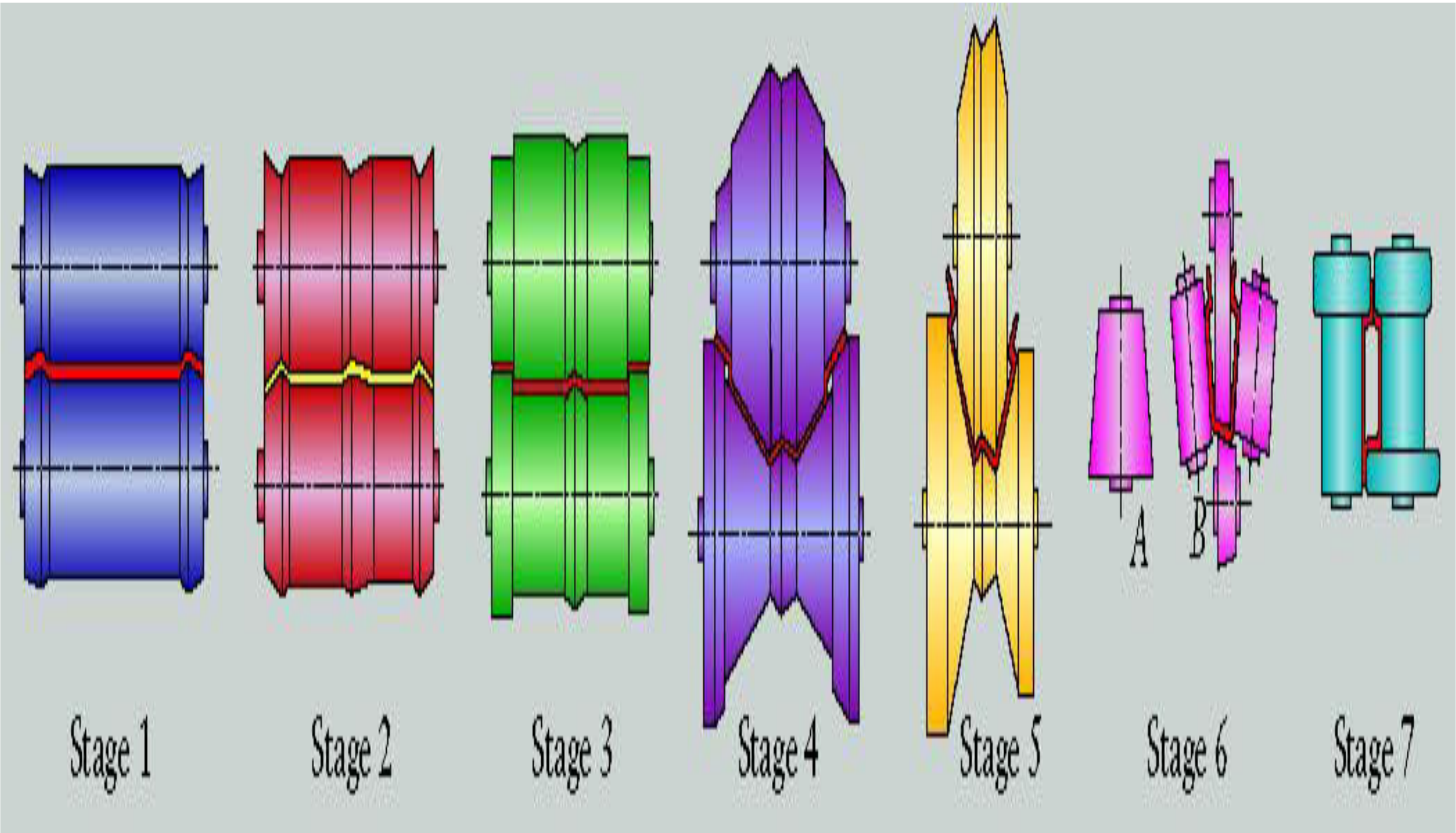
Stages in roll forming



Stages in roll forming of a sheet-metal door frame. In Stage 6, the rolls may be shaped as in *A* or *B*.

Bulging

- The basic forming process of bulging involves placing tabular, conical or curvilinear part into a split-female die and expanding it with, say, a polyurethane plug. The punch is then retracted, the plug returns to its original shape and the part is removed by opening the dies.

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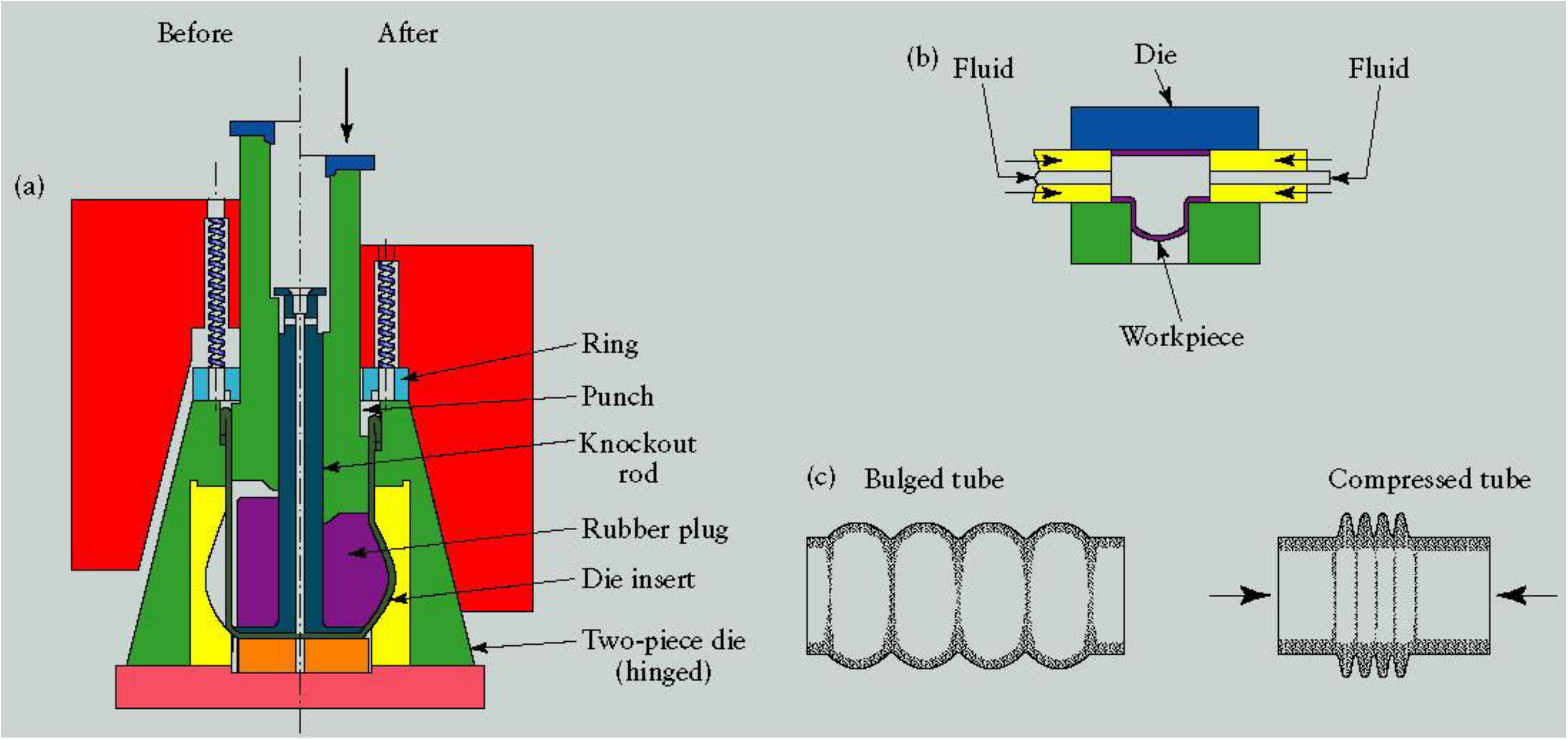
Bulging



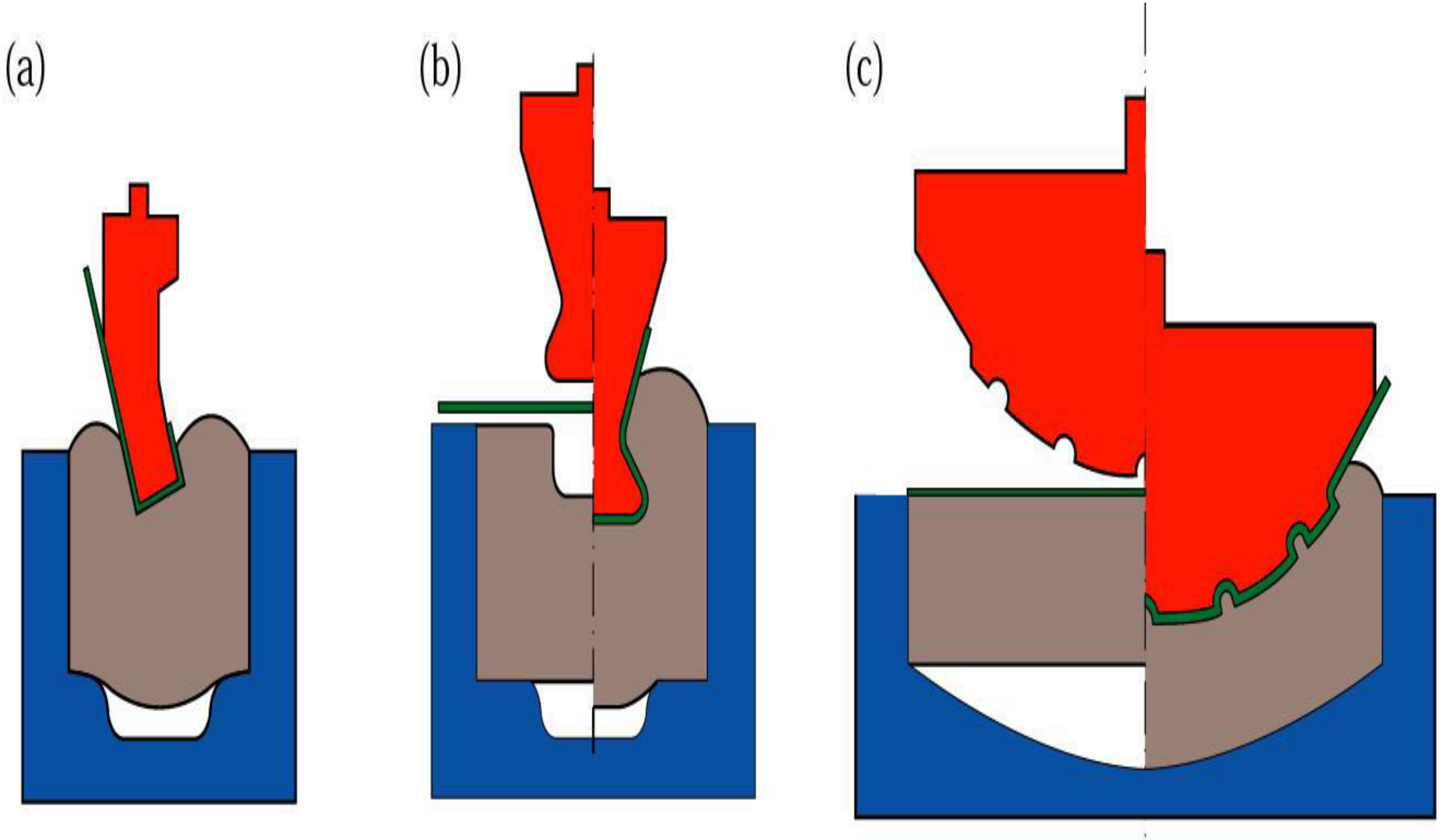
(a) Bulging of a tubular part with a flexible plug. Water pitchers can be made by this method. (b) Production of fittings for plumbing by expanding tubular blanks with internal pressure. The bottom of the piece is then punched out to produce a “T.” (c) Manufacturing of Bellows.

Rubber Forming

- In rubber forming , one of the dies in a set is made of flexible material, such as a rubber or polyurethane membrane. Polyurethanes are used widely because of their resistance to abrasion, long fatigue life and resistance to damage by burrs or sharp edges of the sheet blank. In bending and embossing sheet metal by the rubber forming method, as shown in the following Figure, the female die is replaced with a rubber pad. Parts can also be formed with laminated sheets of various nonmetallic material or coatings.

Manufacturing Technology

Rubber Forming



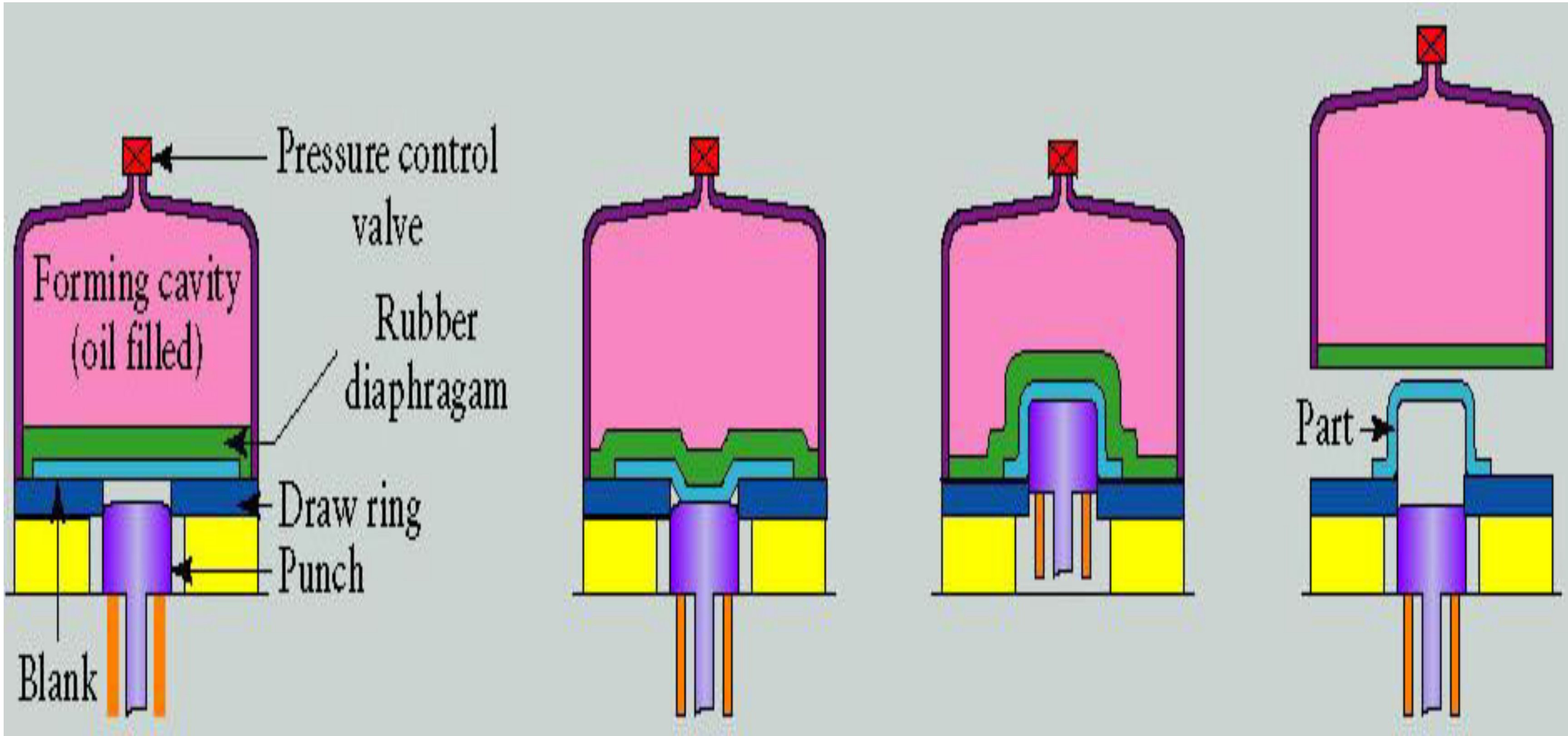
Examples of the bending and the embossing of sheet metal with a metal punch and with a flexible pad serving as the female die.

Hydro forming Process

- In hydro forming or fluid forming process, the pressure over the rubber membrane is controlled throughout the forming cycle, with maximum pressure reaching 100 MPa (15000 psi). This procedure allows close control of the part during forming to prevent wrinkling or tearing.

Manufacturing Technology

Hydro forming Process



The hydroform (or fluid forming) process. Note that, in contrast to the ordinary deep-drawing process, the pressure in the dome forces the cup walls against the punch. The cup travels with the punch; in this way, deep drawability is improved.

Rubber forming and Hydro-forming processes have the following

Advantages:

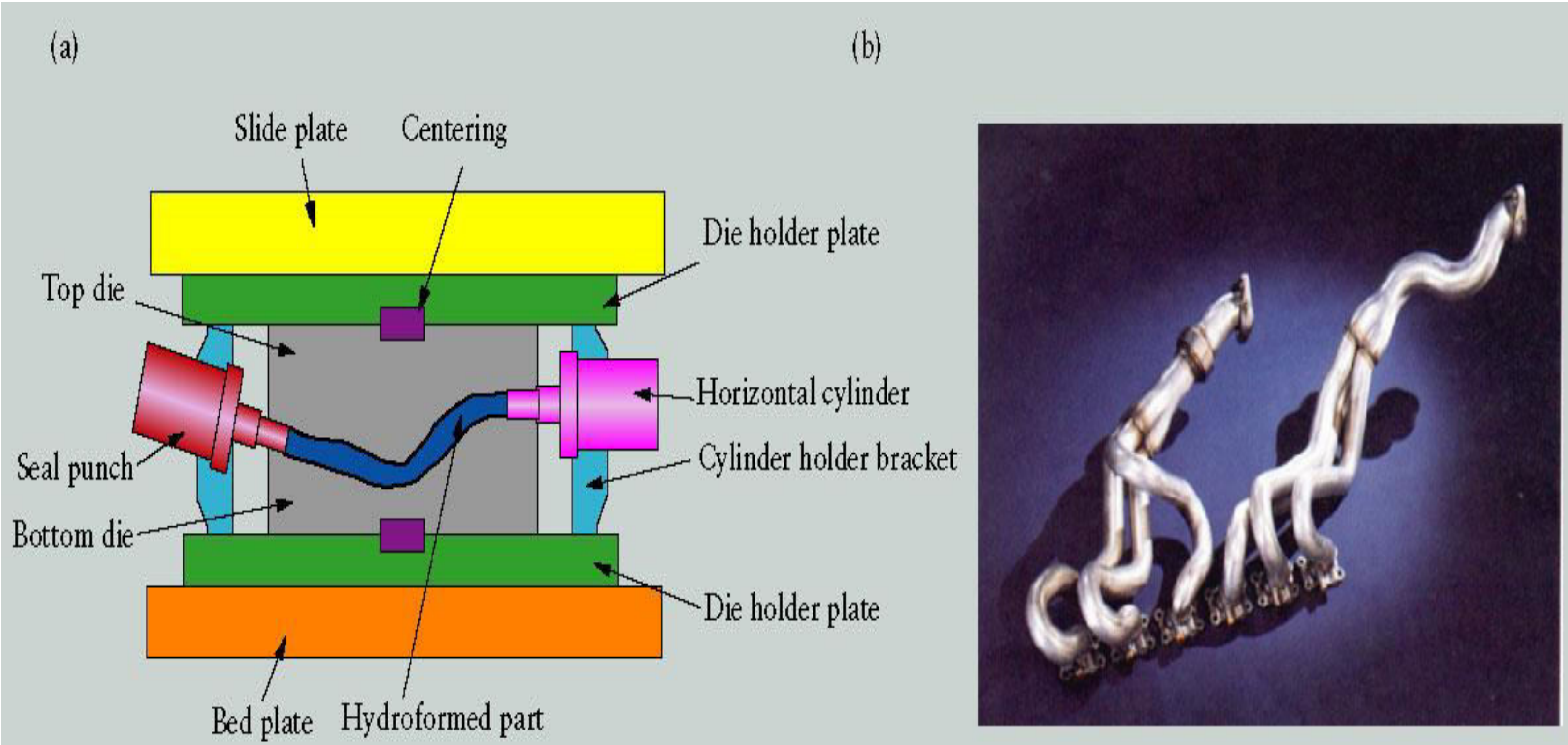
- Low tooling cost
- Flexibility and ease of operation
- Low die wear
- No damage to the surface of the sheet and
- Capability to form complex shapes.

Tube-Hydro forming Process

- In tube hydro forming, steel or other metal tubing is formed in a die and pressurized by a fluid. This procedure can form simple tubes or it can form intricate hollow tubes as shown in the following Figure. Applications of tube-hydro formed parts include automotive exhaust and structural components.

Manufacturing Technology

Tube-Hydro forming Process



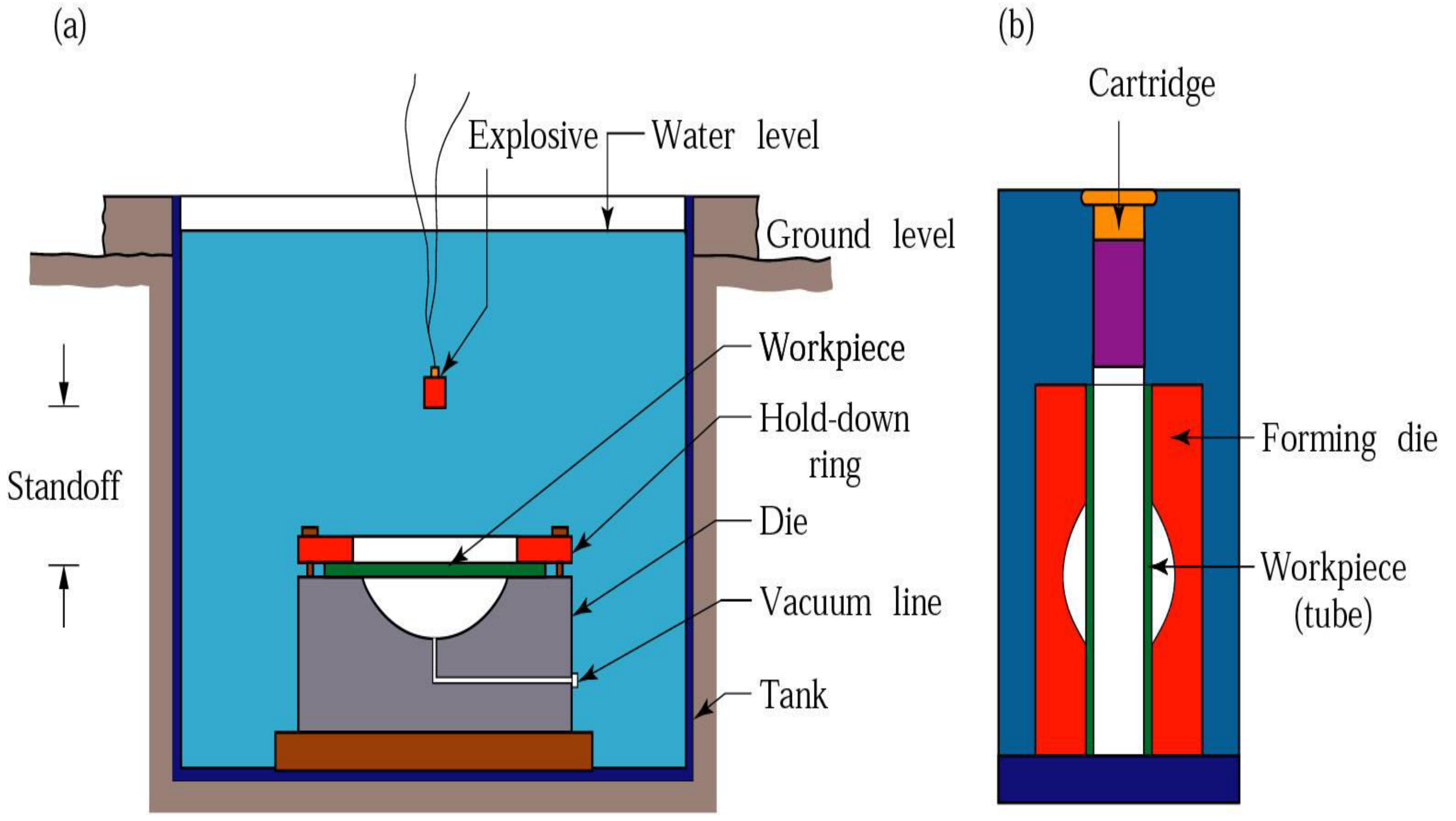
(a) Schematic illustration of the tube-hydroforming process. (b) Example of tube-hydroformed parts. Automotive exhaust and structural components, bicycle frames, and hydraulic and pneumatic fittings are produced through tube hydroforming.

Explosive Forming Process

- Explosive energy used as metal forming
- Sheet-metal blank is clamped over a die
- Assembly is immersed in a tank with water
- Rapid conversion of explosive charge into gas generates a shock wave. The pressure of this wave is sufficient to form sheet metals

Manufacturing Technology

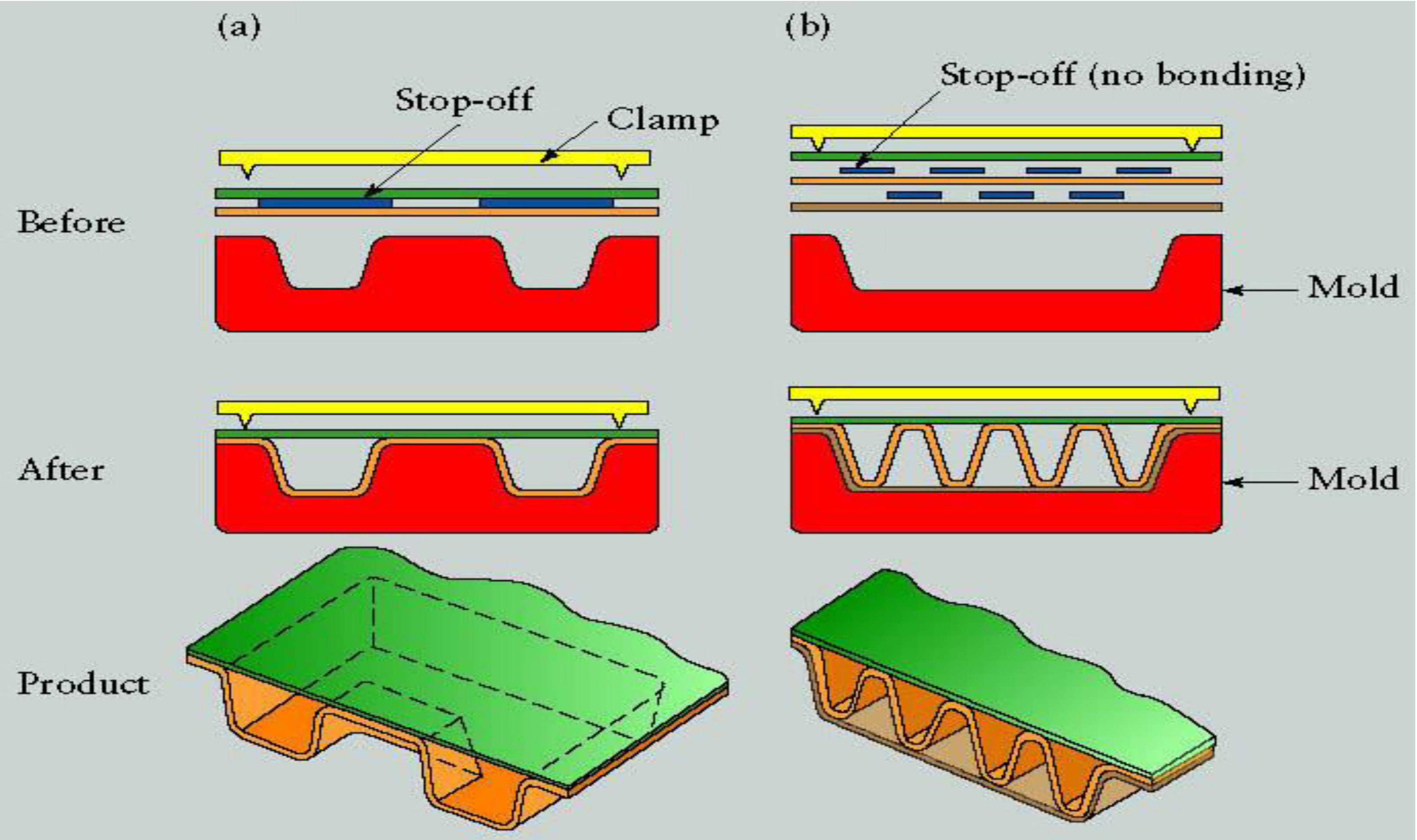
Explosive Forming Process



(a) explosive forming process. (b) confined method of explosive bulging of tubes.

Manufacturing Technology

Diffusion Bonding and Super plastic Forming



Types of structures made by diffusion bonding and superplastic forming of sheet metal. Such structures have a high stiffness-to-weight ratio.

Manufacturing Technology

Super plastic Forming

- **Advantages**
  - Lower strength is required and less tooling costs
  - Complex shapes with close tolerances can be made
  - Weight and material savings
  - Little or no residual stress occurs in the formed parts
- **Disadvantages**
  - Materials must not be super elastic at service temperatures
  - Longer cycle times

Deep Drawing Processes

Deep Drawing

- Drawing operation is the process of forming a flat piece of material (blank) into a hollow shape by means of a punch, which causes the blank to flow into the die-cavity. Round sheet metal block is placed over a circular die opening and held in a place with blank holder & punch forces down into the die cavity. Wrinkling occurs at the edges.
  - Shallow drawing: depth of formed cup $\leq D/2$
  - Deep or moderate drawing: depth of formed cup $> D/2$

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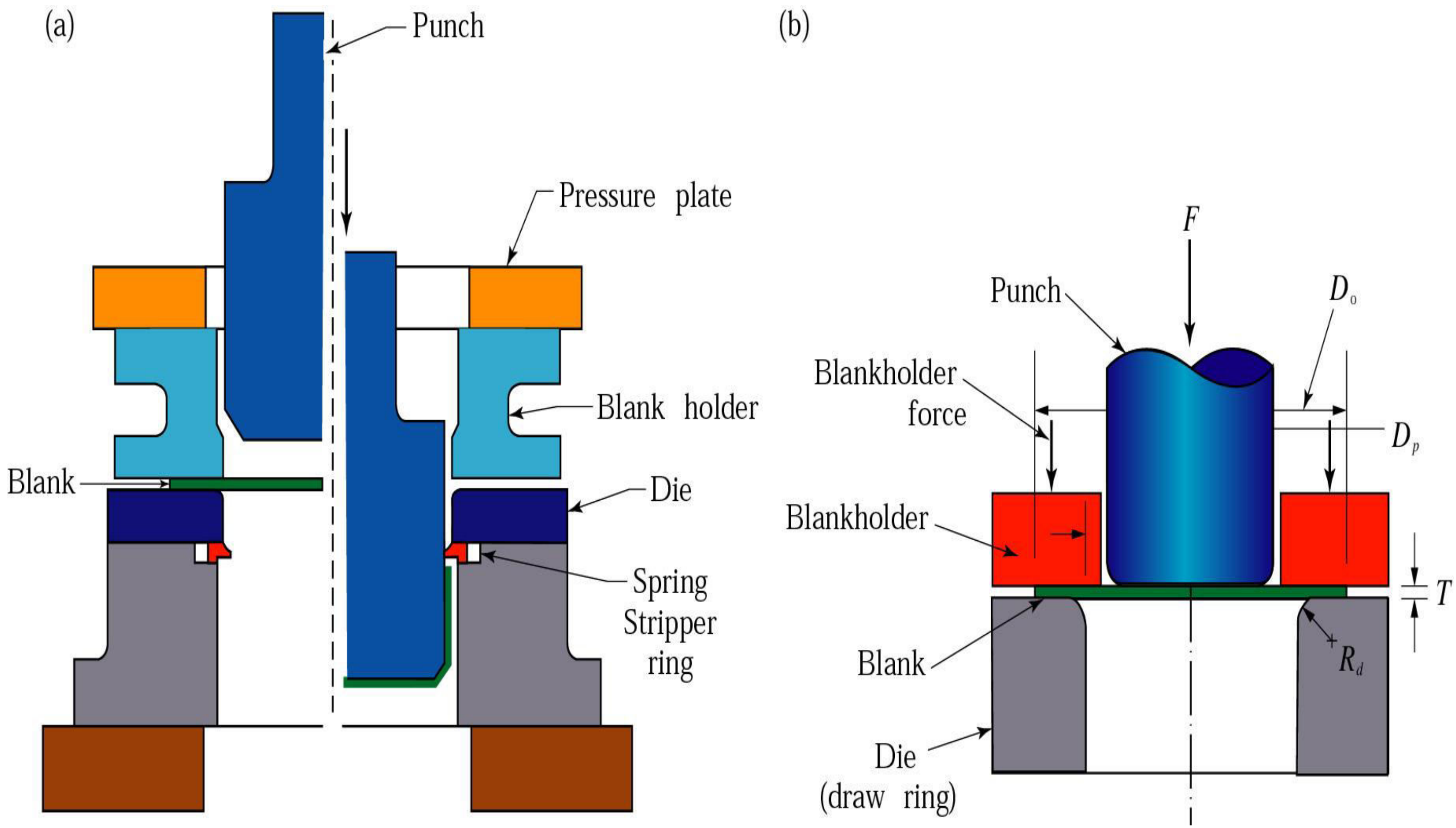
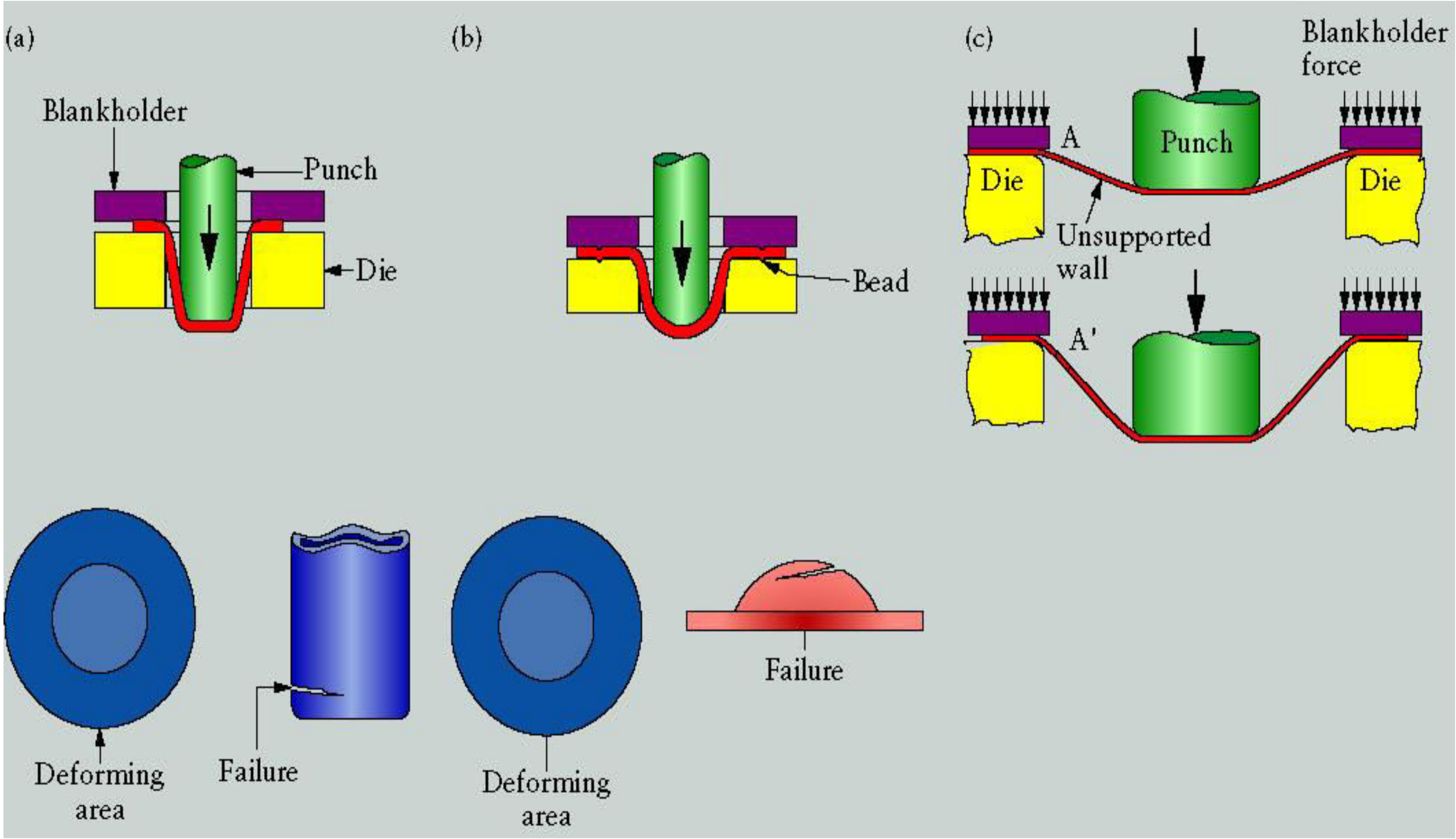
Deep Drawing



(a) deep-drawing process on a circular sheet-metal blank. The stripper ring facilitates the removal of the formed cup from the punch. (b) Process variables in deep drawing. Except for the punch force, *F*, all the parameters indicated in the figure are independent variables.

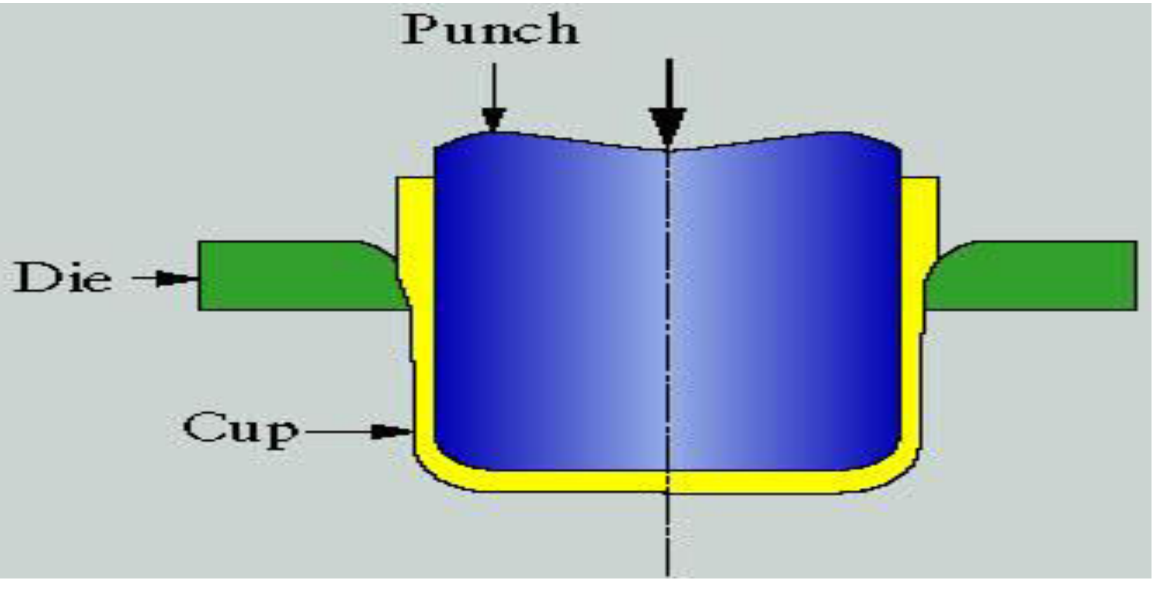
Examples of drawing operations



(a) pure drawing and (b) pure stretching. The bead prevents the sheet metal from flowing freely into the die cavity. (c) Possibility of wrinkling in the unsupported region of a sheet in drawing.

Ironing Process

- If the thickness of the sheet as it enters the die cavity is more than the clearance between the punch and the die, the thickness will have to be reduced; this effect is known as ironing. Ironing produces a cup with constant wall thickness thus, the smaller the clearance, the greater is the amount of ironing.



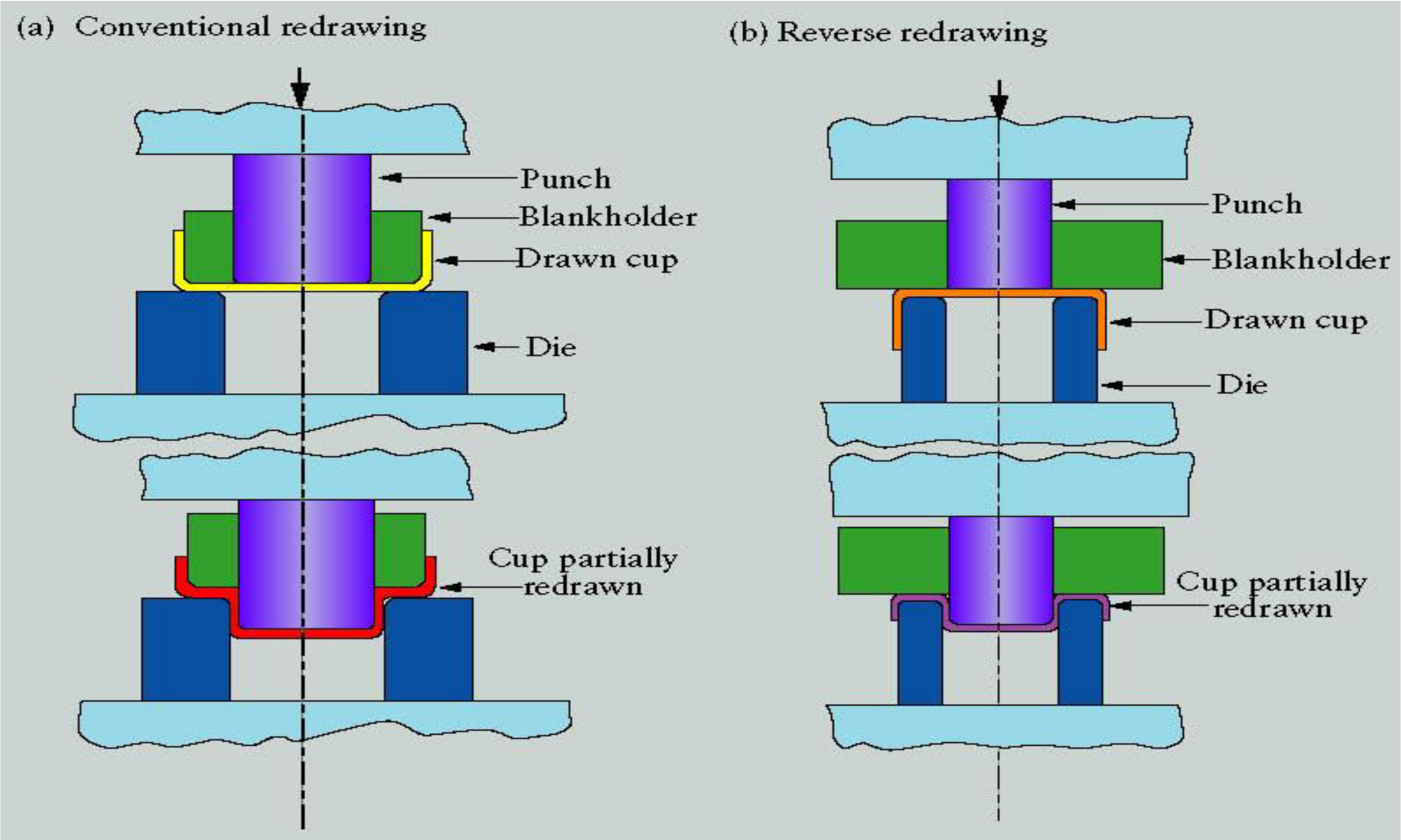
Schematic illustration of the ironing process. Note that the cup wall is thinner than its bottom. All beverage cans without seams (known as two-piece cans) are ironed, generally in three steps, after being deep drawn into a cup. (Cans with separate tops and bottoms are known as three-piece cans.)

Redrawing Operations

- Containers or shells that are too difficult to draw in one operation are generally redrawn. In reverse redrawing, shown in following Figure, the metal is subjected to bending in the direction opposite to its original bending configuration. This reversal in bending results in strain softening. This operation requires lower forces than direct redrawing and the material behaves in a more ductile manner

Manufacturing Technology

Redrawing Operations



Reducing the diameter of drawn cups by redrawing operations: (a) conventional redrawing and (b) reverse redrawing. Small-diameter deep containers undergo many drawing and redrawing operations.

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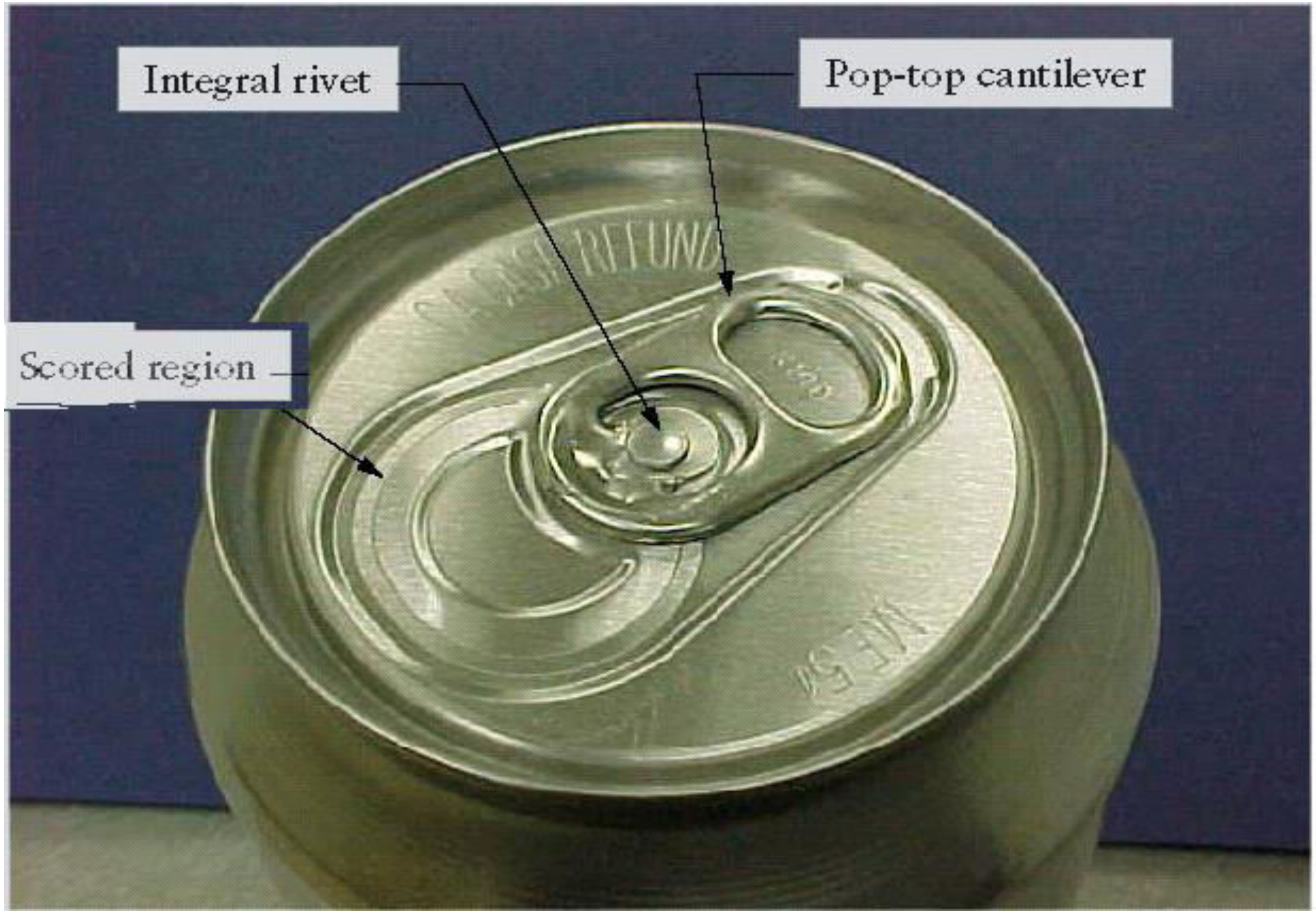
Metal-Forming Process for Aluminum Beverage Can



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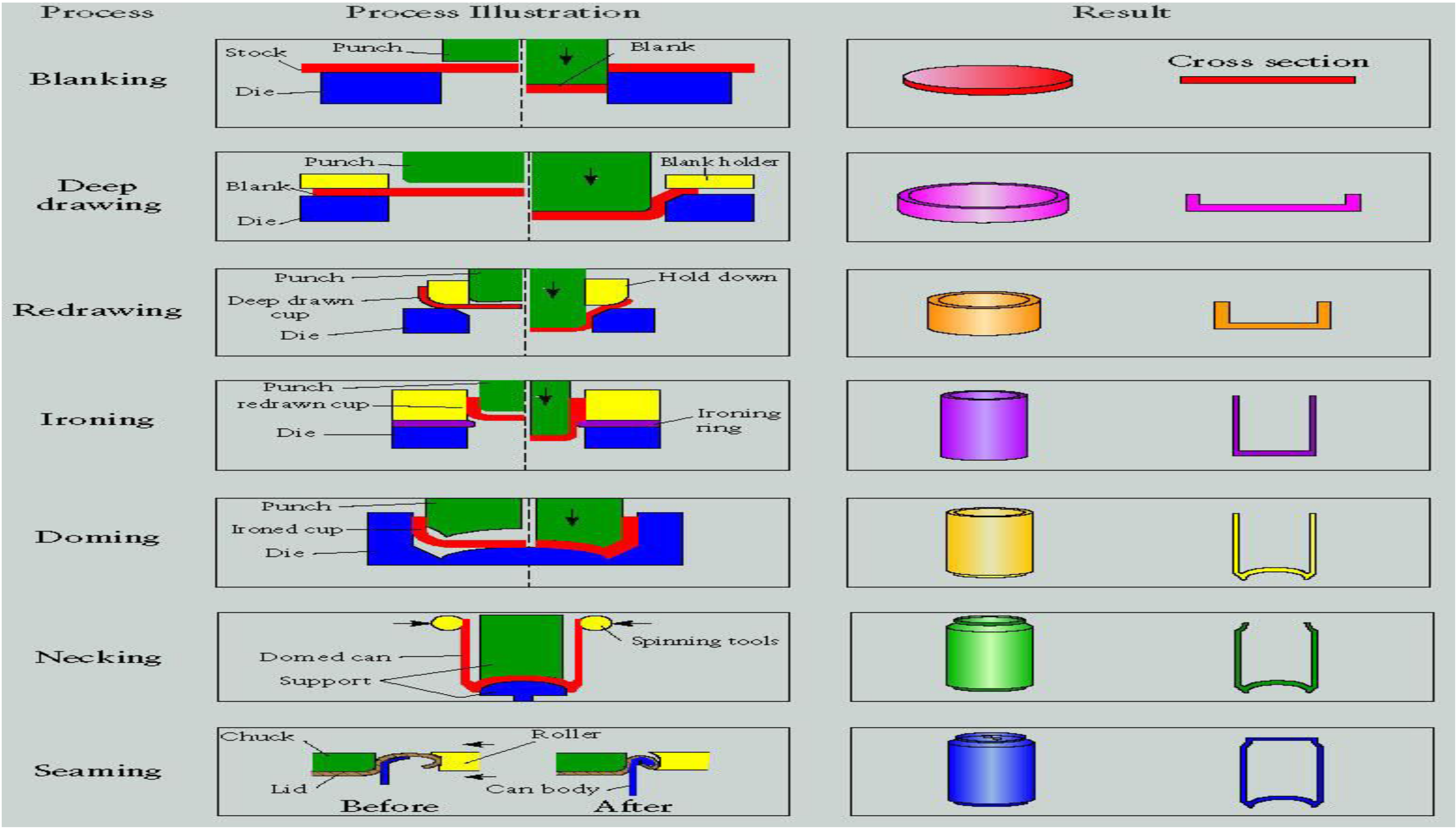
Steps in Manufacturing an Aluminium Can



The metal-forming processes involved in manufacturing a two-piece aluminium beverage can

Manufacturing Technology

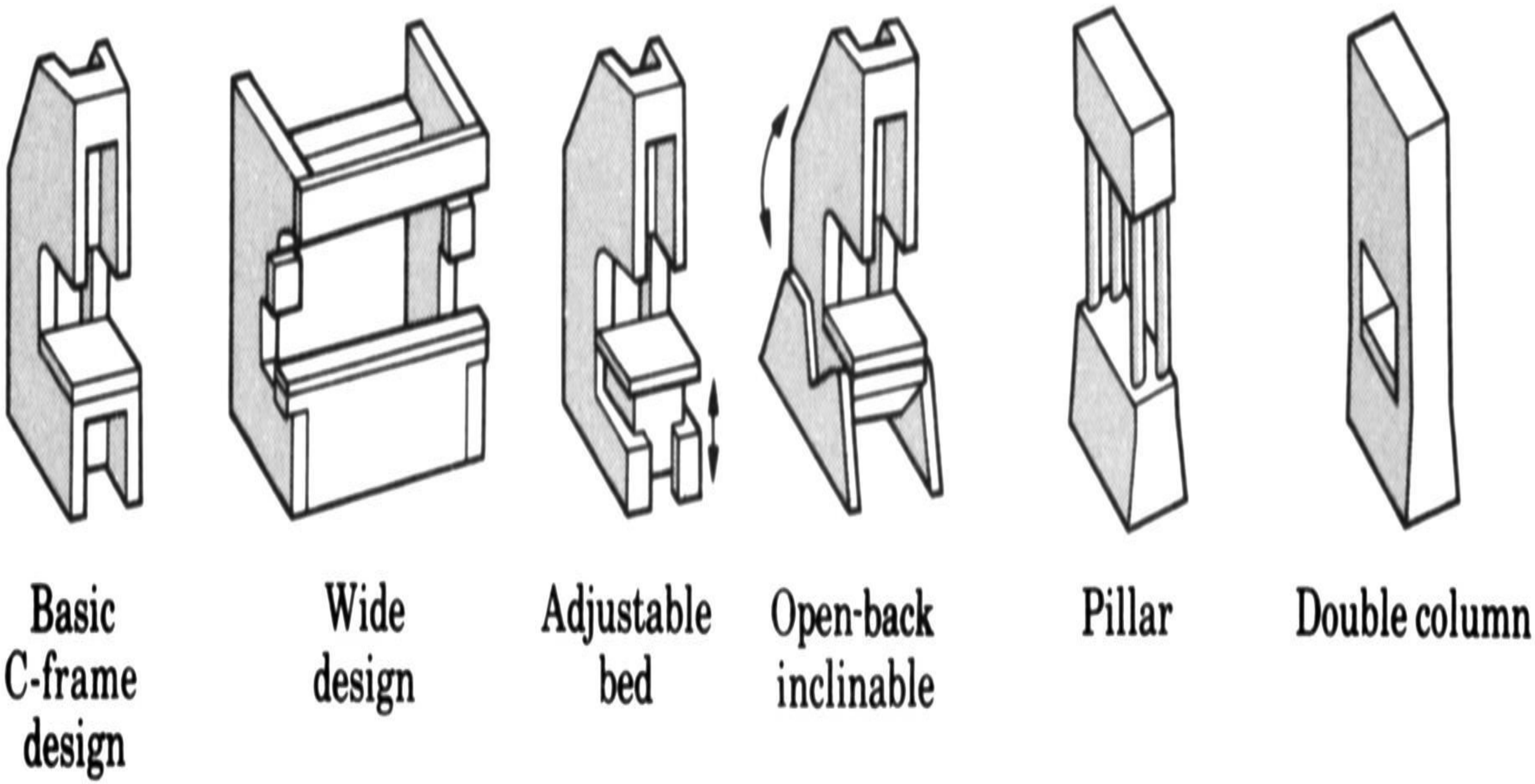
Aluminum Two-Piece Beverage Cans

Aluminum two-piece beverage cans. Note the fine surface finish.

Press for Sheet Metal

- Press selection for sheet metal forming operations depends on several factors:
  - Type of forming operation, and dies and tooling required
  - Size and shape of work pieces
  - Length of stroke of the slide, stroke per minute, speed and shut height (distance from the top of the bed to the bottom of the slide, with the stroke down)
  - Number of slides (single action, double action and triple action)
  - Maximum force required (press capacity, tonnage rating)
  - Type of controls
  - Die changing features
  - Safety features

TYPES OF PRESS FRAMES



Schematic illustration of types of press frames for sheet- forming operations. Each type has its own characteristics of stiffness, capacity, and accessibility.

Manufacturing Technology

Sheet and Plate Metal Products

- Sheet and plate metal parts for consumer and industrial products such as
  - Automobiles and trucks
  - Airplanes
  - Railway cars and locomotives
  - Farm and construction equipment
  - Small and large appliances
  - Office furniture
  - Computers and office equipment

Advantages of Sheet Metal Parts

- High strength
- Good dimensional accuracy
- Good surface finish
- Relatively low cost
- For large quantities, economical mass production operations are available

Manufacturing Technology

Tools and Accessories

- Marking and measuring tools
- Steel Rule
  - It is used to set out dimensions.
- Try Square
  - Try square is used for making and testing angles of 90degree
- Scriber
  - It used to scribe or mark lines on metal work pieces.
- Divider
  - This is used for marking circles, arcs, laying out perpendicular lines, bisecting lines, etc

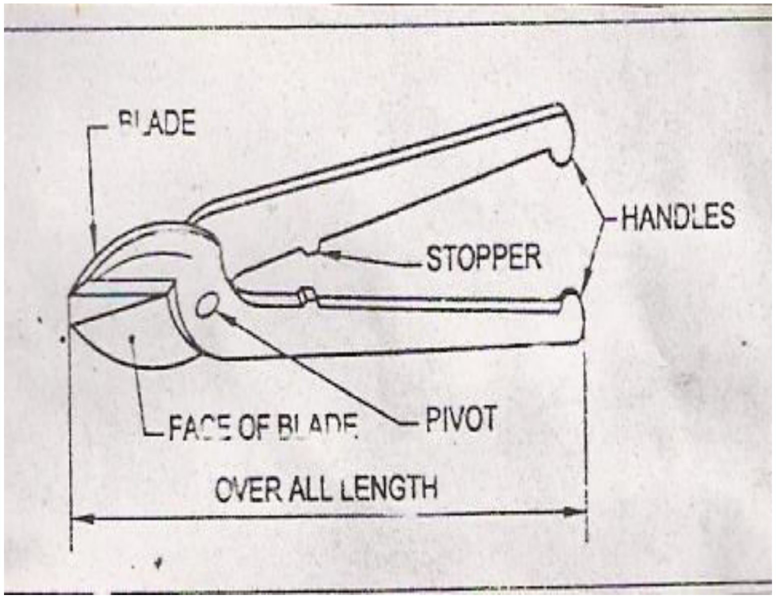
Manufacturing Technology

- Marking and measuring tools

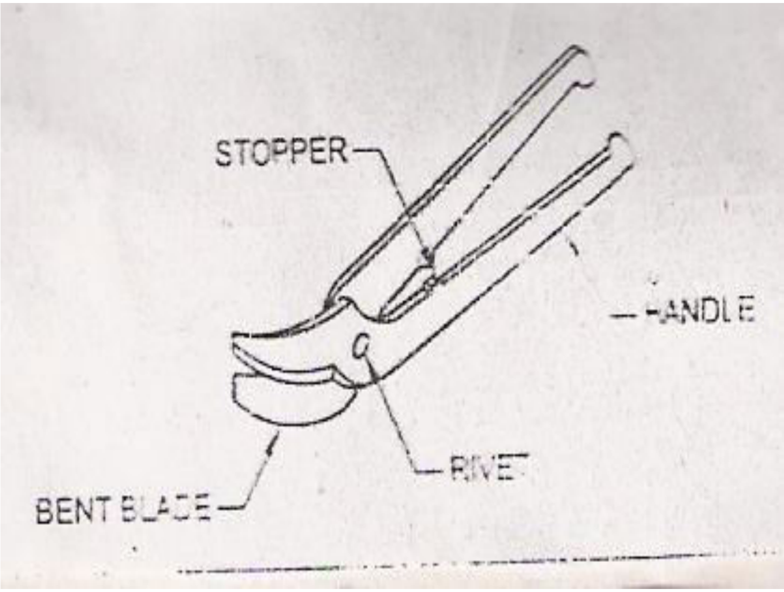
Manufacturing Technology

Cutting Tools

- **Straight snip**
  - They have straight jaws and used for straight line cutting.
- **Curved snip**
  - They have curved blades for making circular cuts.



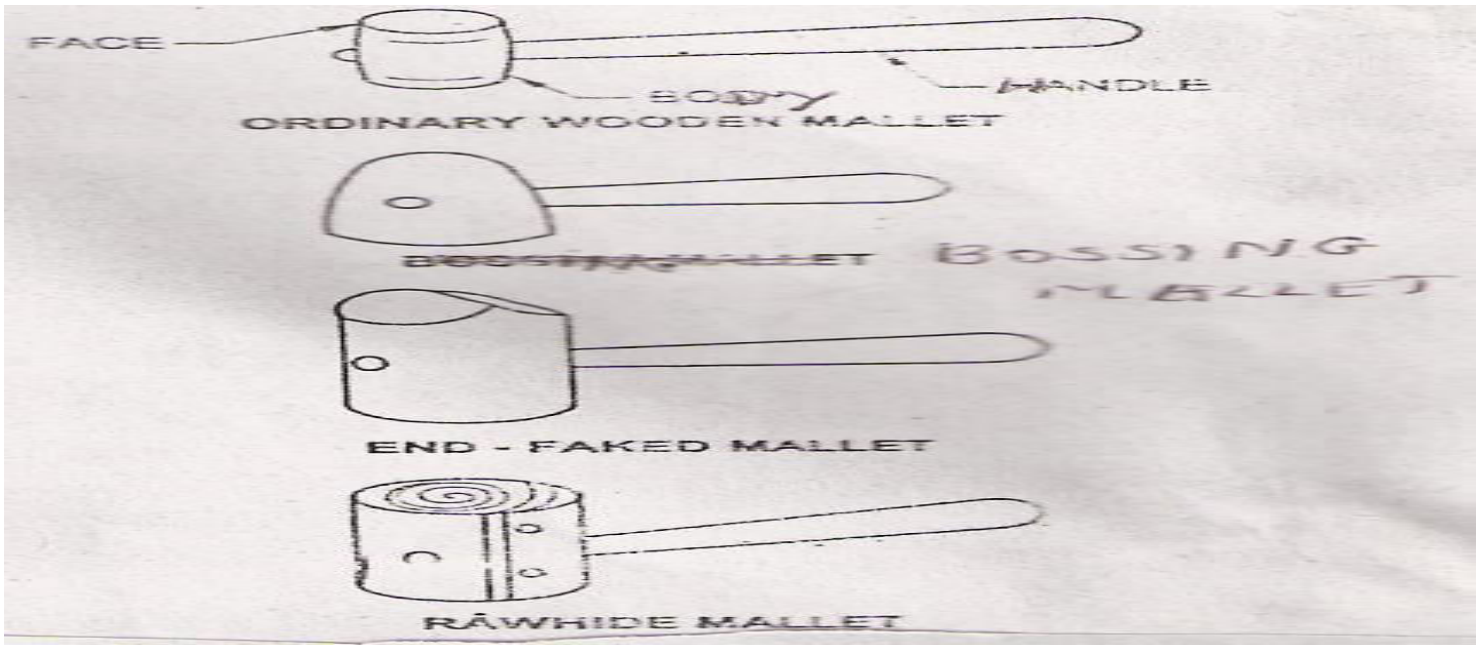
Straight snip



Curved snip

Striking Tools

- **Mallet -** It is wooden-headed hammer of round or rectangular cross section. The striking face is made flat to the work. A mallet is used to give light blows to the Sheet metal in bending and finishing.



Types of Mallets


THANK YOU FOR YOUR ATTENTION

END

UNIT 8 COORDINATE MEASURING MACHINES (CMM)

Structure

8.1 INTRODUCTION

With the advent of numerically controlled machine tools, the demand has grown for some means to support these equipment. There has been growing need to have an apparatus that can do faster first piece inspection and many times, 100% dimensional inspection. The Coordinate Measuring Machine (CMM) plays a vital role in the mechanisation of the inspection process. Some of the CMMs can even be used as layout machines before machining and for checking feature locations after machining.

Coordinate measuring machines are relatively recent developments in measurement technology. Basically, they consist of a platform on which the workpiece being measured is placed and moved linearly or rotated. A probe attached to a head capable of lateral and vertical movements records all measurements. Coordinate measuring machines are also called measuring machines. They are versatile in their capability to record measurement of complex profiles with high sensitivity (0.25 μm) and speed. In this unit, we will discuss the principle and the working of a Coordinate Measuring Machine (CMM).

Objectives

After studying this unit, you should be able to

- familiarise yourself with parts of a CMM, and
- understand the principle and the working of a CMM.

8.2 DESCRIPTION OF PARTS

Co-ordinate Measuring Machines are built rigidly and are very precise. They are equipped with digital readout or can be linked to computers for online inspection of parts. These machines can be placed close to machine tools for efficient inspection and rapid feedback for correction of processing parameter before the next part is made. They are also made more rugged to resist environmental effects in manufacturing plants such as temperature variations, vibration and dirt. Important features of the CMMs are :

(i) To give maximum rigidity to machines without excessive weight, all the moving members, the bridge structure, *Z*-axis carriage, and *Z*-column are made of hollow box construction.

(ii) A map of systematic errors in machine is built up and fed into the computer system so that the error compensation is built up into the software.

(iii) All machines are provided with their own computers with interactive dialogue facility and friendly software.

(iv) Thermocouples are incorporated throughout the machine and interfaced with the computer to be used for compensation of temperature gradients and thus provide increased accuracy and repeatability.

A CMM consists of four main elements :

Main Structure

The machine incorporates the basic concept of three coordinate axes so that precise movement in *x*, *y*, and *z* directions is possible. Each axis is fitted with a linear measurement transducer. The transducers sense the direction of movement and gives digital display. Accordingly, there may be four types of arrangement :

Cantilever

The cantilever construction combines easy access and relatively small floor space requirements. It is typically limited to small and medium sized machines. Parts larger than the machine table can be inserted into the open side without inhibiting full machine travel. Figure 8.1 shows a cantilever structure.

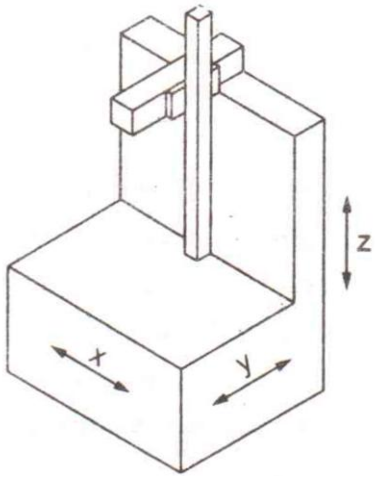


Figure 8.1 : Cantilever Structure

Bridge Type

The bridge arrangement over the table carries the quill (*z*-axis) along the *x*-axis and is sometimes referred to as a travelling bridge. It is claimed that the bridge construction provides better accuracy, although it may be offset by difficulty in making two members track in perfect alignment. This is by far the most popular CMM construction. Figure 8.2 shows a bridge structure.

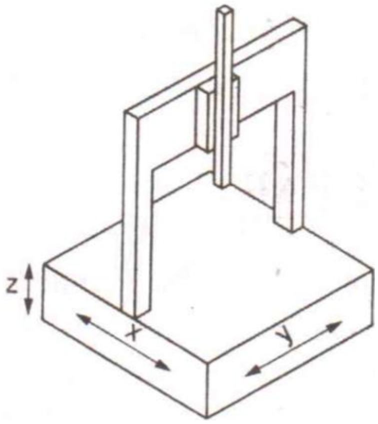


Figure 8.2 : Bridge Structure

Column Type

The column type machine is commonly referred to as a universal measuring machine rather than a CMM. These machines are usually considered gage room instruments rather than production floor machine. The direction of movements of the arms are as shown in Figure 8.3. The constructional difference in column type with the cantilever type is with *x* and *y*-axes movements.

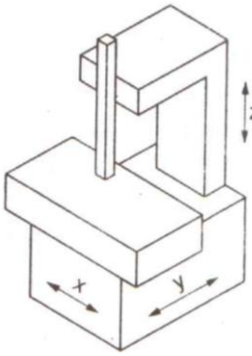


Figure 8.3 : Column Structure

Gantry

In a gantry type arrangement, arms are held by two fixed supports as shown in Figure 8.4. Other two arms are capable of sliding over the supports. Movements of the *x*, *y* and *z*-axes are also as shown in Figure 8.4. The gantry type construction is particularly suited for very large components and allows the operator to remain close to the area of inspection.

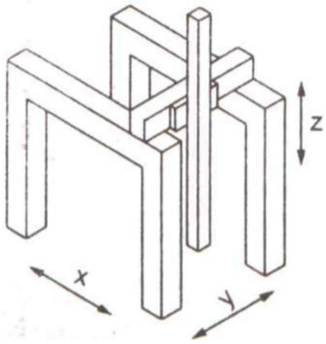


Figure 8.4 : Gantry Structure

Horizontal

Figure 8.5 shows the construction of a horizontal structure. The open structure of this arrangement provides optimum accessibility for large objects such as dies, models, and car bodies. Some horizontal arm machines are referred to as layout machines. There are some horizontal machines where the probe arm can rotate like a spindle to perform tramming operations. Tramming refers to accurate mechanical adjustment of instrument or machine with the help of tram.

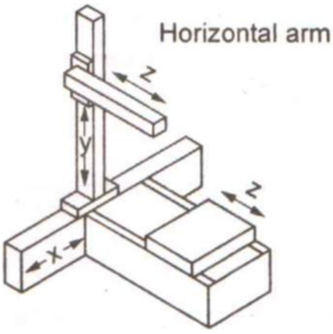


Figure 8.5 : Horizontal Structure

Probing System

It is the part of a CMM that sense the different parameters required for the calculation. Appropriate probes have to be selected and placed in the spindle of the CMM. Originally, the probes were solid or hard, such as tapered plugs for locating holes. These probes required manual manipulation to establish contact with the workpiece, at which time the digital display was read. Nowadays, transmission trigger-probes, optical transmission probes, multiple or cluster probes, and motorized probes are available. They are discussed in brief below:

Inductive and Optical Transmission Probes

Inductive and optical transmission probes have been developed for automatic tool changing. Power is transmitted using inductive linking between modules fitted to the machine structure and attached to the probe. Figure 8.6 shows a schematic of the inductive transmission probe. The hard-wired transmission probe shown is primarily for tool setting and is mounted in a fixed position on the machine structure.

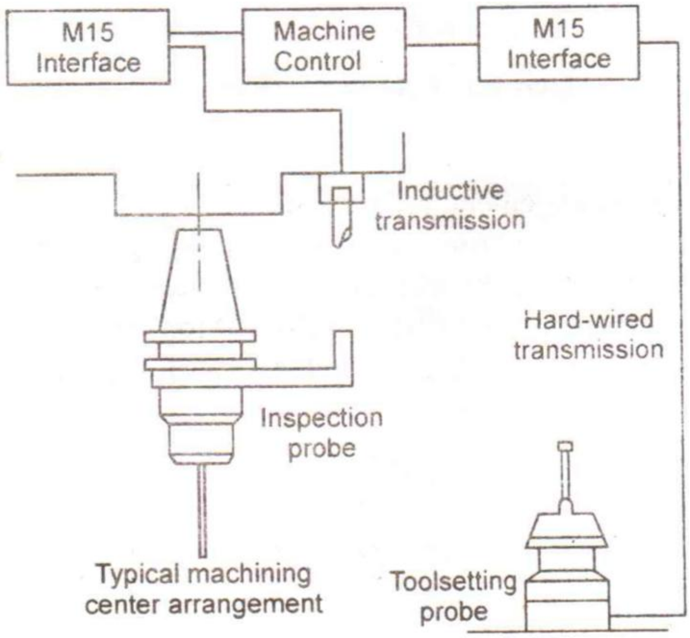


Figure 8.6 : Inductive Probe System and Automatic Probe Changing

The optical transmission probe shown in Figure 8.7 allows probe rotation between gaging moves, making it particularly useful for datuming the probe. The wide-angle system allows greater axial movement of the probe and is suitable for the majority of installation.

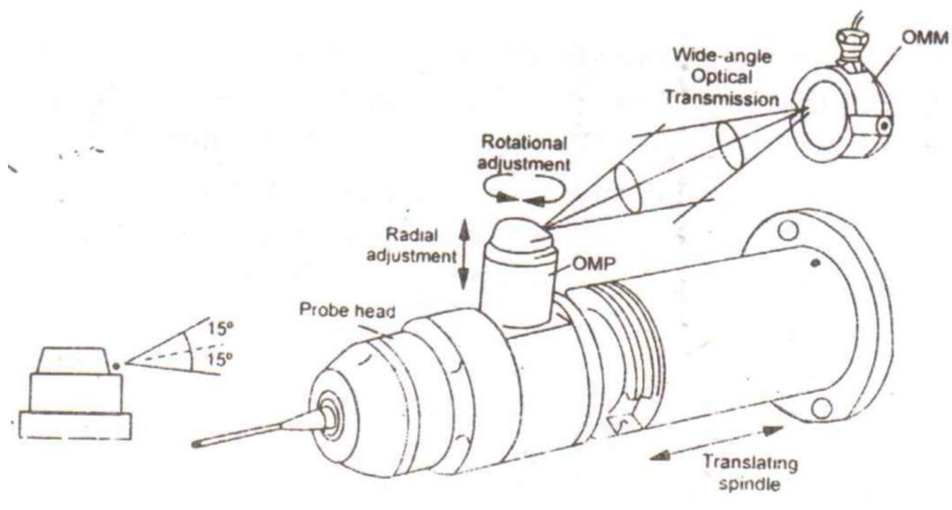
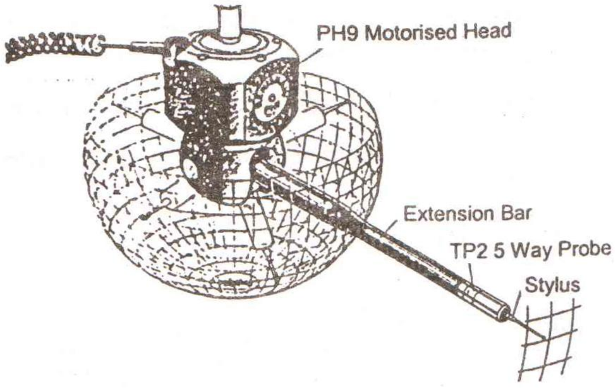


Figure 8.7 : Optical Transmission Probe

Motorized Probe

With the motorized probe, 48 positions in the horizontal axis, 15 in the vertical axis can be programmed for a total of 720 distinct probe orientations. Figure 8.8(b) shows some typical applications for motorized probe. It shows that with a range of light weight extensions, the head can reach into deep holes and recesses. The second diagram shows that head of the probe is sufficiently compact to be regarded as an extension of the machine quill. This enables the inspection of complex components that would otherwise be impossible or involve complex setups.



(a) Motorized Probe

(b) Typical Applications of Motorized Probe

Figure 8.8

Multiple Styluses Probe Heads

Wide ranges of styli have been developed to suit many different gaging applications. Some of the different styli available are shown mounted on a multiple gaging head in Figure 8.9. The selection of stylus is done based on the application for which the probe is to be used.

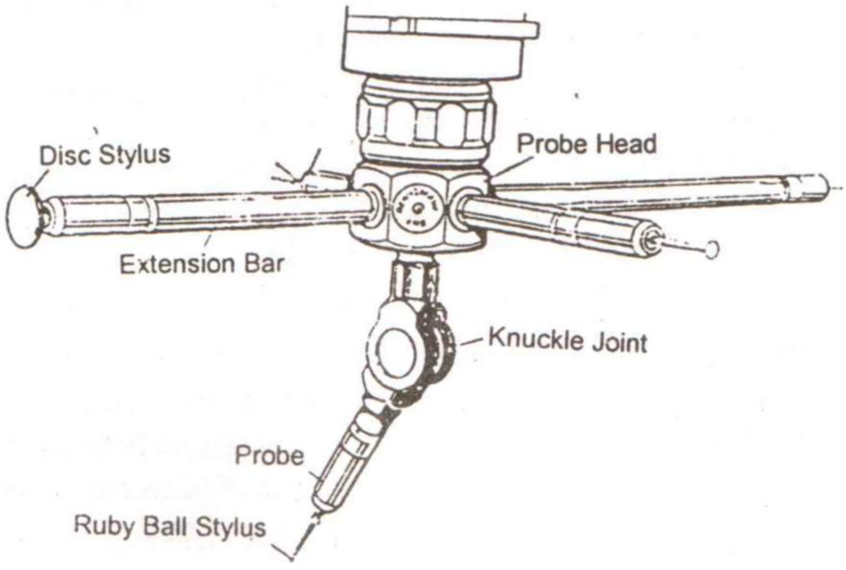


Figure 8.9 : Multiple Stylus Probe Head with Variety of Styli

Machine Control and Computer Hardware

The control unit allows manual measurement and self teach programming in addition to CNC operation. The control unit is microprocessor controlled. Usually a joystick is provided to activate the drive for manual measurement.

Software for Three-dimensional Geometry Analysis

In a CMM, the computer and the software are an inseparable part. They together represent one system. The efficiency and cost effectiveness of a CMM depend to a large extent on the software. The features that the CMM software should include :

- Measurement of diameter, center distances, lengths, geometrical and form errors in prismatic components, etc.
- Online statistics for statistical information in a batch.
- Parameter programming to minimize CNC programming time of similar parts.
- Measurement of plane and spatial curves.
- Data communications.
- Digital input and output commands for process integration.
- Program for the measurement of spur, helical, bevel and hypoid gears.
- Interface to CAD software.

SAQ 1

(a) What are the different structures that the body of a coordinate measuring machine can have? Describe them in brief.

(b) Describe the different parts of a coordinate measuring machine.

8.3 CMM IN COMPUTER AIDED MANUFACTURING

CMM is a very essential and useful tool in CAM. The old standards in communication in CAM were capable of only unidirectional communications, i.e. they translated data which were then converted into design form. But whether the design conforms to the specification could not be known from these standards. Dimensional Measurement Interface System (DMIS) is a new standard in communication used in CAM. It provides a bi-directional communication of inspection data between manufacturing systems and inspection equipment to see what has to be made and what has been made. CMMs enable DMIS bi-directional communication.

The data-collecting unit in a CMM is the probe. Therefore, selection of probe and its positioning is very crucial. Instructions must be given to CMM system for the speed for positioning the probe, the path to be followed by the probe, angle at which the probe approaches etc. After a part has been produced on the CNC machine, finished part would be checked on a CMM with its inspection program. Then, the data about the checked part is sent back to the computer, where the original part geometry is stored. The part geometry as designed is compared with the part produced and the resultant deviation could be identified. It helps in identifying problems in manufacturing. Figure 8.10 shows an interrelation among CNC machine tool, CAD system and a CMM.

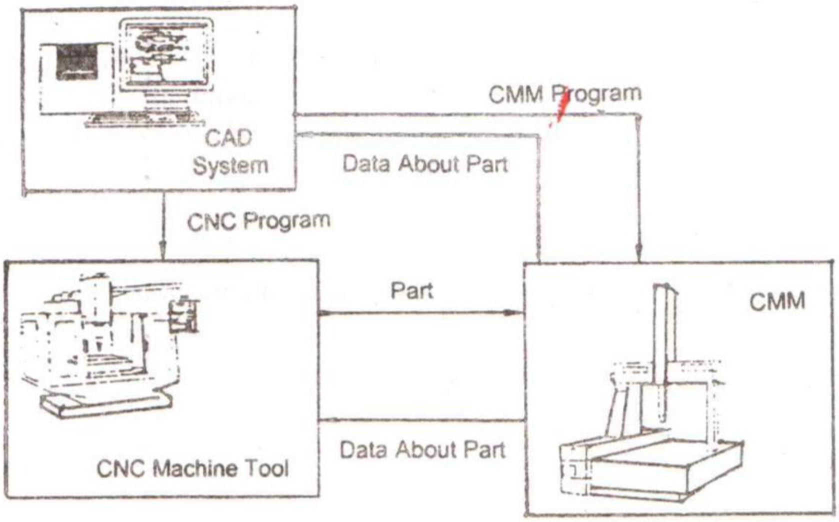


Figure 8.10 : CMM in CAM

8.4 ADVANTAGES OF CMM

CMM has got a number of advantages. The precision and accuracy given by a CMM is very high. It is because of the inherent characteristics of the measuring techniques used in CMM. Following are the main advantages that CMM can offer :

Flexibility

CMMs are essentially universal measuring machines and need not be dedicated to any particular task. They can measure almost any dimensional characteristic of a part configuration, including cams, gears and warped surfaces. No special fixtures or gages are required. Because probe contact is light, most parts can be inspected without being clamped to the table.

Reduced Setup Time

Part alignment and establishing appropriate reference points are very time consuming with conventional surface plate inspection techniques. Software allows the operator to define the orientation of the part on the CMM, and all subsequent data are corrected for misalignment between the parts-reference system and the machine coordinates.

Single Setup

Most parts can be inspected in a single setup, thus eliminating the need to reorient the parts for access to all features.

Improved Accuracy

All measurements in a CMM are taken from a common geometrically fixed measuring system, eliminating the introduction and the accumulation of errors that can result with hand-gage inspection methods and transfer techniques.

Reduced Operator Influence

The use of digital readouts eliminate the subjective interpretation of readings common with dial or vernier type measuring devices. Operator "feel" is virtually eliminated with modern touch-trigger probe systems, and most CMMs have routine measuring procedures for typical part features, such as bores or centre distances. In computer assisted systems; the operator is under the control of a program that eliminates operator choice. In addition, automatic data recording, available on most machines, prevents errors in transcribing readings to the inspection report. This adds upto the fact that less skilled operators can be easily instructed to perform relatively complex inspection procedures.

Improved Productivity

The above-mentioned advantages help make CMMs more productive than conventional inspection techniques. Furthermore, productivity is realized through the computational and analytical capabilities of associated data-handling systems, including calculators and all levels of computers.

SAQ 3

What are the advantages of a co-ordinate measuring machine?

8.5 SUMMARY

In this unit, coordinate measuring machines are discussed. The unit begins with a description of its part. Next to this, the principle of operation and the working of a coordinate measuring machine are discussed. Special consideration in case of coordinate measuring machines and the possible sources of errors in measurement are also noted down. The unit finishes with the discussion of the advantages of a coordinate measuring machine.

8.6 KEY WORDS

Tramming	:	Tramming refers to indicating a cylindrical surface of a part in such a manner as to centralise the surface with the spindle of the machine.
Stylus	:	A pointed instrument used as an input device in the probe of a CMM.
Axial Length Measuring Accuracy	:	It is defined as the absolute value of the difference between the reference lengths of gauges, aligned with a machine axis, and the corresponding measured results from the machine.
Length Measuring Accuracy	:	It is defined as the absolute value of the difference between the calibrated length of the gauge block and the actual measured value.
Probe	:	It is the sensory part of a CMM responsible for sensing different parameters required for the measurement.
DMIS	:	Dimensional Measurement Interface Specification is a new standard in communication being used in Computer Aided Manufacturing. It provides a bi-directional communication of inspection data between CAD system and inspection equipment so as to see what has to be made and what has been made.

8.7 ANSWERS TO SAQs

Please refer the preceding text for answers of all the SAQs.

The Fundamentals of Machine Vision

Intelligent Robotics / Machine Vision
FANUC America Corporation

The Fundamentals of Machine Vision

INTRODUCTION AND OVERVIEW

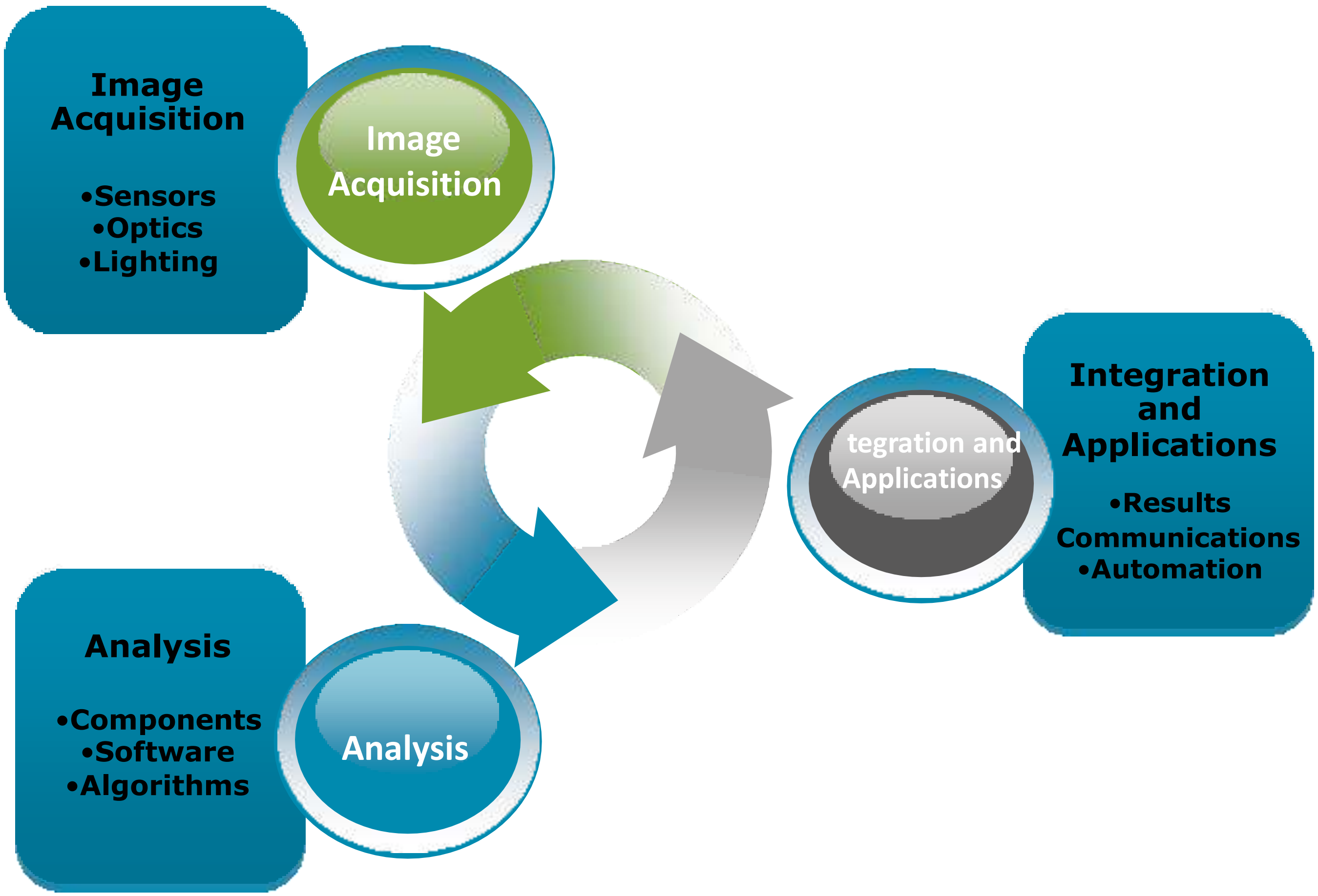
– What is Machine Vision
– The Machine Vision Market
– Industrial Uses of Machine Vision

Introduction and Overview

- What is Machine Vision
  - Machine vision is the substitution of the human visual sense and judgment capabilities with a video camera and computer to perform an inspection task. It is the automatic acquisition and analysis of images to obtain desired data for controlling or evaluating a specific part or activity.
  - Key Points:
    - Automated/Non-Contact
    - Acquisition
    - Analysis
    - Data

Introduction and Overview

- What is Machine Vision

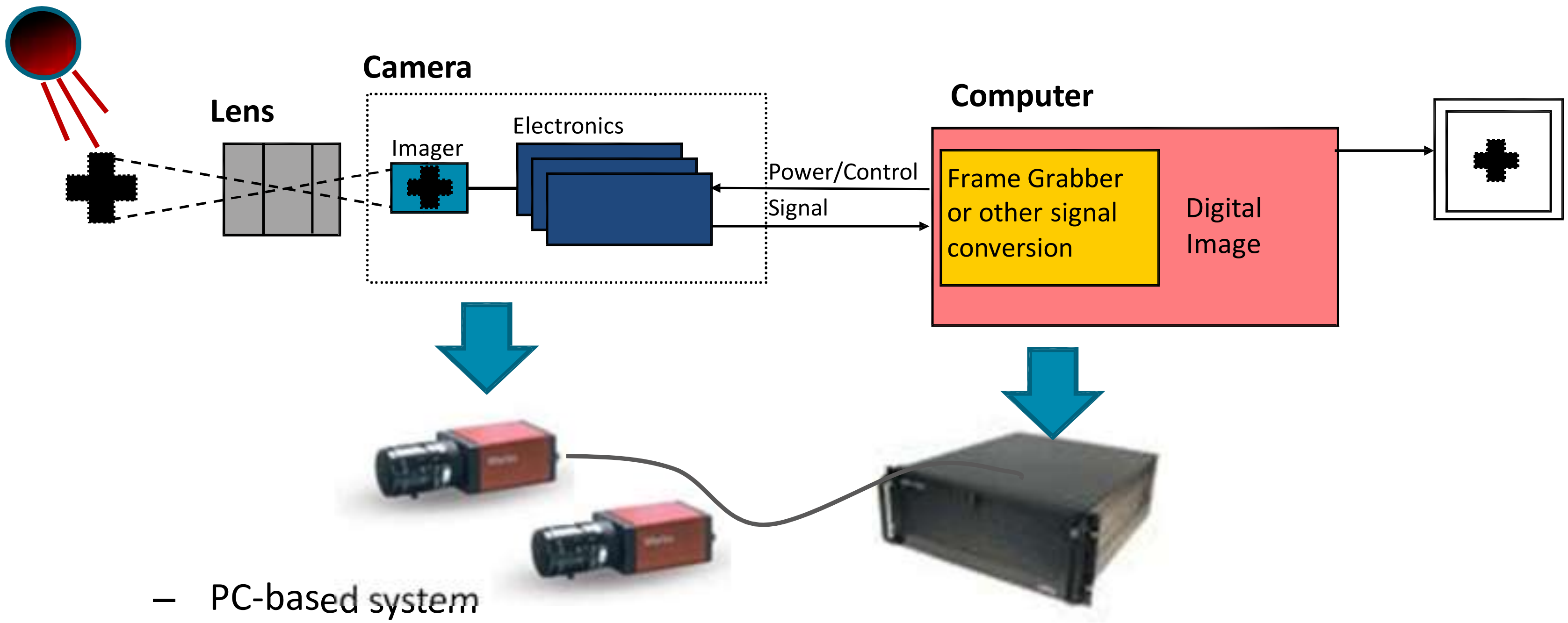


Introduction and Overview

- The Machine Vision Market
  - Choices
    - Well over 400 manufacturers and suppliers
    - Diverse product offerings
  - Confusion
    - Product/component differentiation sometimes is unclear
    - End-users (the buyers) often don’t understand what they are getting
  - What’s important
    - Components and techniques need to be better understood at the end-user level
    - Advanced technology skills are necessary for competent specification and integration

Introduction and Overview

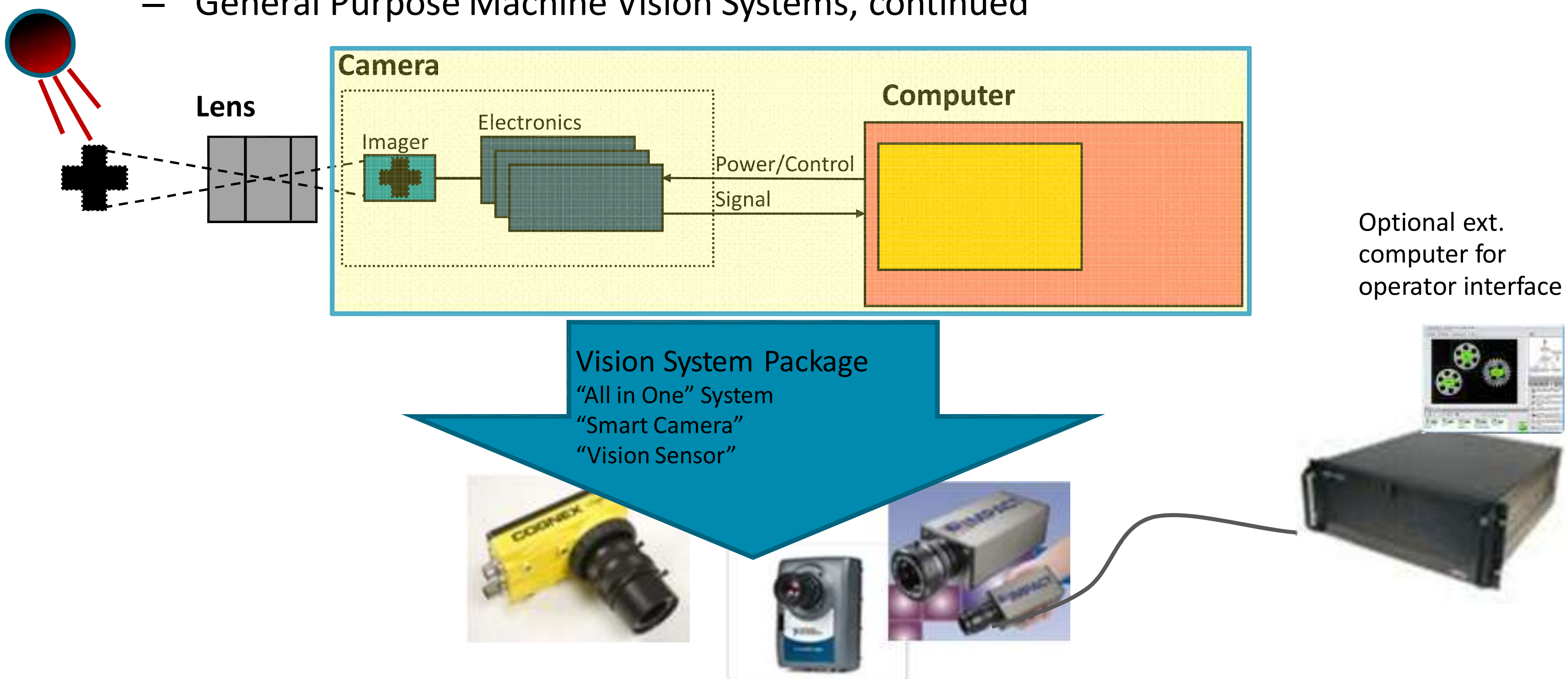
- The Machine Vision Market
  - General Purpose Machine Vision Systems



  - PC-based system
  - Single or multiple cameras interfaced to a computer, standard (Windows, Linux) operating system
  - Diverse imaging devices available
    - analog (RS170), and digital (GigE Vision, FireWire, Camera Link, USB) interfaces

Introduction and Overview

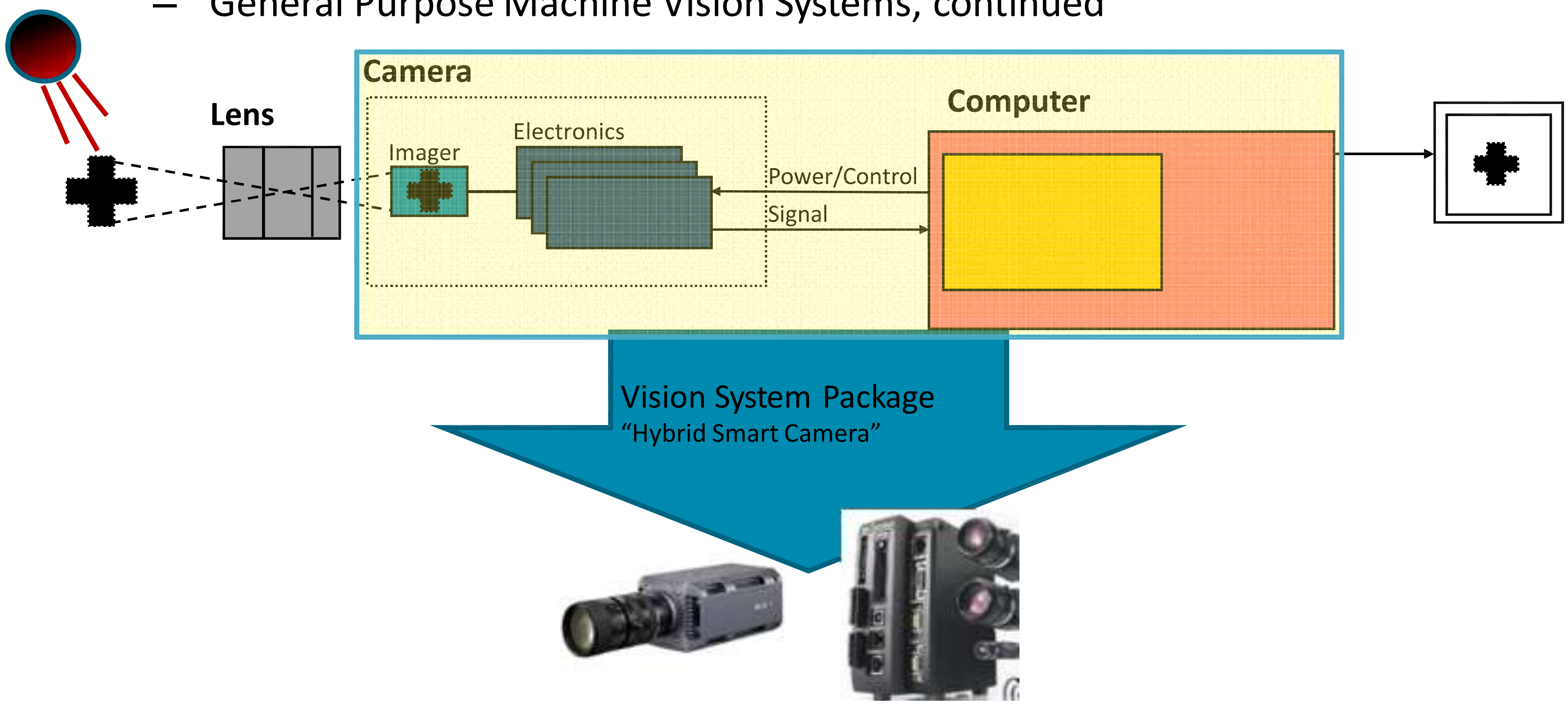
- The Machine Vision Market
  - General Purpose Machine Vision Systems, continued



  - Camera sensor and proprietary computer in one package, proprietary operating system, ethernet communications
  - Application configuration external to the device

Introduction and Overview

- The Machine Vision Market
  - General Purpose Machine Vision Systems, continued



  - Camera sensor or multiple tethered cameras with full computer (keyboard, mouse, monitor, USB, Ethernet), standard (Windows, Linux) or proprietary operating system,

Introduction and Overview

- The Machine Vision Market
  - System feature overview
    - PC-based systems
      - Most flexible and powerful system design
      - Degree of difficulty varies by implementation
      - Pricing varies depending upon architecture
    - Smart Camera/Smart Sensor vision system
      - Includes the easiest to use systems
        - » Some are more difficult to use
      - Greater danger of over-specifying capability
      - Pricing varies widely – can be quite inexpensive
    - Hybrid Smart Camera vision system
      - Includes some of the features of both depending upon product
      - Some architectures may pose integration challenges

Introduction and Overview

- The Machine Vision Market
  - Camera/processor hardware is just an “image delivery system”!!
    - Differentiation of products at the hardware level is limited to:
      - Physical structure and system architecture
        - » Single or multiple views?
          - Smart camera – distributed system
          - PC-based – centralized system
        - » Custom or fixed interface options
      - Available camera resolutions
      - Processing speeds
      - Input/output options
      - Other hardware integration issues

Introduction and Overview

- The Machine Vision Market
  - Peripheral components
    - Lighting
    - Optics
    - I/O devices
    - Frame Grabbers

Introduction and Overview

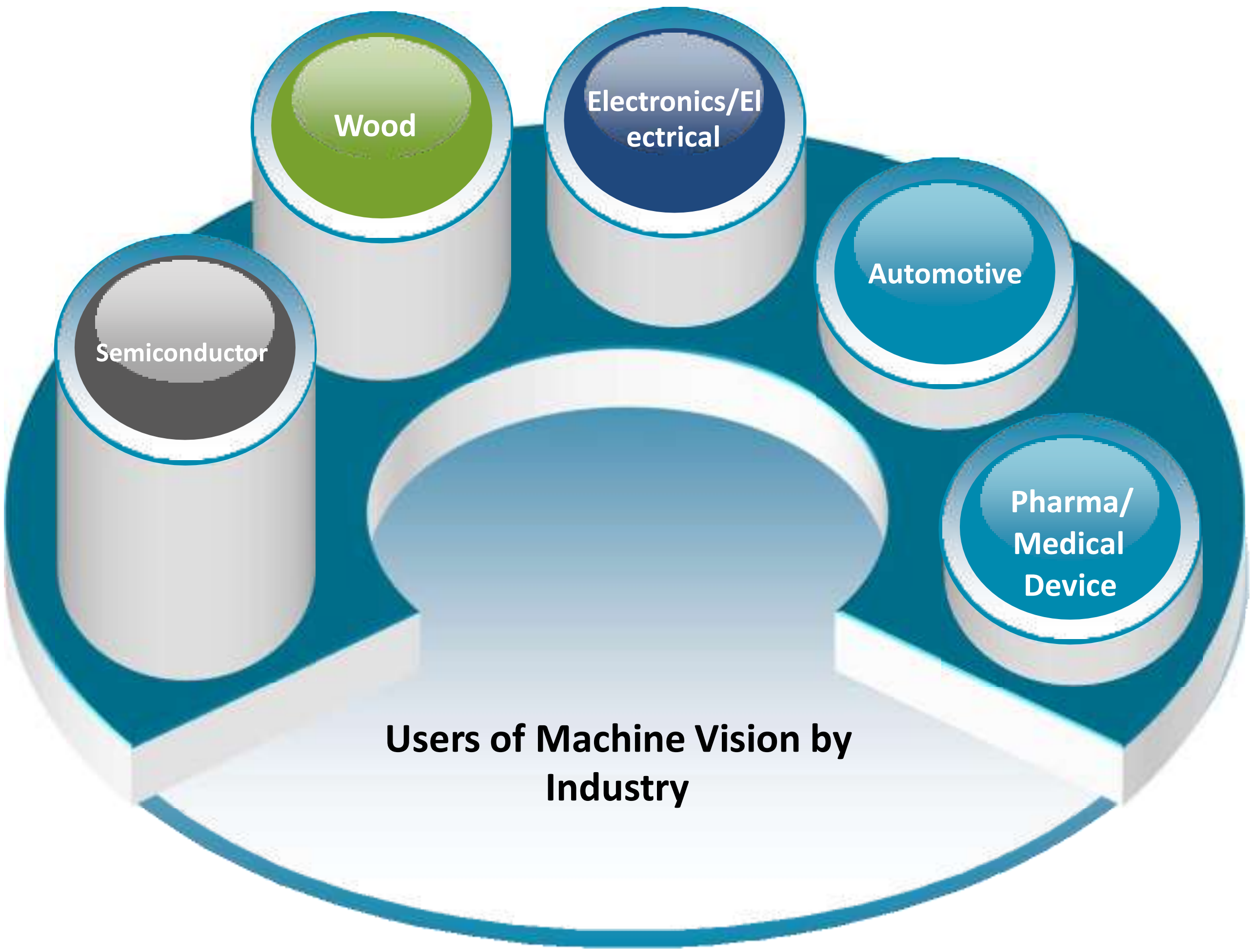
- The Machine Vision Market
  - Application Specific Machine Vision Solutions (ASMV)
    - Stand-alone devices designed for targeted inspection tasks
      - Imaging, lighting, optics, automation
    - Benefit is a generally uncomplicated and easy to use inspection device for a focused application area

Introduction and Overview

- The Machine Vision Market
  - Targeted application components
    - Bar- and 2D- code readers
    - Other “smart sensors”

Introduction and Overview

- Industrial Uses of Machine Vision



Introduction and Overview

- Industrial users of machine vision
  - Agriculture, Automotive, Biometrics/Security, Container, Cosmetic, Electronics/Electrical, Entertainment, Fabricated Metal, Fastener, Food/Beverage, Glass, Lab Automation, Lumber/Wood, Medical Devices, Medical Imaging, Military/Aerospace, Miscellaneous Mfg., Nanotechnology, Paper, Pharmaceutical, Plastics, Primary Metal, Printing, Rubber, Scientific Imaging, Semiconductor, Telecommunications, Textile/Apparel, Tobacco, Transportation

Introduction and Overview

- Industrial Uses of Machine Vision
  - Machine vision application categories
    - Defect detection
    - Gauging
    - Guidance and part tracking
    - Identification
    - OCR/OCV
    - Packaging inspection
    - Pattern Recognition
    - Product Inspection
    - Surface Inspection
    - Web Inspection

The Fundamentals of Machine Vision

IMAGE ACQUISITION

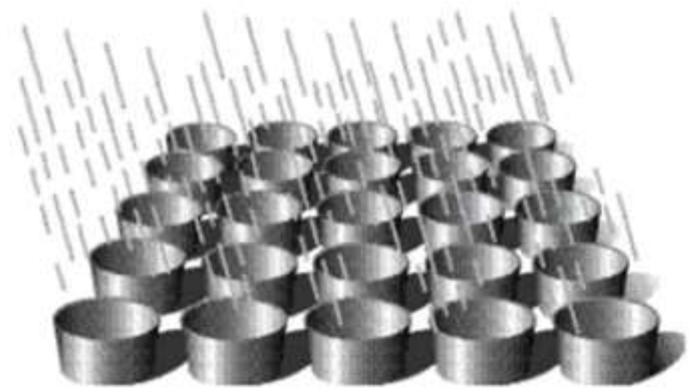
- Sensors & Imaging
- Optics
- Lighting

Image Acquisition

- Nothing happens in a machine vision application without the successful capture of a very high quality image
  - Image quality: correct resolution for the target application with best possible feature contrast
    - Resolution – determined by sensor size and quality of optics
    - Feature contrast – determined by correct lighting technique and quality of optics
  - Imaging is said to contribute more than 85% to the success of any machine vision application
  - The goal of machine vision image acquisition is to create an image that is usable by the technology – not necessarily one that's pleasing to the human eye

Image Acquisition

- Sensors and Imaging
  - All machine vision cameras create an image by exposing arrays of photosensitive material to light energy
    - Think of photon "buckets"
    - Exposure duration is time-limited and typically adjustable
    - The energy in a "bucket" captured during an exposure period becomes a micro-voltage for that "bucket"



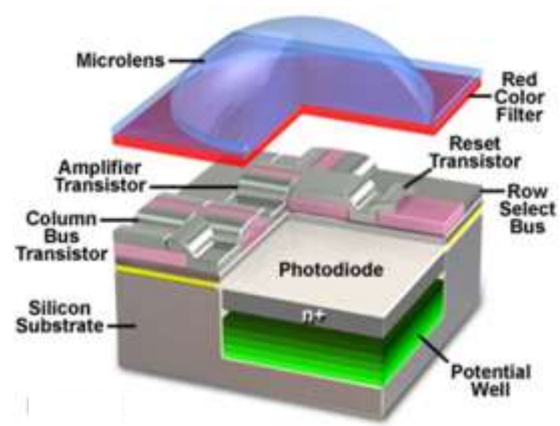


Image Acquisition

- Sensors and Imaging
  - Each element in a camera sensor array is called a pixel (picture element)
  - The energy value for each individual pixel is output as a micro-voltage upon acquisition of each image – the voltage ultimately determines the color level for that pixel
  - The pixel and data transfer architecture varies by sensor type
    - most widely used are CCD and CMOS

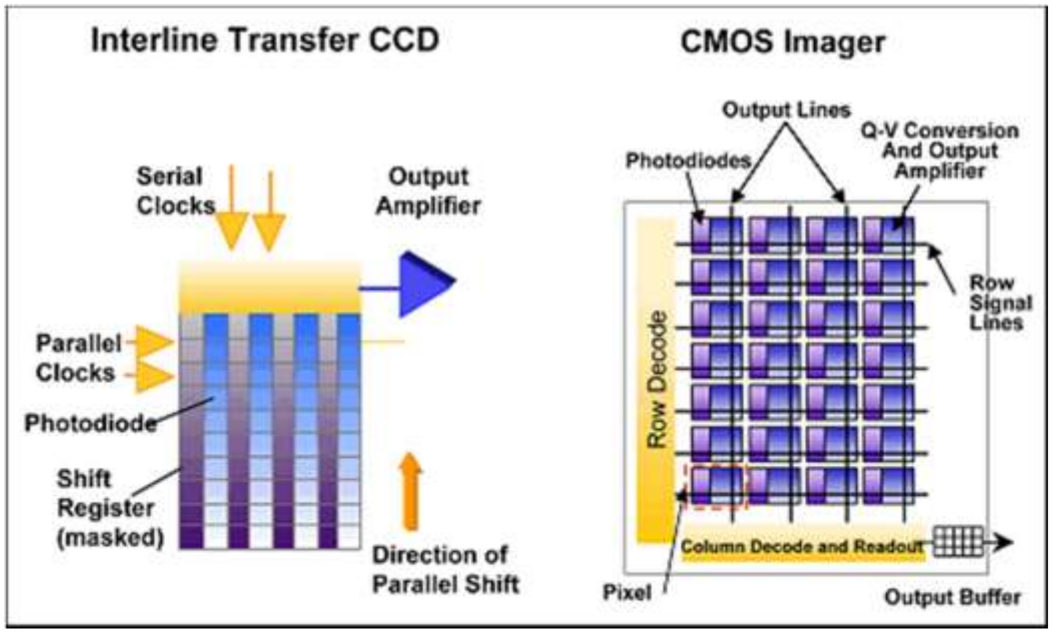
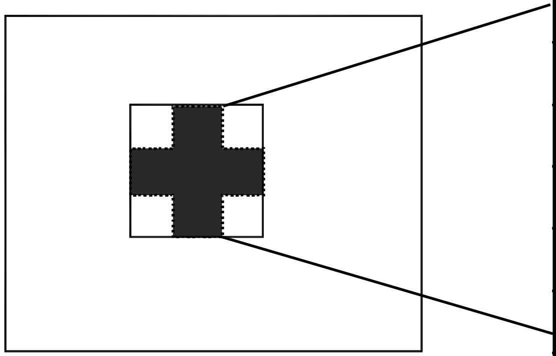


Image Acquisition

- Sensors and Imaging
  - The imaging sensor array comes in different physical layouts
    - Area
    - Line
  - Size of the chip varies widely as does the number of individual picture elements (pixels)
    - Typical area chip for machine vision: from .3 to 5+ Mpix
      - 640 to 2048+ pixels (horizontal)
      - Physical sizes from ¼” diag. up to 1”+
    - Typical line scan array: from 1K to 12K+ pixels
      - Physical sizes from about 15mm to 90mm+

Image Acquisition

- Sensors and Imaging
  - Image representation in the computer



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255	255	255	116	62	44	42	57	120	255	255	255
255	255	255	112	68	41	46	58	117	255	255	255
105	110	111	109	60	42	48	61	115	112	114	108
60	68	62	57	42	41	46	41	43	49	42	41
44	42	41	46	46	42	48	44	42	42	46	42
41	46	42	48	44	42	41	41	46	43	49	42
59	54	60	59	41	46	42	46	46	42	48	46
100	120	120	115	51	41	43	49	110	116	118	105
255	255	255	118	62	44	42	57	115	255	255	255
255	255	255	121	68	41	46	58	120	255	255	255
255	255	255	100	60	42	48	61	105	255	255	255

Image Acquisition

- Sensors and Imaging

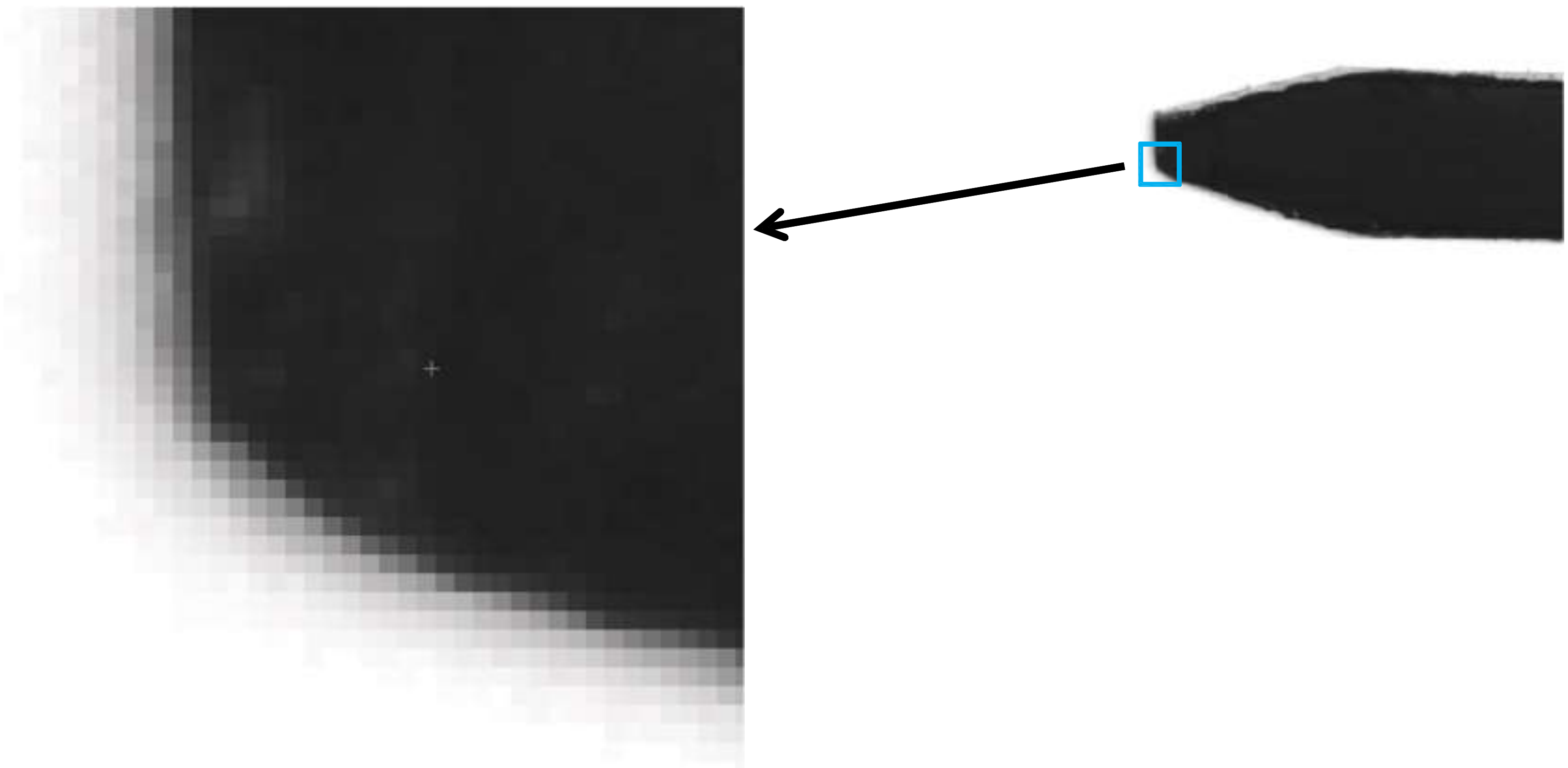
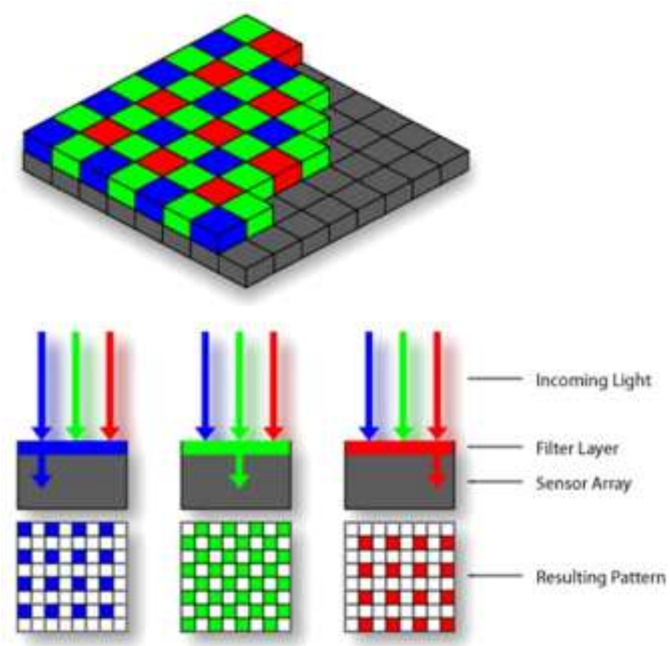


Image Acquisition

- Sensors and Imaging
  - What about color?
    - Bayer filter
    - Three-chip



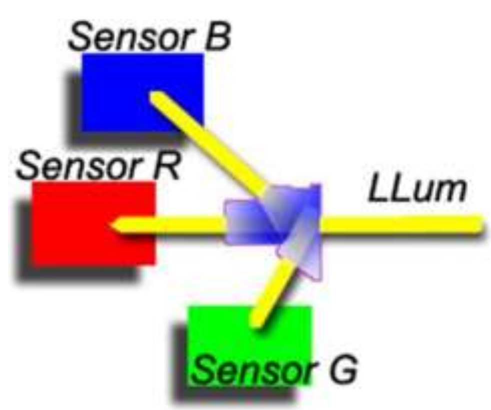


Image Acquisition

- Sensors and Imaging
  - Image resolution
    - Key element in vision component selection
    - The smallest feature resolved by the imager
    - Determinants: What is the size of the field of view (FOV), and what is the required accuracy of the imaging.

Imaged pixel size (relative to real world) = Field of View (FOV) / pixel count

- How many pixels? (for example only actual requirement varies by application

Inspection	Pixels required (usually)
Defect detection	Min. 2x2
Feature location	Min. 3x3
Feature differentiation	Min. 5x5
Gauging	Sub-pixel resolution must be 1/10th the desired tolerance

Image Acquisition

- Sensors and Imaging
  - Image Resolution
    - Examples

We need to detect a 0.1" (diam.) defect (high contrast) on a surface that is 3' square. Given good lighting and high-quality optics, what camera resolution do we need?

The defect diameter should span about 2 pixels so a pixel must cover 0.05". Over 36" therefore, there must be 720 pixels (36 / 0.05). We must select a camera with at least that resolution in the minor axis (vertical) – probably one with a 1024x780 sensor.

We must differentiate an emblem that is approximately 1" high relative to a very similar feature in a low-contrast image. If we use a standard resolution camera (640 x 480), how large should the field of view be?

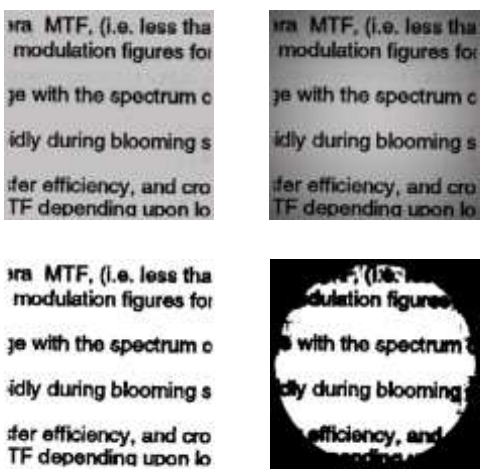
At minimum, a differentiable object must cover 5 pixels. Due to the low contrast, we decide to double that coverage to 10 pixels. The target pixel size will be 0.1" (1" / 10), and the field of view must be no larger than 48" (480 x .01).

Image Acquisition

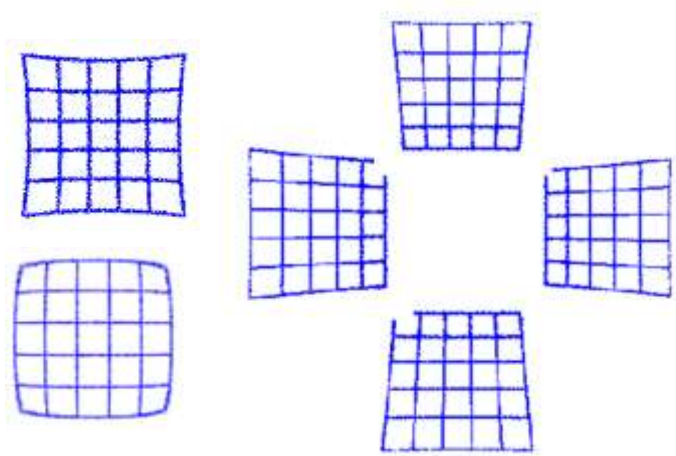
- Optics
  - Application of optical components
    - Machine vision requires fundamental understanding of the physics of lens design and performance
    - Goal: specify the correct lens
      - Create a desired field of view (FOV)
      - Achieve a specific or acceptable working distance (WD)
      - Project the image on a selected sensor based on sensor size – primary magnification (PMAG)
      - Create the highest level of contrast between features of interest and the surrounding background; with the greatest possible imaging accuracy

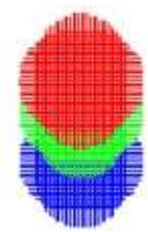
Image Acquisition

- Optics
  - Considerations for lens selection
    - Magnification, focal length, depth of focus (DOF), f-number, resolution, diffraction limits, aberrations (roll-off, chromatic, spherical, field curvature, distortion), parallax, image size, etc.
      - Some geometric aberration may be corrected in calibration
    - The physics of optical design is well known and can be mathematically modeled and/or empirically tested
      - Specification or control of most of the lens criteria is out of our hands



S5 S6

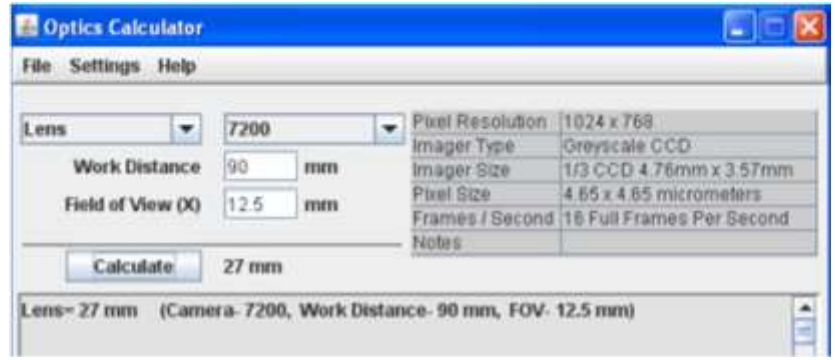


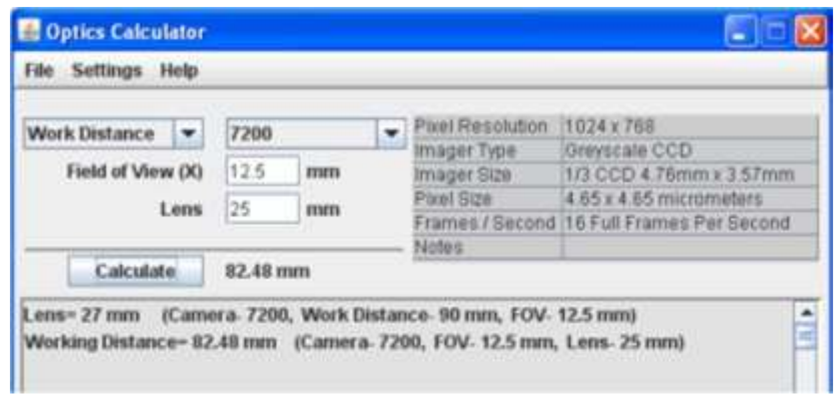


Images: Edmund [Optics;](#) www.edmundoptics.com

Image Acquisition

- Optics
  - Considerations for lens selection
    - Practical specifications for machine vision: PMAG (as dictated by focal length) and WD to achieve a desired FOV
      - Use a simple lens calculator and/or manufacturer lens specifications
      - Simple – state the required FOV, the sensor size based on physical selection of camera and resolution, and a desired working distance – calculate the lens focal length
        - » Note – specified working distance may not be available for a given lens – review specifications
      - Test your results
    - Always use a high-resolution machine vision lens NOT a security lens

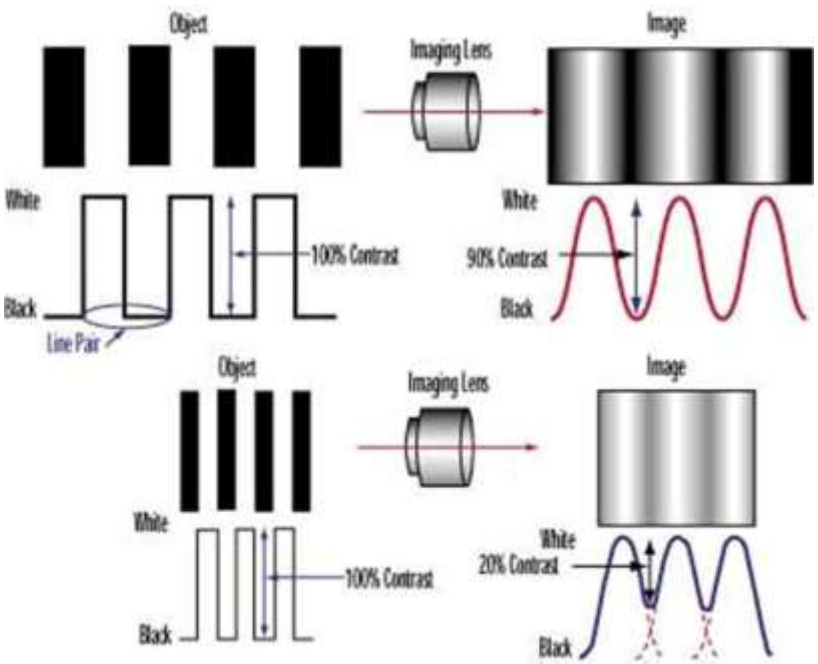


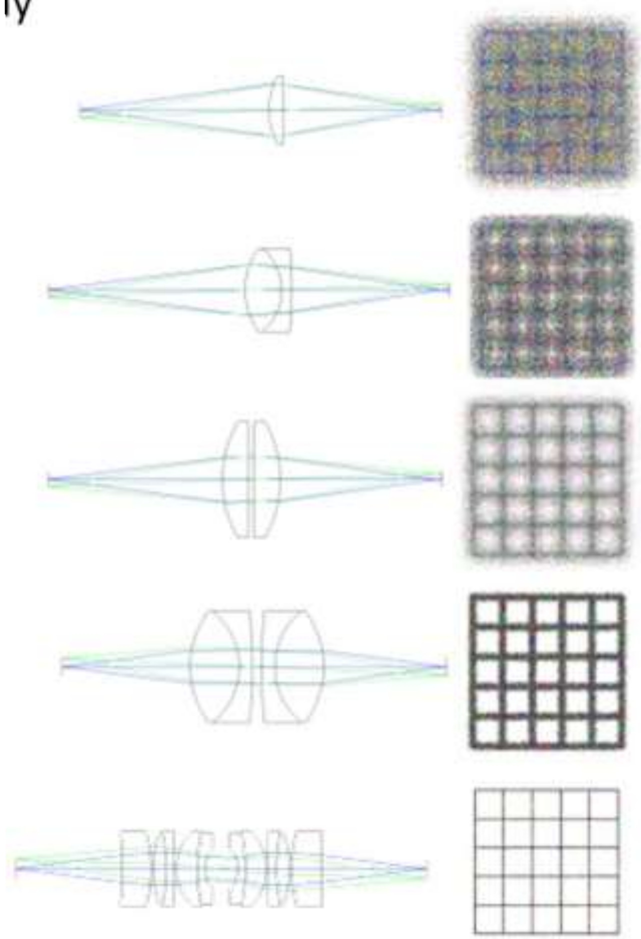


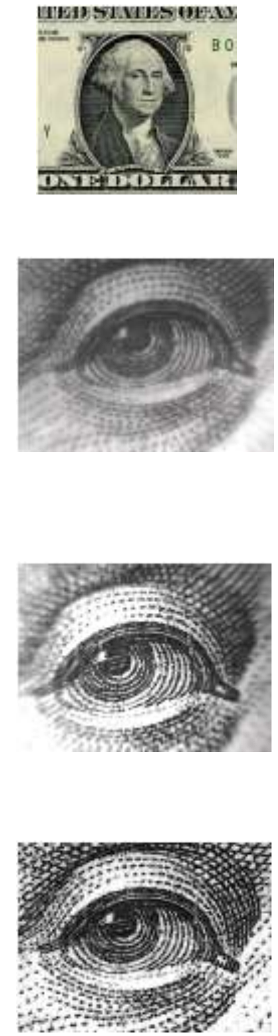
Images: PPT Vision; pptvision.com

Image Acquisition

- Optics
  - Why use machine vision lenses only
    - Light gathering capability and resolution



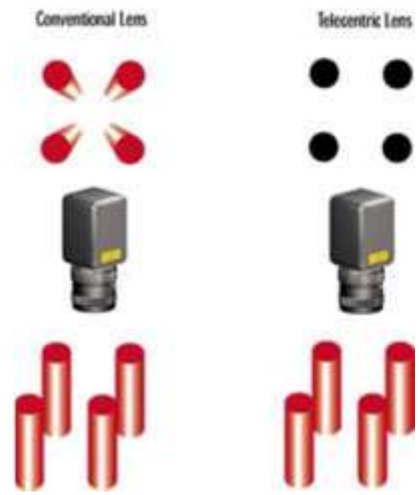




Images: Edmund Optics; www.edmundoptics.com

Image Acquisition

- Optics
  - Specialty Lenses
    - Telecentric
    - Microscope stages
    - Macro, long WD
    - Zoom (caution recommended)



Images: Edmund Optics; www.edmundoptics.com ,
Navitar; www.navitar.com

Image Acquisition

- Lighting
  - Science or art???
  - Correct lighting must
    - Highlight features to be detected relative to background
    - Create repeatable images regardless of part variation
  - Incorrect lighting will put the success/reliability/repeatability/ease-of-use of the vision application at risk
    - Machine vision cameras and software algorithms CANNOT make up for inadequate illumination techniques

Image Acquisition

- Lighting
  - Illumination for machine vision must be designed for imaging, not human viewing
    - Selection must be made relative to light structure, position, color, diffusion
    - We need to know how light works so our light selections are not “hit and miss” guesswork
    - Light is both absorbed and reflected to some degree from all surfaces
      - When an object is clear or translucent, light is also transmitted
      - Angle of incidence = angle of reflection

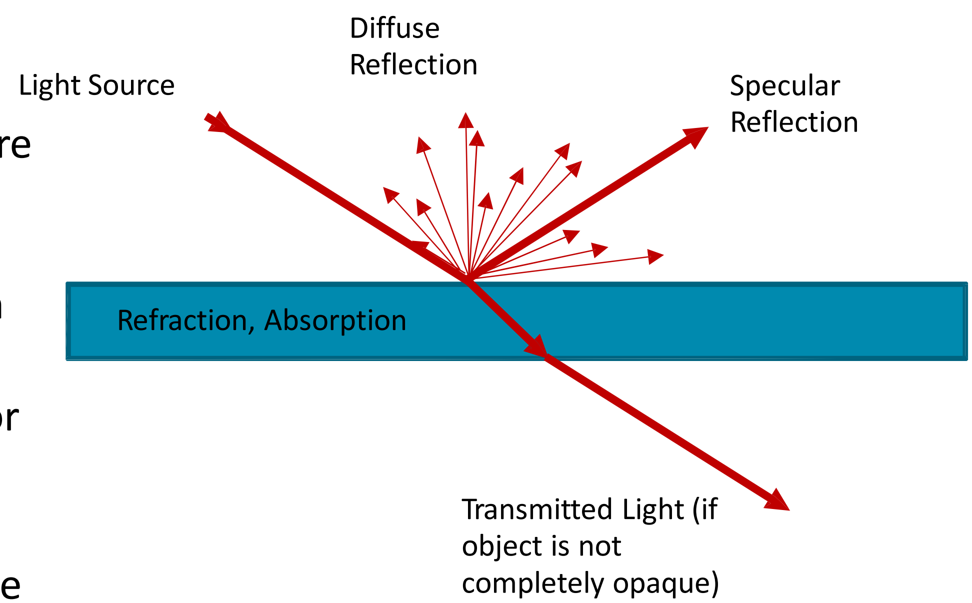


Image Acquisition

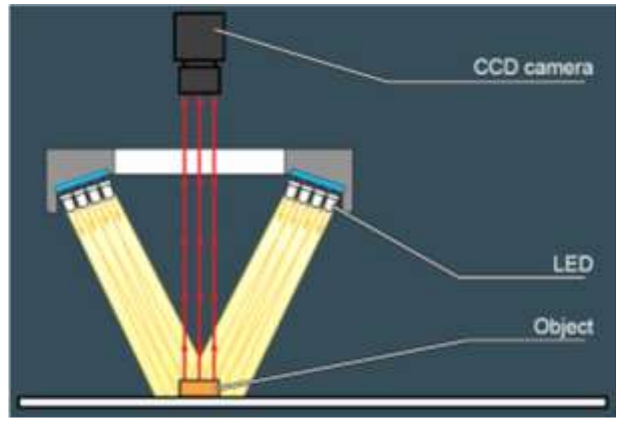
- Lighting
  - Dedicated lighting must be used for machine vision with few exceptions.
  - Where feasible, LED illumination is the best source
    - Long life with minimal degradation of intensity
    - Able to be structured into a variety of shapes
      - May be directional or diffuse
    - May be strobed at very high duty cycles and overdriven to many times nominal current specifications
    - Available in many visible and non-visible colors
  - Other sources – fluorescent, fiber-optics
    - Fluorescent – bright and highly diffuse but can be inconsistent
    - Fiber optic – glass/plastic fibers delivering light from halogen, tungsten-halogen or xenon source, bright, shapeable, focused

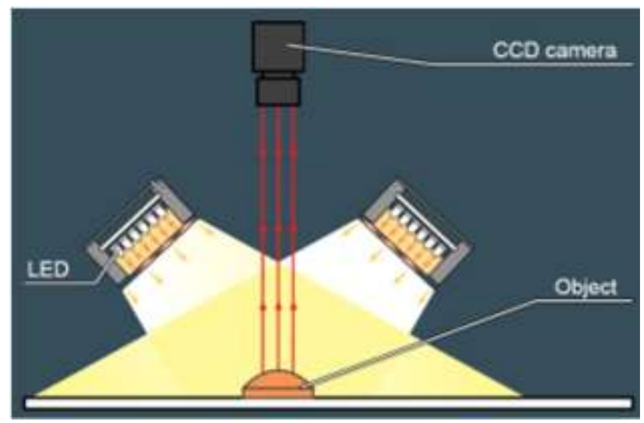
Image Acquisition

- Lighting
  - Lighting Techniques
    - The goal of lighting for machine vision applications usually is to maximize the contrast (grayscale difference) between features of interest and surrounding background
    - Techniques are categorized generally by the direction of the illumination source
      - Most may be achieved with different sources

Image Acquisition

- Lighting Techniques
  - Direct bright-field illumination
    - Sources: high-angle ring lights (shown), spot-lights, bar-lights (shown); LEDs or Fiber-optic guides
    - Uses: general illumination of relatively high-contrast objects; light reflection to camera is mostly specular

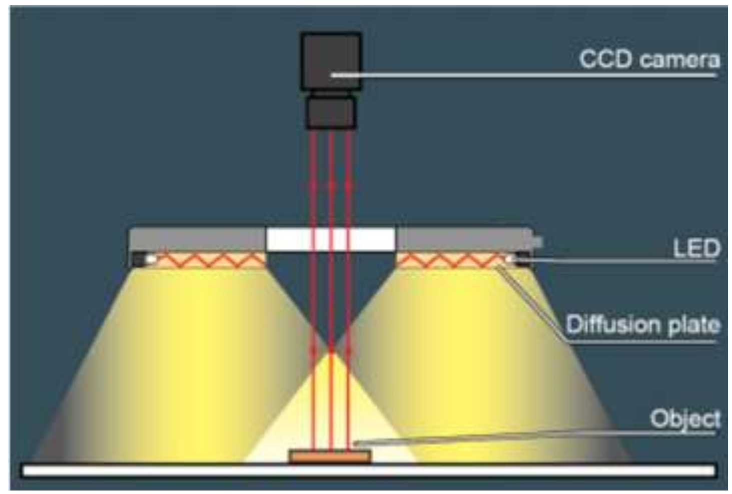




Images: CCS America; www.ccsamerica.com

Image Acquisition

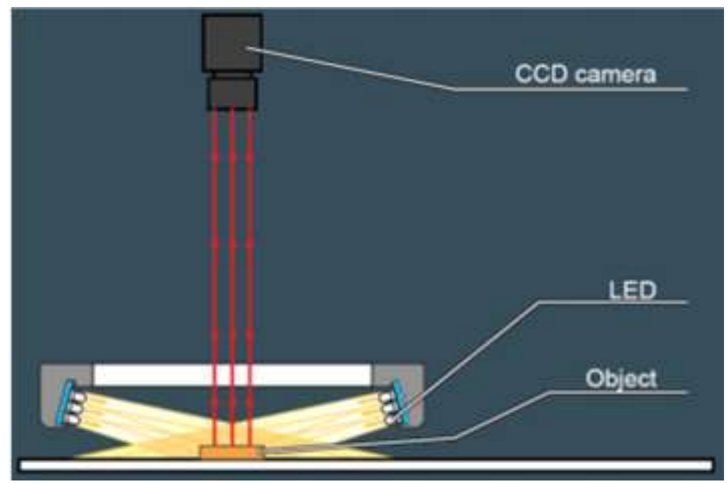
- Lighting Techniques
  - Diffuse bright-field illumination
    - Sources: high-angle diffuse ring lights (shown), diffuse bar-lights; LEDs or fluorescent
    - Uses: general illumination of relatively high-contrast objects; light reflection to camera is mostly diffuse



Images: CCS America; www.ccsamerica.com

Image Acquisition

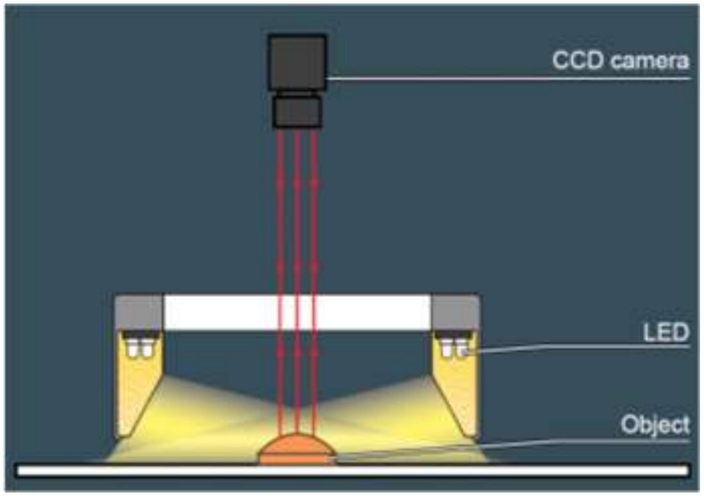
- Lighting Techniques
  - Direct dark-field illumination
    - Sources: low-angle ring lights (shown), spot-lights, bar-lights; LEDs or Fiber-optic guides
    - Uses: illumination of geometric surface features; light reflection to camera is mostly specular
    - "Dark field" is misleading – the "field" or background may be light relative to surface objects



Images: CCS America; www.ccsamerica.com

Image Acquisition

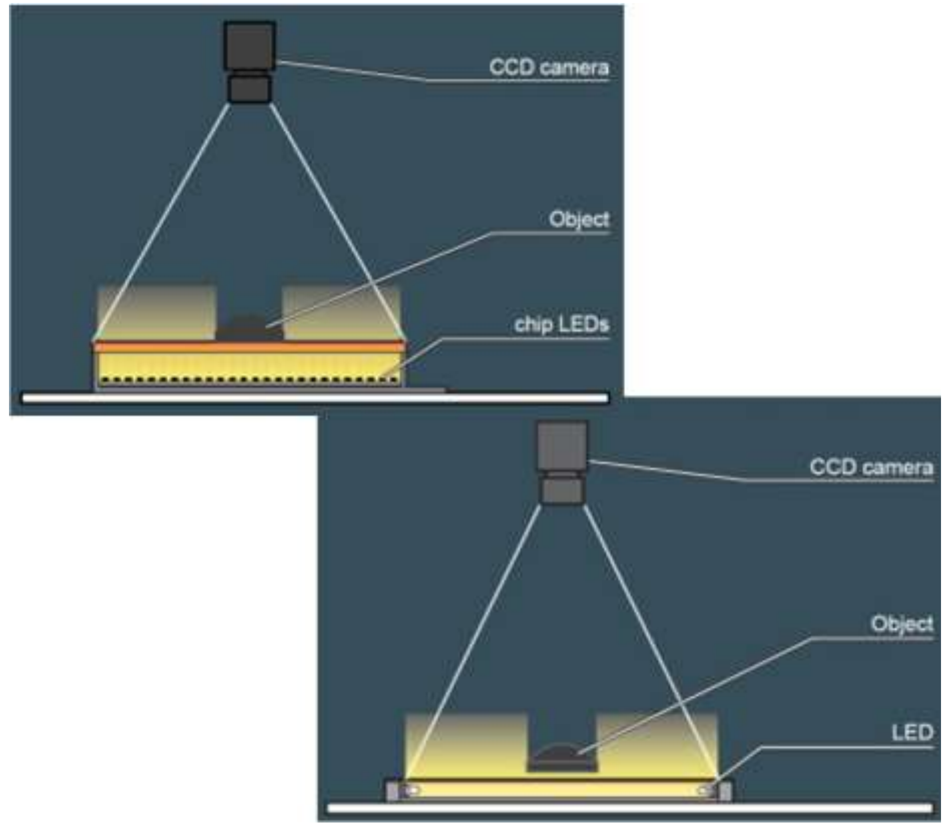
- Lighting Techniques
  - Diffuse dark-field illumination
    - Sources: diffuse, low-angle ring lights (shown), spot-lights, bar-lights; LEDs or fluorescent
    - Uses: non-specular illumination of surfaces, reducing glare; may hide unwanted surface features



Images: CCS America; www.ccsamerica.com

Image Acquisition

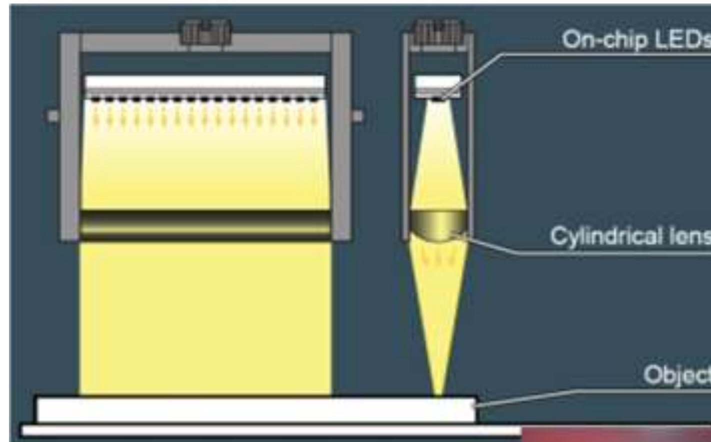
- Lighting Techniques
  - Diffuse backlight
    - Sources: highly diffused LED or fluorescent area lighting
    - Uses: provide an accurate silhouette of a part

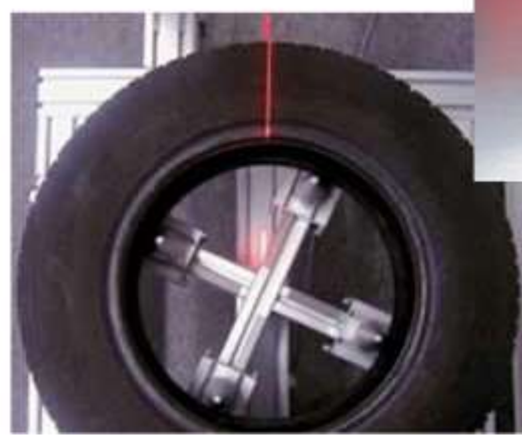


Images: CCS America; www.ccsamerica.com

Image Acquisition

- Lighting Techniques
  - Structured light
    - Sources: Focused LED linear array, focused or patterned lasers
    - Uses: highlight geometric shapes, create contrast based upon shape, provide 3D information in 2D images

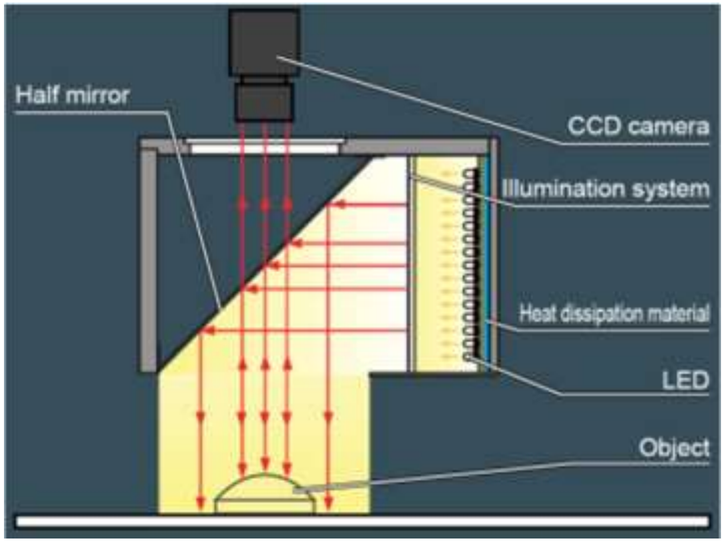




Images: CCS America; [www.ccsamerica.com,](http://www.ccsamerica.com)
Stocker & Yale; www.stockeryale.com

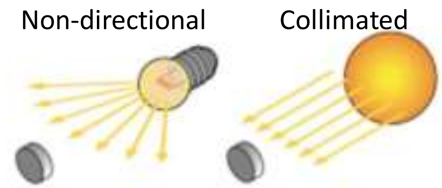
Image Acquisition

- Lighting Techniques
  - On-axis (coaxial) illumination
    - Sources: directed, diffused LED or fiber optic area
    - Uses: produce more even illumination on specular surfaces, may reduce low-contrast surface features, may highlight high-contrast geometric surface features depending on reflective angle

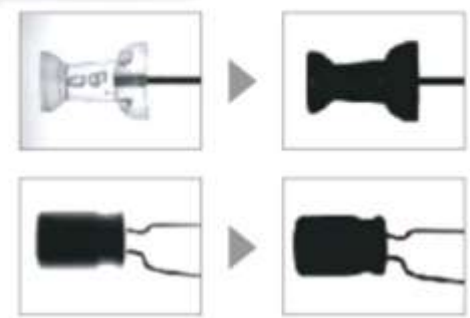


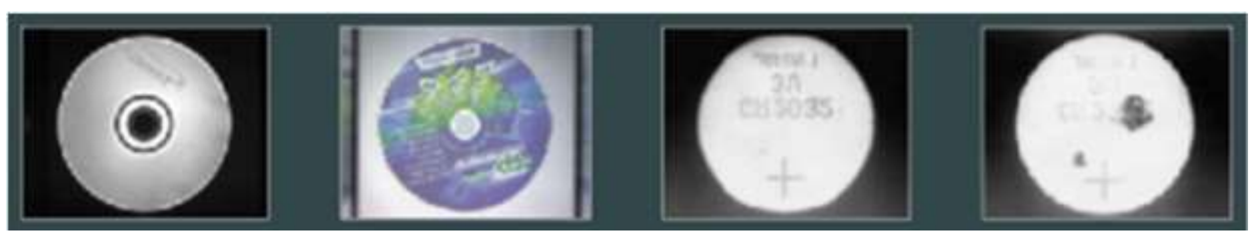
Images: CCS America; www.ccsamerica.com

Image Acquisition



- Lighting Techniques
- Collimated illumination
    - Sources: specialty illuminator (LED, Fiber) utilizing optics to guide the light
    - Uses: highly accurate backlighting, reducing stray light, highlighting surface features as a front light

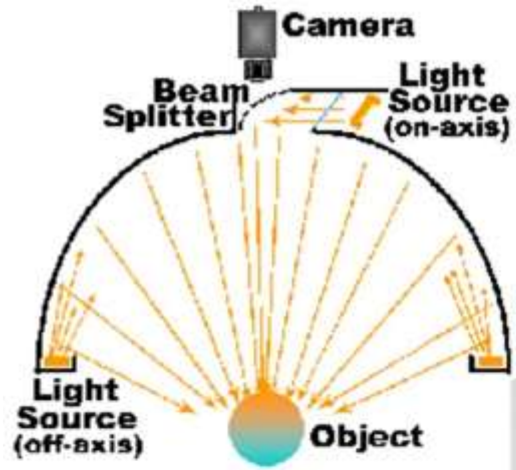


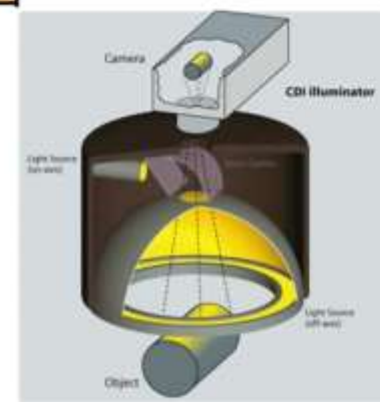


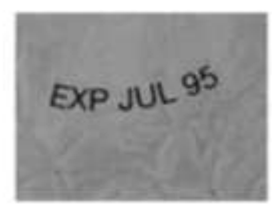
Images: Edmund Optics; www.edmundoptics.com,
CCS America; www.ccsamerica.com

Image Acquisition

- Lighting Techniques
  - Constant Diffuse Illumination (CDI – "cloudy day illumination")
    - Sources: specialty integrated lighting
    - Uses: provides completely non-specular, non-reflecting continuous lighting from all reflective angles; good for reflective or specular surfaces



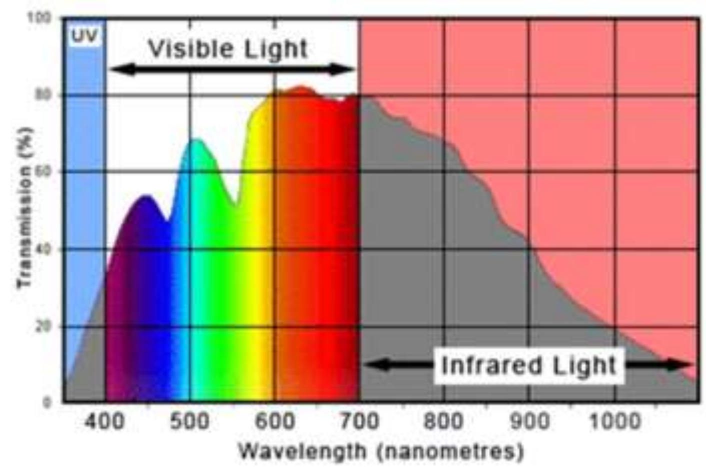




Images: Siemens; www.nerlite.com

Image Acquisition

- Lighting Techniques
  - Other lighting considerations
    - Color
      - Monochromatic light on colored features
      - Camera response to different colors
      - White light and color imaging
      - Non-visible “colors”
    - Light degradation over time; component life, heat dissipation
    - Light intensity and uniformity
    - Strobing
    - Elimination of ambient and other stray light



The Fundamentals of Machine Vision

IMAGE ANALYSIS

– Machine Vision Software
– General Machine Vision Algorithms

Image Analysis

- Machine Vision Software
  - Machine vision software drives component capability, reliability, and usability
  - Main machine vision component differentiation is in the software implementation
    - Available image processing and analysis tools
    - Ability to manipulate imaging and system hardware
    - Method for inspection task configuration/programming
    - Interface to hardware, communications and I/O
    - Operator interface and display capability
  - Often, system software complexity increases with system capability
  - AND greater ease of use usually is at the expense of some algorithmic and/or configuration capabilities

Image Analysis

- Machine Vision Software
  - A dizzying variety of software packages and libraries

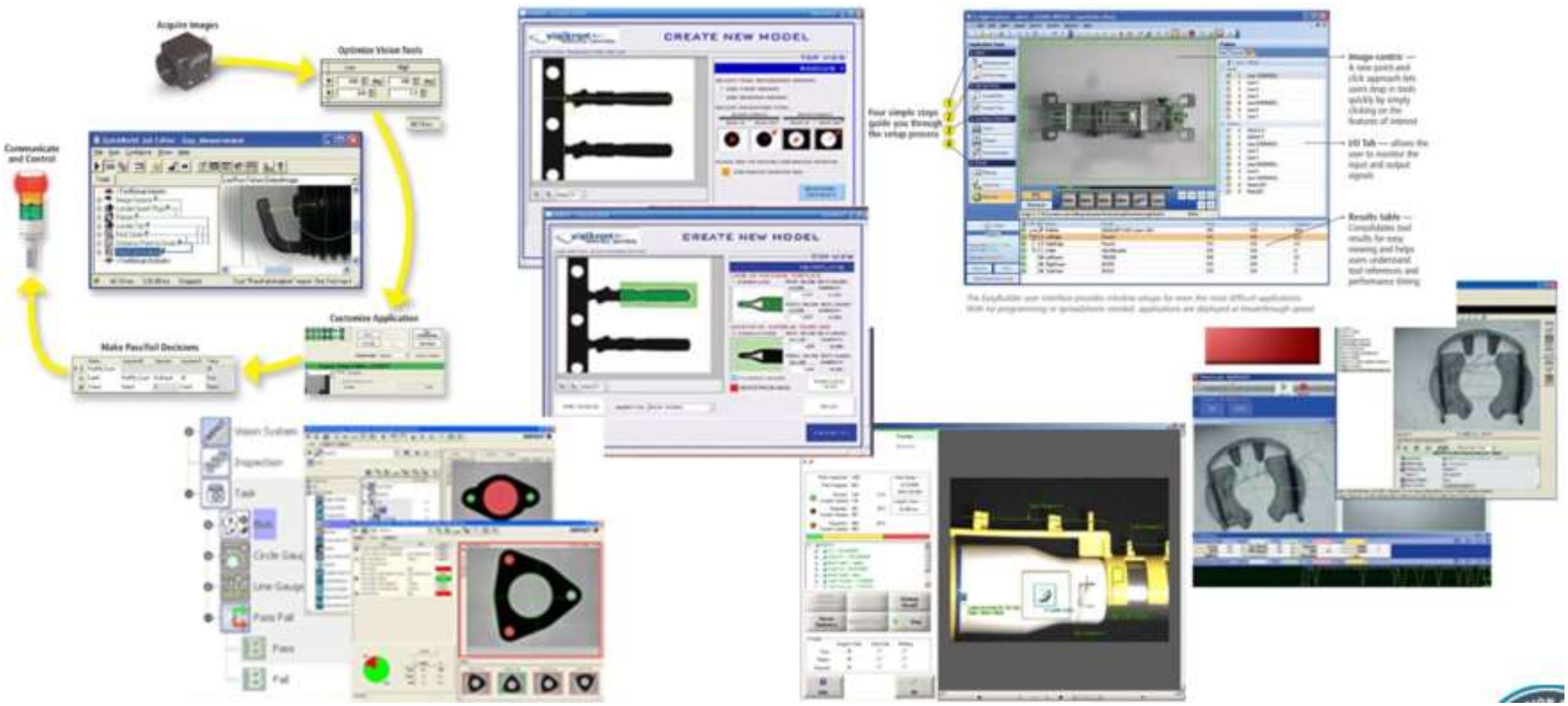
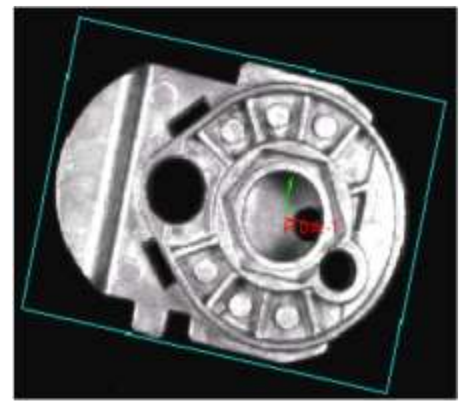


Image Analysis

- Machine Vision Software
  - What's Important
    - Sufficient algorithm depth and capability to perform the required inspection tasks
      - Consider:
        - » Speed of processing
        - » Level of tool parameterization
        - » Ease with which tools can be combined
    - Adequate flexibility in the process configuration to service the automation requirements
    - Enough I/O and communications capability to interface with existing automation as necessary
    - Appropriate software/computer interfacing to implement an operator interface as needed for the application

Image Analysis

- General Machine Vision Algorithms
  - Image transformation/geometric manipulation
  - Content Statistics
  - Image enhancement/preprocessing
  - Connectivity Edge
  - Detection
  - Correlation
  - Geometric Search
  - OCR/OCV
  - Color processing



  - Machine vision algorithms frequently execute over a subset of the image rather than the entire image. The area is often called a “region of interest” or ROI.

Image Analysis

- General Machine Vision Algorithms
  - Geometric manipulation of the image
    - Shifting
    - Rotating
    - Mirroring
    - Inverting
    - Unwrapping
    - Sampling
    - Binarization
    - Warping/Shifting

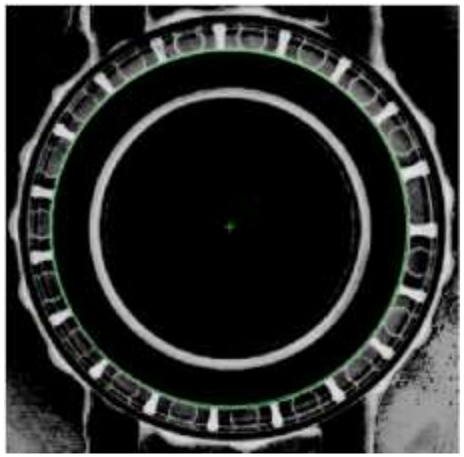
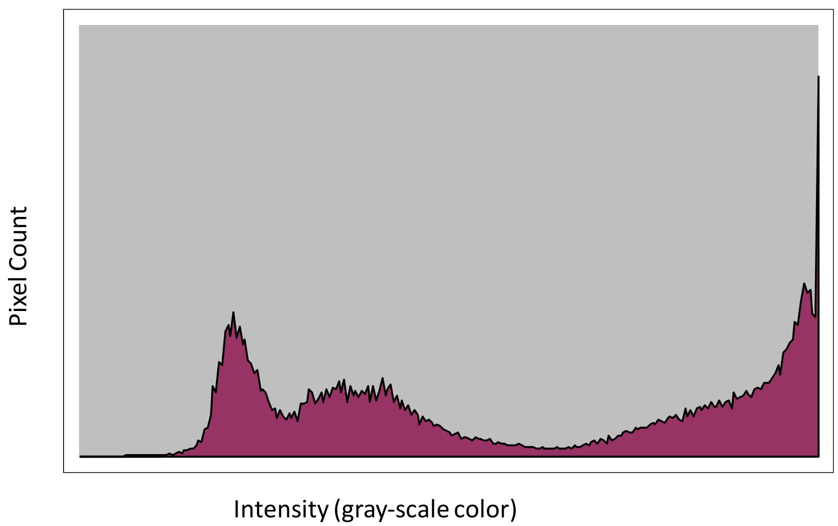


Image Analysis

- General Machine Vision Algorithms
  - Image/ROI content statistics
    - An image histogram shows the count of pixels at each gray-scale within either the image or a specified region.
    - The list can yield a variety of statistical information about the image or ROI.



Imaging Analysis

- General Purpose Machine Vision Algorithms
  - Applications of histogram statistics
    - Thresholding
    - Image equalization
    - Feature presence/absence
    - Surface analysis
    - Color/grayscale analysis
    - Lighting/camera status

Image Analysis

- General Purpose Machine Vision Algorithms
  - Image Enhancement/PreProcessing
    - Algorithms that change the image by physically replacing pixel values
      - Morphology
      - Spatial Filtering
    - Applications
      - Reduce noise
      - Create better contrast
      - Extract edge features

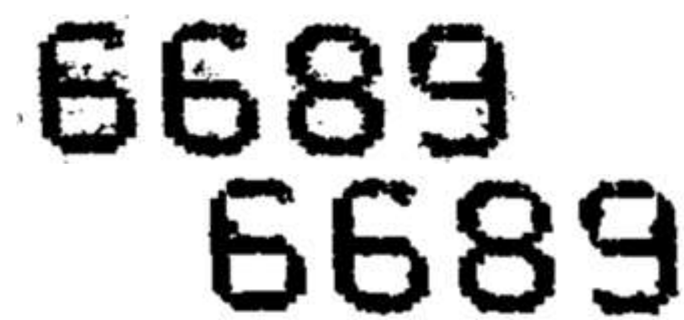


Image Analysis

- General Machine Vision Algorithms
  - Extraction and analysis of 2-dimensional connected shapes (blobs)
  - Connectivity can be a very useful and powerful tool
  - Success often depends upon the image and the level of pre-processing
    - Suited for images with high contrast and consistent color levels

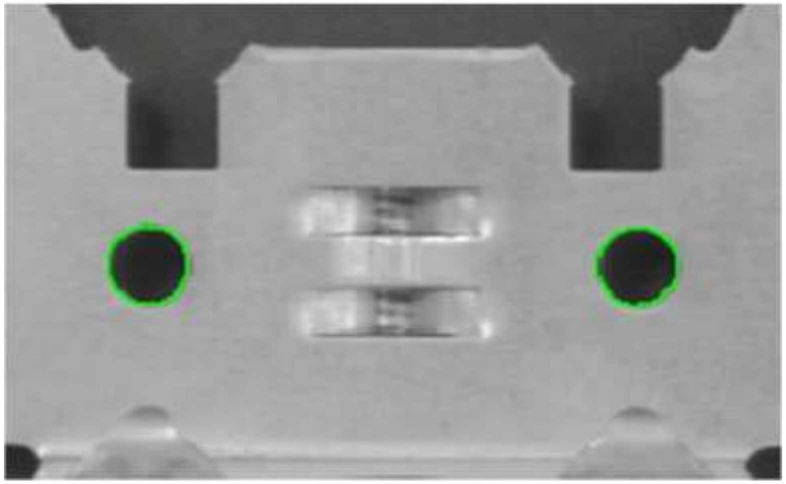


Image Analysis

- General Machine Vision Algorithms
  - Blob Statistics
    - Used to filter and categorize target shapes
      - Area
      - Perimeter
      - Center of Gravity, median
      - Bounding Box, Length, width, angle
      - Circularity, elongation, aspect ratio
  - Uses for Connectivity
    - Object location, identification
    - Cursory gauging
    - Presence/absence

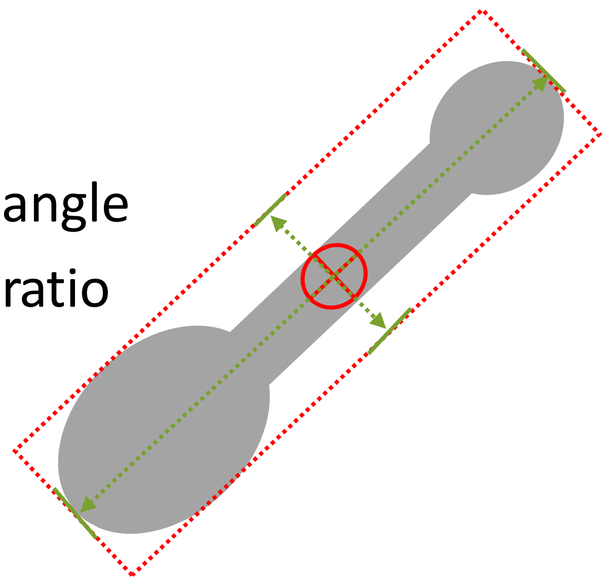


Image Analysis

- General Machine Vision Algorithms
  - Edge detection: isolation of local changes in contrast within the image
  - Edge tools locate whole or sub-pixel edge points
  - Uses for edge tools
    - Gauging
    - Feature presence, verification
  - Other edge tools
    - Line, curve or object approximation
      - Regressions
      - Hough transformation

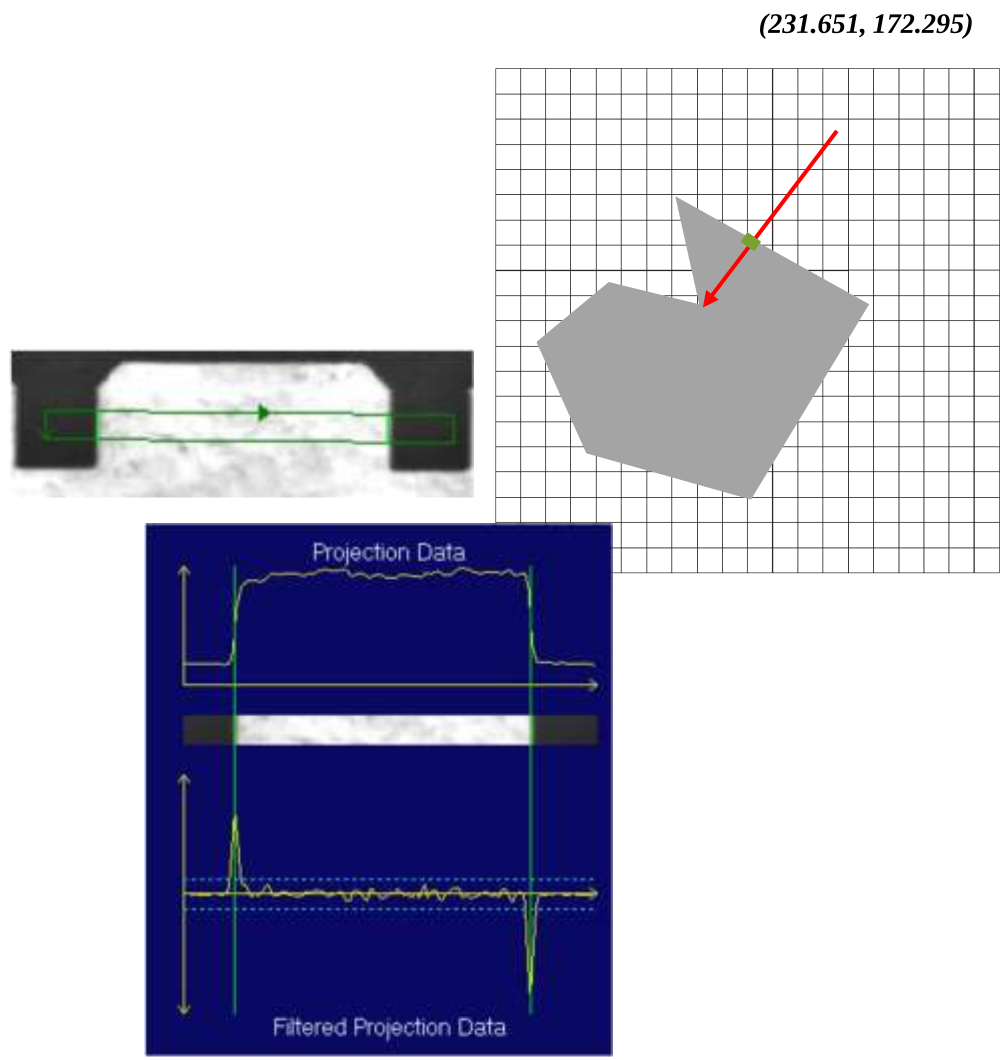


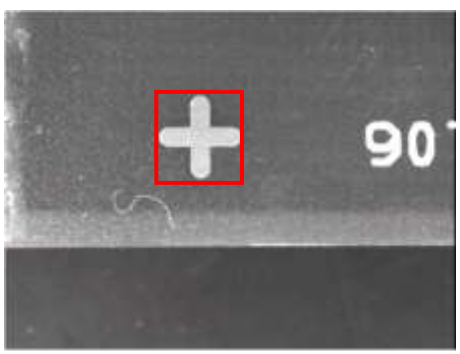
Image Analysis

- General Machine Vision Algorithms
  - Normalized Correlation
  - Finds pre-trained features
  - Other names
    - Template matching
    - Search
    - Pattern matching

Image Analysis

- General Machine Vision Algorithms
  - Normalized Correlation
    - A “model” or “template” is trained from an existing image
      - Models may be, but rarely are, synthesized
    - The model is stored as a complete gray-scale image
    - The target image or ROI is searched by mathematically comparing the model template at all points
    - Typical uses
      - Feature presence/absence
      - Position verification
      - Guidance

Target Image



Trained and Stored Model Template

Search Process

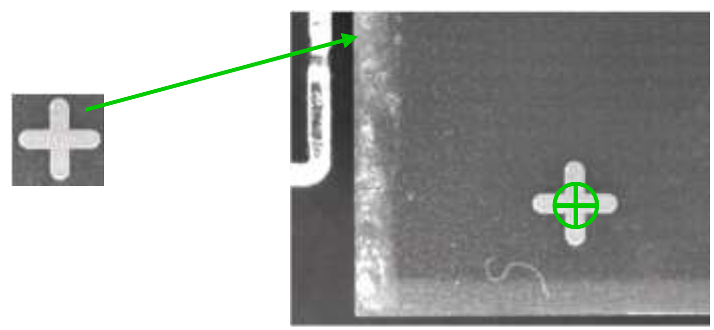
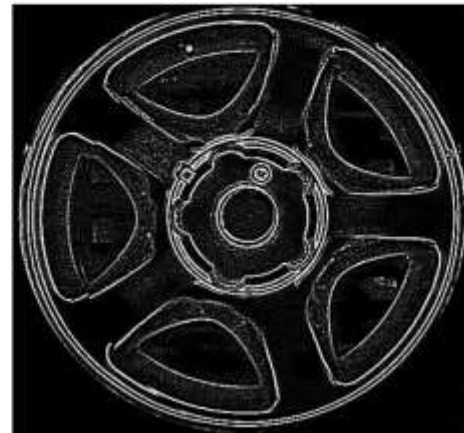


Image Analysis

- General Machine Vision Algorithms
  - Geometric Search
    - Locates features within an image based upon geometric structure, feature relationships
    - Also called pattern matching – algorithm has some branded
    - The search pattern is trained from an image or may be synthesized.
    - Geometric search pattern is a mathematical representation of the target object, not an actual image
    - Training and search process both use contour (e.g., edge) image
    - Process allows for fast, reliable search with full transformation and rotation.



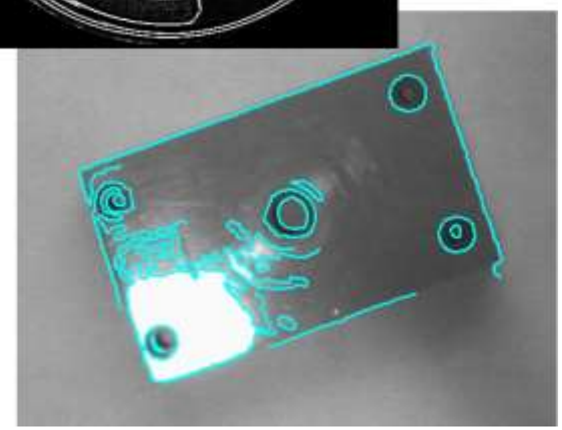
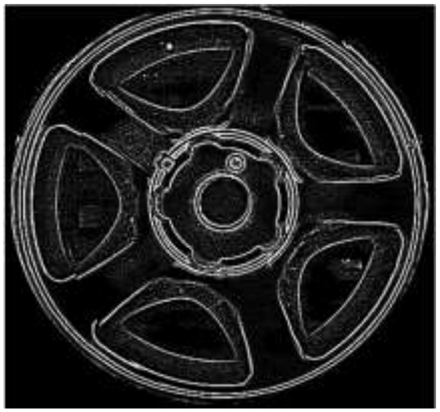
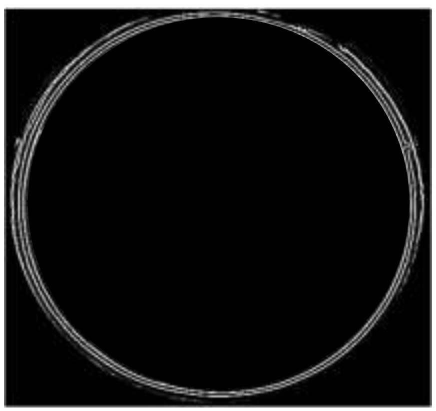


Image Analysis





- General Machine Vision Algorithms
  - Geometric Search
    - Pattern may be editable, or otherwise manipulated to optimize performance
    - Typical uses
      - Guidance
      - Feature location
      - Part verification

Image Analysis

- General Machine Vision Algorithms
  - Common challenges in search algorithms
    - Model selection
    - Confusing scenes

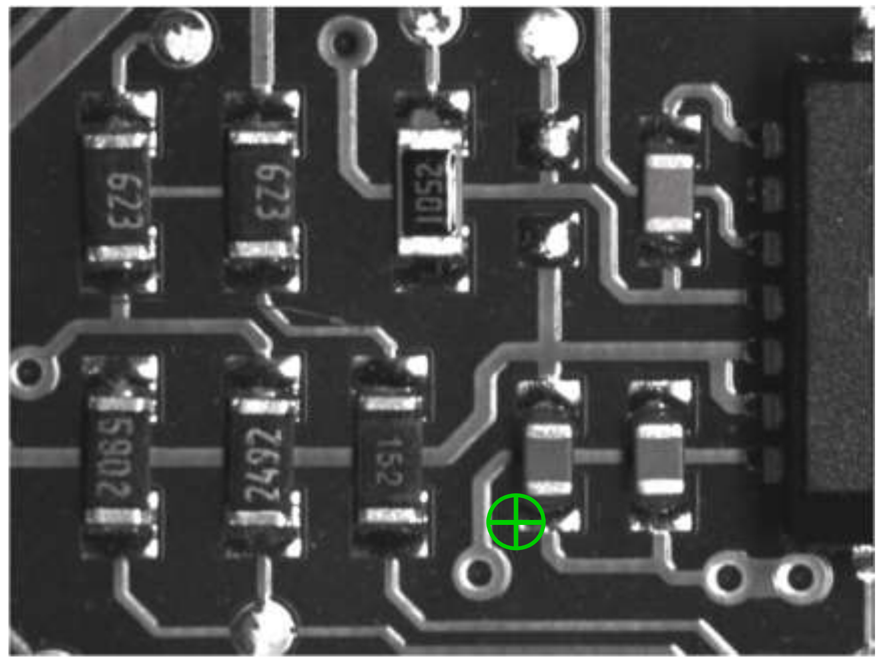
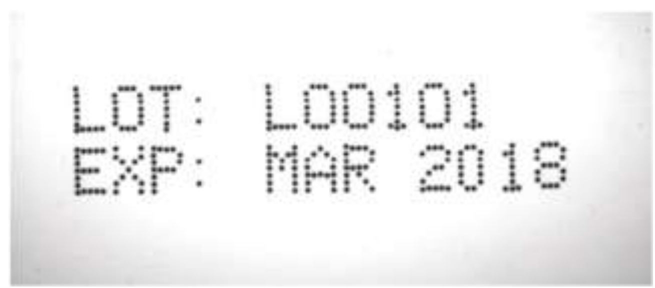


Image Analysis

- General Machine Vision Algorithms
  - OCR/OCV
    - Optical Character Recognition/Verification – reading or verifying printed characters
    - Can be fooled by print variations
    - Verification is difficult depending upon the application
    - Imaging Issues
      - Consistent presentation of the character string
      - May require extensive pre-processing

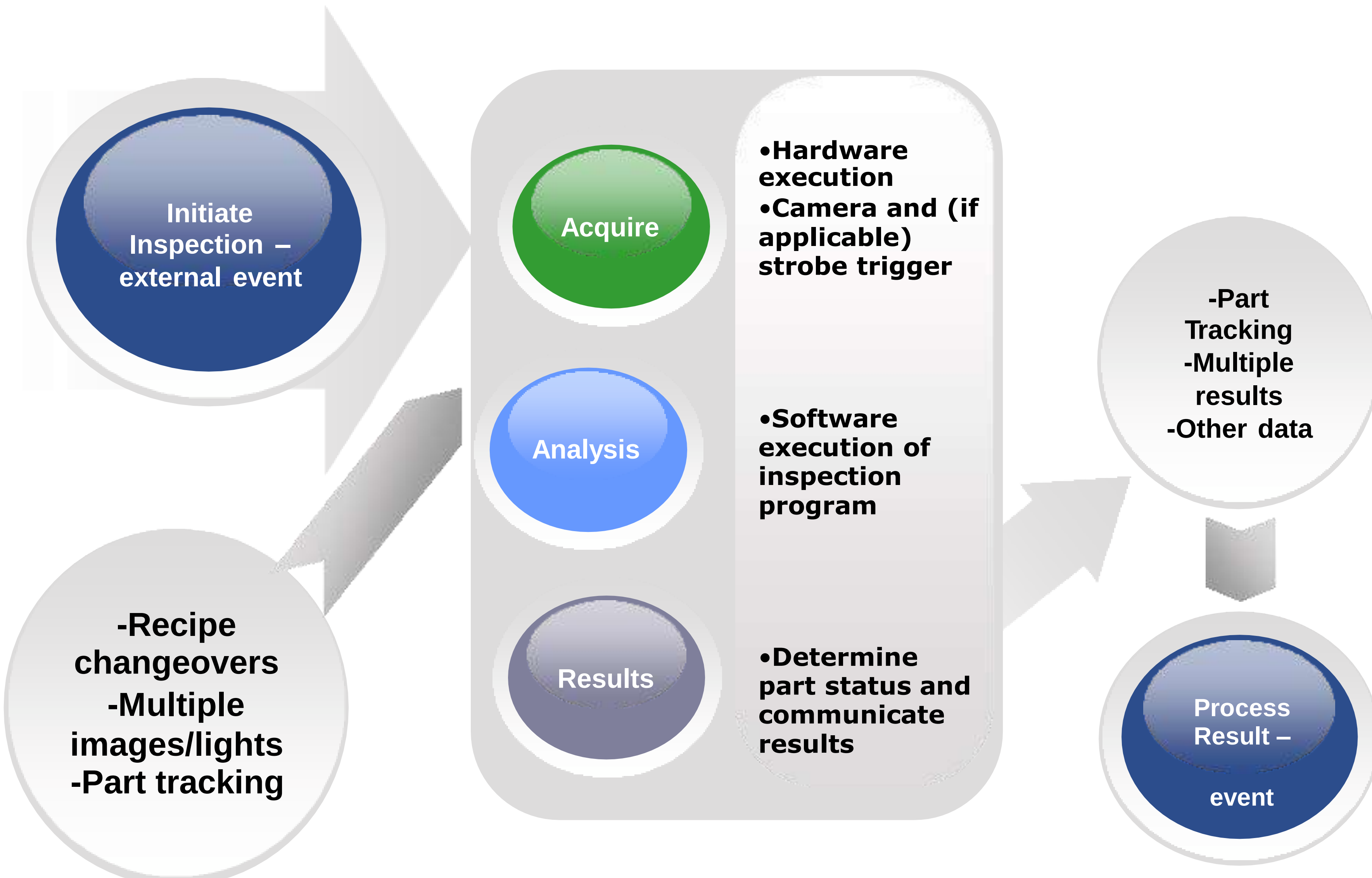


The Fundamentals of Machine Vision

INTEGRATION AND APPLICATIONS

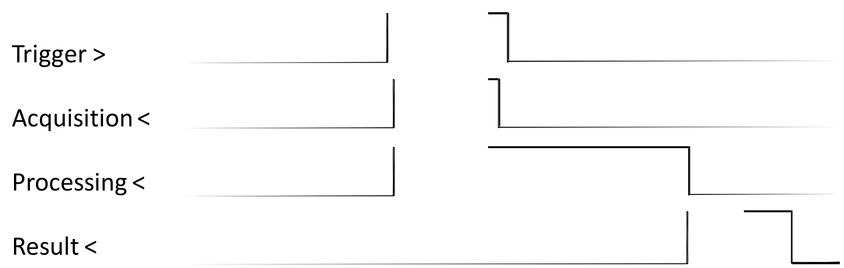
- Integration
- Results and Communications
- Basic Application Concepts

Integration and Applictions



Integration and Applications

- Integration
  - Utilize appropriate handshaking where applicable, particularly with interface to a PLC or external control system (not timers)
  - When part is in motion, interface from vision device to the automation must be discrete, digital I/O to avoid variable latencies



  - Other components – encoders/sensors/reject mechanisms

Integration and Applications

- Integration
  - Mechanical Issues
    - Camera/lighting fixturing
      - Incorporate adjustment as needed to accommodate the application requirements
        - » Goal: place camera on the specific plane required for the inspection at a point where the part can be triggered for the specified field of view, with lighting at the correct position relative to the camera
      - Often easier to adjust part sensor rather than camera
      - Fixtures must be robust and lockable
      - Some don'ts....

Integration and Automation

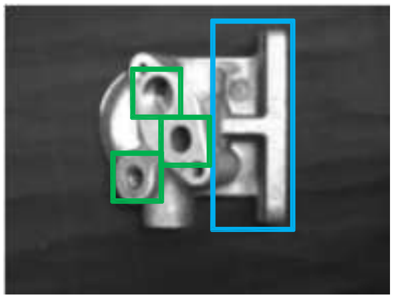
- Integration
  - Mechanical Issues
    - Part presentation
      - After lighting issues, part presentation is the most critical and difficult part of most industrial applications
        - » Direct impact on the lighting and imaging
        - » Part must be presented in a generally repeatable planar representation relative to the camera.
      - If new automation, incorporate appropriate part handling to enhance/benefit the inspection
      - Where possible modify existing automation to constrain part position

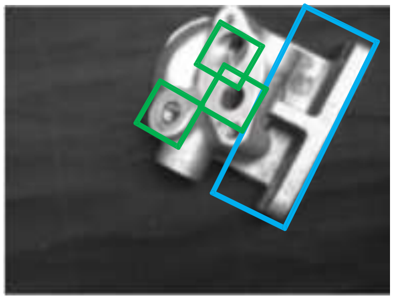
Integration and Automation

- Integration
  - Software and system configuration
    - Where possible, prepare a preliminary imaging set-up using the final lighting and optics configuration and capture real production images
    - Use production images for inspection program development
  - Configuring a basic machine vision inspection
    - Image acquisition/processing
      - Configure camera parameters
        - » Shutter, gain, offset, partial scanning, triggering
        - » Strobe light control
      - Execute an inspection process upon image acquisition
      - Tune the image if needed
        - » Filtering
        - » Morphology

Integration and Automation

- Integration
  - Configuring a basic machine vision inspection
    - Processing steps
      - Locate the part and extract a nominal origin
      - Adjust regions relative to the origin
      - Extract appropriate data within regions of interest
      - Make decisions based upon application parameters for that feature





Integration and Applications

- Results and Communications
  - Installation/testing/startup
    - Always implement control handshaking first
      - Image acquisition, data exchange, and reject timing/co-ordination make up the largest part of on-site systems integration with an automation device
      - Determine final camera/lighting mounting based upon live production imaging
        - » Lock/pin all mounts once image is correct for all parts
    - Test inspection algorithms on all samples with representative failure modes

Integration and Applications

- Results and Communications
  - Discrete digital I/O may be required due to timing/signal latency
  - Other communication protocols can be considered where appropriate
  - Incorporate proper handshaking when implementing signals with external control devices
  - Non-critical data communications (not requiring deterministic timing), such as part recipes, can be implemented with serial (RS232/422), TCP/IP, “Ethernet/IP”, or specialty (Modbus, DataHighway) interfaces.
  - The system design must take into account inherent latencies in these protocols
  - About “network” communications

Integration and Applications

- Basic Application Concepts
  - Configure the desired inspection task utilizing appropriate tools provided by the selected components
  - Typical general-purpose factory floor inspections
    - Flaw detection
    - Assembly Verification/Recognition
    - Gauging/Metrology
    - Location/Guidance
    - OCR/OCV
  - Note that virtually all applications will require the implementation of multiple "tools" to successfully extract the image data

Integration and Applications

- Basic Application Concepts
  - Defect/Flaw Detection
    - A flaw is an object that is different from the normal immediate background
    - Imaging Issues
      - Must have sufficient contrast and geometric features to be differentiable from the background and other "good" objects
      - Typically must be a minimum of 3x3 pixels in size and possibly up to 50x50 pixels if contrast is low and defect classification is required
      - Reliable object classification may not be possible depending upon geometric shape of the flaws
    - Machine vision tools
      - Binary pixel counting, morphology, edge extraction and counting, image subtraction/golden template, blob analysis

Integration and Applications

- Basic Application Concepts
  - Assembly Verification/Object Recognition
    - Feature presence/absence, identification, differentiation of similar features
    - Imaging Issues
      - Must create adequate contrast between feature and background
      - Accommodate part and process variations – locate and correct for part positional changes
      - May require flexible lighting/imaging for varying features
      - For feature presence/absence, feature should cover approx. 1% of the field of view (med. resolution camera), more for identification or differentiation
    - Machine vision tools
      - Edge detection and measurement tools, blob analysis, normalized correlation and pattern matching

Integration and Applications

- Basic Application Concepts
  - Gauging/Metrology
    - Note: There are physical differences between gauging features in an image produced by a camera, and the use of a gage that contacts a part. These differences usually can not be reconciled
    - Gauging concepts
      - Resolution, repeatability, accuracy
      - Sub-pixel measurement
      - Measurement tolerances
      - Resolution must be approximately 1/10 of required accuracy in order to achieve gauge reliability/repeatability

Integration and Applications

- Basic Application Concepts
  - Gauging/Metrology
    - Imaging Issues
      - Lighting to get a repeatable edge
        - » Backlighting, collimated light
      - Telecentric lenses
      - Calibration
        - » Correction for image perspective/plane
        - » Calibration error stack-up
    - Machine vision tools
      - Edge detection and measurement, blob analysis

Integration and Applications

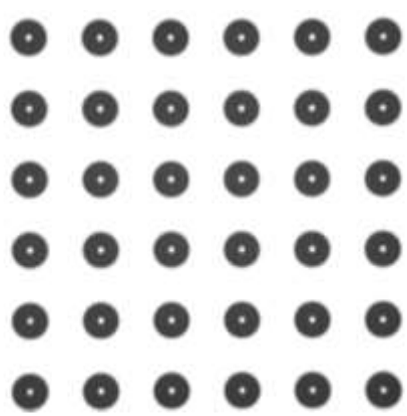
- Basic Application Concepts
  - Location/Guidance
    - Identification and location of an object in 2D or 3D space
    - May be in a confusing field of view
    - Imaging Issues
      - Measurement tolerances and accuracies as described for gauging/metrology applications
      - Sub-pixel resolutions may be better than discrete gauging results
      - For guidance applications, the stack-up error in robot motion may be significant
    - Machine vision tools
      - Blob analysis, normalized correlation, pattern matching

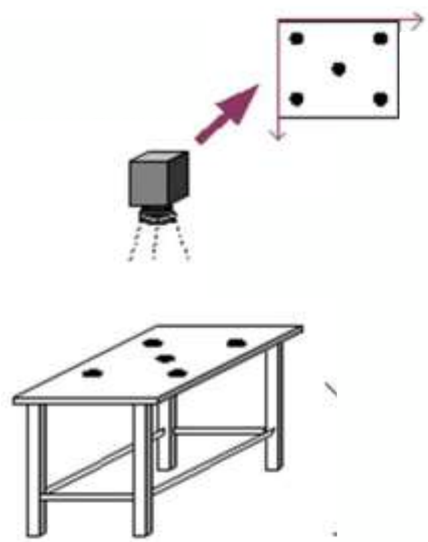
Integration and Applications

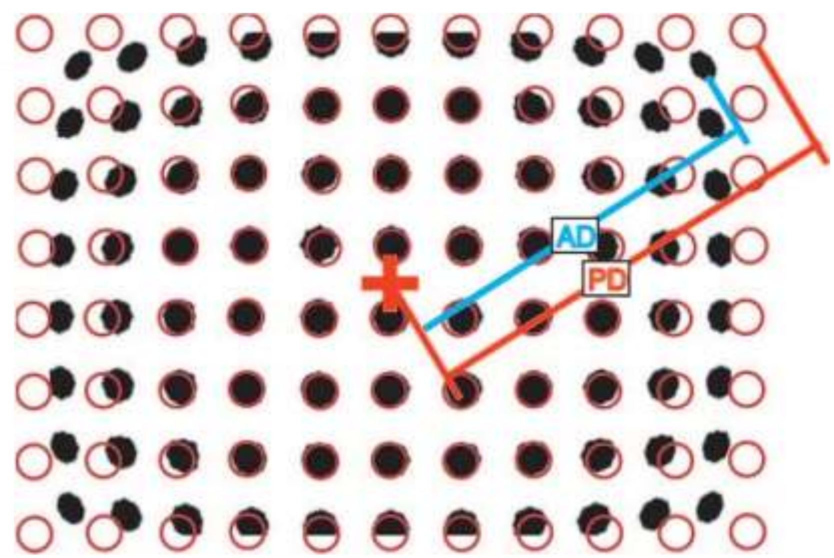
- Basic Application Concepts
  - OCR/OCV
    - Optical Character Recognition/Verification – reading or verifying printed characters
    - Can be fooled by print variations
    - Verification is difficult depending upon the application
    - Imaging Issues
      - Consistent presentation of the character string
      - May require extensive pre-processing
    - Machine vision tools
      - OCR/OCV, golden template match

Integration and Applications

- Basic Application Concepts
  - Camera Calibration
    - Mapping real-world coordinates to the camera (observed) pixel coordinates
    - Correction of planar and optical distortion







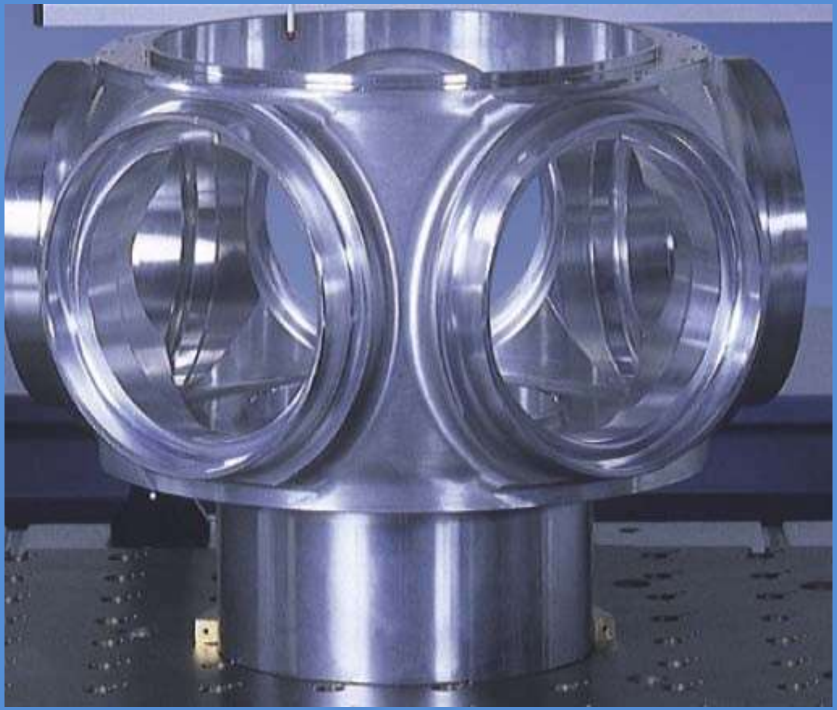
Images: Edmund Optics; www.edmundoptics.com, Cognex; www.cognex.com

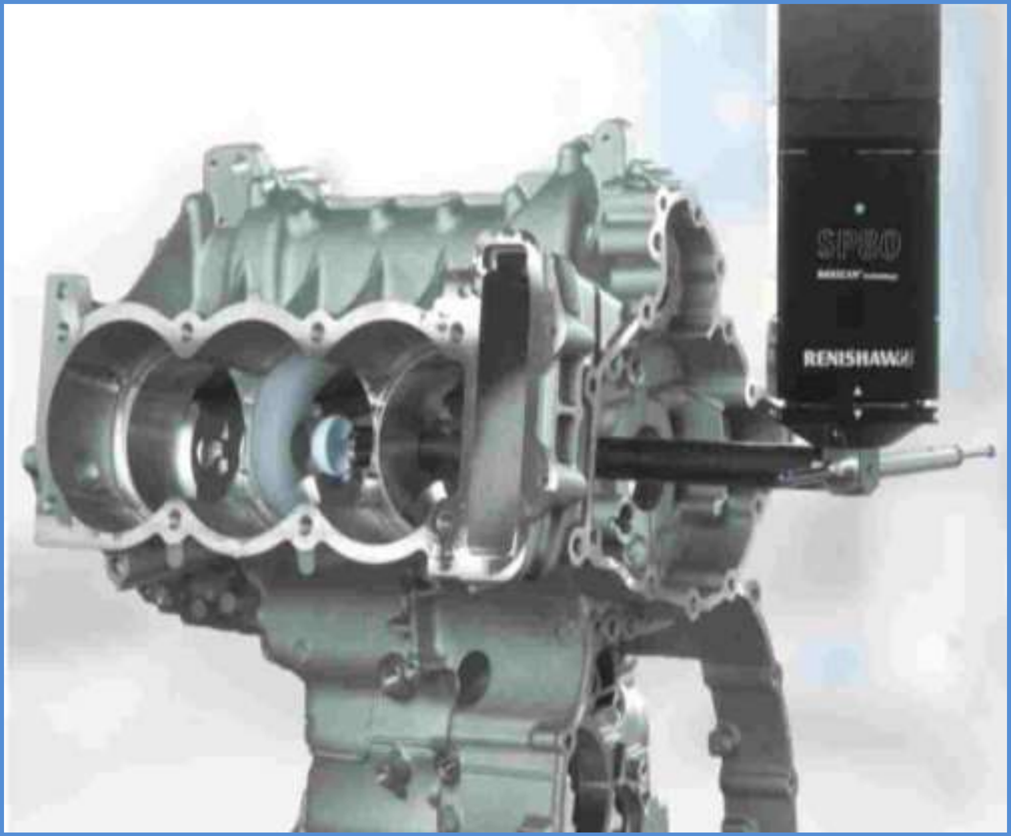
Co-Ordinate Measuring Machine(CMM)

Complex Jobs to be measured

Complex Jobs to be measured

Complex Jobs to be measured





Functions of CMM

- To measure the actual size of w/p comparison with desired shape and evaluation of metrological information such as
  - Size
  - Form
  - Location
  - Position
- Actual size is obtained by probing the surface at discrete measuring points. Every pt is expressed in terms of its x,y,z coordinates

CMM system components

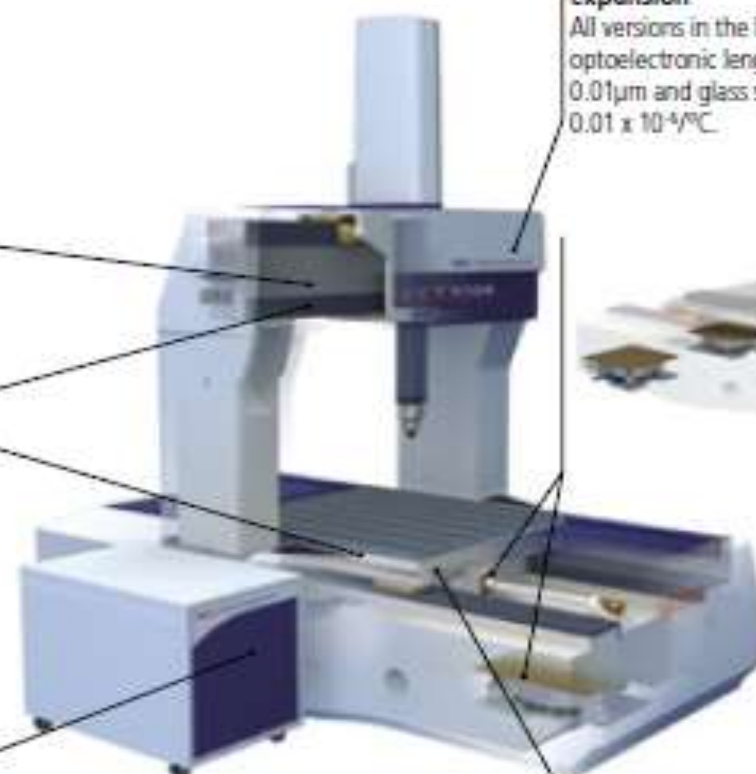
- Mechanical Setup with 3 axes movement & the displacement transducer
- Probe head to probe the work piece in a spatial direction
- Control Unit
- Computer with software to calculate & represent the results

Air bearings on all axes

Self-adjusting air bearings on all axes enable outstanding smoothness, speed and precision in movement. They form the basis for absolute measuring accuracy.

Exceptional geometrical and kinematic accuracy
The excellent geometrical and kinematic accuracy of LEGEX machines is due to the fixed-portal principle.

Thermally stable glass scales with "zero" thermal expansion
All versions in the LEGEX series are equipped with the new optoelectronic length measuring system with a resolution of 0.01µm and glass scales with a thermal expansion coefficient of 0.01×10^{-4}/°C.



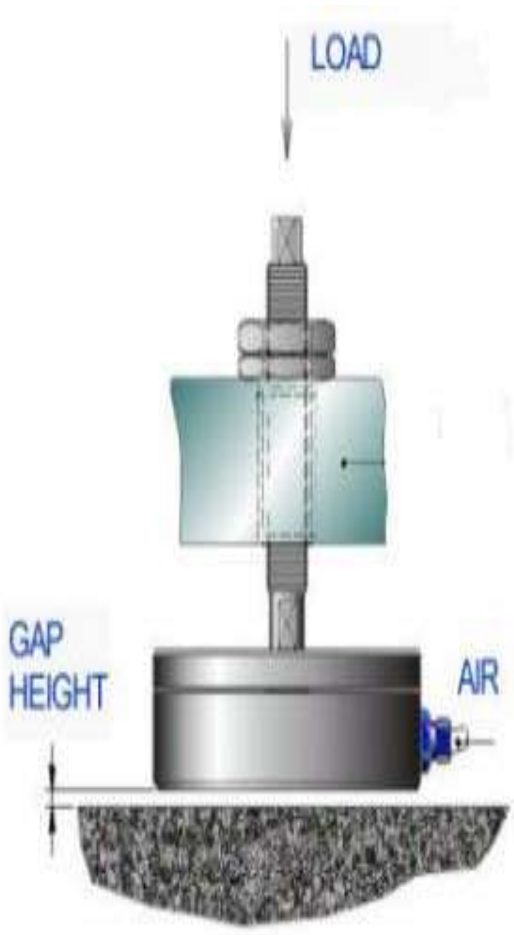
Low-vibration system provides reassuring reliability

Self-levelling high-performance shock absorbers make LEGEX machines reassuringly reliable, even when the floor itself shakes and vibrates.

Faster and more accurate with ceramic-coated guides
The LEGEX versions of the 500 series and upwards come standard with ceramic coating of the Y and X guides as well as the sleeve.

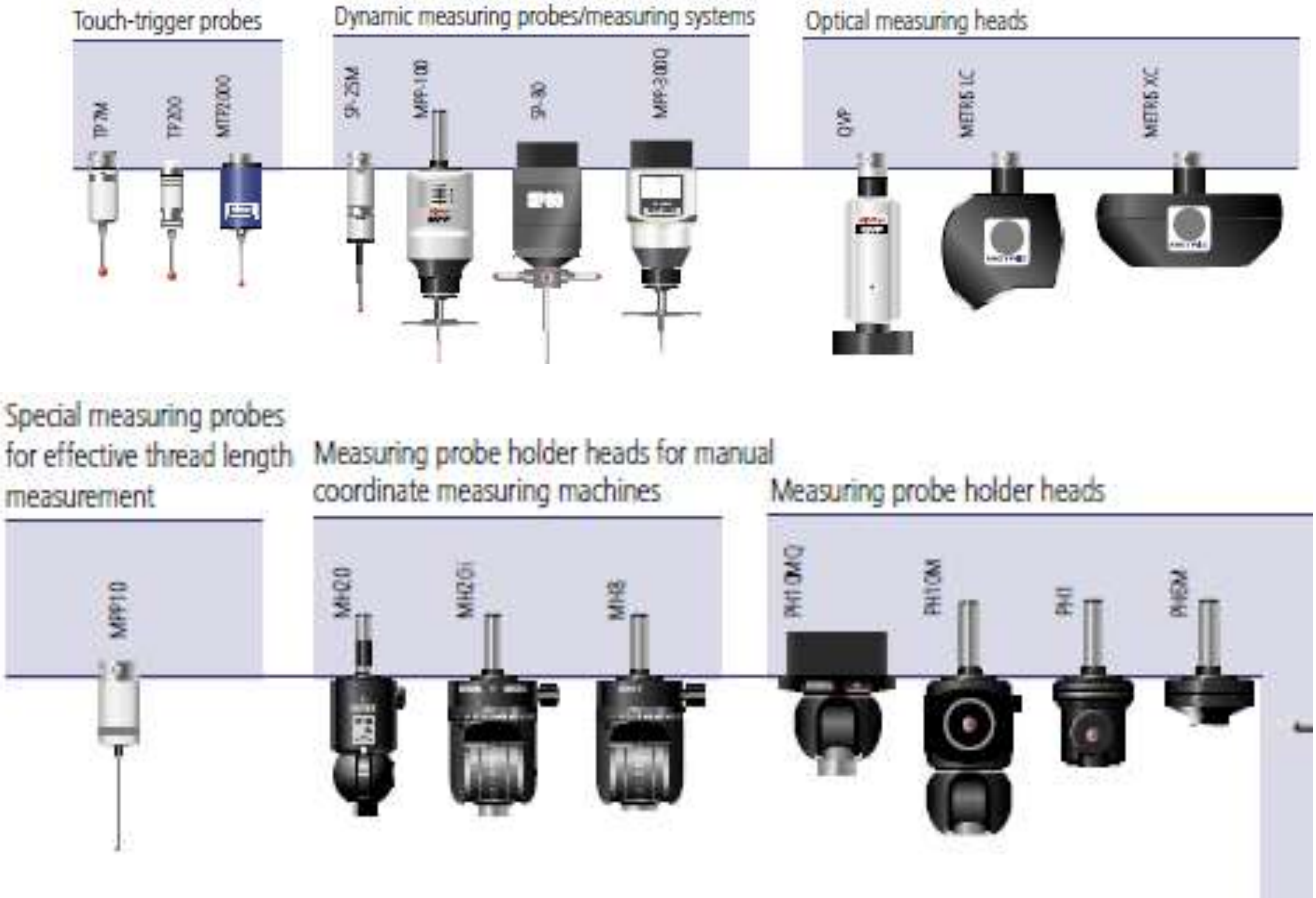
Highly dynamic, flexible digitized drive
The drive control for the LEGEX operates using an extremely powerful 32-bit digital signal processor (DSP). It perfectly controls the digital signals of all control circuits, travel movements, positions and speed for maximum measuring quality.

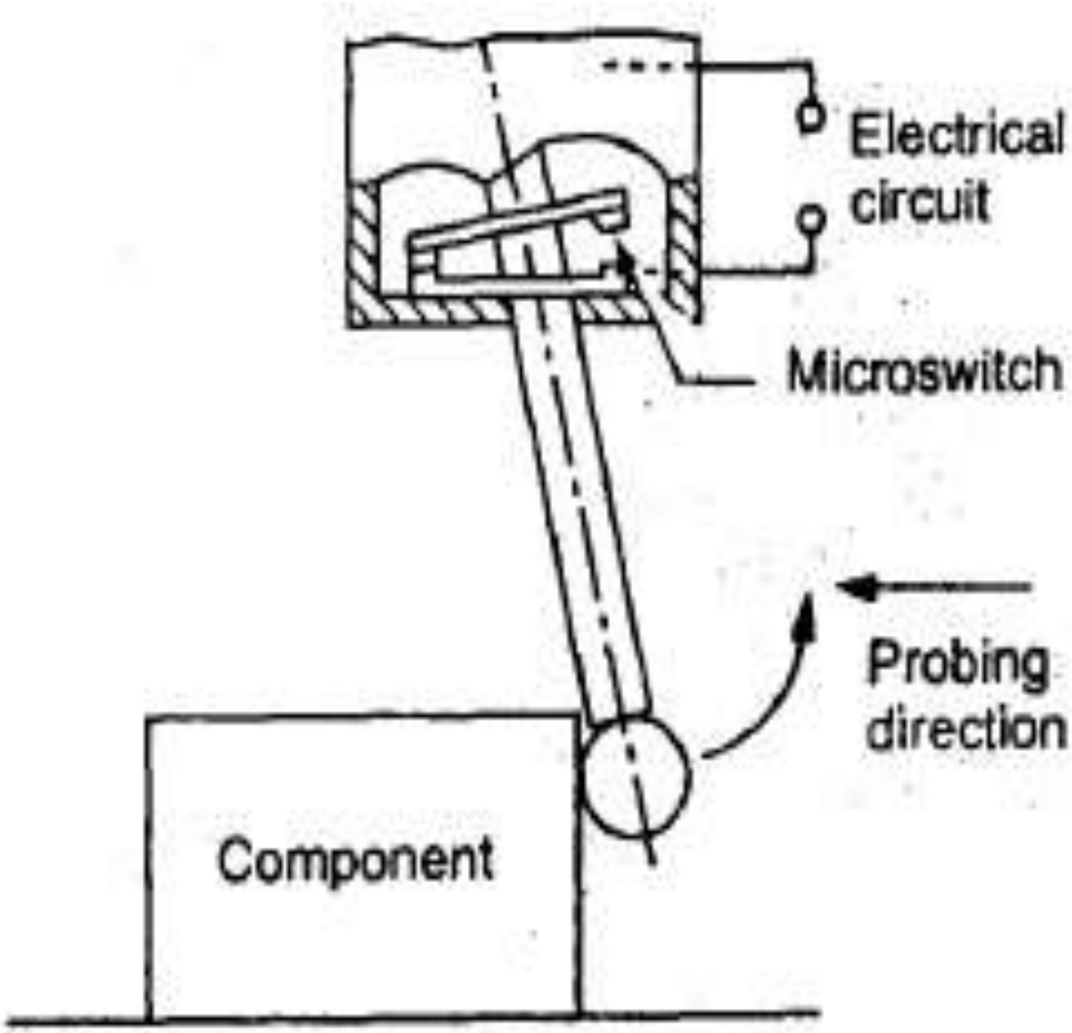
Outstanding accuracy based on new design principles
The measuring table moves in the Y axis in the base using the "moving table" principle, completely independently from the portal. Outstanding geometrical accuracy ensures that deformation of the base due to load movements is eliminated.


LOAD
GAP
HEIGHT
AIR

Air Bearing

- The fluid film of the bearing is achieved by supplying a flow of air through the bearing itself to the bearing surface.
- Numerous bearing designs exist to ensure uniform pressure is distributed across the entire bearing area.
- The design of the air bearing is such that, although the air constantly dissipates from the bearing site, the continual flow of pressurized air through the bearing is sufficient to support the working loads.


Touch-trigger probes
TP7M
TP200
MTP2000
Dynamic measuring probes/measuring systems
SP25M
MPP-100
SP80
MPP-300Q
Optical measuring heads
QVP
METRIS LC
METRIS XC
Special measuring probes for effective thread length measurement
MPP10
Measuring probe holder heads for manual coordinate measuring machines
MH20
MH20i
MH8
Measuring probe holder heads
PH10MQ
PH10M
PH1
PH6M



(a) Part section of Probe head

(b) Outline of Probe head

ACR-1

MRS-ACR3

SCRMPP

SCR200

MRS-FCR25

Step 1: Home the CMM

– establishes global coordinate system(Xm,Ym,Zm)

Step 2: Qualify the Tip(Calibration of probe with respect to probe head)

– compensates for tip diameter

Step 3: Align the Part

– establishes a local coordinate system on the part (Xw,Yw,Zw)

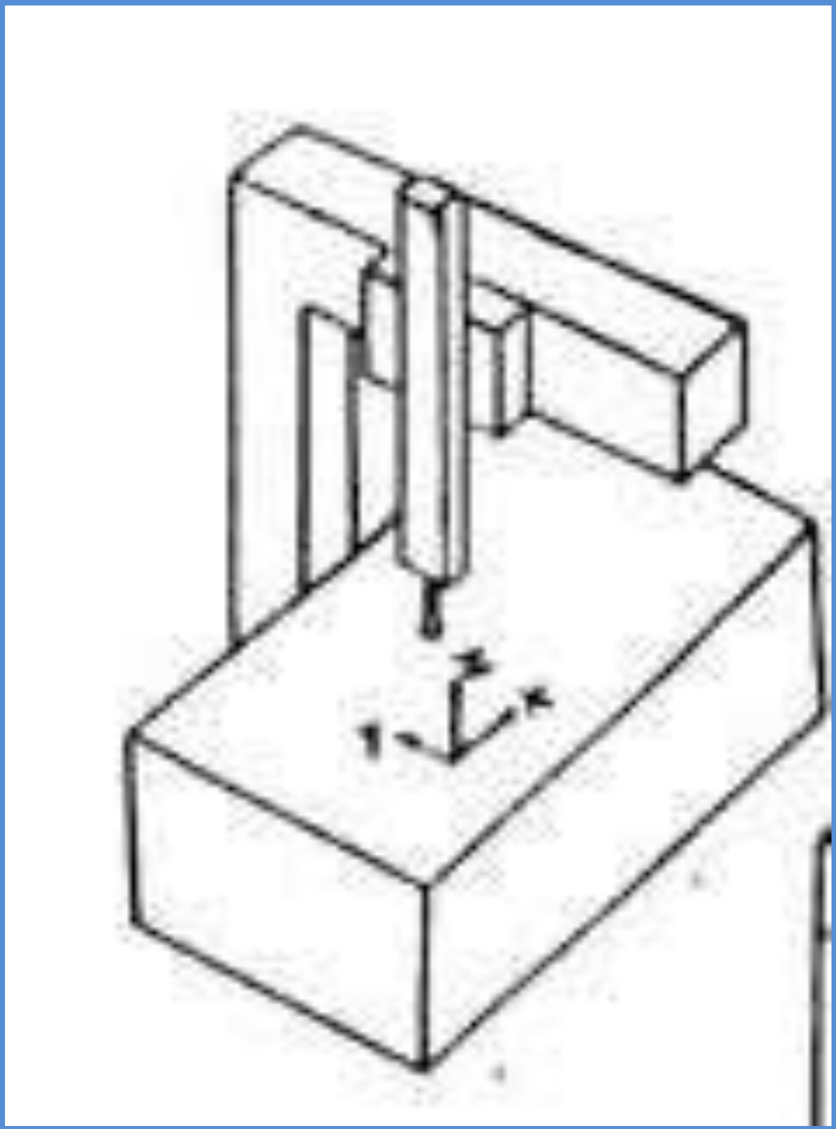
Step 4: Measure the Part

Step 5:Representation of measurement results after

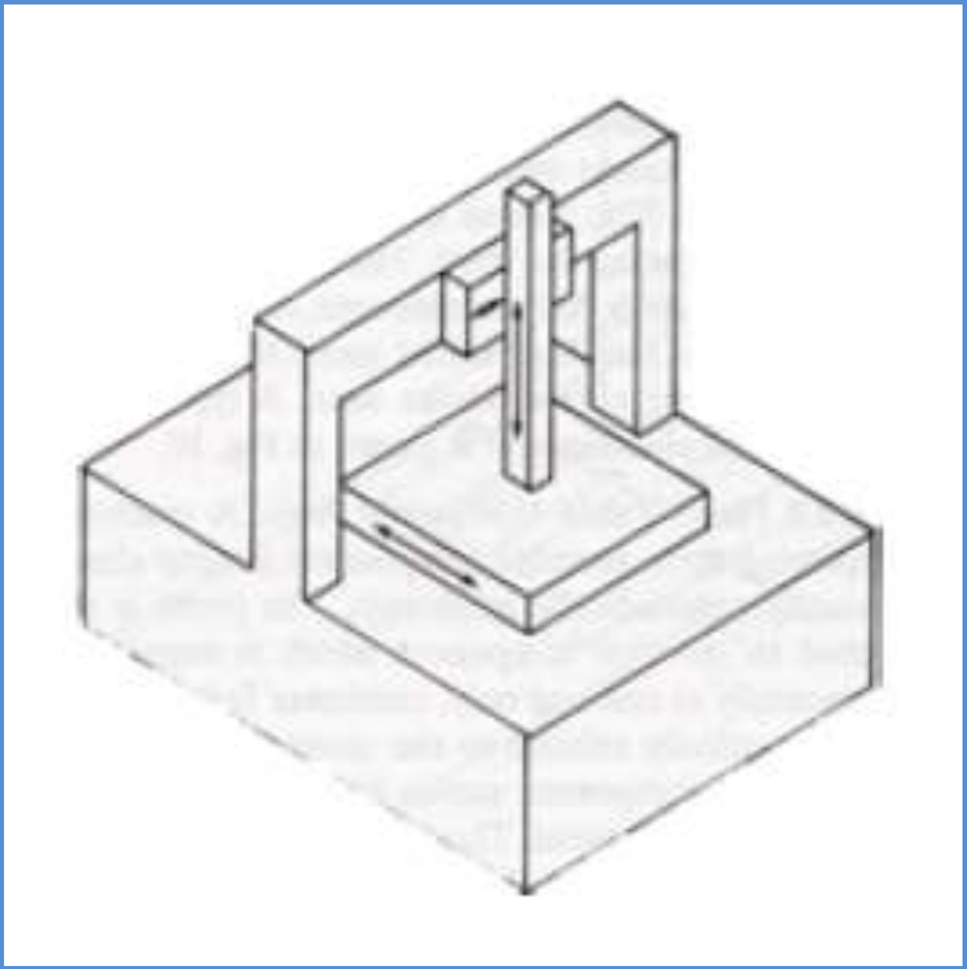
Types of CMM

- Moving bridge
- Fixed bridge
- Cantilever
- Gantry

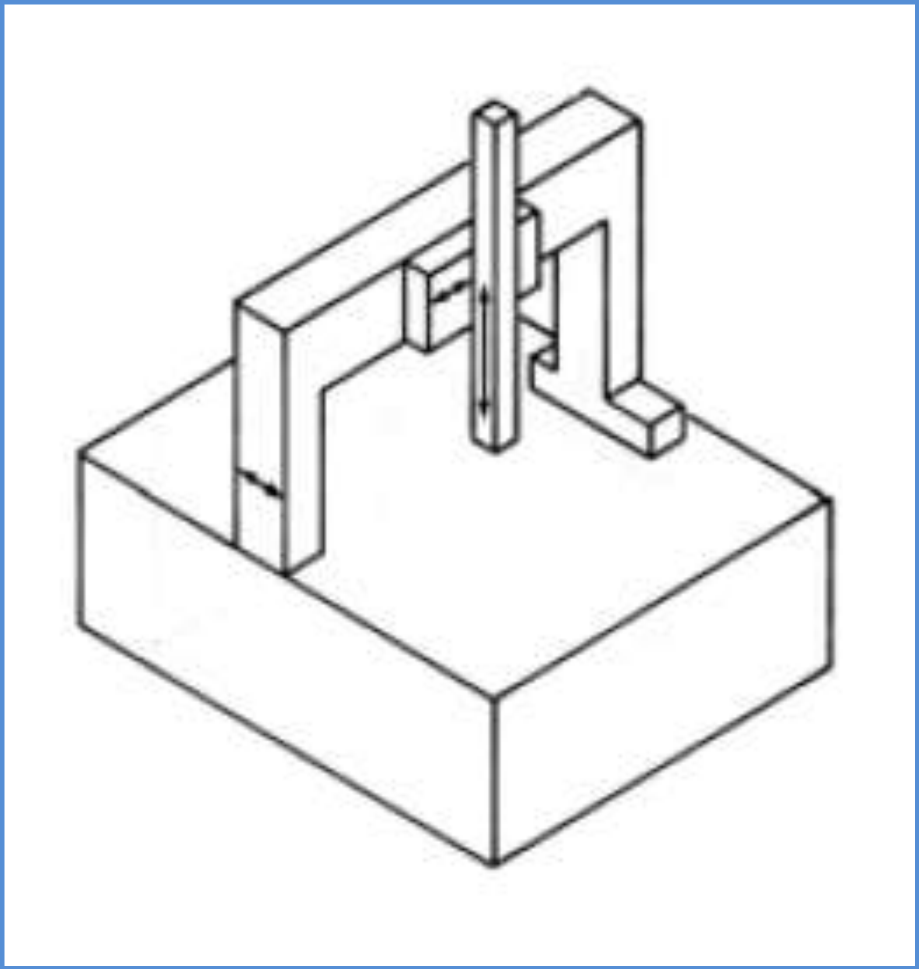
Cantilever CMM(Manual)



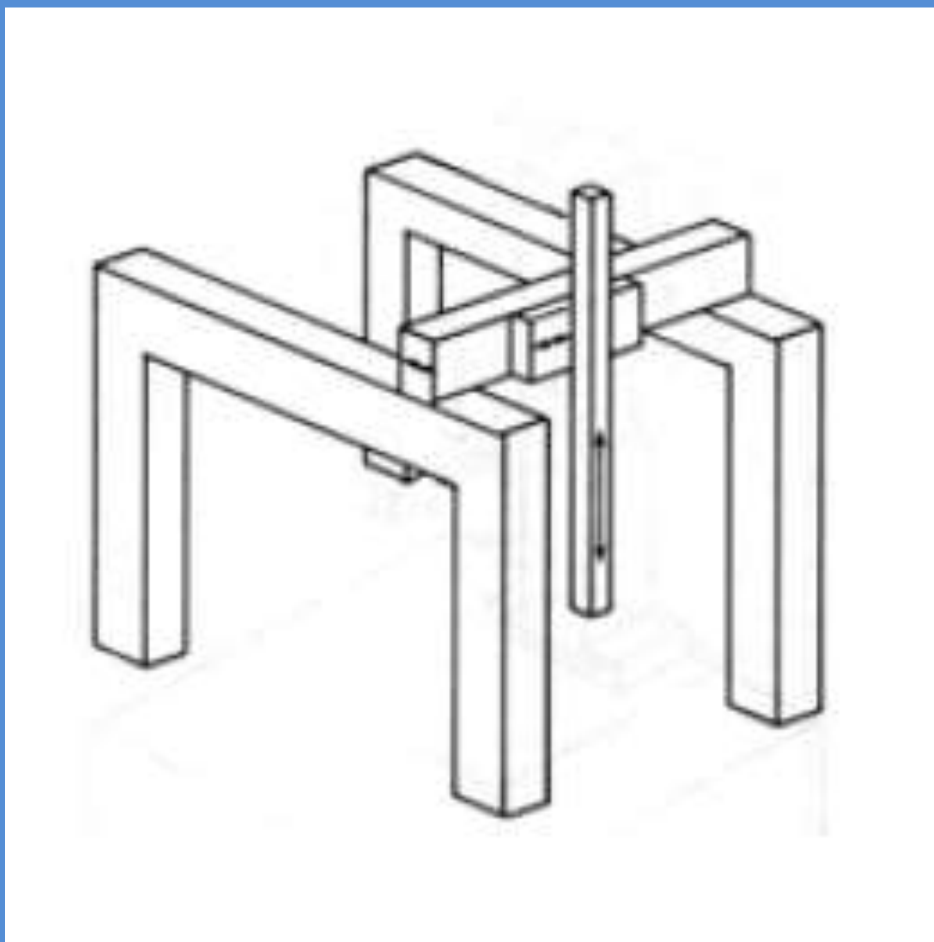
Fixed Bridge CMM



Moving Bridge CMM(Computer Controlled)



Gantry Type CMM



Measuring Ranges

18.11" x 18.11" x 11.81"
(460 x 460 x 300mm)
40.20" x 32.20" x 24.21"
(1021 x 818 x 615mm)

Potential Sources of CMM Error

- **Sources of errors in CMM measurements**
  - Spatial errors
  - Computational errors.
- **Spatial errors** are errors in the measured position of a point on the surface of the Work-piece
- **Computational errors** are the errors in the estimated dimensions and form deviations of the work-piece

Spatial Errors

- The accuracy of the components of the CMM – the guide-ways, the scales, the probe system and the qualification sphere.
- The environment in which the CMM operates – the ambient temperature, temperature gradients, humidity and vibration.
- The probing strategy used – the magnitude and direction of the probe force, the type of probe stylus used and the measuring speed of the probe.
- The characteristics of the work-piece – elasticity, surface roughness, hardness and the mass of the component.

Computational errors

- The CMM software used to estimate the geometry of the work-piece.
- The precision of the computer used on the CMM.
- The number and relative position of the measured points.
- The extent to which the geometry departs from the ideal geometric form.

Surface Treatments, Coatings, and Cleaning

CHAPTER 34

- The preceding chapters have described methods of producing desired shapes from a wide variety of materials; although material and process selection is very important, often the surface properties of a component determine its performance or commercial success.
- This chapter describes various surface-finishing operations that can be performed for technical and aesthetic reasons subsequent to manufacturing a part.
- The chapter presents the surface treatment, cleaning, and coating processes that are commonly performed and includes a discussion of mechanical surface treatments such as shot peening, laser peening, and roller burnishing, with the benefit of imparting compressive residual stresses onto metal surfaces.
- Coating operations are then examined, including cladding, thermal spray operations, physical and chemical vapor deposition, ion implantation, and electroplating.
- The benefits of diamond and diamond-like carbon coatings are also investigated.
- Finally, surface-texturing, painting, and cleaning operations are described.

34.1 Introduction

After a part is manufactured, some of its surfaces may have to be processed further in order to ensure that they receive certain properties and characteristics. It may be necessary to perform **surface treatments** in order to

- *Improve resistance to wear, erosion, and indentation* (e.g., for machine-tool slideways, as shown in Figs. 23.2 and 35.1, wear surfaces of machinery, and shafts, rolls, cams, and gears)
- *Control friction* (on sliding surfaces of tools, dies, bearings, and machine ways)
- *Reduce adhesion* (of electrical contacts)
- *Improve lubrication* (surface modification to retain lubricants)
- *Improve resistance to corrosion and oxidation* (on sheet metals for automobile bodies, gas-turbine components, food packaging, and medical devices)

- *Improve fatigue resistance* (of bearings and shafts with fillets)
- *Rebuild surfaces* (on worn tools, dies, molds, and machine components)
- *Modify surface texture* (appearance, dimensional accuracy, and frictional characteristics)
- *Impart decorative features* (color and texture).

Numerous techniques are used to impart these characteristics to various types of metallic, nonmetallic, and ceramic materials on the basis of mechanisms that involve (a) plastic deformation of the workpiece surface, (b) chemical reactions, (c) thermal means, (d) deposition, (e) implantation, and (f) organic coatings and paints. We begin with surface-hardening techniques and then continue with descriptions of different types of coatings that are applied to surfaces by various means. Some of these techniques also are used in the manufacture of semiconductor devices, as described in Chapter 28.

Techniques that are used to impart texture on workpiece surfaces and types of organic coatings used for various purposes are then described. The chapter ends with a discussion of methods used for cleaning manufactured surfaces before the components are assembled into the completed product and made ready for service. Environmental considerations regarding the fluids used and the waste material from various surface-treatment processes are also included, as they are an important factor to be considered.

34.2 Mechanical Surface Treatments

Several techniques are used to mechanically improve the surface properties of manufactured components. The more common methods are the following:

Shot Peening. In shot peening, the workpiece surface is impacted repeatedly with a large number of cast steel, glass, or ceramic shot (small balls), which make overlapping indentations on the surface. This action, using shot sizes that range from 0.125 to 5 mm in diameter, causes plastic surface deformation at depths up to 1.25 mm. Because the plastic deformation is not uniform throughout the part's thickness, shot peening causes compressive residual stresses on the surface, thus improving the fatigue life of the component by delaying the initiation of fatigue cracks. Unless the process parameters are controlled properly, the plastic deformation of the surface can be so severe that it can damage the surface. The extent of deformation can be reduced by *gravity peening*, which involves larger shot sizes, but fewer impacts on the workpiece surface.

Shot peening is used extensively on shafts, gears, springs, oil-well drilling equipment, and jet-engine parts, such as turbine and compressor blades. However, note that if these parts are subjected to high temperatures, the residual stress will begin to relax (thermal relaxation) and their beneficial effects will be diminished greatly. An example is gas-turbine blades performing at their operating temperatures.

Laser Shot Peening. In this process, also called *laser shock peening* and first developed in the mid-1960s (but not commercialized until much later), the workpiece surface is subjected to planar laser shocks (pulses) from high-power lasers. This surface-treatment process produces compressive residual-stress layers that are typically 1 mm deep with less than 1% of cold working of the surface. Laser peening has been applied successfully and reliably to jet-engine fan blades and to materials such as titanium, nickel alloys, and steels for improved fatigue resistance and some corrosion resistance. Laser intensities necessary for the process are on the order of 100 to 300 J/cm^2 and have a pulse duration of about 30 nanoseconds. Currently, the basic limitation of laser shot peening for industrial, cost-effective applications is the high cost of the high-power lasers (up to 1 kW) that must operate at energy levels of 100 J/pulse.

Water-jet Peening. In this more recently developed process, a water jet at pressures as high as 400 MPa impinges on the surface of the workpiece, inducing compressive residual stresses and surface and subsurface hardening at the same level as in shot peening. The water-jet peening process has been used successfully on steels and aluminum alloys. The control of process variables (jet pressure, jet velocity, the design of the nozzle, and its distance from the surface) is important in order to avoid excessive surface roughness and surface damage.

Ultrasonic Peening. This process uses a hand tool based on a piezoelectric transducer. Operating at a frequency of 22 kHz, it can have a variety of heads for different applications.

Roller Burnishing. In this process, also called *surface rolling*, the surface of the component is cold worked by a hard and highly polished roller or set of rollers. The process is used on various flat, cylindrical, or conical surfaces (Fig. 34.1). Roller burnishing improves surface finish by removing scratches, tool marks, and pits and induces beneficial compressive surface residual stresses. Consequently, corrosion resistance is improved, since corrosive products and residues cannot be entrapped. In a variation of this process called *low-plasticity burnishing*, the roller travels only once over the surface, inducing residual stresses and minimal plastic deformation.

Internal cylindrical surfaces also are burnished by a similar process, called **ballizing** or **ball burnishing.** In this process, a smooth ball (slightly larger than the bore diameter) is pushed through the length of the hole.

Roller burnishing is used to improve the mechanical properties of surfaces as well as their surface finish. It can be used either by itself or in combination with other finishing processes, such as grinding, honing, and lapping. The equipment can be mounted on various CNC machine tools for improved productivity and consistency of performance. All types of metals (soft or hard) can be roller burnished. Roller burnishing is typically used on hydraulic-system components, seals, valves, spindles, and fillets on shafts.

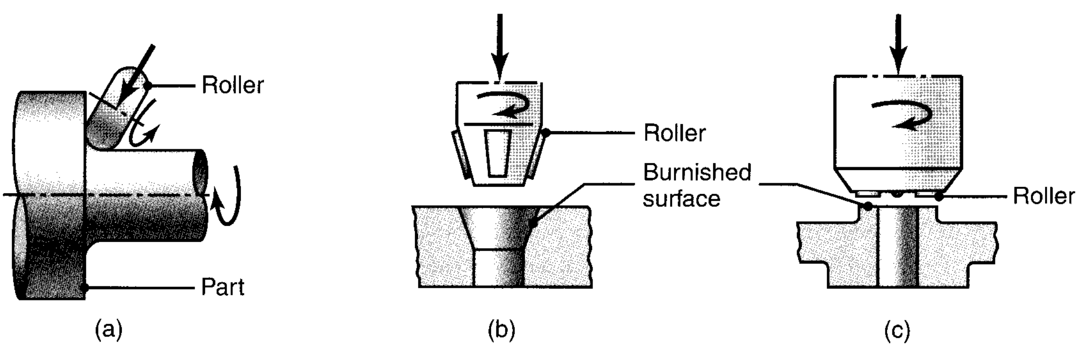


FIGURE 34.1 Burnishing tools and roller burnishing of (a) the fillet of a stepped shaft to induce compressive surface residual stresses for improved fatigue life; (b) a conical surface; and (c) a flat surface.

Explosive Hardening. In explosive hardening, the surfaces are subjected to high transient pressures through the placement and detonation of a layer of an explosive sheet directly on the workpiece surface. The contact pressures that develop as a result can be as high as 35 GPa and can last about 2 to 3 μs. Major increases in surface hardness can be achieved with this method, with very little change (less than 5%) in the shape of the component. Railroad rail surfaces, for example, are explosively hardened.

34.3 Mechanical Plating and Cladding

Mechanical Plating. In mechanical plating (also called *mechanical coating, impact plating*, or *peen plating*), fine metal particles are compacted over the workpiece surfaces by glass, ceramic, or porcelain beads that are propelled by rotary means (such as tumbling). This process, which is basically one of cold-welding particles onto a surface, typically is used for hardened-steel parts for automobiles, with plating thickness usually less than 25 μm.

Cladding. In this process, also called *clad bonding*, metals are bonded with a thin layer of corrosion-resistant metal through the application of pressure by rolls or other means. A typical application is the cladding of aluminum (*Alclad*), in which a corrosion-resistant layer of aluminum alloy (usually in sheet or tubular form) is clad over an aluminum-alloy body (core). The cladding layer is anodic to the core and usually has a thickness that is less than 10% of the total thickness.

Examples of cladding are 2024 aluminum clad with 1230 aluminum, and 3003, 6061, and 7178 aluminum clad with 7072 aluminum. Other applications are steels clad with stainless-steel or nickel alloys. The cladding material also may be applied with dies (as in cladding steel wire with copper) or explosives. Multiple-layer cladding is also utilized in special applications.

Laser cladding consists of the fusion of a different material over the substrate. It has been applied successfully to metals and ceramics, especially for enhanced friction and good wear behavior of the components.

34.4 Case Hardening and Hard Facing

Surfaces may be hardened by thermal means in order to improve their frictional and wear properties, as well as their resistance to indentation, erosion, abrasion, and corrosion. The most common methods are described next.

Case Hardening. Traditional methods of case hardening (*carburizing, carbonitriding, cyaniding, nitriding, flame hardening*, and *induction hardening*) are described in Section 4.10 and summarized in Table 4.1. In addition to common heat sources (gas and electricity), an electron beam or laser beam can be used as a heat source in surface hardening of both metals and ceramics. Case hardening, as well as some of the other surface-treatment processes described in this chapter, induces residual stresses on surfaces. The formation of martensite during case hardening causes compressive residual stresses on surfaces. Such stresses are desirable, because they improve the fatigue life of components by delaying the initiation of fatigue cracks.

Hard Facing. In this process, a relatively thick layer, edge, or point of wear-resistant hard metal is deposited on the workpiece surface by the fusion-welding techniques described in Chapter 30. Numerous layers (known as *weld overlay*) can be deposited to repair worn parts. Hard facing enhances the wear resistance of the materials; hence, such materials are used in the manufacture of tools, dies, and various industrial components. Worn parts also can be hard faced for extended use.

Spark Hardening. Hard coatings of tungsten, chromium, or molybdenum carbides can be deposited by an electric arc in a process called *spark hardening, electric spark hardening*, or *electrospark deposition*. The deposited layer is typically 250 μm thick. Hard-facing alloys can be used as electrodes, rods, wires, or powder in spark hardening. Typical applications for these alloys are as valve seats, oil-well drilling tools, and dies for hot metalworking.

34.5 Thermal Spraying

Thermal spraying is a series of processes in which coatings of various metals, alloys, carbides, ceramics, and polymers are applied to metal surfaces by a spray gun with a stream heated by an oxyfuel flame, an electric arc, or a plasma arc. The earliest applications of thermal spraying (in the 1910s) involved metals (hence the term **metallizing** has also been used), and these processes are under continuous refinement. The surfaces to be sprayed are first cleaned of oil and dirt, and then roughened by, for example, grit blasting, to improve their bond strength (see Section 26.8). The coating material can be in the form of wire, rod, or powder, and when the droplets or particles impact the workpiece, they solidify and bond to the surface.

Depending on the process, particle velocities typically range from a low of about 150 to 1000 m/s, but can be higher for special applications. Temperatures are in the range from 3000° to 8000°C. The coating is hard and wear resistant, with a layered structure of deposited material. However, the coating can have a porosity as high as 20% due to entrapped air and oxide particles because of the high temperatures involved. Bond strength depends on the particular process and techniques used and is mostly mechanical in nature (hence the importance of roughening the surface prior to spraying), but can be metallurgical in some cases. Bond strength generally ranges from 7 to 80 MPa, depending on the particular process used.

Typical applications of thermal spraying include aircraft engine components (such as those used in rebuilding worn parts), structures, storage tanks, tank cars, rocket motor nozzles, and components that require resistance to wear and corrosion. In an automobile, thermal spraying typically can be applied to crankshafts, valves, fuel-injection nozzles piston rings, and engine blocks. The process is also used in the gas and petrochemical industries, for the repair of worn parts and to restore dimensional accuracy to parts that have not been machined or formed properly.

The source of energy in thermal-spraying processes is of two types: combustion and electrical.

Combustion Spraying

- **Thermal wire spraying** (Fig. 34.2a): The oxyfuel flame melts the wire and deposits it on the surface. The bond is of medium strength, and the process is relatively inexpensive.
- **Thermal metal-powder spraying** (Fig. 34.2b): This process is similar to flame wire spraying, but uses a metal powder instead of the wire.

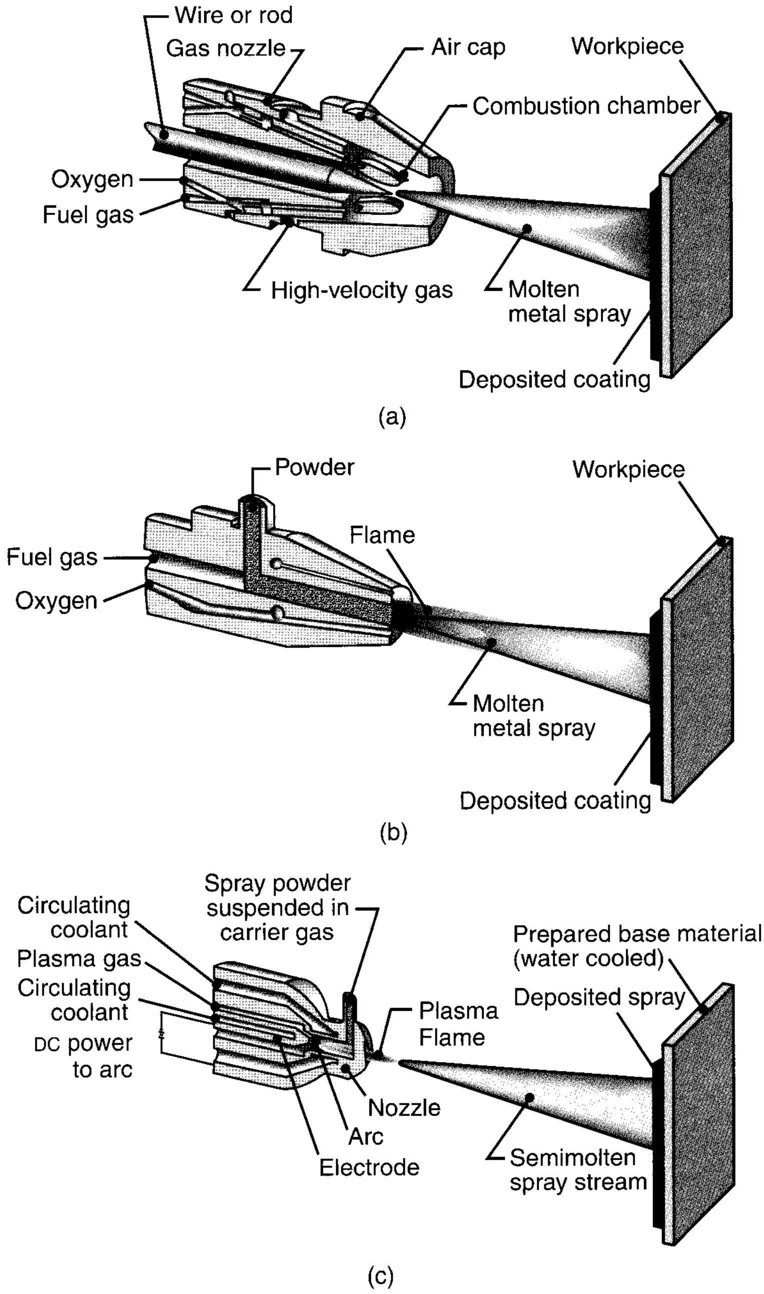


FIGURE 34.2 Schematic illustrations of thermal-spray operations: (a) thermal wire spray, (b) thermal metal-powder spray, and (c) plasma spray.

- **Detonation gun:** Controlled and repeated explosions take place by means of an oxyfuel–gas mixture. The detonation gun has a performance similar to that of plasma.
- **High-velocity oxyfuel-gas spraying** (HVOF): This process produces a high performance similar to that of the detonation gun, but is less expensive.

Electrical Spraying

- **Twin-wire arc:** An arc is formed between two consumable wire electrodes. The resulting bond has good strength, and the process is the least expensive.

- **Plasma**: Either conventional, high-energy, or vacuum (Fig. 34.2c) plasma produces temperatures on the order of 8300°C and results in good bond strength with very low oxide content. **Low-pressure plasma spray** (LPPS) and **vacuum plasma spray** both produce coatings with high bond strength and with very low levels of porosity and surface oxides.

Cold Spraying. In this more recent development, the particles to be sprayed are at a lower temperature and are not melted; thus, oxidation is minimal. The spray jet in cold spraying is narrow and highly focused; it has very high impact velocities, thereby improving the bond strength of the particles on the surface.

EXAMPLE 34.1 Repair of a Worn Turbine-engine Shaft by Thermal Spraying

The shaft of the helical gear for a GE T-38 gas-turbine engine had two worn regions on its nitrided surfaces. The case-hardened depth was 0.3 mm. Even though the helical gears were in good condition, the part was considered scrap because there was no approved method of repair. The worn regions first were machined undersize, grit blasted, and coated with tungsten carbide (12% cobalt content; see Section 22.5) using the high-velocity oxyfuel-gas thermal-spraying (HVOF) technique. Then the part was finish machined to the dimensions of the original shaft. The total cost of repair was a fraction of the projected cost of replacing the part.

Source: Courtesy of Plasma Technology, Inc.

34.6 Vapor Deposition

Vapor deposition is a process in which the substrate (workpiece surface) is subjected to chemical reactions by gases that contain chemical compounds of the material to be deposited. The coating thickness is usually a few microns, which is much less than the thicknesses that result from the techniques described in Sections 34.2 and 34.3. The deposited materials can consist of metals, alloys, carbides, nitrides, borides, ceramics, or oxides. Control of the coating composition, thickness, and porosity are important. The substrate may be metal, plastic, glass, or paper. Typical applications for vapor deposition are the coating of cutting tools, drills, reamers, milling cutters, punches, dies, and wear surfaces.

There are two major vapor-deposition processes: physical vapor deposition and chemical vapor deposition.

34.6.1 Physical Vapor Deposition

The three basic types of *physical vapor deposition* (PVD) processes are (1) vacuum deposition, or arc evaporation; (2) sputtering; and (3) ion plating. These processes are carried out in a high vacuum and at temperatures in the range from 200° to 500°C. In PVD, the particles to be deposited are carried physically to the workpiece, rather than being carried by chemical reactions (as in chemical vapor deposition).

Vacuum Deposition. In vacuum deposition (or evaporation), the metal is evaporated at a high temperature in a vacuum and is deposited on the substrate (which is usually at room temperature or slightly higher for improved bonding). Coatings of uniform thickness can be deposited, even on complex shapes. In **arc deposition** (PV/ARC), the coating material (cathode) is evaporated by several arc evaporators

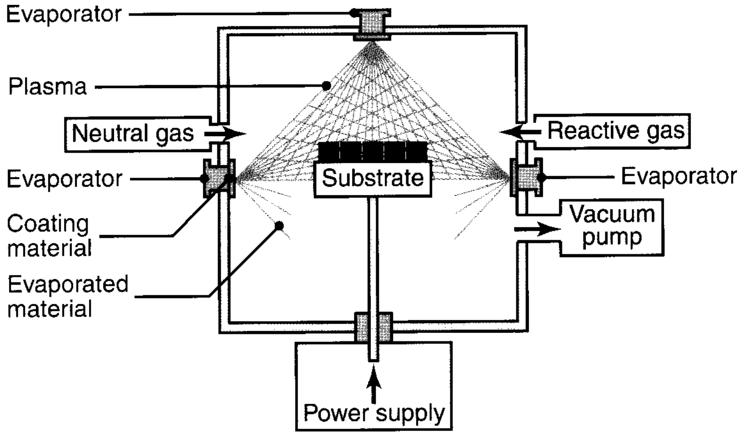


FIGURE 34.3 (a) Schematic illustration of the physical-vapor-deposition process. Note that there are three arc evaporators and the parts to be coated are placed on a tray inside the chamber.

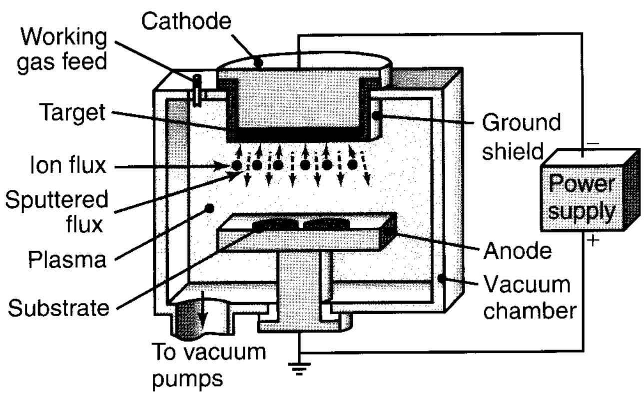


FIGURE 34.4 Schematic illustration of the sputtering process.

(Fig. 34.3) using highly localized electric arcs. The arcs produce a highly reactive plasma, which consists of ionized vapor of the coating material. The vapor condenses on the substrate (anode) and coats it. Applications of this process are both functional (oxidation-resistant coatings for high-temperature applications, electronics, and optics) and decorative (hardware, appliances, and jewelry). **Pulsed-laser deposition** is a more recent, related process in which the source of energy is a pulsed laser.

Sputtering. In *sputtering*, an electric field ionizes an inert gas (usually argon). The positive ions bombard the coating material (cathode) and cause sputtering (ejection) of its atoms. The atoms then condense on the workpiece, which is heated to improve bonding (Fig. 34.4). In **reactive sputtering,** the inert gas is replaced by a reactive gas (such as oxygen), in which case the atoms are oxidized and the oxides are deposited. Carbides and nitrides also are deposited by reactive sputtering. Alternatively, very thin polymer coatings can be deposited on metal and polymeric substrates with a reactive gas, causing polymerization of the plasma. **Radio-frequency** (RF) sputtering is used for nonconductive materials, such as electrical insulators and semiconductor devices.

Ion Plating. *Ion plating* is a generic term that describes various combined processes of sputtering and vacuum evaporation. An electric field causes a glow, generating a plasma (Fig. 34.5). The vaporized atoms in this process are ionized only partially. **Ion-beam-enhanced (assisted) deposition** is capable of producing thin films as coatings for semiconductor, tribological, and optical applications. Bulky parts can be coated in large chambers using high-current power supplies of 15 kW and voltages of 100,000 DC. **Dual ion-beam deposition** is a hybrid coating technique that combines PVD with simultaneous ion-beam bombardment. This technique results in good adhesion on metals, ceramics, and polymers. Ceramic bearings and dental instruments are examples of its applications.

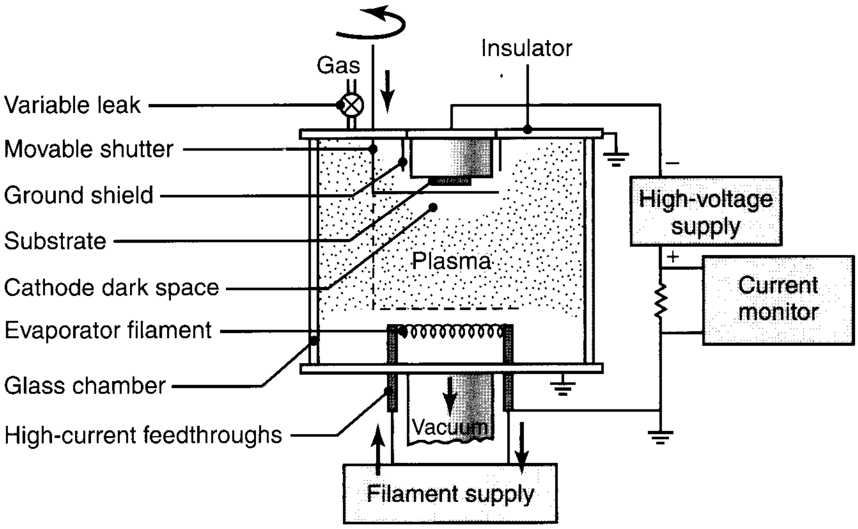


FIGURE 34.5 Schematic illustration of an ion-plating apparatus.

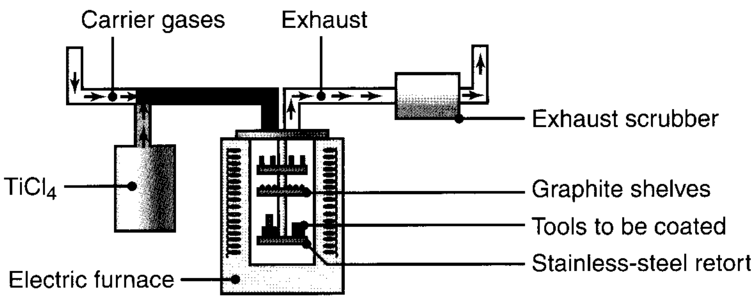


FIGURE 34.6 Schematic illustration of the chemical-vapor-deposition process. Note that parts and tools to be coated are placed on trays inside the chamber.

34.6.2 Chemical Vapor Deposition

Chemical vapor deposition (CVD) is a *thermochemical* process (Fig. 34.6). In a typical application, such as coating cutting tools with titanium nitride (TiN), the tools are placed on a graphite tray and heated at 950° to 1050°C at atmospheric pressure in an inert atmosphere. Titanium tetrachloride (a vapor), hydrogen, and nitrogen are then introduced into the chamber. The chemical reactions form titanium nitride on the tool surfaces. For a coating of titanium carbide, methane is substituted for the other gases.

Deposited coatings usually are thicker than those obtained with PVD. A typical cycle for CVD is long, consisting of (a) three hours of heating, (b) four hours of coating, and (c) six to eight hours of cooling to room temperature. The thickness of the coating depends on the flow rates of the gases used, the time, and the temperature.

The types of coatings and the workpiece materials allowable are fairly unrestricted in CVD. Almost any material can be coated and any material can serve as a substrate, although bond strength may vary. The CVD process is also used to produce diamond coatings without binders, unlike polycrystalline diamond films, which use

1 to 10% binder materials. A more recent development in CVD is **medium-temperature CVD** (MTCVD). This technique results in a higher resistance to crack propagation than CVD affords.

34.7 Ion Implantation and Diffusion Coating

In *ion implantation*, ions (charged atoms) are introduced into the surface of the workpiece material. The ions are accelerated in a vacuum to such an extent that they penetrate the substrate to a depth of a few microns. Ion implantation (not to be confused with ion plating) modifies surface properties by increasing surface hardness and improving resistance to friction, wear, and corrosion. The process can be controlled accurately, and the surface can be masked to prevent ion implantation in unwanted locations.

Ion implantation is particularly effective on materials such as aluminum, titanium, stainless steels, tool and die steels, carbides, and chromium coatings. The process is typically used on cutting and forming tools, dies and molds, and metal prostheses, such as artificial hips and knees. When used in some specific applications, such as semiconductors (Section 28.3), ion implantation is called **doping**—meaning "alloying with small amounts of various elements."

Diffusion Coating. This is a process in which an alloying element is diffused into the surface of the substrate (usually steel), altering its surface properties. The alloying elements can be supplied in solid, liquid, or gaseous states. The process has acquired different names (depending on the diffused element), as shown in Table 4.1, which lists diffusion processes such as *carburizing*, *nitriding*, and *boronizing*.

34.8 Laser Treatments

As described in various chapters of this book, lasers are having increasingly broader applications in manufacturing processes (laser machining, forming, joining, rapid prototyping, and metrology) and surface engineering (laser peening, alloying, surface treatments, and texturing). Powerful, efficient, reliable, and less expensive lasers are now available for a variety of cost-effective surface treatments, as outlined in Fig. 34.7.

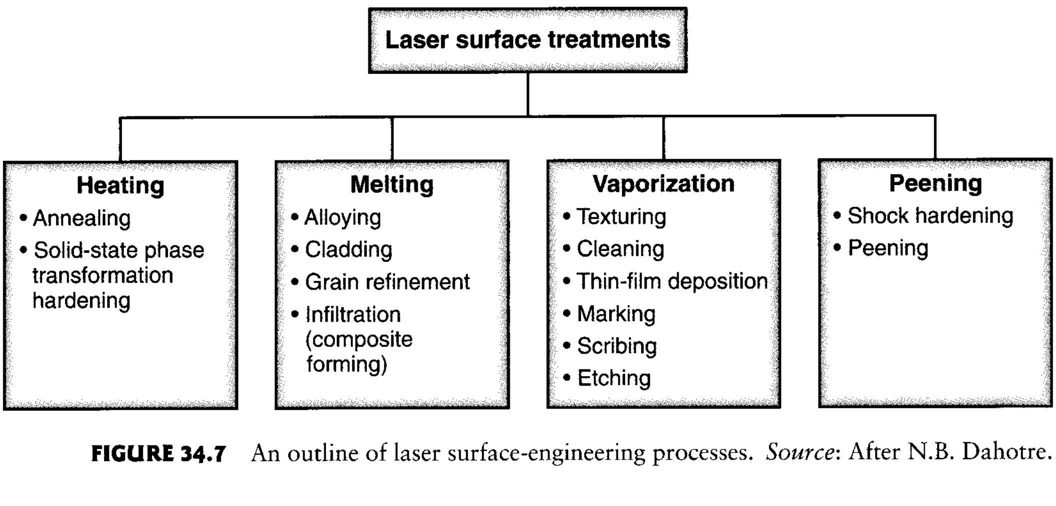


FIGURE 34.7 An outline of laser surface-engineering processes. *Source*: After N.B. Dahotre.

EXAMPLE 34.2 Applications of Laser Surface Engineering

In this example, several applications of lasers in engineering practice are given. The most commonly used lasers are Nd:YAG and CO_2; excimer lasers are generally used for surface texturing (see also Table 27.2).

Localized surface hardening—Cast irons: diesel-engine cylinder liners, automobile steering assemblies, and camshafts. Carbon steels: gears and electromechanical parts.

Surface alloying—Alloy steels: bearing components. Stainless steels: diesel-engine valves and seat inserts. Tool and die steels: dies for forming and die casting.

Cladding—Alloy steels: automotive valves and valve seats. Superalloys: turbine blades.

Ceramic coating—Aluminum–silicon alloys: automotive-engine bore.

Surface texturing—Metals, plastics, ceramics, and wood: all types of products.

34.9 Electroplating, Electroless Plating, and Electroforming

Plating, like other coating processes, imparts the properties of resistance to wear, resistance to corrosion, high electrical conductivity, and better appearance and reflectivity, as well as similar desirable properties.

Electroplating. In electroplating, the workpiece (cathode) is plated with a different metal (anode), which is transferred through a water-based electrolytic solution (Fig. 34.8). Although the plating process involves a number of reactions, the process consists basically of the following sequence:

1. The metal ions from the anode are discharged by means of the potential energy from the external source of electricity, or are delivered in the form of metal salts.

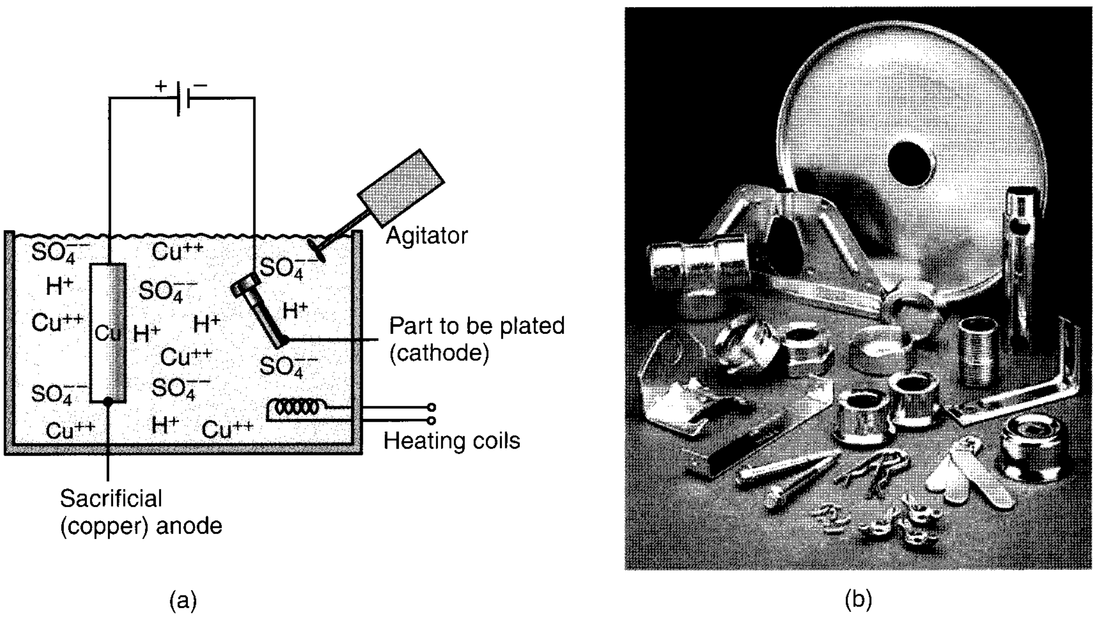


FIGURE 34.8 (a) Schematic illustration of the electroplating process. (b) Examples of electroplated parts. *Source*: Courtesy of BFG Electroplating.

2. The metal ions are dissolved into the solution.
3. The metal ions are deposited on the cathode.

The volume of the plated metal can be calculated from the equation

$$\text{Volume} = cIt, \tag{34.1}$$

where I is the current in amperes, t is time, and c is a constant that depends on the plate metal, the electrolyte, and the efficiency of the system; typically, c is in the range from 0.03 to 0.1 mm^3/amp-s. Note that, for the same volume of material deposited, the larger the workpiece surface plated, the thinner is the layer. The time required for elecroplating is usually long, because the deposition rate is typically on the order of 75 μm/hour. Thin-plated layers are typically on the order of 1 μm; for thick layers, the plating can be as much as 500 μm.

The *plating solutions* are either strong acids or cyanide solutions. As the metal is plated from the solution, it needs to be periodically replenished, and this is accomplished through two principal methods: salts of metals are occasionally added to the solution, or a *sacrificial anode* of the metal to be plated is used in the electroplating tank and dissolves at the same rate that the metal is deposited.

There are three main forms of electroplating:

1. In **rack plating**, the parts to be plated are placed in a rack, which is then conveyed through a series of process tanks.
2. In **barrel plating**, small parts are placed inside a permeable barrel, which is placed inside the process tank(s). This form of electroplating is commonly performed with small parts, such as bolts, nuts, gears, and fittings. Electrolytic fluid can penetrate through the barrel and provide the metal for plating, and electrical contact is provided through the barrel and through contact with other parts.
3. In **brush processing**, the electrolytic fluid is pumped through a handheld brush with metal bristles. The workpiece can be very large in this circumstance, and the process is suitable for field repair or plating and can be used to apply coatings on large equipment without disassembly.

Simple electroplating can be achieved in a single-process bath or tank, but more commonly, a sequence of operations is used in a plating line. For example, the following tanks and processes may be part of an electroplating operation:

- Chemical cleaning and degreasing tanks will be used to remove surface contaminants and enhance surface adhesion of the plated coating.
- The workpieces may be exposed to a strong acid bath (pickling solution) to reduce or eliminate the thickness of the oxide coating on the workpiece.
- A base coating may be applied. This may involve the same or a different metal than that of the ultimate surface. For example, if the desired metal coating will not adhere well to the substrate, an intermediate coating can be applied. Also, if thick films are desired, a plating tank can be used to quickly develop a film, and a subsequent tank with brightener additives in the electrolytic solution is used to develop the ultimate surface finish.
- A separate tank performs final electroplating.
- Rinse tanks will be used throughout the sequence.

Rinse tanks are necessary for a number of reasons. Some plating is performed with cyanide salts delivering the required metal ions. If any residue acid (such as that from a pickling tank) is conveyed to the cyanide-solution tank, poisonous hydrogen-cyanide gas is exhausted. (This is a significant safety concern, and environmental

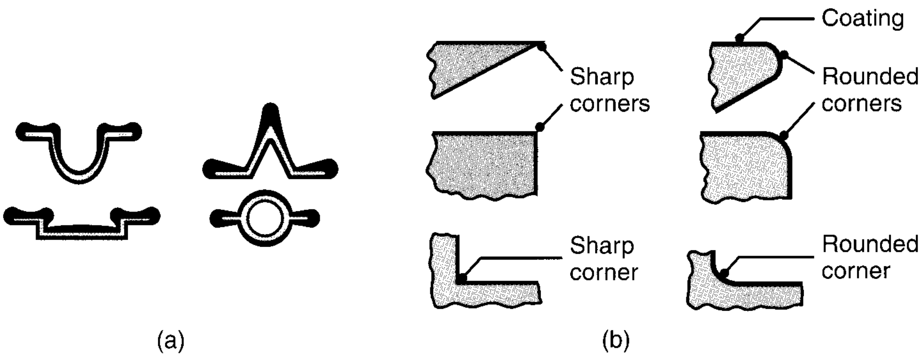


FIGURE 34.9 (a) Schematic illustration of nonuniform coatings (exaggerated) in electroplated parts. (b) Design guidelines for electroplating. Note that sharp external and internal corners should be avoided for uniform plating thickness.

controls are essential in plating facilities.) Also, residue plating solution will contain some metal ions, and it is often desirable to recover those ions by capturing them in a rinse tank.

The rate of film deposition depends on the local current density and is not necessarily uniform on a part. Workpieces with complex shapes may require an altered geometry because of varying plating thicknesses, as shown in Fig. 34.9.

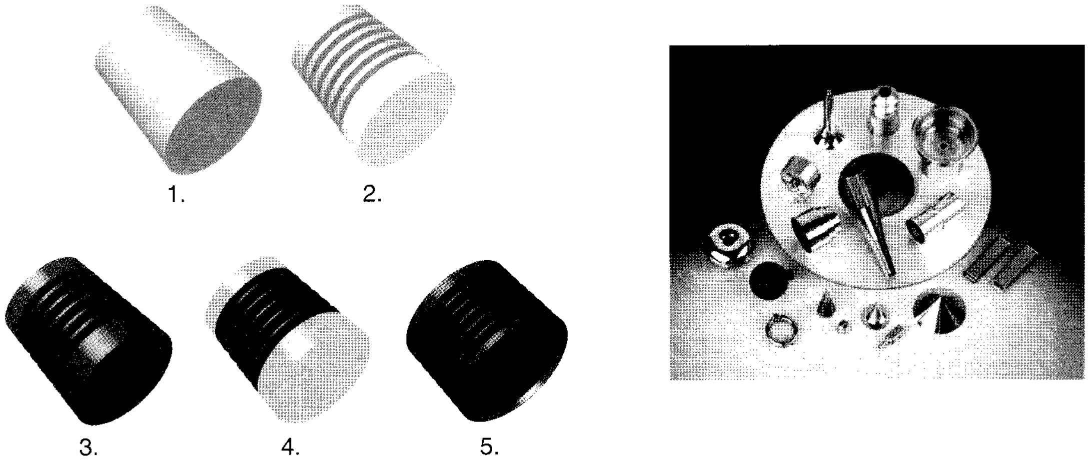
Common plating metals are chromium, nickel (for corrosion protection), cadmium, copper (corrosion resistance and electrical conductivity), and tin and zinc (corrosion protection, especially for sheet steel). **Chromium plating** is done by first plating the metal with copper, then with nickel, and finally with chromium. **Hard chromium plating** is done directly on the base metal and results in a surface hardness of up to 70 HRC (see Fig. 2.14) and a thickness of about 0.05 mm or more. This method is used to improve the resistance to wear and corrosion of tools, valve stems, hydraulic shafts, and diesel- and aircraft-engine cylinder liners. It is also used to rebuild worn parts.

Examples of electroplating include copper-plating aluminum wire and phenolic boards for printed circuits, chrome-plating hardware, tin-plating copper electrical terminals (for ease of soldering), galvanizing sheet metal (see also Section 34.11), and plating components such as metalworking dies that require resistance to wear and galling (cold welding of small pieces from the workpiece surface). Metals such as gold, silver, and platinum are important electroplating materials in the electronics and jewelry industries for electrical contact and decorative purposes, respectively.

Plastics (such as ABS, polypropylene, polysulfone, polycarbonate, polyester, and nylon) also can be electroplating substrates. Because they are not electrically conductive, plastics must be preplated by a process such as electroless nickel plating. Parts to be coated may be simple or complex, and size is not a limitation.

Electroless Plating. This process is carried out by a chemical reaction and without the use of an external source of electricity. The most common application utilizes nickel as the plating material, although copper also is used. In electroless nickel plating, nickel chloride (a metallic salt) is reduced (with sodium hypophosphite as the reducing agent) to nickel metal, which is then deposited on the workpiece. The hardness of nickel plating ranges between 425 and 575 HV; the plating can subsequently be heat treated to 1000 HV. The coating has excellent wear and corrosion resistance.

Cavities, recesses, and the inner surfaces of tubes can be plated successfully. Electroless plating also can be used with nonconductive materials, such as plastics



(a) (b)

FIGURE 34.10 (a) Typical sequence in electroforming. (1) A mandrel is selected with the correct nominal size. (2) The desired geometry (in this case, that of a bellows) is machined into the mandrel. (3) The desired metal is electroplated onto the mandrel. (4) The plated material is trimmed if necessary. (5) The mandrel is dissolved through chemical machining. (b) A collection of electroformed parts. *Source*: Courtesy of Servometer®, Cedar Grove, NJ.

and ceramics. The process is more expensive than electroplating. However, unlike that of electroplating, the coating thickness of electroless plating is always uniform.

Electroforming. A variation of electroplating, electroforming actually is a metal-fabricating process. Metal is electrodeposited on a *mandrel* (also called a *mold* or a *matrix*), which is then removed; thus, the coating itself becomes the product (Fig. 34.10). Both simple and complex shapes can be produced by electroforming, with wall thicknesses as small as 0.025 mm. Parts may weigh from a few grams to as much as 270 kg. Production rates can be increased through the use of multiple mandrels.

Mandrels are made from a variety of materials: metallic (zinc or aluminum) or nonmetallic (which can be made electrically conductive with the proper coatings). Mandrels should be able to be removed physically without damaging the electroformed part. They also may be made of low-melting alloys, wax, or plastics, all of which can be melted away or dissolved with suitable chemicals.

The electroforming process is particularly suitable for low production quantities or intricate parts (such as molds, dies, waveguides, nozzles, and bellows) made of nickel, copper, gold, and silver. The process is also suitable for aerospace, electronics, and electro-optics applications.

34.10 Conversion Coatings

Conversion coating, also called *chemical-reaction priming*, is the process of producing a coating that forms on metal surfaces as a result of chemical or electrochemical reactions. Various metals (particularly steel, aluminum, and zinc) can be conversion coated. Oxides that naturally form on their surfaces represent a form of conversion coating.

Phosphates, chromates, and *oxalates* are used to produce these coatings, for purposes such as providing corrosion protection, prepainting, and decorative finishing.

An important application is the conversion coating of workpieces to serve as lubricant carriers in cold-forming operations, particularly zinc-phosphate and oxalate coatings (see Section 33.7.6). The two common methods of coating are *immersion* and *spraying*. The equipment required depends on the method of application, the type of product, and quality considerations.

Anodizing. This is an oxidation process (*anodic oxidation*) in which the workpiece surfaces are converted to a hard and porous oxide layer that provides corrosion resistance and a decorative finish. The workpiece is the anode in an electrolytic cell immersed in an acid bath, which results in chemical adsorption of oxygen from the bath. Organic dyes of various colors (usually black, red, bronze, gold, or gray) can be used to produce stable, durable surface films. Typical applications for anodizing are aluminum furniture and utensils, architectural shapes, automobile trim, picture frames, keys, and sporting goods. Anodized surfaces also serve as a good base for painting, especially on aluminum, which otherwise is difficult to paint.

Coloring. As the name implies, coloring involves processes that alter the color of metals, alloys, and ceramics. This change is caused by the conversion of surfaces (by chemical, electrochemical, or thermal processes) into chemical compounds such as oxides, chromates, and phosphates. An example is the *blackening* of iron and steels, a process that utilizes solutions of hot, caustic soda and results in chemical reactions that produce a lustrous, black oxide film on surfaces.

34.11 Hot Dipping

In *hot dipping*, the workpiece (usually steel or iron) is dipped into a bath of molten metal, such as (a) zinc, for galvanized-steel sheet and plumbing supplies; (b) tin, for tinplate and tin cans for food containers; (c) aluminum (aluminizing); and (d) *terne*, an alloy of lead with 10 to 20% tin. Hot-dipped coatings on discrete parts provide long-term corrosion resistance to galvanized pipes, plumbing supplies, and many other products.

A typical continuous *hot-dipped galvanizing* line for sheet steel is shown in Fig. 34.11. The rolled sheet is first cleaned electrolytically and scrubbed by brushing. The sheet is then annealed in a continuous furnace with controlled atmosphere and temperature and dipped in molten zinc at about 450°C. The thickness of the zinc coating is controlled by a wiping action from a stream of air or steam, called an *air knife* (similar to air-drying in car washes). Proper draining for the removal of excess coating materials is important.

The coating thickness is usually given in terms of coating weight per unit surface area of the sheet, typically 150 to 900 g/m^2. The service life depends on the thickness of the zinc coating and the environment to which it is exposed. Various **precoated sheet steels** are used extensively in automobile bodies. Proper draining to remove excess coating materials is an important consideration.

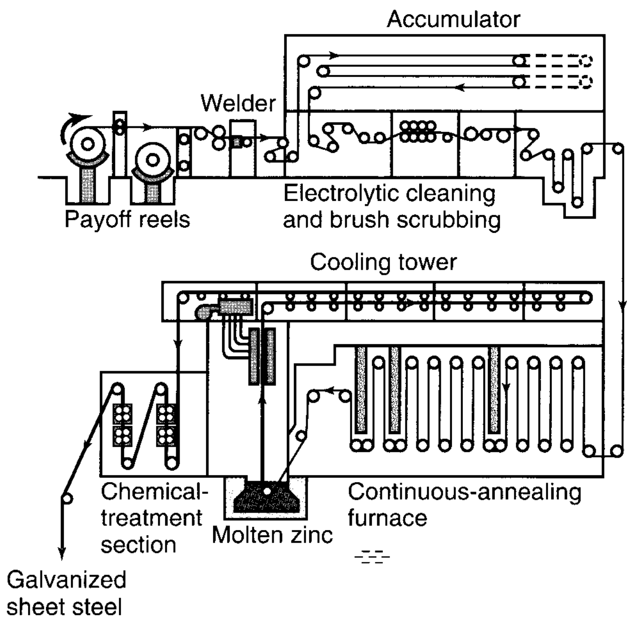


FIGURE 34.11 Flow line for the continuous hot-dipped galvanizing of sheet steel. The welder (upper left) is used to weld the ends of coils to maintain continuous material flow. *Source*: Courtesy of the American Iron and Steel Institute.

34.12 Porcelain Enameling; Ceramic and Organic Coatings

Metals can be coated with a variety of glassy (*vitreous*) coatings to provide corrosion and electrical resistance, and protection at elevated temperatures. These coatings usually are classified as **porcelain enamels** and generally include enamels and ceramics. The root of the word "porcelain" is *porcellana*, in Italian meaning "marine shell." Note that the word *enamel* also is used as a term for glossy paints, indicating a smooth, hard coating.

Enamels. Porcelain enamels are glassy inorganic coatings that consist of various metal oxides and are available in various colors and transparencies. *Enameling* (which was a fully developed art by the Middle Ages) involves fusing the coating material to the substrate by heating both of them at 425° to 1000°C to liquefy the oxides. The coating may be applied by dipping, spraying, or electrodeposition, and thicknesses are usually from 0.05 to 0.6 mm. The viscosity of the material can be controlled using binders so that the coating adheres to vertical surfaces during application. Depending on their composition, enamels have varying resistances to alkali, acids, detergents, cleansers, and water.

Typical applications for porcelain enameling are household appliances, plumbing fixtures, chemical-processing equipment, signs, cookware, and jewelry. Porcelain enamels also are used as protective coatings on jet-engine components. Metals coated are typically steels, cast iron, and aluminum. Glasses are used as a lining (for chemical resistance) where the thickness of the glass is much greater than that of the enamel. **Glazing** is the application of glassy coatings onto ceramic wares to give them decorative finishes and to make them impervious to moisture.

Ceramic Coatings. Materials such as powders of hard metals, aluminum oxide, and zirconium oxide are applied to a substrate at room temperature by means of binders. These coatings act as thermal barriers and have been applied (usually by thermal spraying techniques) to hot-extrusion dies, turbine blades, diesel-engine components, and nozzles for rocket motors to extend the life of these components. They also are used for electrical-resistance applications to withstand repeated arcing. Plasma arcs are used where temperatures may reach 15,000°C, which is much higher than those obtained by flames.

Organic Coatings. Metal surfaces can be coated or precoated with a variety of organic coatings, films, and laminates to improve appearance and corrosion resistance. Coatings are applied to the coil stock on continuous lines (see Fig. 13.10), with thicknesses generally from 0.0025 to 0.2 mm. Such coatings have a wide range of properties: flexibility, durability, hardness, resistance to abrasion and chemicals, color, texture, and gloss. Coated sheet metal is subsequently formed into various products, such as TV cabinets, appliance housings, paneling, shelving, residential-building siding, gutters, and metal furniture.

More critical applications involve, for example, the protection of naval aircraft, which are subjected to high humidity, rain, seawater, pollutants (such as those from ship exhaust stacks), aviation fuel, deicing fluids, and battery acid, as well as being impacted by particles such as dust, gravel, stones, and deicing salts. For aluminum structures, organic coatings consist typically of an epoxy primer and a polyurethane topcoat with a lifetime of four to six years. Primer performance is an important factor in the durability of the coating.

EXAMPLE 34.3 Ceramic Coatings for High-temperature Applications

Certain product characteristics (such as wear resistance and thermal and electrical insulation—particularly at elevated temperatures) can be imparted through ceramic coatings, rather than to the base metals or materials themselves. Selecting materials with such bulk properties can be expensive and may not meet the structural strength requirements of a particular application.

For example, a wear-resistance component does not have to be made completely from a wear-resistant material, since the properties of only a thin layer of its surface are relevant to wear. Consequently, coatings have important applications. Table 34.1 shows various ceramic coatings and their typical applications at elevated temperatures. These coatings may be applied either singly or in layers—as is done in multiple-layer coated cutting tools (see Fig. 22.8).

TABLE 34.1

Property	Type of ceramic	Applications
Wear resistance	Chromium oxide, aluminum oxide, aluminum titania	Pumps, turbine shafts, seals, and compressor rods for the petroleum industry; plastics extruder barrels; extrusion dies
Thermal insulation	Zirconium oxide (yttria stabilized), zironium oxide (calcia stabilized), magnesium zirconate	Fan blades, compressor blades, and seals for gas turbines; valves, pistons, and combustion heads for automotive engines
Electrical insulation	Magnesium aluminate, aluminum oxide	Induction coils, brazing fixtures, general electrical applications

34.13 Diamond Coating and Diamond-like Carbon

The properties of *diamond* that are relevant to manufacturing engineering were described in Section 8.7. Important advances have been made in the diamond coating of metals, glass, ceramics, and plastics using various techniques, such as chemical vapor deposition (CVD), plasma-assisted vapor deposition, and ion-beam-enhanced deposition.

Examples of diamond-coated products are scratchproof windows (such as those used in aircraft and military vehicles for protection in sandstorms); sunglasses; cutting tools (such as inserts, drills, and end mills); wear faces of micrometers and calipers; surgical knives; razors; electronic and infrared heat seekers and sensors; light-emitting diodes; diamond-coated speakers for stereo systems; turbine blades; and fuel-injection nozzles.

Techniques also have been developed to produce **freestanding diamond films** on the order of 1 mm thick and up to 125 mm in diameter. These films include smooth, optically clear diamond film, unlike the hazy gray diamond film formerly produced. This film is then laser cut to desired shapes and brazed onto cutting tools (for example).

The development of these techniques, combined with the important properties of diamond (hardness, wear resistance, high thermal conductivity, and transparency to ultraviolet light and microwave frequencies), has enabled the production of various aerospace and electronic parts and components.

Studies also are continuing regarding the growth of diamond films on crystalline-copper substrate by the implantation of carbon ions. An important application is in making computer chips (see Chapter 28). Diamond can be doped to form *p*- and *n*-type ends on semiconductors to make transistors, and its high thermal conductivity allows the closer packing of chips than would be possible with silicon or gallium-arsenide chips, significantly increasing the speed of computers. Diamond is also an attractive material for future MEMS devices (see Chapter 29), because of its favorable friction and wear characteristics.

Diamond-like Carbon. *Diamond-like carbon* (DLC) coatings, a few nanometers in thickness, are produced by a low-temperature, ion-beam-assisted deposition process. The structure of DLC is between that of diamond and graphite. Less expensive than diamond films, but with similar properties (such as low friction, high hardness, and chemical inertness, as well as having a smooth surface), DLC has applications in such areas as tools and dies, gears, engine components, bearings, MEMS devices, and microscale probes. As a coating on cutting tools, DLC has a hardness of about 5000 HV (compared with about double that for diamond).

34.14 Surface Texturing

As stated throughout the preceding chapters, each manufacturing process (such as casting, forging, powder metallurgy, injection molding, machining, grinding, polishing, electrical-discharge machining, grit blasting, and wire brushing) produces a certain surface texture and appearance. Obviously, some of these processes can be used to modify the surface produced by a previous process—for example, grinding the surface of a cast part. However, manufactured surfaces can be modified further by secondary operations for technical, functional, optical, or aesthetic reasons.

Called *surface texturing*, these additional processes generally consist of the following techniques:

- **Etching:** Using chemicals or sputtering techniques.
- **Electric arcs.**
- **Lasers:** Using excimer lasers with pulsed beams; applications include molds for permanent-mold casting, rolls for temper mills, golf-club heads, and computer hard disks.
- **Atomic oxygen:** Reacting with surfaces to produce a fine, cone-like surface texture.

The possible adverse effects of these processes on material properties and the performance of the textured parts are important considerations.

34.15 Painting

Because of its decorative and functional properties (such as environmental protection, low cost, relative ease of application, and the range of available colors), *paint* has been widely used as a surface coating. The engineering applications of painting range from appliances and machine tools to automobile bodies and aircraft fuselages. Paints generally are classified as

- **Enamels:** Produce a smooth coat with a glossy or semiglossy appearance.
- **Lacquers:** Form a film by evaporation of a solvent.
- **Water-based paints:** Applied easily, but have a porous surface and absorb water, making them more difficult to clean than the first two types.

Paints are available with good resistance to abrasion, temperature extremes, and fading; are easy to apply; and dry quickly. The selection of a particular paint

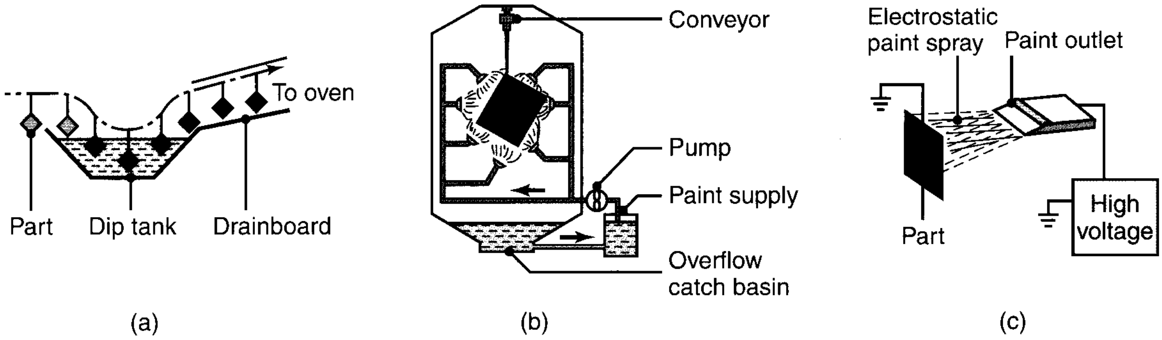


FIGURE 34.12 Methods of paint application: (a) dip coating, (b) flow coating, and (c) electrostatic spraying (used particularly for automotive bodies).

depends on specific requirements. Among these are resistance to mechanical actions (abrasion, marring, impact, and flexing) and to chemical reactions (acids, solvents, detergents, alkalis, fuels, staining, and general environmental attack).

Common methods of applying paint are dipping, brushing, rolling, and spraying (Fig. 34.12). In **electrocoating** or **electrostatic spraying**, paint particles are charged *electrostatically* and are attracted to surfaces to be painted, producing a uniformly adherent coating. Unlike paint losses in conventional spraying, which may be as much as 70% of the paint, the loss can be as little as 10% in electrostatic spraying. However, deep recesses and corners can be difficult to coat with this method. The use of *robotic controls* for guiding the spray nozzles is common (see Section 37.6.3).

34.16 Cleaning of Surfaces

The importance of surfaces in manufacturing and the effects of deposited or adsorbed layers of various elements and contaminants on surface characteristics have been stressed throughout this text. A clean surface can have both beneficial and detrimental effects. Although a surface that is not clean may reduce the tendency for adhesion and galling, cleanliness generally is essential for a more effective application of coatings, painting, adhesive bonding, welding, brazing, and soldering, as well as for the reliable functioning of manufactured parts in machinery, assembly operations, and food and beverage containers.

Cleaning involves the removal of solid, semisolid, or liquid contaminants from a surface and is an important part of manufacturing operations and the economics of production. The word *clean* or the degree of cleanliness of a surface is somewhat difficult to define. Two simple and common tests are as follows:

1. Wiping the surface of, say, a dinner plate with a clean cloth and observing any residues on the cloth.
2. Observing whether water continuously coats the surface of a plate (the *waterbreak test*). If water collects as individual droplets, the surface is not clean. (You can test this phenomenon by wetting dinner plates that have been cleaned to different degrees.)

The type of cleaning process required depends on the type of *metalworking-fluid residues* and *contaminants* to be removed. For example, water-based fluids are easier and less expensive to remove than oil-based fluids. Contaminants (also called *soils*) may consist of rust, scale, chips (and other metallic and nonmetallic debris), metalworking fluids, solid lubricants, pigments, polishing and lapping compounds, and general environmental elements.

Basically, there are three types of cleaning methods:

Mechanical Cleaning. This operation consists of physically disturbing the contaminants, often with wire or fiber brushing, abrasive blasting (jets), tumbling, or steam jets. Many of these processes are particularly effective in removing rust, scale, and other solid contaminants. **Ultrasonic cleaning** is also placed into this category.

Electrolytic Cleaning. In this process, a charge is applied to the part to be cleaned in an aqueous (often alkaline) cleaning solution. The charge results in bubbles of hydrogen or oxygen (depending on polarity) being released at the part's surface. The bubbles are abrasive and aid in the removal of contaminants.

Chemical Cleaning. Chemical cleaning usually involves the removal of oil and grease from surfaces. The operation consists of one or more of the following processes:

- **Solution:** The soil dissolves in the cleaning solution.
- **Saponification:** A chemical reaction converts animal or vegetable oils into a soap that is soluble in water.
- **Emulsification:** The cleaning solution reacts with the soil or lubricant deposits and forms an emulsion; the soil and the emulsifier then become suspended in the emulsion.
- **Dispersion:** The concentration of soil on the surface is decreased by surface-active elements in the cleaning solution.
- **Aggregation:** Lubricants are removed from the surface by various agents in the cleanser and are collected as large dirt particles.

Cleaning Fluids. Common cleaning fluids used in conjunction with electrochemical processes for more effective cleaning include the following:

- **Alkaline solutions:** A complex combination of water-soluble chemicals, alkaline solutions are the least expensive and most widely used cleaning fluids in manufacturing operations. Small parts may be cleaned in rotating drums or barrels. Most parts are cleaned on continuous conveyors by spraying them with the solution and rinsing them with water.
- **Emulsions:** Emulsions generally consist of kerosene and oil-in-water and various types of emulsifiers.
- **Solvents:** Typically petroleum solvents, chlorinated hydrocarbons, and mineral spirits, solvents generally are used for short runs. Fire and toxicity are major hazards.
- **Hot vapors:** Chlorinated solvents can be used to remove oil, grease, and wax. The solvent is boiled in a container and then condensed. This hot-vapor process is simple, and the cleaned parts are dry.
- **Acids, salts,** and **mixtures of organic compounds:** These are effective in cleaning parts covered with heavy paste or oily deposits and rust.

Design Guidelines for Cleaning. Cleaning discrete parts with complex shapes can be difficult. Some design guidelines are as follows:

- Avoid deep, blind holes.
- Make several smaller components instead of one large component, which may be difficult to clean.
- Provide appropriate drain holes in the parts to be cleaned.

The *treatment* and *disposal* of cleaning fluids, as well as of various fluids and waste materials from the processes described in this chapter, are among the most important considerations for environmentally safe manufacturing operations. (See also Section I.4.)

SUMMARY

- Surface treatments are an important aspect of all manufacturing processes. They are used to impart specific chemical, physical, and mechanical properties, such as appearance, and corrosion, friction, wear, and fatigue resistance. Several techniques are available for modifying surfaces.
- The processes used include mechanical working and surface treatments, such as heat treatment, deposition, and plating. Surface coatings include enamels, nonmetallic materials, and paints.
- Clean surfaces can be important in the further processing (e.g., coating, painting, or welding) and use of the product. Cleaning can have a significant economic impact on manufacturing operations. Various mechanical and chemical cleaning methods may be utilized.

KEY TERMS

Anodizing
Ballizing
Blackening
Case hardening
Chemical cleaning
Chemical vapor deposition
Cladding
Cleaning fluids
Coloring
Conversion coating
Diamond coating
Diamondlike carbon
Diffusion coating
Electroforming
Electroless plating
Electroplating
Enamel
Explosive hardening
Freestanding diamond film
Glazing
Hard-chromium plating
Hard facing
Hot dipping
Ion implantation
Ion plating
Laser peening
Mechanical plating
Metallizing
Painting
Physical vapor deposition
Porcelain enamel
Roller burnishing
Shot peening
Spraying
Sputtering
Surface texturing
Thermal spraying
Vacuum evaporation
Vapor deposition
Waterbreak test
Water-jet peening

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REVIEW QUESTIONS

34.1. Explain why surface treatments may be necessary for various parts made by one or more processes.

34.2. What are the advantages of roller burnishing?

34.3. Explain the difference between case hardening and hard facing.

34.4. Describe the principles of physical and chemical vapor deposition. What applications do these processes have?

34.5. What is the principle of electroforming? What are the advantages of electroforming?

34.6. Explain the difference between electroplating and electroless plating.

34.7. How is hot dipping performed?

34.8. What is an air knife? How does it function?

34.9. Describe the common painting systems presently in use in industry.

34.10. What is a conversion coating? Why is it so called?

34.11. Describe the difference between thermal spraying and plasma spraying.

34.12. What is cladding, and why is it performed?

QUALITATIVE PROBLEMS

34.13. Describe how roller-burnishing processes induce compressive residual stresses on the surfaces of parts.

34.14. Explain why some parts may be coated with ceramics. Give some examples.

34.15. Give examples of part designs that are suitable for hot-dip galvanizing.

34.16. Comment on your observations regarding Fig. 34.9.

34.17. It is well known that coatings may be removed or depleted during the service life of components, particularly at elevated temperatures. Describe the factors involved in the strength and durability of coatings.

34.18. Make a list of the coating processes described in this chapter and classify them in relative terms as "thick" or "thin."

34.19. Why is galvanizing important for automotive-body sheet metals?

34.20. Explain the principles involved in various techniques for applying paints.

QUANTITATIVE PROBLEMS

34.21. Taking a simple example, such as the parts shown in Fig. 34.1, estimate the force required for roller burnishing. (*Hint:* See Sections 2.6 and 14.4.)

34.22. Estimate the plating thickness in electroplating a 20-mm solid-metal ball using a current of 10 A and a plating time of 1.5 hours. Assume that $c = 0.08$ in Eq. (34.1).

SYNTHESIS, DESIGN, AND PROJECTS

34.23. Which surface treatments are functional, and which are decorative? Are there any treatments that serve both functions? Explain.

34.24. An artificial implant has a porous surface area where it is expected that the bone will attach and grow into the implant. Without consulting the literature, make recommendations for producing a porous surface; then review the literature and describe the actual processes used.

34.25. If one is interested in obtaining a textured surface on a coated piece of metal, should one apply the coating first or apply the texture first? Explain.

34.26. It is known that a mirror-like surface finish can be obtained by plating workpieces that are ground; that is, the surface finish improves after coating. Explain how this occurs.

34.27. It has been observed in practice that a thin layer of chrome plating, such as that on older model automobile bumpers, is better than a thick layer. Explain why, considering the effect of thickness on the tendency for cracking.

34.28. Outline the reasons that the topics described in this chapter are important in manufacturing processes and operations.

34.29. Shiny, metallic balloons have festive printed patterns that are produced by printing screens and then plated onto the balloons. How can metallic coatings be plated onto a rubber sheet?

34.30. Because they evaporate, solvents and similar cleaning solutions have adverse environmental effects. Describe your thoughts on what modifications could be made to render cleaning solutions more environmentally friendly.

34.31. A roller-burnishing operation is performed on a shaft shoulder to increase fatigue life. It is noted that the resultant surface finish is poor, and a proposal is made to machine the surface layer to further improve fatigue life. Will this be advisable? Explain.

34.32. The shot-peening process can be demonstrated with a ball-peen hammer (in which one of the heads is round). Using such a hammer, make numerous indentations on the surface of a piece of aluminum sheet (a) 2 mm and (b) 10 mm thick, respectively, placed on a hard flat surface such as an anvil. Note that both pieces develop curvatures, but one becomes concave and the other convex. Describe your observations and explain why this happens. (*Hint:* See Fig. 2.14.)

34.33. Obtain several pieces of small metal parts (such as bolts, rods, and sheet metal) and perform the waterbreak test on them. Then clean the surfaces with various cleaning fluids and repeat the test. Describe your observations.

34.34. Inspect various products, such as small and large appliances, silverware, metal vases and boxes, kitchen utensils, and hand tools, and comment on the type of coatings they may have and the reasons they are coated.

Engineering Metrology, Instrumentation, and Quality Assurance

PART VIII

The preceding chapters have described the techniques used to modify the surfaces of components and products to obtain certain desirable properties, discussing the advantages and limitations of each technique along the way. Although dimensional accuracies obtained in individual manufacturing processes were described, we have not yet described how parts are *measured* and *inspected* before they are assembled into products.

Dimensions and other surface features of a part are measured to ensure that it is manufactured consistently and within the specified range of dimensional tolerances. The vast majority of manufactured parts are components or a subassembly of a product, and they must fit and be assembled properly so that the product performs its intended function during its service life. For example, (a) a piston should fit into a cylinder within specified tolerances, (b) a turbine blade should fit properly into its slot on a turbine disk, and (c) the slideways of a machine tool must be produced with a certain accuracy so that the parts produced on that machine are accurate within their desired specifications.

Measurement of the relevant dimensions and features of parts is an integral aspect of **interchangeable parts manufacturing**, the basic concept behind standardization and mass production. For example, if a ball bearing in a machine is worn and has to be replaced, all one has to do is purchase a similar one with the same specification or part number. The same is now done with all products, ranging from bolts and nuts, to gears, to electric motors.

The first of the next two chapters describes the principles involved in, and the various instruments and modern machines used for, measuring dimensional features such as length, angle, flatness, and roundness. Testing and inspecting parts are important aspects of manufacturing operations; thus, the methods used for the nondestructive and destructive testing of parts are also described.

One of the most important aspects of manufacturing is **product quality**. Chapter 36 discusses the technological and economic importance of *building quality into a product* rather than inspecting the product after it is made, as has been done traditionally. This concept is even more significant in view of competitive manufacturing in a global economy.

CHAPTER

35 Engineering Metrology and Instrumentation

- This chapter describes the importance of the measurement of manufactured parts, noting that measurement of parts and their certification to a certain standard is essential to ensuring part fit and thus proper operation.
- A wide variety of measurement strategies, gages, equipment, and machines has been developed, as described in this chapter.
- The topics discussed include traditional measurement with simple rulers; gages and instruments, such as micrometers and calipers; and digital equipment and computer-controlled equipment, such as coordinate-measurement machines.
- The chapter describes features of measuring instruments and the importance of automated measurements, ending with an introduction to the principles of dimensioning and tolerancing.

35.1 Introduction

This chapter presents the principal methods of measurement and the characteristics of the instruments used in manufacturing. **Engineering metrology** is defined as the measurement of dimensions such as length, thickness, diameter, taper, angle, flatness, and profile. Consider, for example, the slideways for machine tools (Fig. 35.1); these components must have specific dimensions, angles, and flatness in order for the machine to function properly and with the desired dimensional accuracy.

Traditionally, measurements have been made *after* the part has been produced—an approach known as **postprocess inspection.** Here, the term *inspection* means "checking the dimensions of what has been produced or is being produced and determining whether those dimensions comply with the specified dimensional tolerances and other specifications." Today, however, measurements are being made while the part is being produced on the machine—an approach known as **in-process, online,** or **real-time inspection.**

An important aspect of metrology in manufacturing processes is the **dimensional tolerance** (i.e., the permissible variation in the dimensions of a part). Tolerances are important because of their impact on the proper functioning of a product, part interchangeability, and manufacturing costs. Generally, the smaller the tolerance, the higher are the production costs. The chapter ends with a discussion of dimensional limits and fits used in engineering practice.

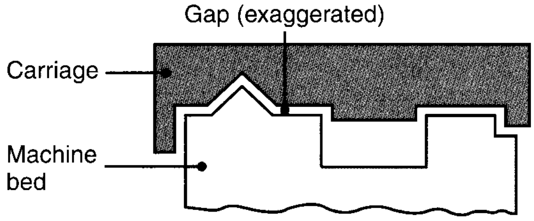

FIGURE 35.1 Cross section of a machine-tool slideway; see also Fig. 23.2. The width, depth, angles, and other dimensions all must be produced and measured accurately for the machine tool to function as expected.

35.2 Measurement Standards

Our earliest experience with measurement is usually with a simple *ruler* to measure lengths (linear dimensions). Rulers are used as a *standard* against which dimensions are measured. Traditionally, in English-speaking countries, the units *inch* and *foot* have been used, which originally were based on parts of the human body. Consequently, it was common to find significant variations in the length of 1 foot.

In most of the world, however, the *meter* has been used as a length standard. Originally, 1 meter was defined as one ten-millionth of the distance between the North Pole and the equator. The original meter length subsequently was standardized as the distance between two scratches on a platinum–iridium bar kept under controlled conditions in a building outside Paris. In 1960, the meter officially was defined as 1,650,763.73 wavelengths (in a vacuum) of the orange light given off by electrically excited krypton 86 (a rare gas). The precision of this measurement was set as 1 part in 10^9. The meter is now a unit of length in the Système International d'Unités (SI) and is the international standard.

Numerous measuring instruments and devices are used in engineering metrology, each of which has its own application, resolution, precision, and other features. Two terms commonly used to describe the type and quality of an instrument are as follows:

1. **Resolution** is the smallest difference in dimensions that the measuring instrument can detect or distinguish. A wooden yardstick, for example, has far less resolution than a micrometer.
2. **Precision**, sometimes incorrectly called accuracy, is the degree to which the instrument gives repeated measurements of the same standard. For example, an aluminum ruler will expand or contract depending on temperature variations in the environment in which it is used; thus, its precision can be affected even by being held by the hand.

In engineering metrology, the words **instrument** and **gage** often are used interchangeably. Temperature control is very important, particularly for making measurements with precision instruments. The standard measuring temperature is 20°C, and all gages are calibrated at this temperature. In the interest of accuracy, measurements should be taken in controlled environments maintaining the standard temperature, usually within ±0.3°C.

EXAMPLE 35.1 Length Measurements throughout History

Many standards for length measurement have been developed during the past 6000 years. A common standard in Egypt around 4000 B.C. was the King's elbow, which was equivalent to 0.4633 m. One *elbow* was equal to 1.5 feet (or 2 hand spans, 6 hand widths, or 24 finger thicknesses). In 1101 A.D., King Henry I declared a new standard called the *yard* (0.9144 m), which was the distance from his nose to the tip of his thumb.

During the Middle Ages, almost every kingdom and city established its own length standard—some with identical names. In 1528, the French physician

Jean Fernel proposed the distance between Paris and Amiens (a city 120 km north of Paris) as a general length reference. During the 17th century, some scientists suggested that the length of a certain pendulum be used as a standard. In 1661, British architect Sir Christopher Wren suggested that a pendulum with a period of one-half second be used. The Dutch mathematician Christian Huygens proposed a pendulum that had a length one-third of Wren's and a period of 1 second.

To put an end to the confusion of length measurement, a definitive length standard began to be developed in 1790 in France with the concept of a *mètre* (from the Greek word *metron*, meaning "measure"). A gage block 1 meter long was made of pure platinum with a rectangular cross section and was placed in the National Archives in Paris in 1799. Copies of this gage were made for other countries over the years.

During the three years from 1870 to 1872, international committees met and decided on an international meter standard. The new bar was made of 90% platinum and 10% iridium, with an x-shaped cross section and overall dimensions of 20 × 20 mm. Three marks were engraved at each end of the bar. The standard meter is the distance between the central marks at each end, measured at 0°C. Today, extremely accurate measurement is based on the speed of light in a vacuum, which is calculated by multiplying the wavelength of the standardized infrared beam of a laser by its frequency.

35.3 Geometric Features of Parts; Analog and Digital Measurements

In this section, we list the most common quantities and geometric features that typically are measured in engineering practice and in products made by the manufacturing processes described throughout this book:

- *Length*—including all linear dimensions of parts.
- *Diameter*—outside and inside, including parts with different outside and inside diameters (steps) along their length.
- *Roundness*—including out-of-roundness, concentricity, and eccentricity.
- *Depth*—such as that of drilled or bored holes and cavities in dies and molds
- *Straightness*—such as that of shafts, bars, and tubing.
- *Flatness*—such as that of machined and ground surfaces.
- *Parallelism*—such as that of two shafts or slideways in machines.
- *Perpendicularity*—such as that of a threaded bar inserted into a flat plate.
- *Angles*—including internal and external angles.
- *Profile*—such as curvatures in castings, in forgings, and on car bodies.

A wide variety of instruments and machines is available to accurately and rapidly measure the preceding quantities on stationary parts or on parts that are in continuous production. Because of major and continuing trends in automation and the computer control of manufacturing operations, modern measuring equipment is now an *integral* part of production machines. The implementation of digital instrumentation and developments in computer-integrated manufacturing (described in Part IX of the book) have together led to the total integration of measurement technologies within manufacturing systems.

It is important to recognize the advantages of *digital* over *analog* instruments. As will be obvious from our description of traditional measuring equipment in Section 35.4, accurate measurement on an analog instrument, such as a vernier caliper or micrometer (Fig. 35.2a), relies on the skill of the operator to properly interpolate and read the graduated scales. In contrast, a digital caliper does not require any particular skills, because measurements are indicated directly (Fig. 35.2b).

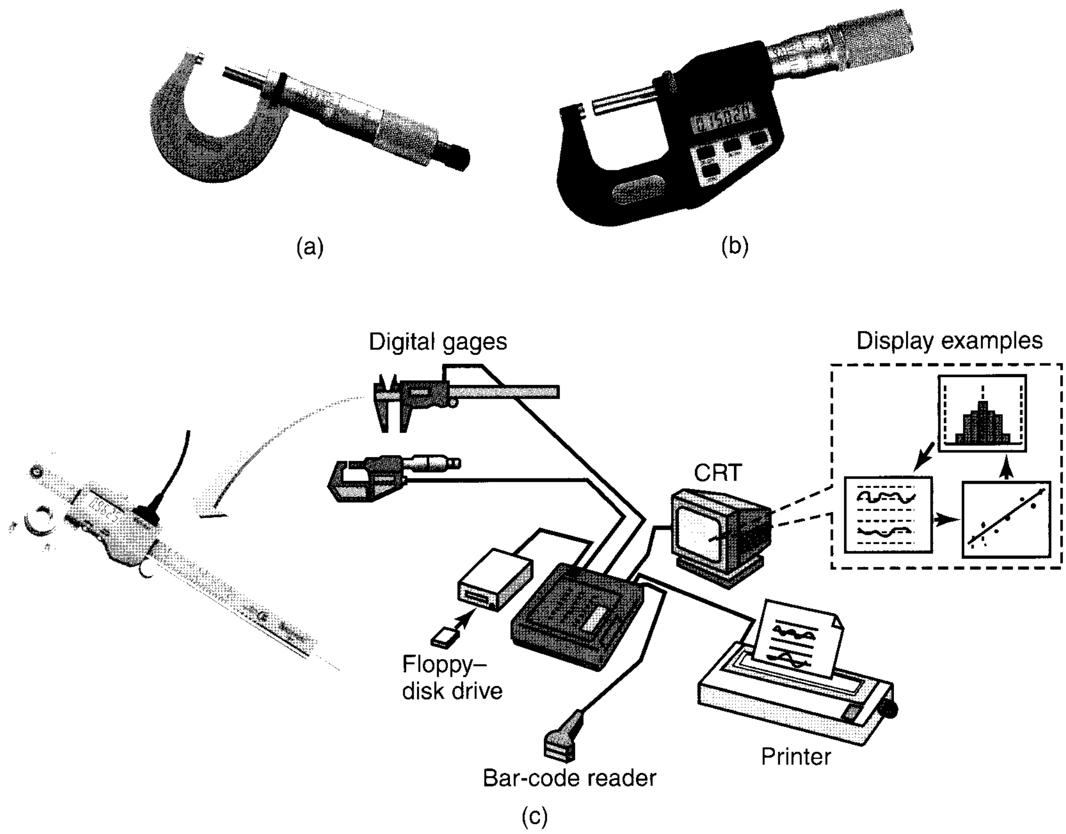

FIGURE 35.2 (a) A vernier (analog) micrometer. (b) A digital micrometer with a range of 0 to 1 in. (0 to 25 mm) and a resolution of 50 μin. (1.25 μm). Generally, it is much easier to read dimensions on this instrument than on analog micrometers. (c) Schematic illustration showing the integration of digital gages with miroprocessors for real-time data acquisition for statistical process control. *Source*: (a) Courtesy of L.C. Starrett Co. (b) Courtesy of Mitutoyo Corp.

More importantly, digital equipment can be integrated easily into other equipment (Fig. 35.2c), including production machinery and systems for statistical process control (SPC), as described in detail in Chapter 36.

35.4 Traditional Measuring Methods and Instruments

This section describes the characteristics of traditional measuring methods and instruments that have been used over many years and are still used extensively in many parts of the world. However, these instruments are rapidly being replaced with more efficient and advanced instruments and measuring machines, as described in Section 35.5.

35.4.1 Line-graduated Instruments

These instruments are used for measuring lengths or angles. *Graduated* means "marked to indicate a certain quantity."

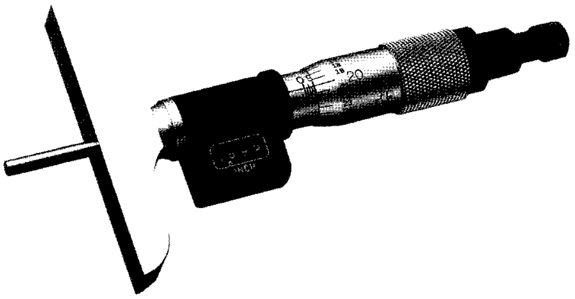

FIGURE 35.3 A digital micrometer depth gage.
Source: Courtesy of Starrett Co.

Linear Measurement (Direct Reading)

- **Rules:** The simplest and most commonly used instrument for making linear measurements is a *steel rule* (*machinist's rule*), bar, or tape with fractional or decimal graduations. Lengths are measured directly to an accuracy that is limited to the nearest division, usually 1 mm.
- **Calipers:** These instruments can be used to measure inside or outside lengths. Also called *caliper gages* and *vernier calipers* (named for P. Vernier, who lived in the 1600s), they have a graduated beam and a sliding jaw. *Digital calipers* are in increasingly wider use.
- **Micrometers:** These instruments are commonly used for measuring the thickness and inside or outside dimensions of parts. *Digital micrometers* are equipped with digital readouts (Fig. 35.2b) in metric or English units. Micrometers also are available for measuring internal diameters (*inside micrometer*) and depths (*micrometer depth gage*, Fig. 35.3). The anvils on micrometers can be equipped with conical or ball contacts to measure recesses, threaded-rod diameters, and wall thicknesses of tubes and curved sheets.

Linear Measurement (Indirect Reading). These instruments typically are *calipers* and *dividers* without any graduated scales. They are used to transfer the measured size to a direct-reading instrument, such as a rule. Because of the experience required to use them and their dependence on graduated scales, the accuracy of indirect-measurement tools is limited. *Telescoping gages* can be used for the indirect measurement of holes or cavities.

Angle Measurement

- **Bevel protractor:** This is a direct-reading instrument similar to a common protractor, except that it has a movable element. The two blades of the protractor are placed in contact with the part being measured, and the angle is read directly on the vernier scale. Another common type of bevel protractor is the *combination square*, which is a steel rule equipped with devices for measuring 45° and 90° angles.
- **Sine bar:** Measuring with this method involves placing the part on an inclined bar (sine bar) or plate and adjusting the angle by placing gage blocks on a surface plate. After the part is placed on the sine bar, a dial indicator is used to scan the top surface of the part. Gage blocks (see Section 35.4.4) are added or removed as necessary until the top surface is parallel to the surface plate. The angle on the part is then calculated from trigonometric relationships.
- **Surface plates:** These plates are used to place both parts to be measured and the measuring instruments. They typically are made of cast iron or natural stones (such as granite) and are used extensively in engineering metrology. Granite surface plates have the desirable properties of being resistant to corrosion, being nonmagnetic, and having low thermal expansion, thereby minimizing thermal distortion.

Comparative Length Measurement. Instruments used for measuring comparative lengths (also called *deviation-type* instruments) amplify and measure variations or deviations in the distance between two or more surfaces. These instruments, of which the most common example is a **dial indicator** (Fig. 35.4), compare dimensions

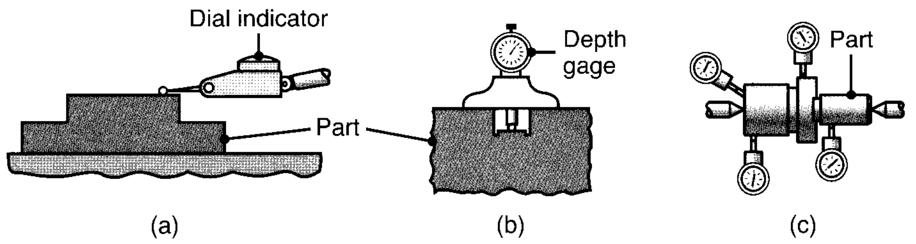

FIGURE 35.4 Three uses of dial indicators: to measure (a) roundness and (b) depth, and (c) for multiple-dimension gaging of a part.

(hence the word *comparative*). They are all simple mechanical devices that convert linear displacements of a pointer to the amount of rotation of an indicator on a circular dial. The indicator is set to zero at a certain reference surface, and the instrument or the surface to be measured (either external or internal) is brought into contact with the pointer. The movement of the indicator is read directly on the circular dial (as either plus or minus some number) to accuracies as high as 1 μm. Dial indicators with electrical and fluidic amplification mechanisms and with a digital readout also are available.

35.4.2 Measuring Geometric Features

Straightness. *Straightness* commonly can be checked with a straightedge or a dial indicator (Fig. 35.5). An *autocollimator* (which resembles a telescope with a light beam that bounces back from the object) is used to accurately measure small angular deviations on a flat surface. *Laser beams* are now commonly used to align individual machine elements in the assembly of machine components.

Flatness. *Flatness* can be measured by mechanical means with a *surface plate* and a *dial indicator*. This method can be used to measure perpendicularity, which also can be measured by precision-steel squares.

Another method for measuring flatness is **interferometry**, which uses an *optical flat*. This device is a glass disk or fused-quartz disk with parallel flat surfaces that is placed on the surface of the workpiece (Fig. 35.6a). When a *monochromatic* light beam (a light beam with one wavelength) is aimed at the surface at an angle, the optical flat splits the light beam into two beams, appearing as light and dark bands to the naked eye (Fig. 35.6b). The number of fringes that appear is related to the distance between the surface of the part and the bottom surface of the optical flat (Fig. 35.6c). Consequently, a truly flat workpiece surface (i.e., one in which the angle between the two surfaces is zero) will not split the light beam, and fringes will not appear. When surfaces are not flat, the fringes are curved (Fig. 35.6d). The interferometry method is also used for observing surface textures and scratches (Fig. 35.6e).

Diffraction gratings consist of two optical flat glasses of different lengths with closely spaced parallel lines scribed on their surfaces. The grating on the shorter glass is inclined slightly. As a result, *interference fringes* develop when it is viewed over the longer glass. The position of these fringes depends on the relative position of the two sets of glasses. With modern equipment and with the use of electronic counters and photoelectric sensors, a resolution of 2.5 μm can be obtained with gratings having 40 lines/mm.

Roundness. This feature usually is described as a deviation from true roundness (which, mathematically, is manifested in a circle). The term *out-of-roundness* (ovality) is actually more descriptive of the shape of the part (Fig. 35.7a) than the word

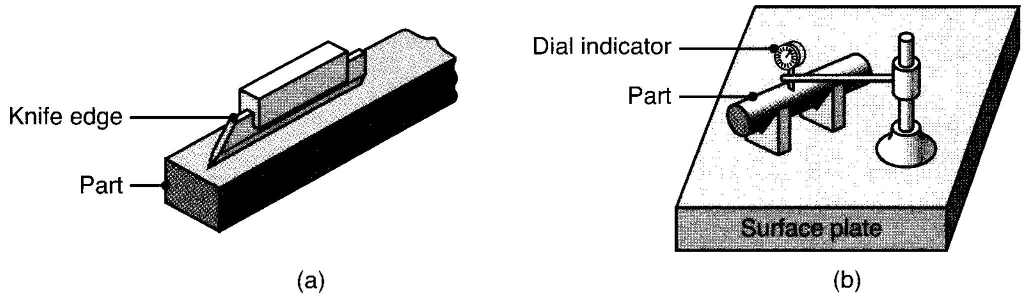

FIGURE 35.5 Measuring straightness manually with (a) a knife-edge rule and (b) a dial indicator. *Source*: After F.T. Farago.

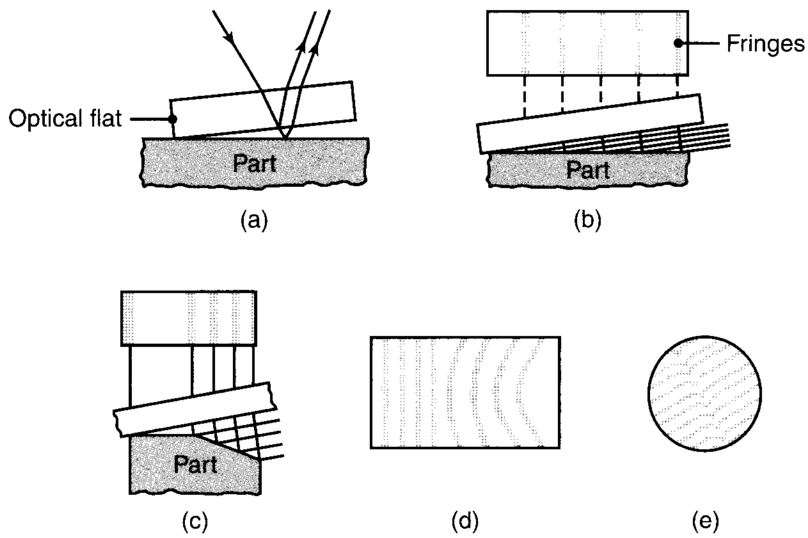

FIGURE 35.6 (a) Interferometry method for measuring flatness with an optical flat. (b) Fringes on a flat, inclined surface. An optical flat resting on a perfectly flat workpiece surface will not split the light beam, and no fringes will be present. (c) Fringes on a surface with two inclinations. *Note*: The greater the incline, the closer together are the fringes. (d) Curved fringe patterns indicate curvatures on the workpiece surface. (e) Fringe pattern indicating a scratch on the surface.

roundness. True roundness is essential to the proper functioning of rotating shafts, bearing races, pistons, cylinders, and steel balls in bearings.

Methods of measuring roundness generally fall into two categories:

1. The round part is placed on a *V-block* or between centers (Figs. 35.7b and c, respectively) and is rotated while the point of a dial indicator is in contact with the part surface. After a full rotation of the workpiece, the difference between the maximum and minimum readings on the dial is noted. This difference is called the **total indicator reading** (TIR) or the **full indicator movement**. This method can also be used to measure the straightness (squareness) of end faces of shafts that are machined, such as the facing operation shown in Fig. 23.1e.
2. In *circular tracing*, the part is placed on a platform, and its roundness is measured by rotating the platform (Fig. 35.7d). Alternatively, the probe can be rotated around a stationary part to take the measurement.

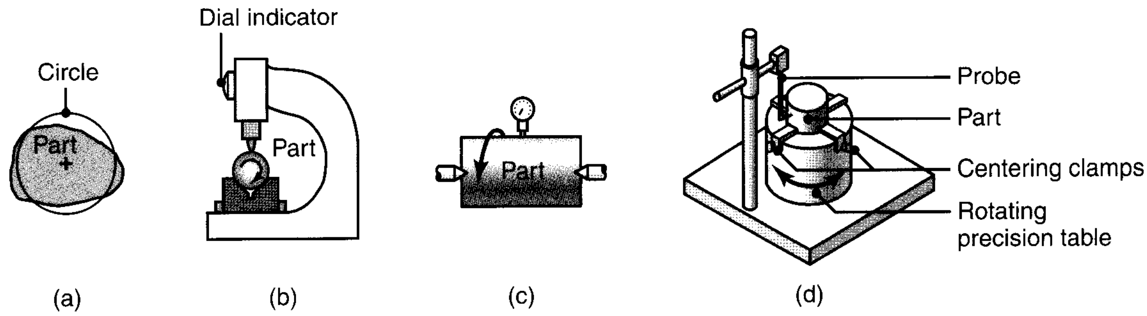

FIGURE 35.7 (a) Schematic illustration of out-of-roundness (exaggerated). Measuring roundness with (b) a V-block and dial indicator, (c) a round part supported on centers and rotated, and (d) circular tracing. *Source*: After F.T. Farago.

Profile. *Profile* may be measured by means such as (a) comparing the surface with a template or profile gage (as in the measurement of radii and fillets) for conformity and (b) using a number of dial indicators or similar instruments. The best method, however, is using the advanced measuring machines described in Section 35.5.

Screw Threads and Gear Teeth. Threads can be measured by means of *thread gages* of various designs that compare the thread produced against a standard thread. Some of the gages used are *threaded plug gages*, *screw-pitch gages*, micrometers with cone-shaped points, and *snap gages* (see Section 35.4.4) with anvils in the shape of threads. Gear teeth are measured with (a) instruments that are similar to dial indicators, (b) calipers (Fig. 35.8a), and (c) micrometers using pins or balls of various diameters (Fig. 35.8b). Advanced methods include the use of optical projectors and coordinate-measuring machines.

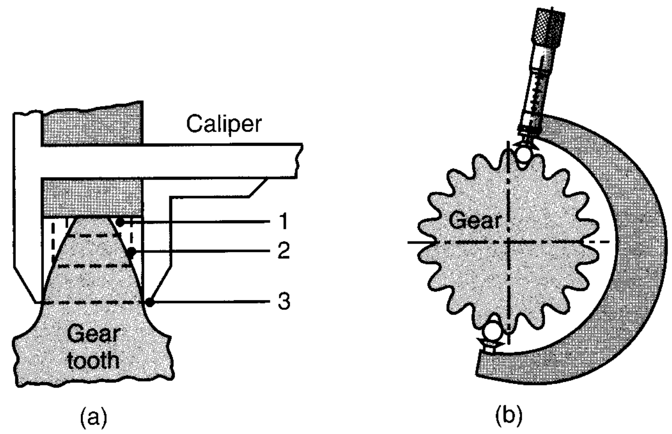

FIGURE 35.8 Measuring gear-tooth thickness and profile with (a) a gear-tooth caliper and (b) pins or balls and a micrometer. *Source*: Courtesy of American Gear Manufacturers Association.

35.4.3 Optical Contour Projectors

These instruments, also called **optical comparators**, were first developed in the 1940s to check the geometry of cutting tools for machining screw threads, but are now used for checking all profiles (Fig. 35.9). The part is mounted on a table or between centers, and the image is projected onto a screen at magnifications of 100× or higher. Linear and angular measurements are made directly on the screen, which is marked with reference lines and circles. For angular measurements, the screen can be rotated.

35.4.4 Gages

This section describes several common gages that have simple solid shapes and cannot be classified as instruments although they are very valuable in metrology.

Gage Blocks. *Gage blocks* are individual square, rectangular, or round blocks of various sizes. For general use, they are made from heat-treated and stress-relieved alloy

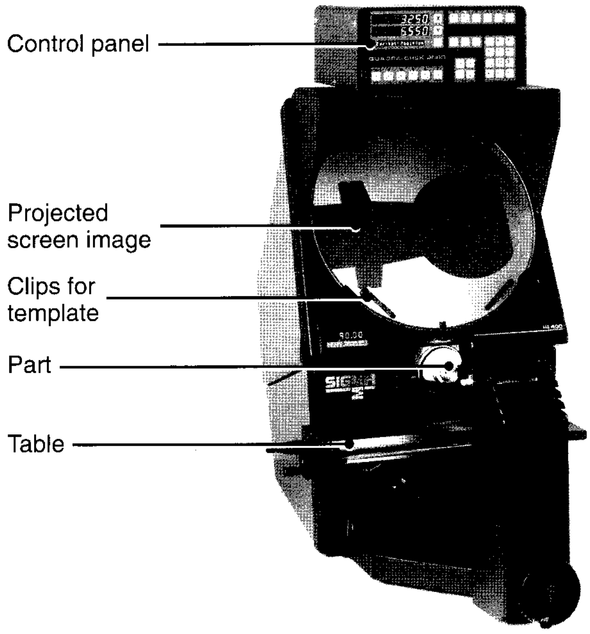

FIGURE 35.9 A bench-model horizontal-beam contour projector with a 16-in.-diameter (400-mm) screen with 150-W tungsten halogen illumination. *Source*: Courtesy of L.S. Starrett Company, Precision Optical Division.

steels. The better gage blocks are made of ceramics (often zirconia) and chromium carbide—unlike steels, these materials do not rust, but they are brittle and must be handled carefully. *Angle blocks* are made the same way and are used for angular gaging. Gage blocks have a flatness within 1.25 μm. Environmental temperature control is important when gages are used for high-precision measurements.

Fixed Gages. These gages are replicas of the shapes of the parts to be measured. Although *fixed gages* are easy to use and inexpensive, they indicate only whether a part is too small or too large compared with an established standard.

- **Plug gages** are commonly used for holes (Figs. 35.10a and b). The *GO gage* is smaller than the *NOT GO* (or *NO GO*) *gage* and slides into any hole that has a dimension smaller than the diameter of the gage. The *NOT GO* gage must not go into the hole. Two gages are required for such measurements, although both may be on the same device—either at opposite ends or in two steps at one end (*step-type gage*). Plug gages also are available, for measuring internal tapers (in which deviations between the gage and the part are indicated by the looseness of the gage), splines, and threads (in which the *GO* gage must screw into the threaded hole).
- **Ring gages** (Fig. 35.10c) are used to measure shafts and similar round parts. Ring thread gages are used to measure external threads. The *GO* and *NOT*

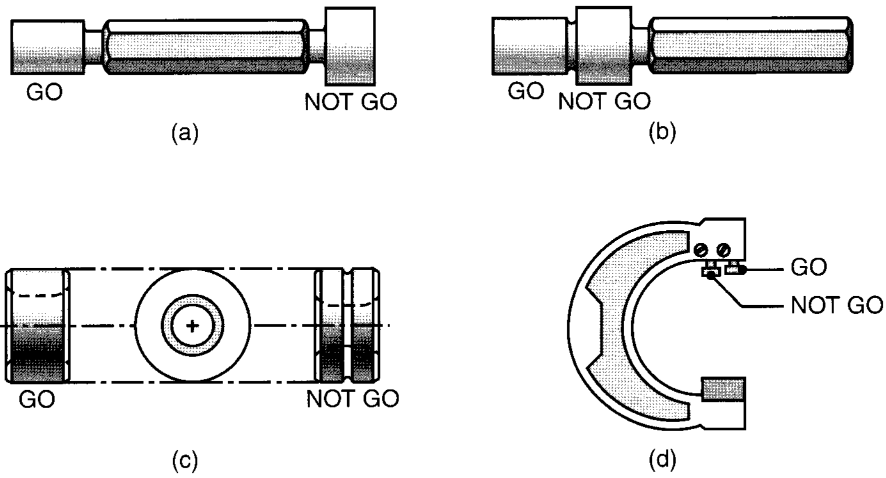

FIGURE 35.10 (a) Plug gage for holes, with *GO* and *NOT GO* on opposite ends of the gage. (b) Plug gage with *GO* and *NOT GO* on one end. (c) Plain ring gages for gaging round rods. Note the difference in knurled surfaces to identify the two gages. (d) Snap gage with adjustable anvils.

GO features on these gages are identified by the type of knurling on the outside diameters of the rings.

- **Snap gages** (Fig. 35.10d) commonly are used to measure external dimensions. They are made with adjustable gaging surfaces for use with parts that have different dimensions. One of the gaging surfaces can be set at a different gap from the other, thus making the device a one-unit *GO*-and-*NOT-GO* gage.

Air Gages. The basic operation of an *air gage* (also called a **pneumatic gage**) is shown in Fig. 35.11a. The gage head (air plug) has two or more holes, typically 1.25 mm in diameter, through which pressurized air (supplied by a constant-pressure line) escapes. The smaller the gap between the gage and the hole, the more difficult it is for the air to escape, and hence, the higher is the back pressure. The back pressure, which is sensed

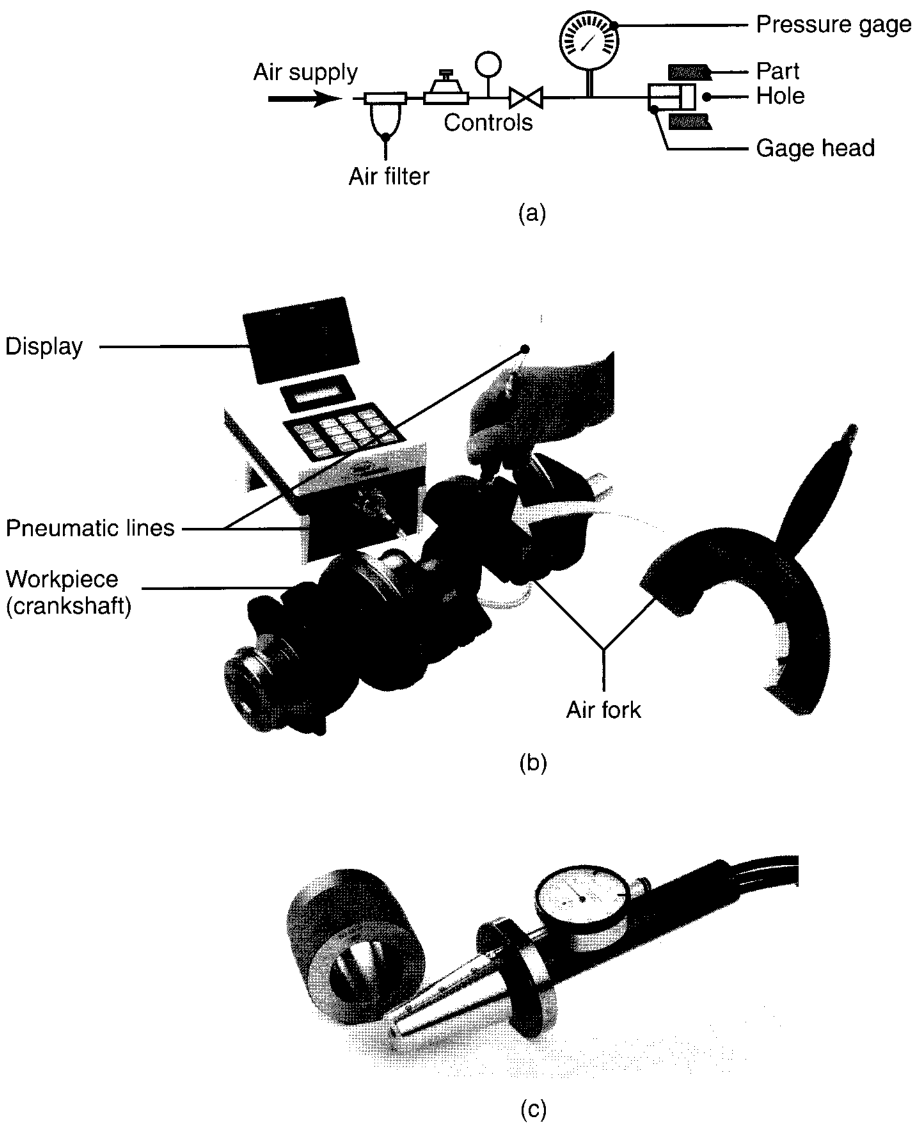

FIGURE 35.11 (a) Schematic illustration of the principle of an air gage. (b) Illustration of an air-gage system used to measure the main bearing dimension on a crankshaft. (c) A conical head for air gaging; note the three small airholes on the conical surface. *Source*: (b) Courtesy of Mahr Federal, Inc. (c) Courtesy of Stotz Gaging Co.

and indicated by a pressure gage, is calibrated to measure the dimensional variations of holes.

The air gage can be rotated during use to indicate and measure any out-of-roundess of the hole. The outside diameters of parts (such as pins and shafts) also can be measured when the air plug is in the shape of a ring slipped over the part. In cases where a ring is not suitable, a fork-shaped gage head (with the airholes at the tips) can be used (Fig. 35.11b). Various shapes of air heads, such as the conical head shown in Fig. 35.11c, can be prepared for use in specialized applications on parts with different geometric features.

Air gages are easy to use, and the resolution can be as fine as 0.125 μm. If the surface roughness of the part is too high, the readings may be unreliable. The compressed-air supply must be clean and dry for proper operation. The part being measured does not have to be free of dust, metal particles, or similar contaminants, because the air will blow them away. The noncontacting nature and the low pressure of an air gage has the benefit of not distorting or damaging the measured part, as could be the case with mechanical gages—thus giving erroneous readings.

35.5 Modern Measuring Instruments and Machines

A wide variety of measuring instruments and gages has been developed. They range from simple, hand-operated devices to computer-controlled machines with very large workspaces.

Electronic Gages. Unlike mechanical systems, *electronic gages* sense the movement of the contacting pointer through changes in the electrical resistance of a strain gage, inductance, or capacitance. The electrical signals are then converted and displayed as linear dimensions with a digital readout. A handheld electronic gage for measuring bore diameters is shown in Fig. 35.12. When its handle is squeezed slightly, the tool can be inserted into the bore, and the bore diameter is read directly. A microprocessor-assisted electronic gage for measuring vertical length is shown in Fig. 35.13.

A commonly used electronic gage is the **linear-variable differential transformer** (LVDT), for measuring small displacements. Electronic caliper gages with diamond-coated edges are available. The chemical vapor deposition (CVD) coating on these gages has a wear resistance superior to that of steel or tungsten-carbide edges; it also resists corrosion.

FIGURE 35.12 An electronic gage for measuring bore diameters. The measuring head is equipped with three carbide-tipped steel pins for wear resistance. The LED display reads 29.158 mm. *Source*: Courtesy of TESA SA.

Although they are more expensive than other types of gages, electronic gages have advantages in ease of operation, rapid response, a digital readout, less possibility of human error, versatility, flexibility, and the capability to be integrated into automated systems through microprocessors and computers.

Laser Micrometers. In this instrument, a laser beam scans the workpiece (Fig. 35.14), typically at a rate of 350 times per second. Laser micrometers are capable of resolutions as high as 0.125 μm. They are suitable not only for stationary parts, but also for in-line measurement of stationary, rotating, or vibrating parts, as well as parts in continuous, high-speed production. In addition, because there is no physical contact, they can measure parts that are at elevated temperatures or are too flexible to be measured by other means. The laser beams can be of various types (such as scanning or rastoring for stationary parts), yielding **point-cloud** descriptions of part surfaces. Laser micrometers are of the shadow type or are charge-coupled device (CCD) based for in-line measurement while a part is in production.

Laser micrometers are available with various capacities and features. They can be handheld for manual operation, or they can be mounted on and integrated with computer-controlled machines and statistical-process control units.

Laser Interferometry. This technique is used to check and calibrate machine tools for various geometric features during assembly. The method has better accuracies than those of gages or indicators. Laser interferometers are also used to automatically compensate for positioning errors in coordinate-measuring machines and computer-numerical control machines.

Photoelectric Digital Length Measurement. This type of measurement is done by an instrument that can measure the overall dimensions, thickness, and depth of a variety of parts. Resolution settings can range from 5 to 0.01 μm.

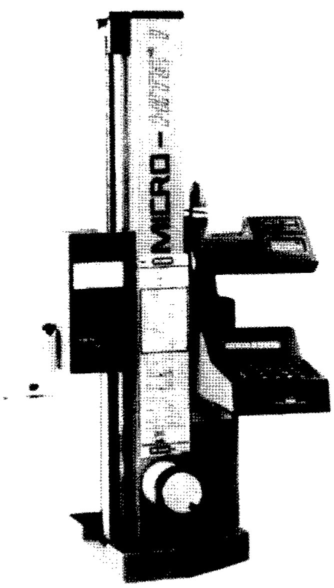

FIGURE 35.13 An electronic vertical-length measuring instrument with a resolution of 1 μm (40 μin). *Source*: Courtesy of TESA SA.

35.5.1 Coordinate-measuring Machines

As schematically shown in Fig. 35.15a, a *coordinate-measuring machine* (CMM) consists basically of a platform on which the workpiece being measured is placed and is then moved linearly or rotated. A probe (Fig. 35.15b; see also Fig. 25.6) is attached to a head (capable of various movements) and records all measurements. In addition to the tactile probe shown, other types of probes are scanning, laser (Fig. 35.15c), and vision probes, all of which are nontactile. A CMM for inspection of a typical part is shown in Fig. 35.15d.

Coordinate-measuring machines are very versatile and capable of recording measurements of complex profiles with high resolution (0.25 μm) and high speed. They are built rigidly and ruggedly to resist environmental effects in manufacturing plants, such as temperature variations and vibration. They can be placed close to machine tools for efficient inspection and rapid feedback; that way, processing parameters are corrected before the next part is made. Although large CMMs can be expensive, most machines with a touch probe and computer-controlled three-dimensional movement are suitable for use in small shops and generally cost under $20,000.

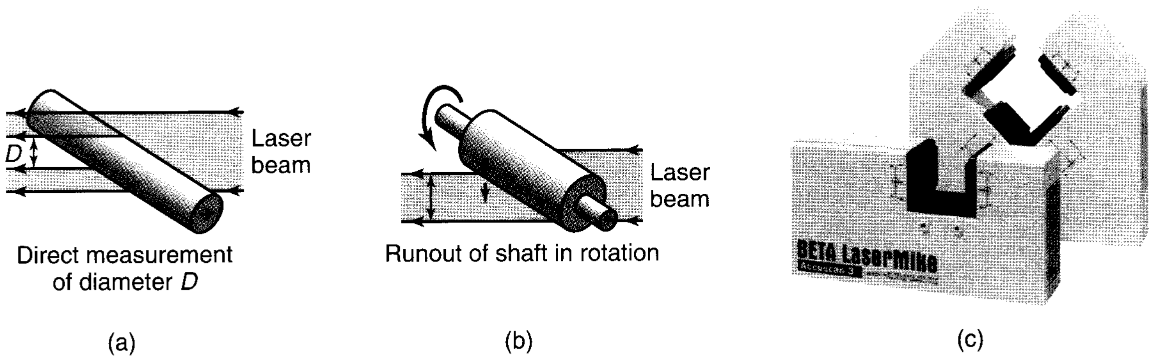

FIGURE 35.14 (a) and (b) Two types of measurements made with a laser scan micrometer. (c) Two types of laser micrometers. Note that the instrument in the front scans the part (placed in the opening) in one dimension; the larger instrument scans the part in two dimensions. *Source*: Courtesy of BETA LaserMike.

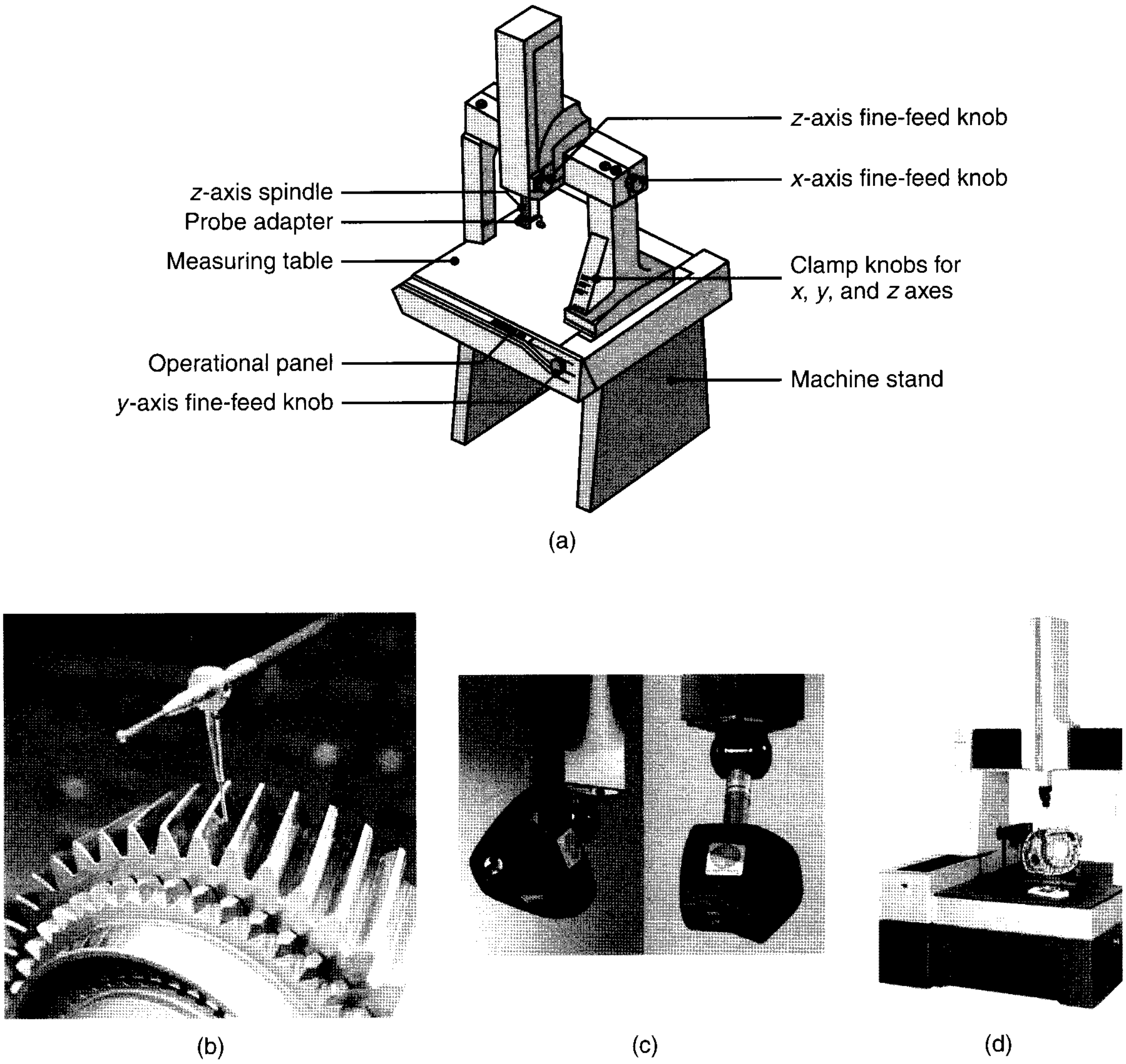

FIGURE 35.15 (a) Schematic illustration of a coordinate-measuring machine. (b) A touch signal probe. (c) Examples of laser probes. (d) A coordinate-measuring machine with a complex part being measured. *Source*: (b) through (d) Courtesy of Mitutoyo America Corp.

EXAMPLE 35.2 Coordinate-measuring Machine for Car Bodies

A large horizontal CNC coordinate-measuring machine used to measure all dimensions of a car body is shown in Fig. 35.16. This machine has a measuring range of 6 × 1.6 × 2.4 m high and a resolution of 0.1 μm. The system has temperature compensation within a range from 16° to 26°C to maintain measurement accuracy. For efficient measurements, the machine has two heads with touch-trigger probes that are controlled simultaneously and have full three-dimensional movements. The measuring speed is 5 mm/s. The probes are software controlled, and the machine is equipped with safety devices to prevent the

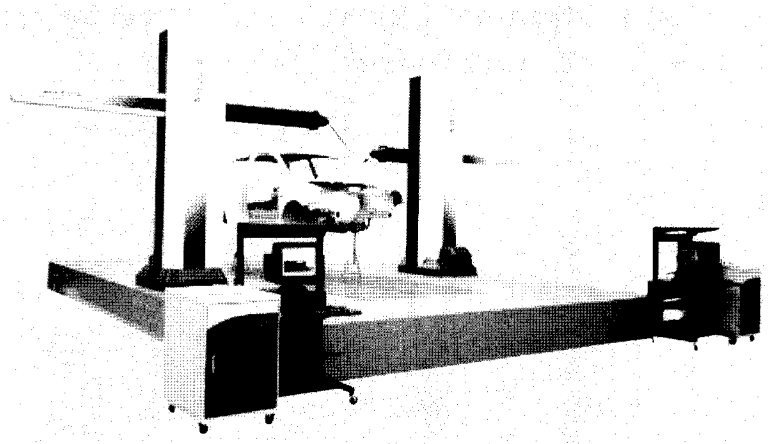

FIGURE 35.16 A large coordinate-measuring machine with two heads measuring various dimensions on a car body.

probes from inadvertently hitting any part of the car body during their movements. The equipment shown around the base of the machine includes supporting hardware and software that controls all movements and records all measurements.

Source: Courtesy of Mitutoyo America Corporation.

35.6 Automated Measurement and Inspection

Automated measurement and inspection is based on various **online sensor systems** that monitor the dimensions of parts while they are being made and, if necessary, use these measurements as input to make corrections (Section 37.7). Manufacturing cells and flexible manufacturing systems (Chapter 39) have led to the adoption of advanced measuring techniques and systems.

To appreciate the importance of online monitoring of dimensions, consider the following question: If a machine has been producing a certain part with acceptable dimensions, what factors contribute to the subsequent deviation in the dimensions of the same part produced by the same machine? There are several technical, as well as human, factors involved:

- Static and dynamic *deflections* of the machine because of vibrations and fluctuating forces are caused by machine characteristics and variations in the properties and dimensions of the incoming material.
- *Distortion* of the machine because of thermal effects are caused by such factors as changes in the temperature of the environment, changes of metalworking fluids, and changes of machine bearings and various components.
- *Wear* of tools, dies, and molds can affect the dimensional accuracy of the parts produced.
- Human *errors* and miscalculations cause problems.

As a result of these factors, the dimensions of parts will vary, thus making continuous monitoring during production necessary.

35.7 General Characteristics and Selection of Measuring Instruments

The characteristics and quality of measuring instruments are generally described by various specific terms, defined as follows (in alphabetical order):

- **Accuracy:** The degree of agreement of the measured dimension with its true magnitude.
- **Amplification:** The ratio of instrument output to the input dimension; also called *magnification.*
- **Calibration:** The adjustment or setting of an instrument to give readings that are accurate within a reference standard.
- **Drift:** An instrument's capability to maintain its calibration over time; also called *stability.*
- **Linearity:** The accuracy of the readings of an instrument over its full working range.
- **Magnification:** The ratio of instrument output to the input dimension; also called *amplification.*
- **Precision:** Degree to which an instrument gives repeated measurement of the same standard.
- **Repeat accuracy:** The same as accuracy, but repeated many times.
- **Resolution:** Smallest dimension that can be read on an instrument.
- **Rule of 10** *(gage maker's rule)*: An instrument or gage should be 10 times more accurate than the dimensional tolerances of the part being measured. A factor of 4 is known as the *mil standard rule.*
- **Sensitivity:** Smallest difference in dimension that an instrument can distinguish or detect.
- **Speed of response:** How rapidly an instrument indicates a measurement, particularly when a number of parts are measured in rapid succession.
- **Stability:** An instrument's capability to maintain its calibration over time; also called *drift.*

The selection of an appropriate measuring instrument for a particular application also depends on (a) the size and type of parts to be measured, (b) the environment (temperature, humidity, dust, and so on), (c) the operator skills required, and (d) the cost of equipment.

35.8 Geometric Dimensioning and Tolerancing

Individually manufactured parts and components eventually are assembled into products. We take it for granted that when a thousand lawn mowers are manufactured and assembled, each part of the mower will mate properly with its intended components. For example, the wheels of the lawn mower will slip easily into their axles, or the pistons will fit properly into the cylinders, being neither too tight nor too loose.

Likewise, when we have to replace a broken or worn bolt on an old machine, we purchase an identical bolt. We are confident from similar experiences in the past that the new bolt will fit properly in the machine. The reason we feel confident is that the bolt is manufactured according to certain standards and the dimensions of all similar bolts will vary by only a small, specified amount that do not affect their function.

In other words, all bolts are manufactured within a certain range of dimensional tolerance; thus, all similar bolts are *interchangeable.* We also expect that the new bolt will function satisfactorily for a certain length of time, unless it is abused or misused. Bolts are periodically subjected to various tests during their production to make sure that their quality is within certain specifications.

Dimensional Tolerance. *Dimensional tolerance* is defined as the permissible or acceptable variation in the dimensions (height, width, depth, diameter, and angles) of a part. The root of the word "tolerance" is the Latin *tolerare*, meaning "to endure" or "to put up with." Tolerances are unavoidable, because it is virtually impossible and unnecessary to manufacture two parts that have precisely the same dimensions.

Furthermore, because close dimensional tolerances can increase the product cost significantly, a narrow tolerance range is economically undesirable. However, for some parts, close tolerances are necessary for their proper functioning and are worth the added expense associated with narrow tolerance ranges. Examples are precision measuring instruments and gages, hydraulic pistons, and bearings for aircraft engines.

Measuring dimensional tolerances and features of parts rapidly and reliably can be a challenging task. For example, each of the 6 million parts on a Boeing 747-400 aircraft requires the measurement of about 25 features, representing a total of 150 million measurements. Surveys have shown that the dimensional tolerances on state-of-the-art manufactured parts are shrinking by a factor of 3 every 10 years and that this trend will continue. It is estimated that accuracies of (a) conventional turning and milling machines will rise from the present 7.5 to 1 μm, (b) diamond-wheel wafer-slicing machines for semiconductor fabrication to 0.25 μm, (c) precision diamond turning machines to 0.01 μm, and (d) ultraprecision ion-beam machines to less than 0.001 μm. (See also Fig. 25.16.)

Importance of Tolerance Control. Dimensional tolerances become important only when a part is to be assembled or mated with another part. Surfaces that are free and not functional do not need close tolerance control. For example, the accuracy of the holes and the distance between the holes for a connecting rod are far more critical than the rod's width and thickness at various locations along its length (see Fig. 14.7).

To appreciate the importance of dimensional tolerances, let's assemble a simple round shaft (axle) and a wheel with a round hole. Assume that we want the axle's diameter to be 25 mm (Fig. 35.17). We go to a hardware store and purchase a 25-mm round rod and a wheel with a 25-mm hole. Will the rod fit into the hole without our having to force it, or will it be loose in the hole? The 25-mm dimension is the **nominal size** of the shaft. If we purchase such a rod from a different store, at a different time, and select one randomly from a large lot, the chances are that each rod will

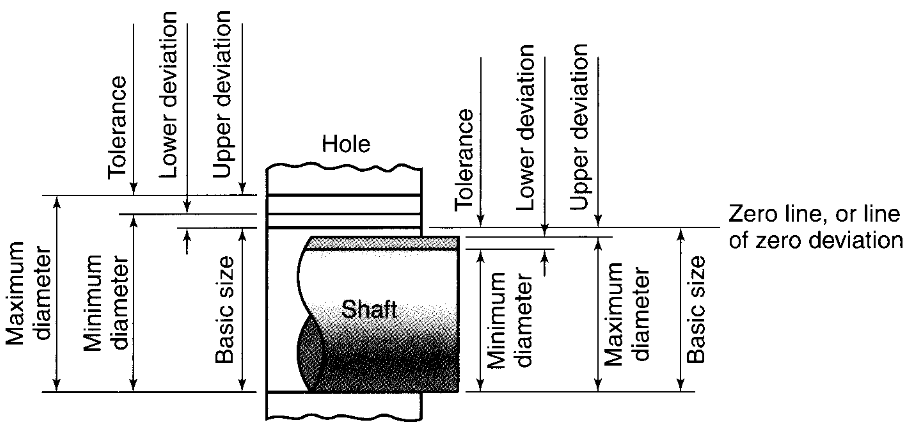

FIGURE 35.17 Basic size, deviation, and tolerance on a shaft, according to the ISO system.

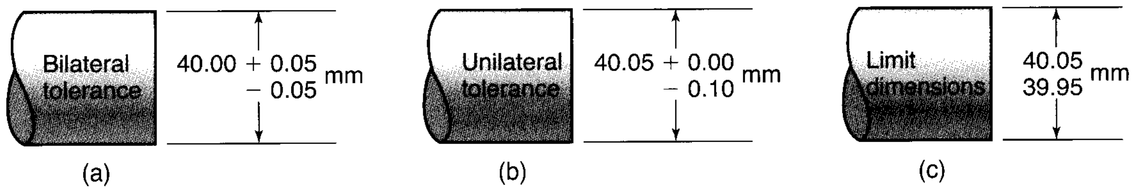

FIGURE 35.18 Various methods of assigning tolerances on a shaft: (a) bilateral tolerance, (b) unilateral tolerance, and (c) limit dimensions.

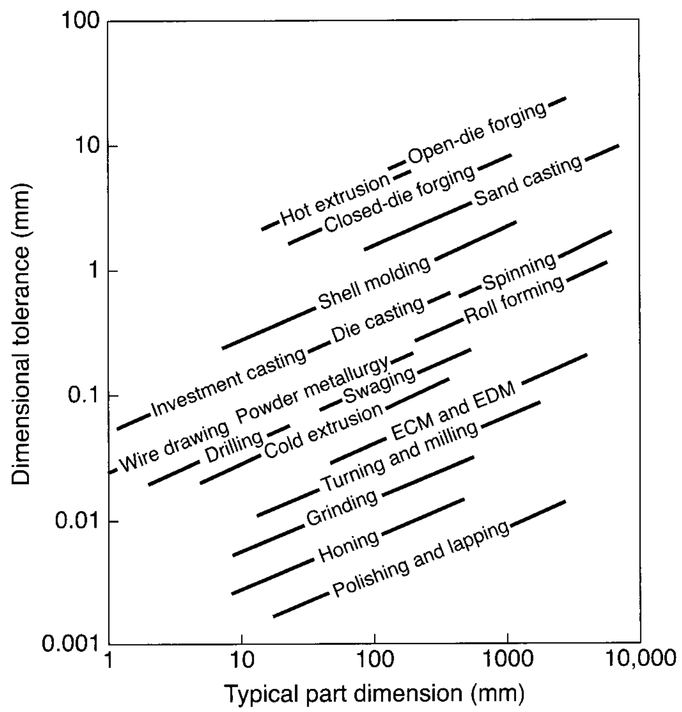

FIGURE 35.19 Dimensional tolerances as a function of part size for various manufacturing processes. Note that because many factors are involved, there is a broad range for tolerances.

have a slightly different diameter. Machines with the same setup may produce rods of slightly different diameters, depending on a number of factors, such as speed of operation, temperature, lubrication, and variations in the properties of the incoming material. If we now specify a *range* of diameters for both the rod and the hole of the wheel, we can predict the type of fit correctly.

Certain terminology has been established to clearly define these geometric quantities. One such system is the International Organization for Standardization (ISO) system shown in Fig. 35.17. Note that both the shaft and the hole have minimum and maximum diameters, the difference being the tolerance for each member. A proper engineering drawing would specify these parameters with numerical values, as shown in Fig. 35.18.

The range of dimensional tolerances possible in manufacturing processes is given in various figures and tables throughout this book. There is a general relationship between tolerances and part size (Fig. 35.19) and between tolerances and the surface finish of parts manufactured by various processes (Fig. 35.20). Note the wide range of tolerances and surface finishes obtained. Also, the larger the part, the greater is its obtainable tolerance range.

Definitions. Several terms are used to describe features of dimensional relationships between mating parts. Details of the definitions are available in the ANSI/ASME B4.2, ANSI/ASME Y14.5, and ISO/TC10/SC5 standards. Because of the complex geometric relationships involved among all of the parts to be assembled, the definitions of these terms can be somewhat confusing.

The commonly used terms for geometric characteristics are defined briefly as follows, in alphabetical order:

- **Allowance:** The specified difference in dimensions between mating parts; also called *functional dimension* or *sum dimension*.
- **Basic size:** Dimension from which limits of size are derived with the use of tolerances and allowances.
- **Bilateral tolerance:** Deviation (plus or minus) from the basic size.

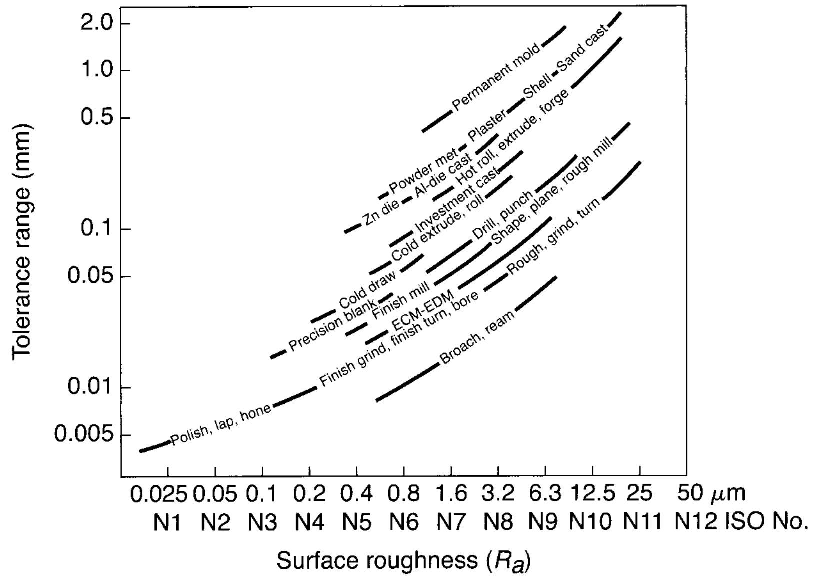

FIGURE 35.20 Dimensional tolerance range and surface roughness obtained in various manufacturing processes. These tolerances apply to a 25-mm workpiece dimension. *Source*: After J.A. Schey.

- **Clearance:** The space between mating parts.
- **Clearance fit:** Fit that allows for rotation or sliding between mating parts.
- **Datum:** A theoretically exact axis, point, line, or plane.
- **Feature:** A physically identifiable portion of a part, such as hole, slot, pin, or chamfer.
- **Fit:** The range of looseness or tightness that can result from the application of a specific combination of allowance and tolerance in the design of mating-part features.
- **Geometric tolerances:** Tolerances that involve shape features of the part.
- **Hole-basis system:** Tolerances based on a zero line on the hole; also called *standard hole practice* or *basic hole system.*
- **Interference:** Negative clearance.
- **Interference fit:** A fit having limits of size so prescribed that an interference always results when mating parts are assembled.
- **International tolerance** (IT) **grade:** A group of tolerances that vary with the basic size of the part, but provide the same relative level of accuracy within a grade.
- **Limit dimensions:** The maximum and minimum dimensions of a part; also called *limits.*
- **Maximum material condition** (MMC)**:** The condition whereby a feature of a certain size contains the maximum amount of material within the stated limits of that size.
- **Nominal size:** An approximate dimension that is used for the purpose of general identification.
- **Positional tolerancing:** A system of specifying the true position, size, and form of the features of a part, including allowable variations.
- **Shaft-basis system:** Tolerances based on a zero line on the shaft; also called *standard shaft practice* or *basic shaft system.*
- **Standard size:** Nominal size in integers and common subdivisions of length.
- **Transition fit:** A fit with small clearance or interference that allows for accurate location of mating parts.

- **Unilateral tolerancing:** Deviation from the nominal dimension in one direction only.
- **Zero line:** Reference line along the basic size from which a range of tolerances and deviations are specified.

Because the dimensions of holes are more difficult to control than those of shafts, the hole-basis system is commonly used for specifying tolerances in shaft and hole assemblies. The symbols used to indicate geometric characteristics are shown in Figs. 35.21a and b.

Type of feature	Type of tolerance	Characteristic	Symbol
Individual (no datum reference)	Form	Flatness	⏥
		Straightness	—
		Circularity (roundness)	○
		Cylindricity	⌭
Individual or related	Profile	Profile of a line	⌒
		Profile of a surface	⌓
Related (datum reference required)	Orientation	Perpendicularity	⊥
		Angularity	∠
		Parallelism	//
	Location	Position	⌖
		Concentricity	◎
	Runout	Circular runout	↗
		Total runout	⌰

(a)

[.605] Basic or exact dimension	Ⓟ Projected tolerance zone
[-A-] Datum feature symbol	Ø Diametrical (cylindrical) tolerance zone or feature
Ⓜ Maximum material condition	[⌖ | Ø.005 Ⓜ | A] Feature control frame
Ⓢ Regardless of feature size	(A1) Datum target symbol
Ⓛ Least material condition	

(b)

FIGURE 35.21 Geometric characteristic symbols to be indicated on engineering drawings of parts to be manufactured. *Source*: Courtesy of The American Society of Mechanical Engineers. .

Limits and Fits. *Limits and fits* are essential in specifying dimensions for holes and shafts. There are two standards on limits and fits, as described by the American National Standards Institute (see ANSI/ASME B4.1, B4.2, and B4.3). One standard is based on the traditional inch unit. The other is based on the metric unit and has been developed in greater detail. In these standards, capital letters always refer to the hole and lowercase letters to the shaft.

SUMMARY

- In modern manufacturing technology, many parts are processed to a high degree of precision and thus require measuring instrumentation with several features and characteristics.
- Many devices are available for inspection—from simple gage blocks to electronic gages with high resolution. The selection of a particular measuring instrument depends on factors such as the type of measurement for which it will be used, the environment in which it will be used, and the accuracy of measurement required.
- Major advances have been made in automated measurement, linking measuring devices to microprocessors and computers for accurate in-process control of manufacturing operations. Reliable linking, monitoring, display, distribution, and manipulation of data are important factors, as are the significant costs involved in implementing them.
- Dimensional tolerances and their selection are important factors in manufacturing. Tolerances not only affect the accuracy and operation of all types of machinery and equipment, but also can influence product cost significantly.
- The smaller (tighter) the range of tolerances specified, the higher is the cost of production. Tolerances should be as broad as possible, but should also maintain the functional requirements of the product.

KEY TERMS

Air gage
Analog instruments
Autocollimator
Bevel protractor
Comparative length-measuring instruments
Coordinate-measuring machine
Dial indicator
Diffraction gratings
Digital instruments
Dimensional tolerance
Electronic gages
Fits
Fixed gage
Gage block
Interferometry
Laser micrometer
Limits
Line-graduated instruments
Measurement standards
Micrometer
Optical contour projector
Optical flat
Plug gage
Pneumatic gage
Precision
Resolution
Ring gage
Sensitivity
Snap gage
Tolerance
Total indicator reading
Vernier caliper

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REVIEW QUESTIONS

35.1. Explain what is meant by standards for measurement.

35.2. What is the basic difference between direct-reading and indirect-reading linear measurements? Name the instruments used in each category.

35.3. What is meant by comparative length measurement?

35.4. Explain how flatness is measured. What is an optical flat?

35.5. Describe the principle of an optical comparator.

35.6. Why have coordinate measuring machines become important instruments?

35.7. What is the difference between a plug gage and a ring gage?

35.8. What are dimensional tolerances? Why is their control important?

35.9. Explain the difference between tolerance and allowance.

35.10. What is the difference between bilateral and unilateral tolerance?

35.11. How is straightness measured?

QUALITATIVE PROBLEMS

35.12. Why are the words "accuracy" and "precision" often incorrectly interchanged?

35.13. Why do manufacturing processes produce parts with a wide range of tolerances? Explain, giving several examples.

35.14. Explain the need for automated inspection.

35.15. Dimensional tolerances for nonmetallic parts usually are wider than for metallic parts. Explain why. Would this also be true for ceramics parts?

35.16. Comment on your observations regarding Fig. 35.20. Why does dimensional tolerance increase with increasing surface roughness?

35.17. Review Fig. 35.19, and comment on the range of tolerances and part dimensions produced by various manufacturing processes.

35.18. In the game of darts, is it better to be accurate or to be precise? Explain.

35.19. What are the advantages and limitations of *GO* and *NOT GO* gages?

35.20. Comment on your observations regarding Fig. 35.18.

35.21. Why is it important to control temperature during the measurement of dimensions? Explain, with examples.

35.22. Describe the characteristics of electronic gages.

35.23. What method would you use to measure the thickness of a foam-rubber part? Explain.

QUANTITATIVE PROBLEMS

35.24. Assume that a steel rule expands by 0.07% due to an increase in environmental temperature. What will be the indicated diameter of a shaft with a diameter of 30.00 mm at room temperature?

35.25. If the same steel rule as in Problem 35.24 is used to measure aluminum extrusions, what will be the indicated diameter at room temperature? What if the part were made of a thermoplastic?

35.26. A shaft must meet a design requirement of being at least 28.0 mm in diameter, but it can be 0.380 mm oversized. Express the shaft's tolerance as it would appear on an engineering drawing.

SYNTHESIS, DESIGN, AND PROJECTS

35.27. Describe your thoughts on the merits and limitations of digital measuring equipment over analog instruments. Give specific examples.

35.28. Take an ordinary vernier micrometer (see Fig. 35.2a) and a simple round rod. Ask five of your classmates to measure the diameter of the rod with this micrometer. Comment on your observations.

35.29. Obtain a digital micrometer and a steel ball of, say, 6-mm diameter. Measure the diameter of the ball when it (a) has been placed in a freezer, (b) has been put into boiling water, and (c) when it has been held in your hand for different lengths of time. Note the variations, if any, of measured dimensions, and comment on them.

35.30. Repeat Problem 35.29, but with the following parts: (a) the plastic lid of a small jar, (b) a thermoset part such as the knob or handle from the lid of a saucepan, (c) a small juice glass, and (d) an ordinary rubber eraser.

35.31. What is the significance of the tests described in Problems 35.29 and 35.30?

35.32. Explain the relative advantages and limitations of a tactile probe versus a laser probe.

35.33. Make simple sketches of some forming- and cutting-machine tools (as described in Parts III and IV of the book) and integrate them with the various types of measuring equipment described in this chapter. Comment on the possible difficulties involved in doing so.

35.34. Inspect various parts and components in consumer products, and comment on how tight dimensional tolerances have to be in order for these products to function properly.

35.35. As you know, very thin sheet-metal parts can distort differently when held from various locations and edges of the part, just as a thin paper plate or aluminum foil does. How, then, could you use a coordinate-measuring machine for "accurate" measurements? Explain.

35.36. Explain how you would jusify the considerable cost of a coordinate-measuring machine such as that shown in Fig. 35.16.