MODULE 1: METAL CASTING

ELDHO PAUL
Dept. of Mechanical Engg.
MACE
Kothamangalam

Course Outcome 1 (CO1)

Illustrate the basic principles of foundry practices and special casting processes, their Advantages, Limitations and Applications

1. Why draft allowances are important for patterns.
2. What are the importance of permeability of molding sand?
3. How runner extension is helpful for good casting quality.
4. Internal corners are more prone to solidification shrinkages than external corners. Explain?
5. Which of the casting processes would be suitable for making small toys in large numbers? Why?

SYLLABUS

Module I

Casting:-Characteristics of sand - patterns- cores- -chaplets- simple problems- solidification of metals and Chvorinov's rule - Elements of gating system- risering -chills –simple problems- Special casting process- Defects in castings- Super alloy Production Methods.

Module	TOPIC	No. of hours	Course outcomes
1.1	Casting:-Characteristics of sand -pattern and allowances -type of patterns- cores-core prints-chaplets-simple problems.	2	CO1
1.2	Elements of gating system-gating system, pouring time, choke area -risering Caine's method-chills –simple problems.	2	CO1 CO5
1.3	Special casting process:-shell molding, precision investment, die casting, centrifugal casting, continues casting, squeeze casting surface roughness obtainable and application of each casting process.	2	
1.4	Defects in castings :- Shaping faults arising in pouring, Inclusions and sand defects, Gas defects, Shrinkage defects, Contraction defects, Dimensional errors, Compositional errors and segregation; significance of defects on Mechanical properties . (Kalpakjian, Beeley, Rao).	2	CO1
1.5	Superalloy Production Methods: Vacuum Induction Melting; Electroslag Remelting; Vacuum Arc Remelting (ASM).	1	

CASTINGS-HISTORY

Casting since about 3200 BCE…

Bronze age to iron age

Ancient Greece; bronze statue casting circa 450BCE

Iron works in early Europe, e.g. cast iron cannons from England circa 1543

Etruscan casting with runners circa 500 BCE

CASTING -INTRODUCTION

- One of the oldest and versatile manufacturing processes.
- Process of producing metal/alloy component parts of desired shape by pouring molten metal/alloy into the prepared mold and then allowing the metal/alloy to cool and solidify.
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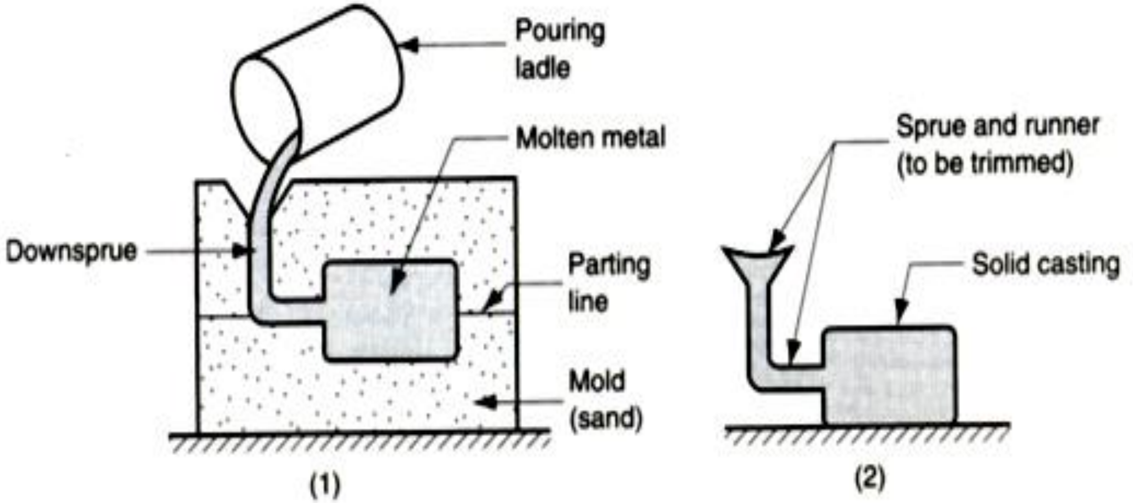


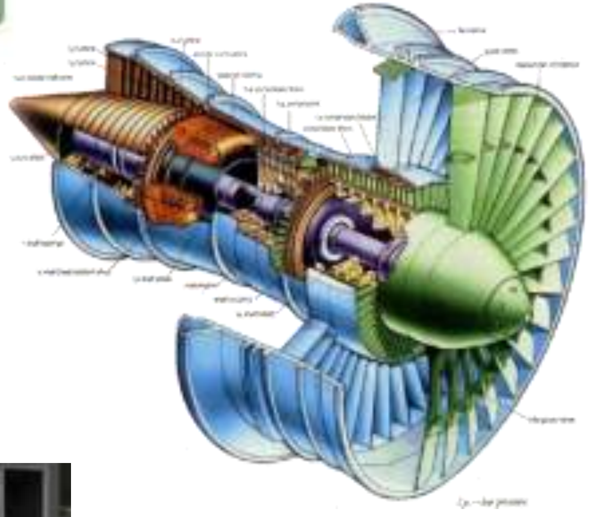
- **Disadvantages**
  - Energy intensive
  - Pollution control problems
  - Defects-very difficult to obtain castings with exact dimensional accuracy, surface quality and inherent soundness.

Advantages

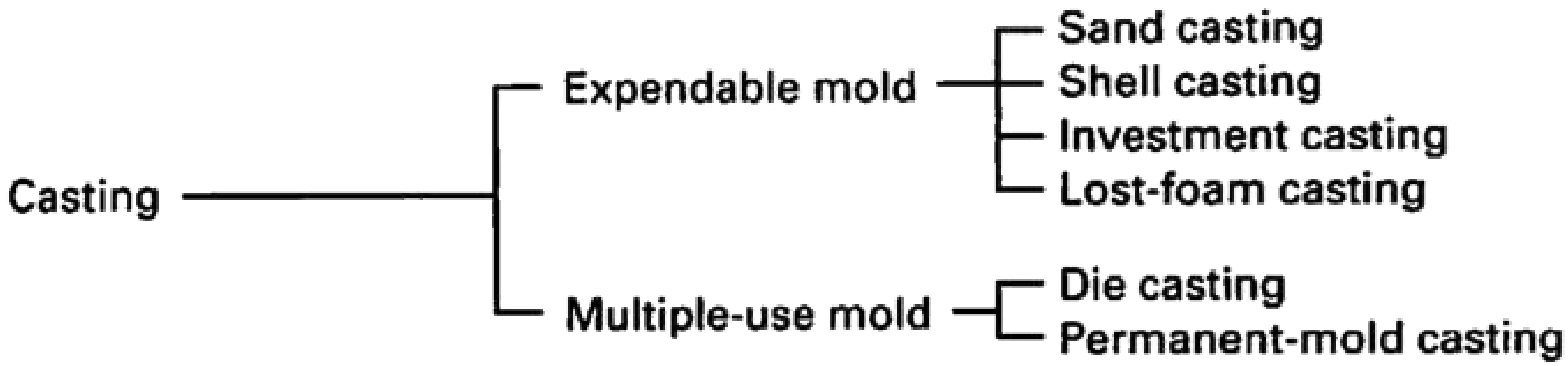
- Casting provides good freedom of design in terms of shape, size and product quality.
- Casting imparts uniform directional properties.
- Better damping capacity to cast parts.
- Casting produces machinable parts.
- Very difficult, heavy and bulky parts which are not easy to fabricate can be cast.
- Castings can be designed for minimum stress concentration inorder to achieve more strength and increased service life.
- Objects can be made as a single piece- construction cost can be reduced.
- Certain metals and alloys can be processed into usable forms only by casting (e.g.. cast irons).
  - **Inexpensive (especially for small quantities)**
  - Only way to produce brittle alloy parts

Casting applications

- M/c Tool Structure
- Turbine vanes
- Pump Filter and valve
- Aircraft jet engine blades
- Sanitary fittings
- Mill housings
- Railway crossings
- Power generators
- Super charger casing



CASTING TYPES



Casting

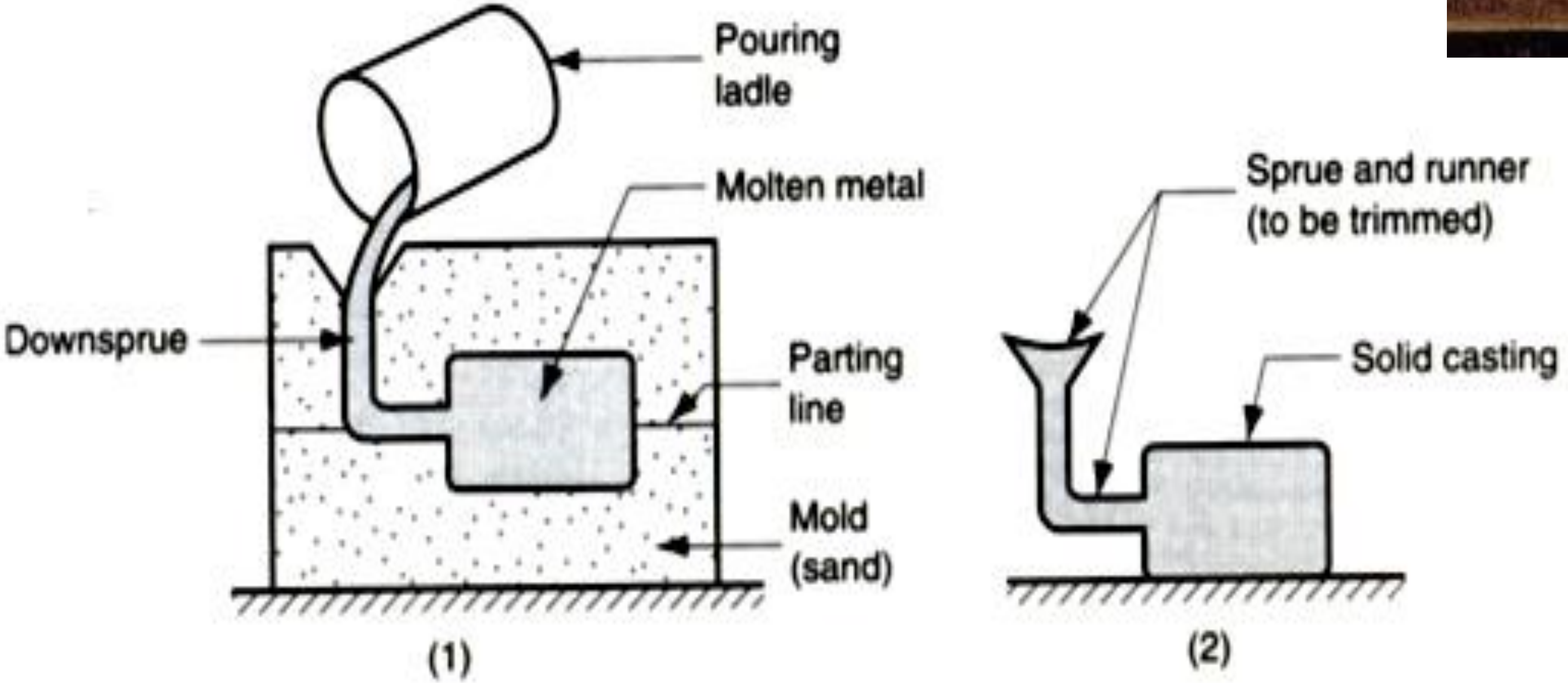
- Shortest route to get complex shapes even with internal features like through and blind holes
- Mechanical properties don't limit the capability of process
- Compatible for custom, batch and mass production
- Compatible for very few mm/gm size to m/ton size casting
- Common method for composite materials

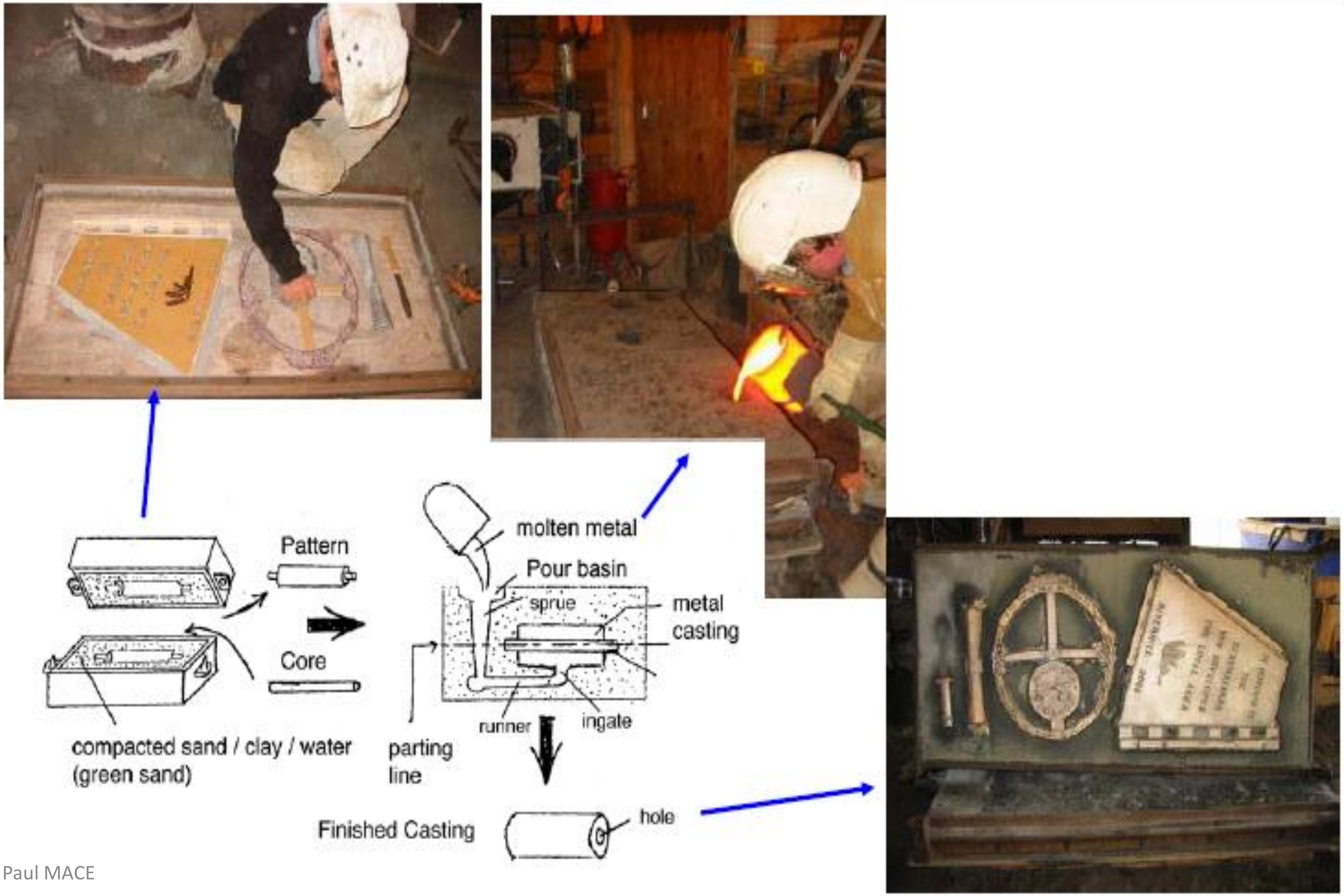
- Moderate surface finishing and tolerance
- Possibility of external and internal defects
- Tendency of interaction with ambient air
- Often Needs machining processing and heat treatment
- Difficult for high melting temperature metals
- Chemical and metallurgical heterogeneity

- ..\..\Manufacturing Process\btech MP\for CASTING students\Sand Casting_1.WebM

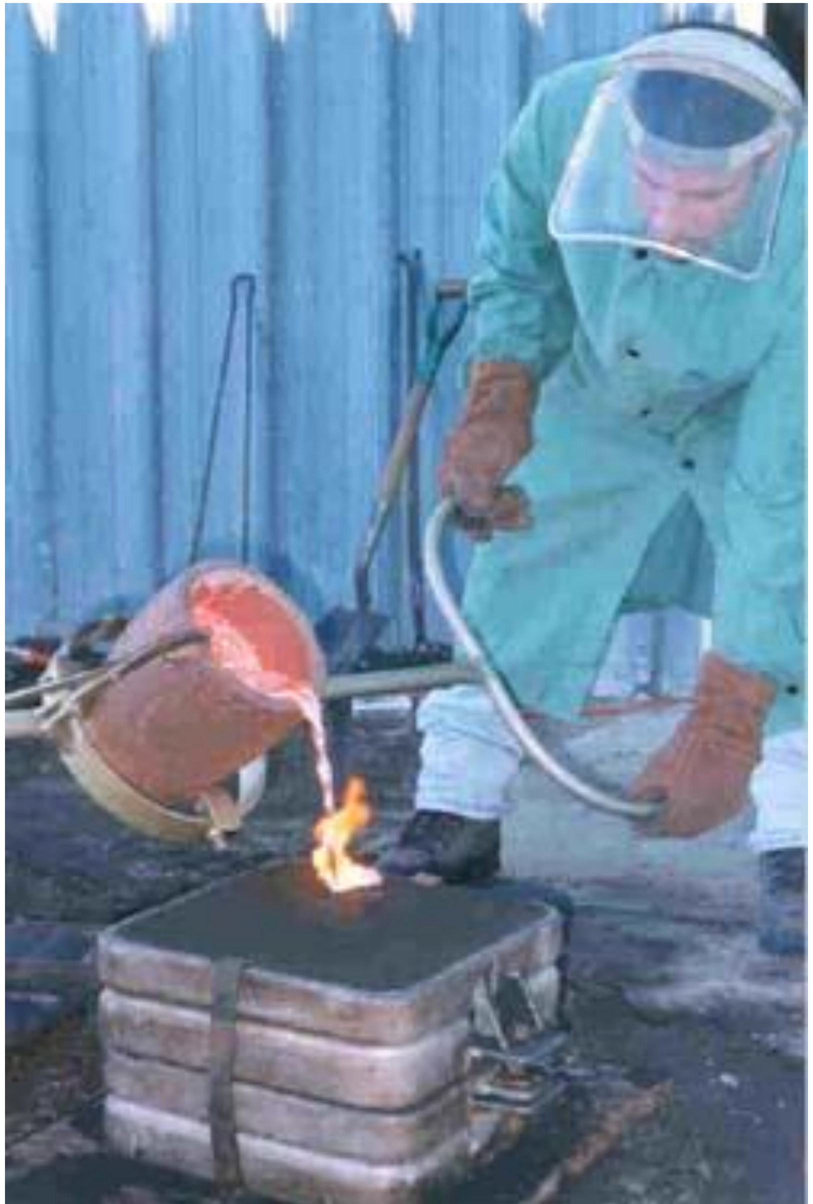
SAND CASTING PROCESS

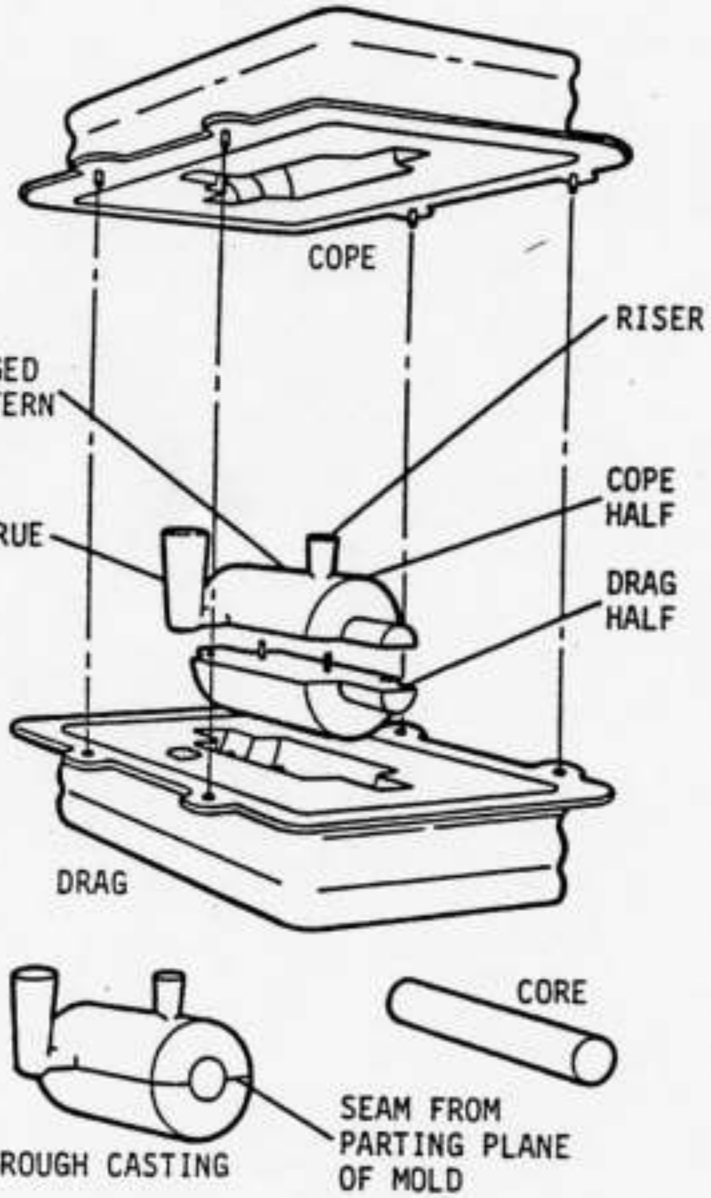
- Pattern making
- Molding & Core Making
- Melting and Pouring
- Solidification and Cooling
- Fettling
- Finishing and Inspection



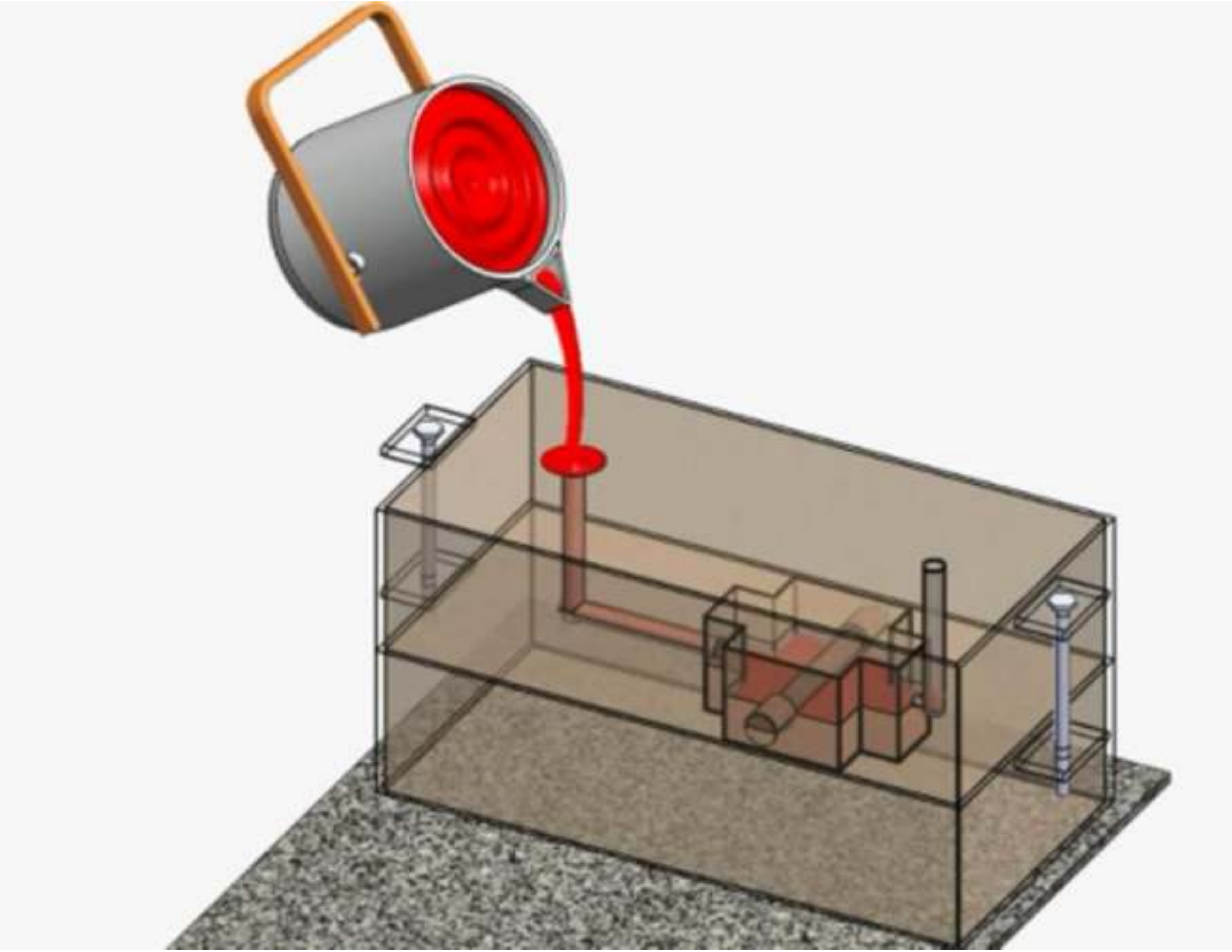


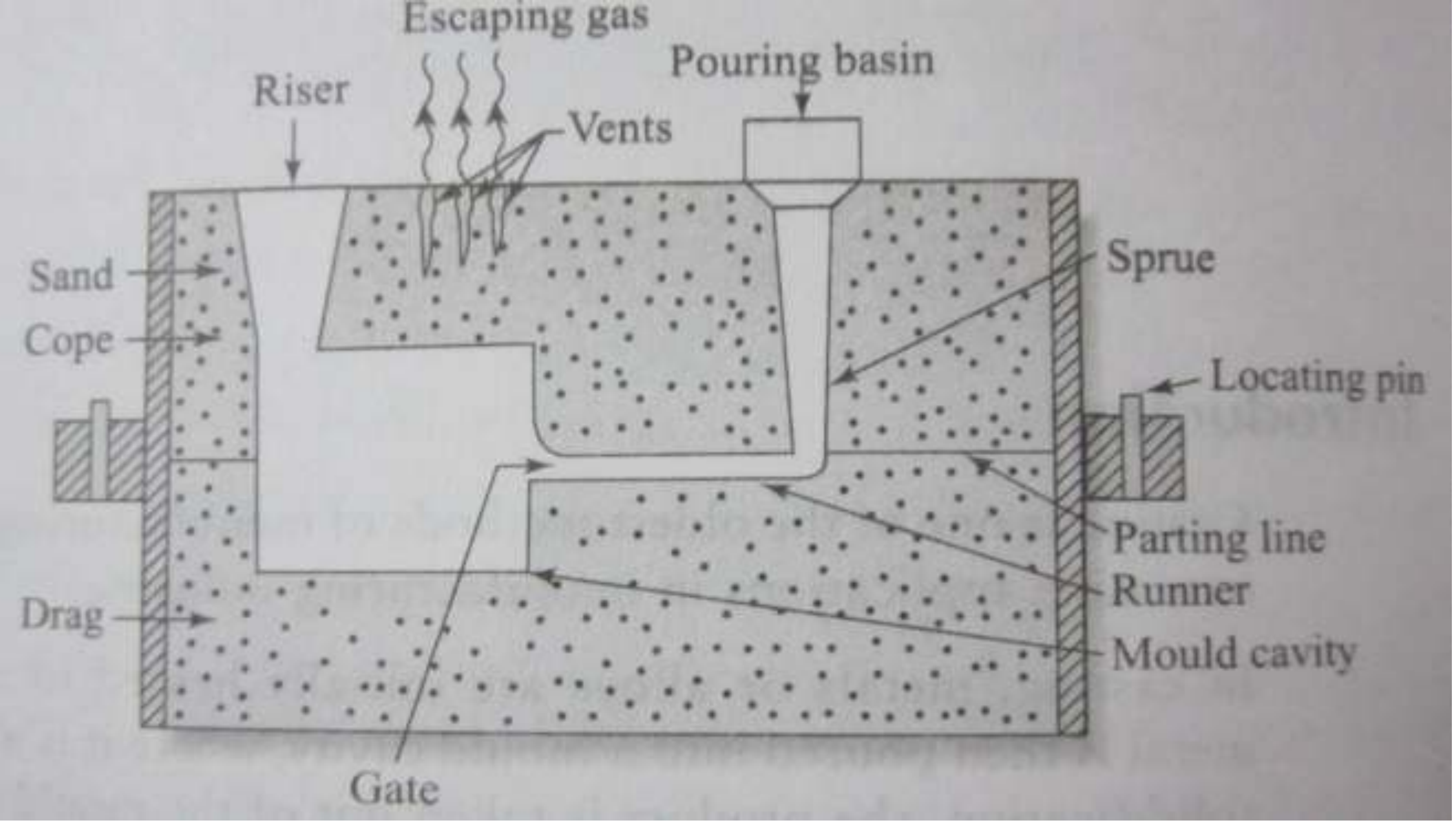
Pattern
Core
compacted sand / clay / water
(green sand)
molten metal
Pour basin
sprue
metal
casting
parting
line
runner
ingate
Finished Casting
hole



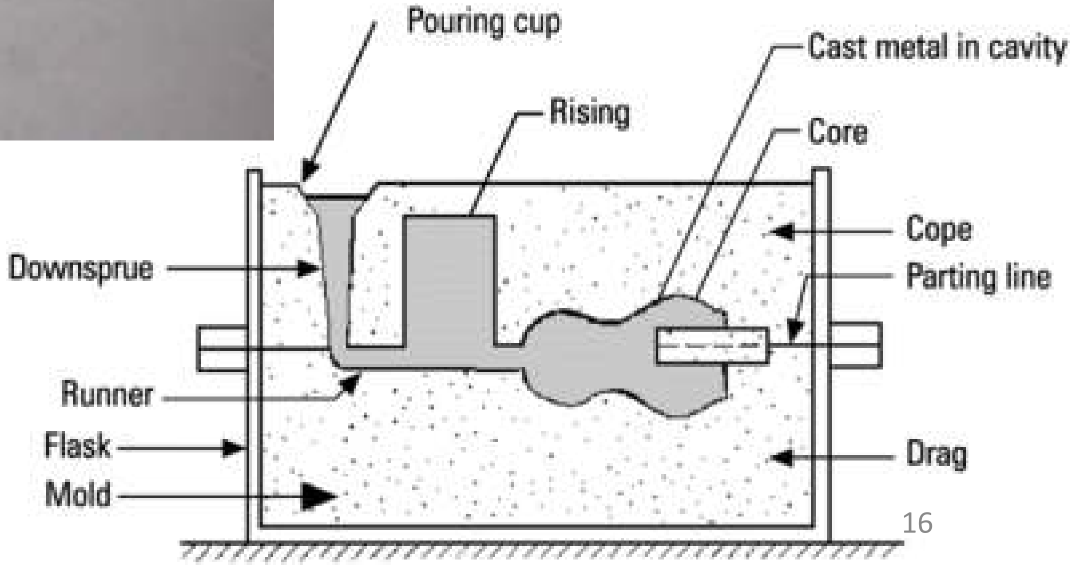


SAND CASTING





Escaping gas
Pouring basin
Riser
Vents
Sand
Cope
Sprue
Locating pin
Parting line
Runner
Drag
Mould cavity
Gate

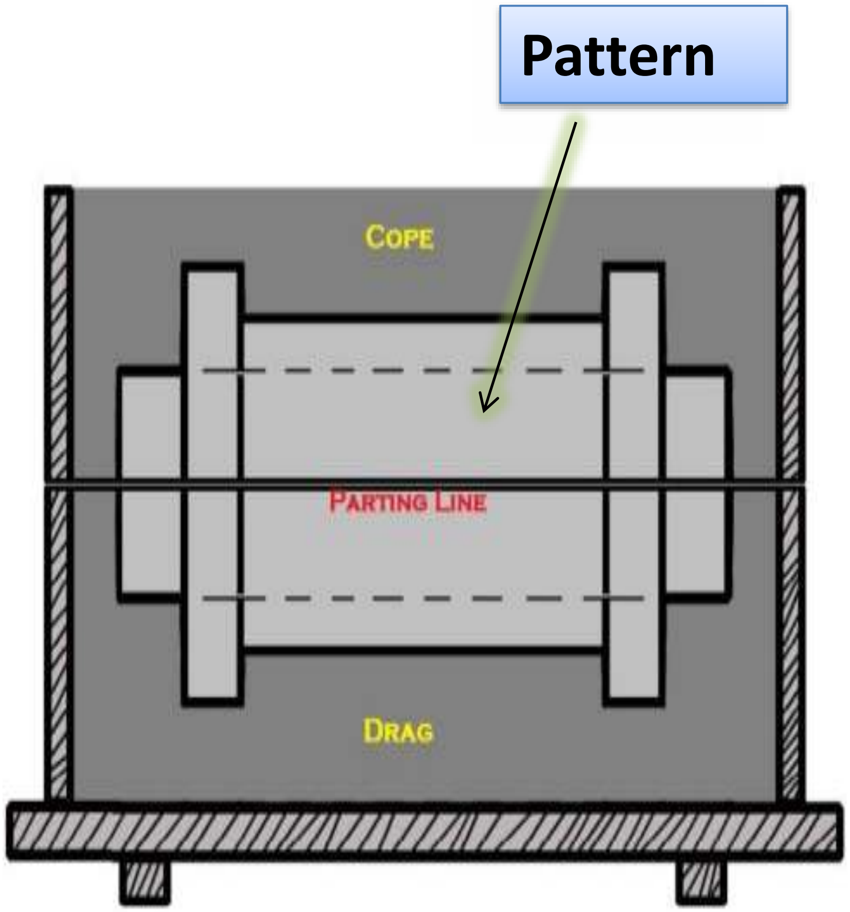


Pouring cup
Cast metal in cavity
Rising
Core
Cope
Downsprue
Parting line
Runner
Flask
Drag
Mold

Casting Terms

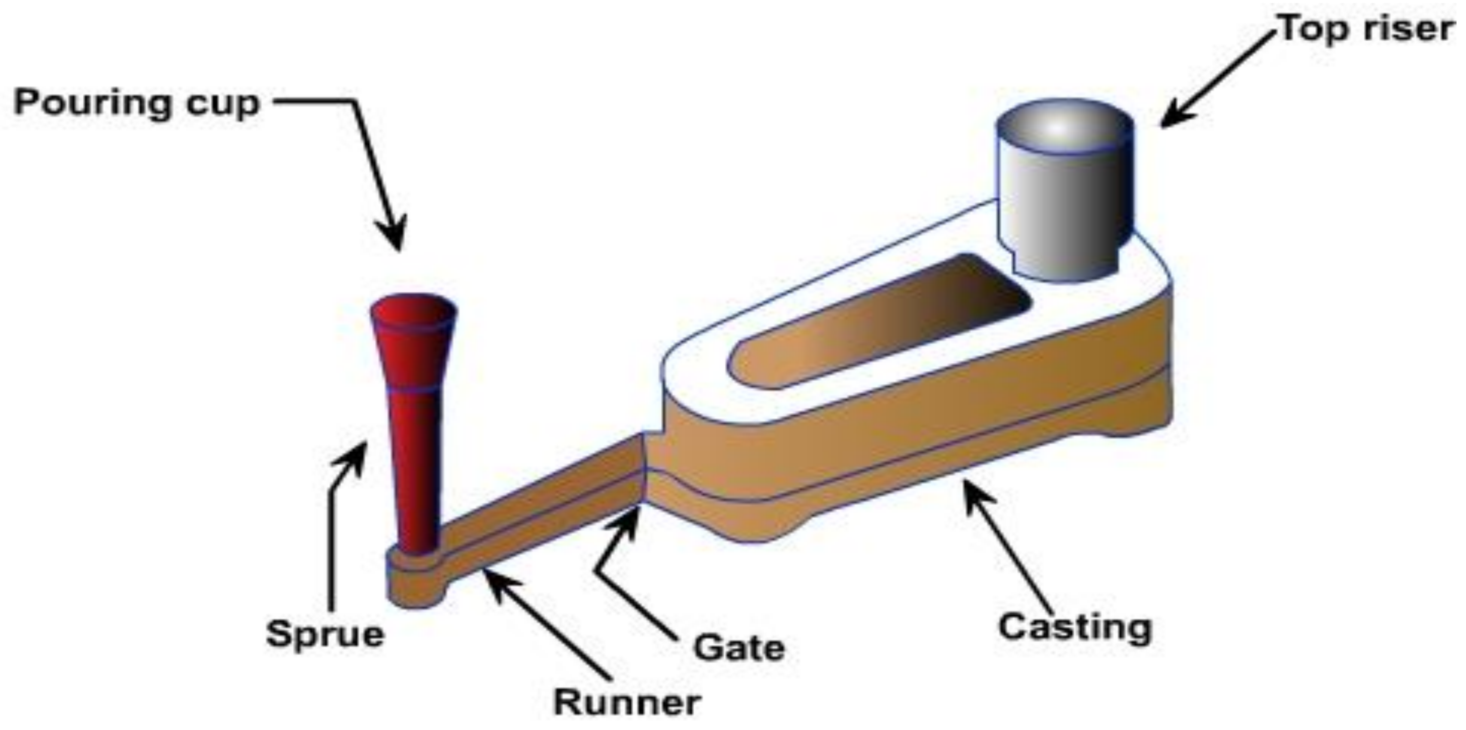
Important

1. ***Cope and Drag*** refer respectively to the top and bottom parts of a two-part casting flask, used in sand casting.
2. ***Pattern***: It is the replica of the final object to be made. The mold cavity is made with the help of pattern. Wood or metals.
3. ***Parting line***: This is the dividing line between the two molding flasks that makes up the mold.

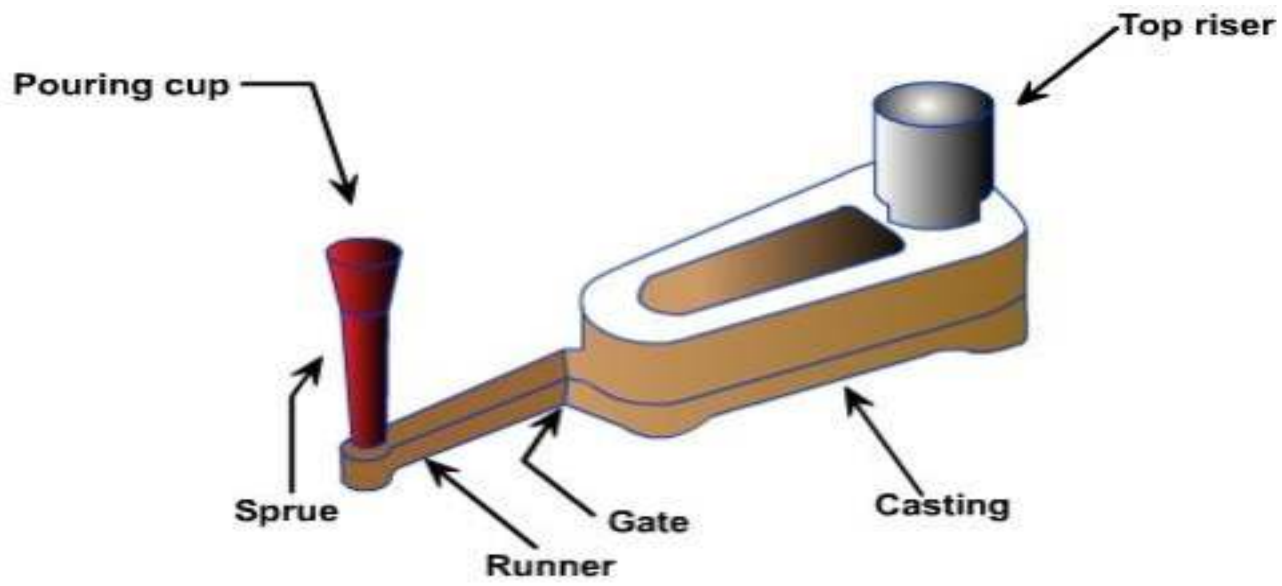


4. ***Pouring basin***: A small funnel shaped cavity at the top of the mold into which the molten metal is poured.

5. ***Sprue***: The passage through which the molten metal, from the pouring basin, reaches the mold cavity. In many cases it controls the flow of metal into the mold.



6. ***Runner***: The channel through which the molten metal is carried from the sprue to the gate.
7. ***Riser***: A column of molten metal placed in the mold to feed the castings as it shrinks and solidifies. Also known as feed head.
8. ***Gate***: A channel through which the molten metal enters the mold cavity.

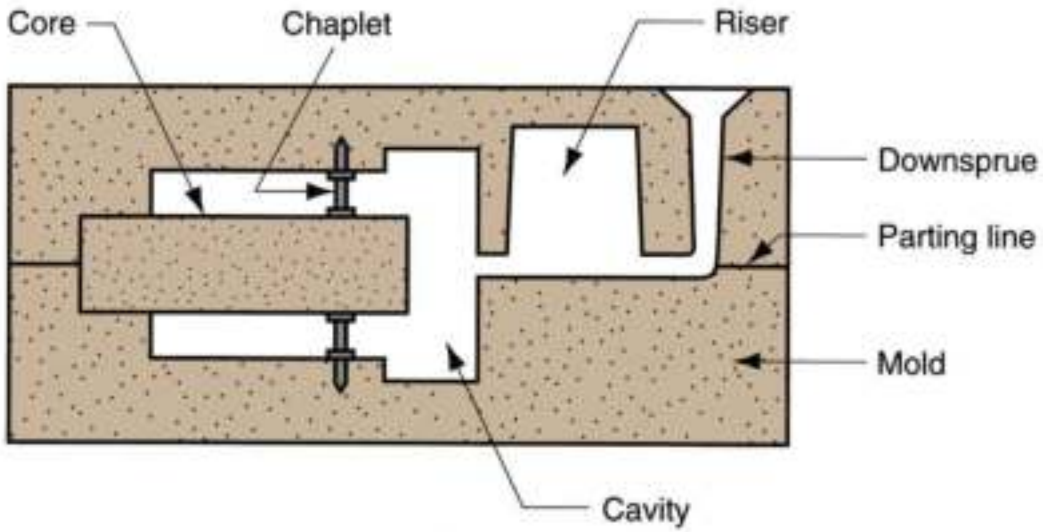


9. ***Core***: A separate part of the mold, made of sand and generally baked, which is used to create openings and various shaped cavities in the castings.

- For producing the hollow section the entry of the liquid metal is prevented by having a **core** in the corresponding portion of the mold cavity
- The projection of the pattern for locating the core in the mold are called **core print**

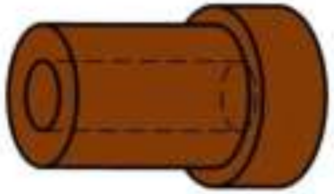
10. ***Chaplets***: Chaplets are used to support the cores inside the mold cavity to take care of its own weight and overcome the Metallostatic force.

11. ***Vent***: Small opening in the mold to facilitate escape of air and gases.



(a)

(b)



(c)

Sand Casting- Basic Steps

- Pattern making and core making
- Molding (flask, cope, drag, sand and binders, gate, runner, riser, pouring basin, sprue, mold closing)
- Melting metal/alloy
- Pouring
- Mold breaking
- Fettling(Removing sand adhering to the casting)
- Machining
- Qualification
- Store- dispatch

PATTERN

- Pattern is the model or the replica of the object to be casted and is used to prepare the mould cavity .

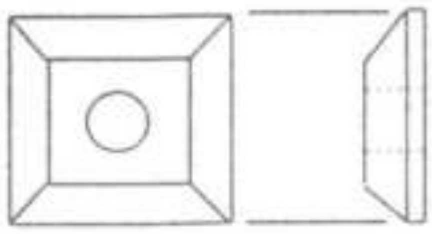
- **Selection of pattern:**
  - Service requirements, e.g. quantity, quality and intricacy of casting i.e., minimum thickness desired, degree of accuracy and finish required.
  - Type of production of castings and the type of molding process.
  - Possibility of design changes.
  - Number of castings to be produced, i.e., possibility of repeat orders.

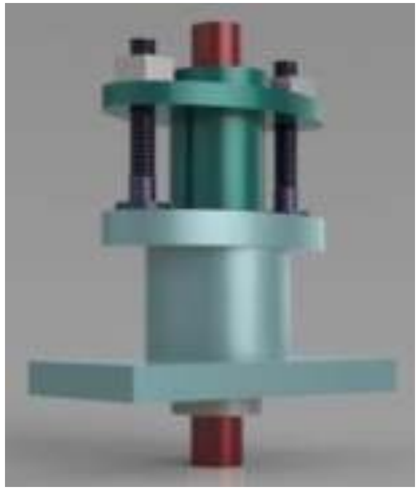
- **Desirable properties of pattern materials:**
  - easily worked, shaped and joined
  - light in weight
  - strong, hard and durable, so that it may be resistant to wear and abrasion, to corrosion, and to chemical action.
  - dimensionally stable in all situation.
  - easily available at low cost.
  - repairable and reused.
  - Able to take good surface finish.

- **Pattern Materials:**
  - Wood, Metal, Plastic, Plaster, Wax.

Pattern types

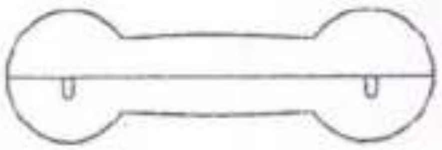
1. **Single piece pattern (Solid pattern)**
   - Simplest type of patterns and inexpensive since it is made of one piece.
   - One of the surfaces is expected to be flat which is used as the parting line.
   - Usually used for large castings of simple shapes.
   - For e.g.. Stuffing box of steam engine





2. **Split pattern**
   - are usually made in two parts, so that one part will produce the lower half of the mould, and the other, the upper half.
   - are held in their proper relative positions by means of dowel-pins fastened in one piece and fitting holes bored in the other.
   - The surface formed at the line of separation of the two parts, usually at the centerline of the pattern, is called the parting surface or parting line.

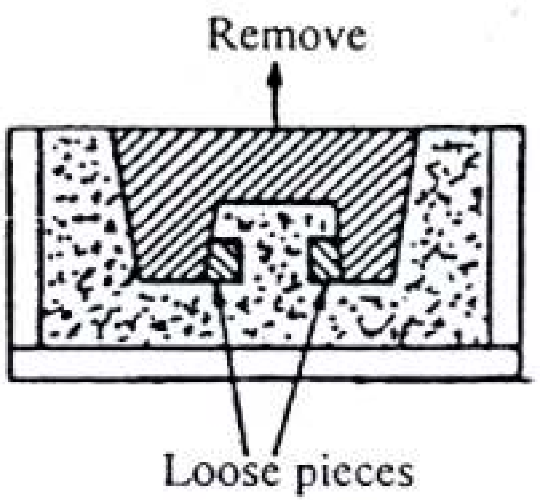
   For e.g.. Spindles, Cylinders, Steam Valve bodies, Water Stop cocks,Taps,Bearings,Small pulleys and wheels etc.,

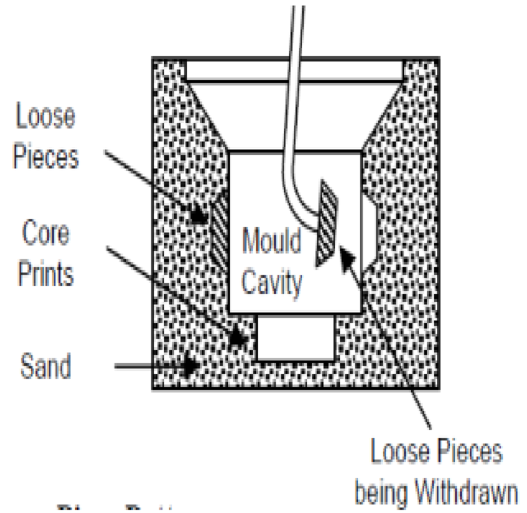



VIDEO ON
TYPES OF PATTERN

3. Loose Piece Pattern

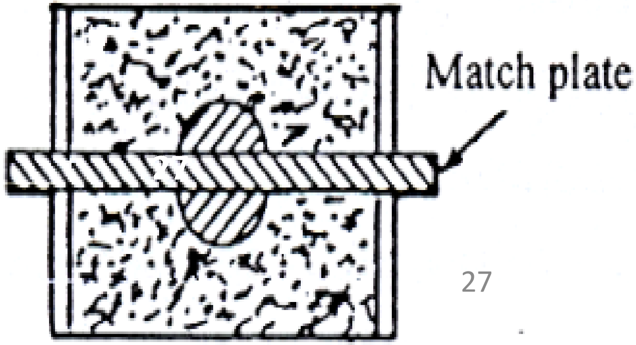
- Used when the withdrawal of the pattern from the mold is not possible because of its contour
- During molding operation, the obstructing part of the contour is held as a loose piece by wire/dowel pin.
- After Molding, Loose pieces are recovered through the gap generated by the main pattern.



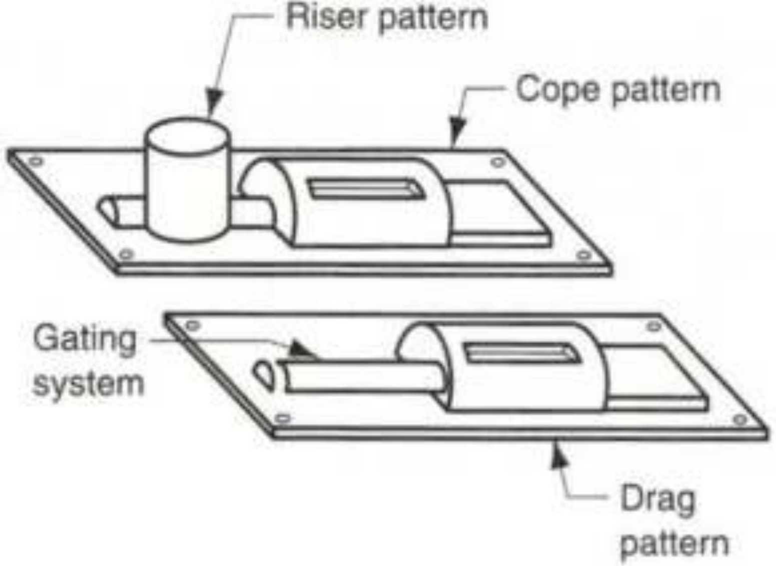


4. Match Plate Pattern

- Consists of a Match Plate, on either side of which split patterns are mounted.
- Has runner and gates attached with Match Plate.
- Number of patterns can be mounted on a match plate
- Preferred for producing small casting on large scale
- For eg. Piston ring of IC Engine



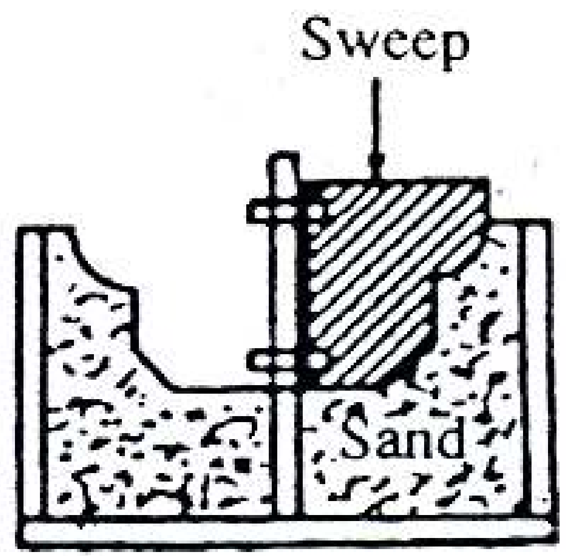
5. **Cope and Drag Pattern**



- The pattern is split about a suitable and convenient surface or line.
- Cope and drag halves of a split pattern are separately mounted on two match plate
- The cope and drag flask are made separately and brought together to produce the complete mould
- Production of Large castings

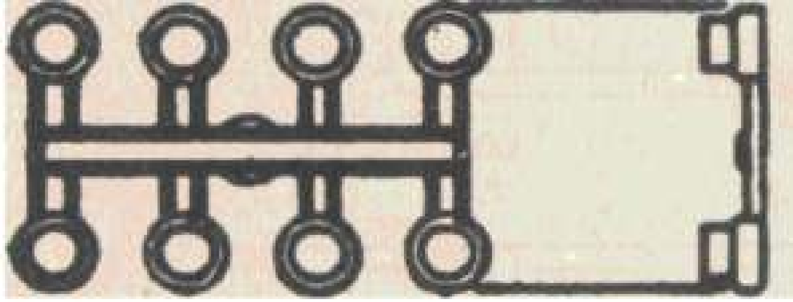
6. **Sweep Pattern**

- Preferred for Large castings of circular sections and symmetrical shapes
- Consists of wooden board having a shape corresponding to the desired casting and arranged to rotate about the central axis
- Avoids the necessity of making 3-D full pattern
- For eg. Cast Iron Large Kettles



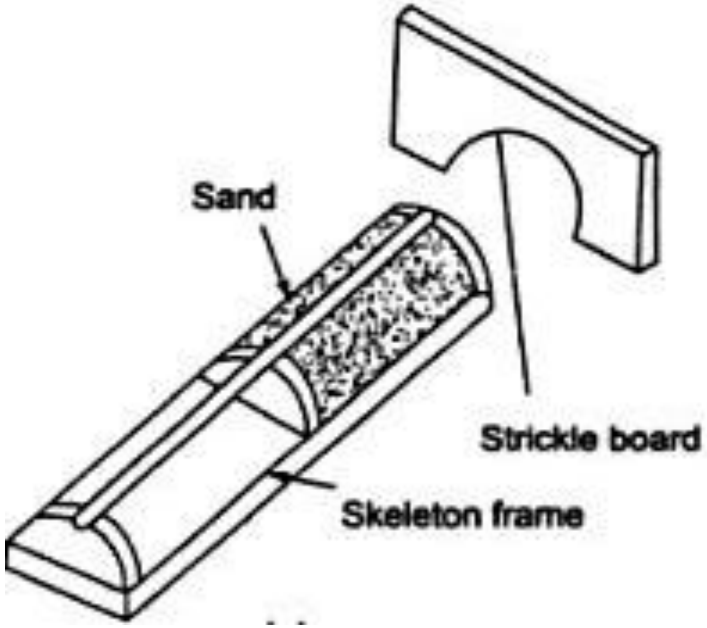
7. **Gated Pattern**

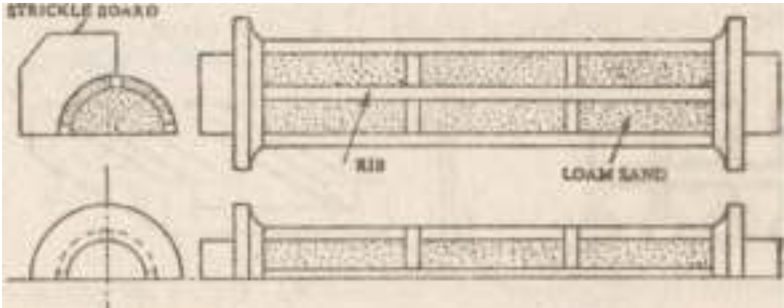
- Group of patterns are attached with gates and runners to facilitate the easy flow of the molten metal.
- Time spend for cutting the gates and runners is eliminated
- Used for the mass production of small castings.



8. **Skeleton Pattern**

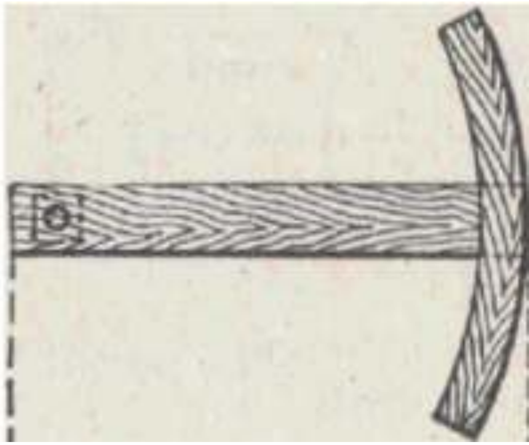
- Simple frames that outline the shape of the part to be casted.
- The frame is filled with loam sand and rammed.
- Strickle Board is used to shape the sand.
- Used for large castings with simple geometrical shapes.
- For eg. Water pipes, Turbine Casings etc.,

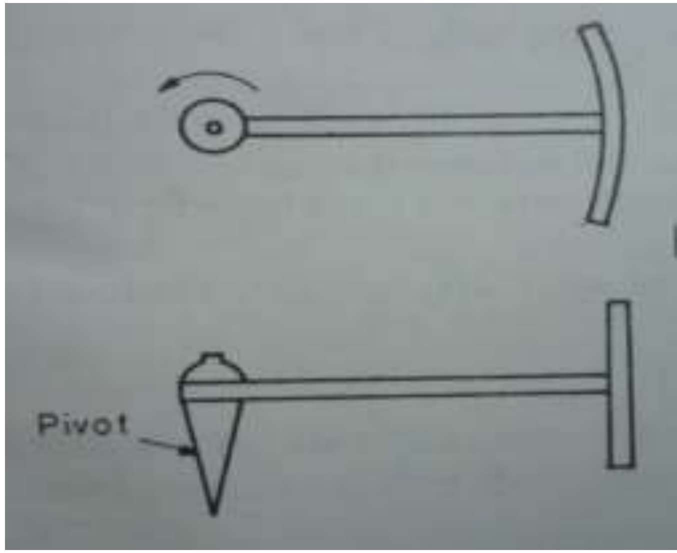




9. **Segmental Pattern**

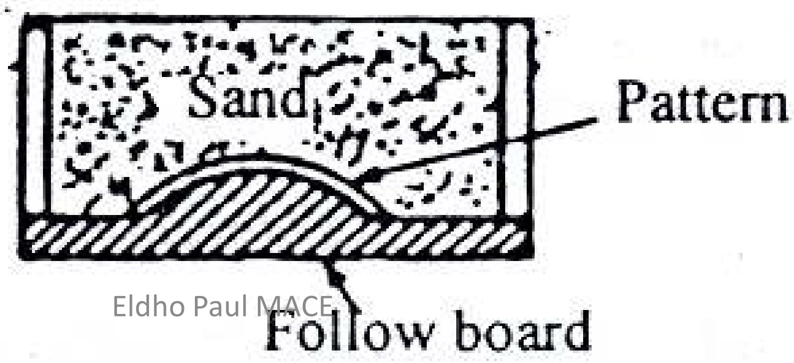
- Similar to sweep pattern but is in the form of a segment and is used for producing circular shapes.
- When one portion of the mold is created , pattern is lifted up and moved to the next portion to make the next segment of the mold
- For eg., Big Gears and Wheels

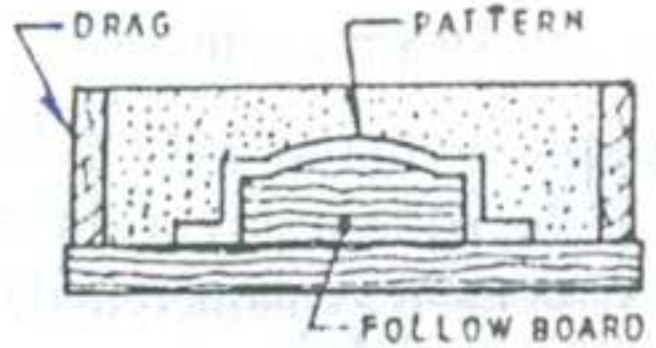




10. **Follow Board Pattern**

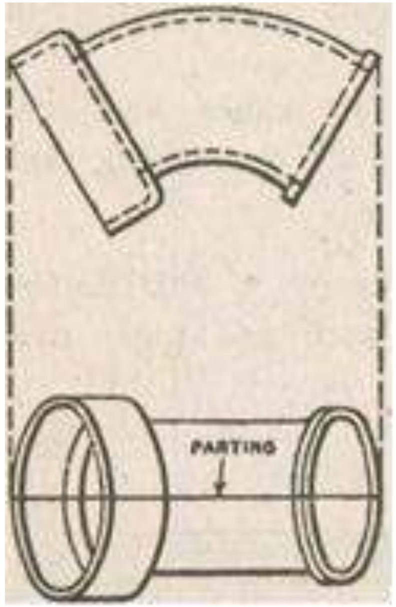
- Used for supporting a thin and fragile pattern which may collapse under pressure when the sand above is rammed.
- Also forms the parting line of the mold or castings

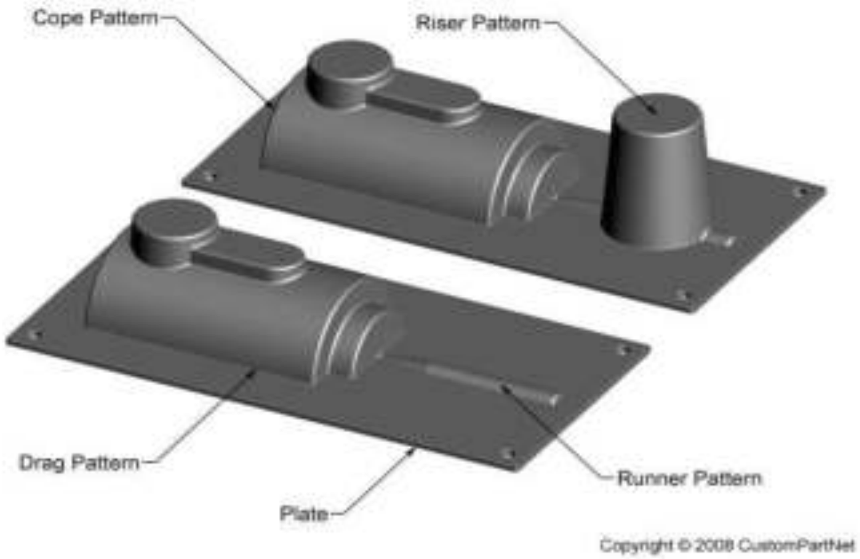




11. Shell pattern

- The shell pattern is used largely for drainage fittings and pipe work
- The shell pattern is a hollow construction like a shell and the outside shape is used as a pattern to make the mould, while the inside is used as a core-box for making cores.





Cope and drag pattern

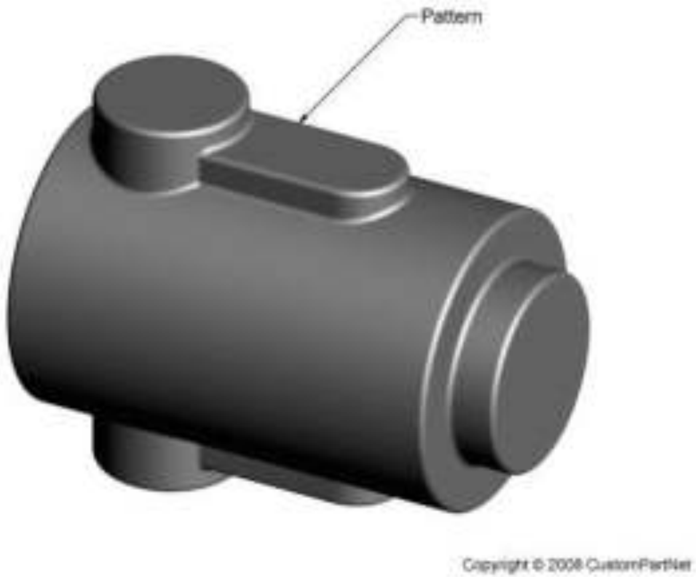
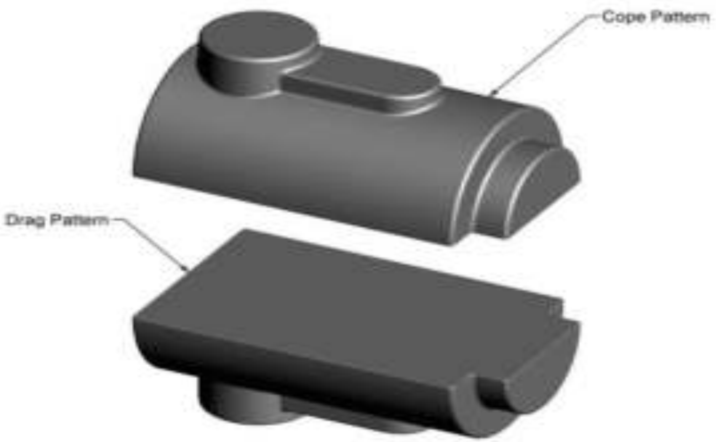
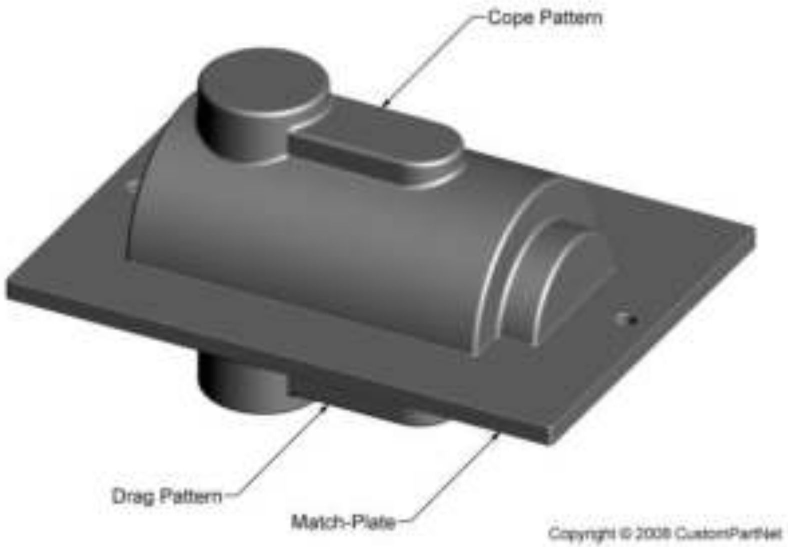


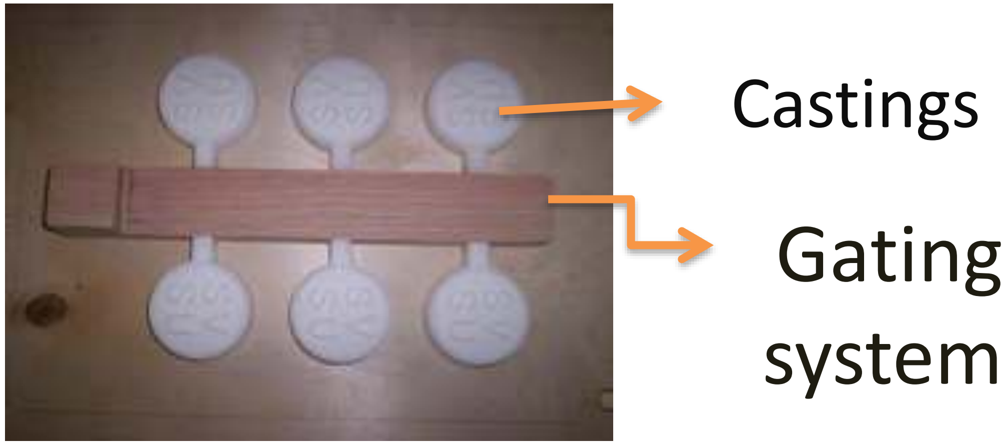
Fig: Single piece pattern



split piece pattern

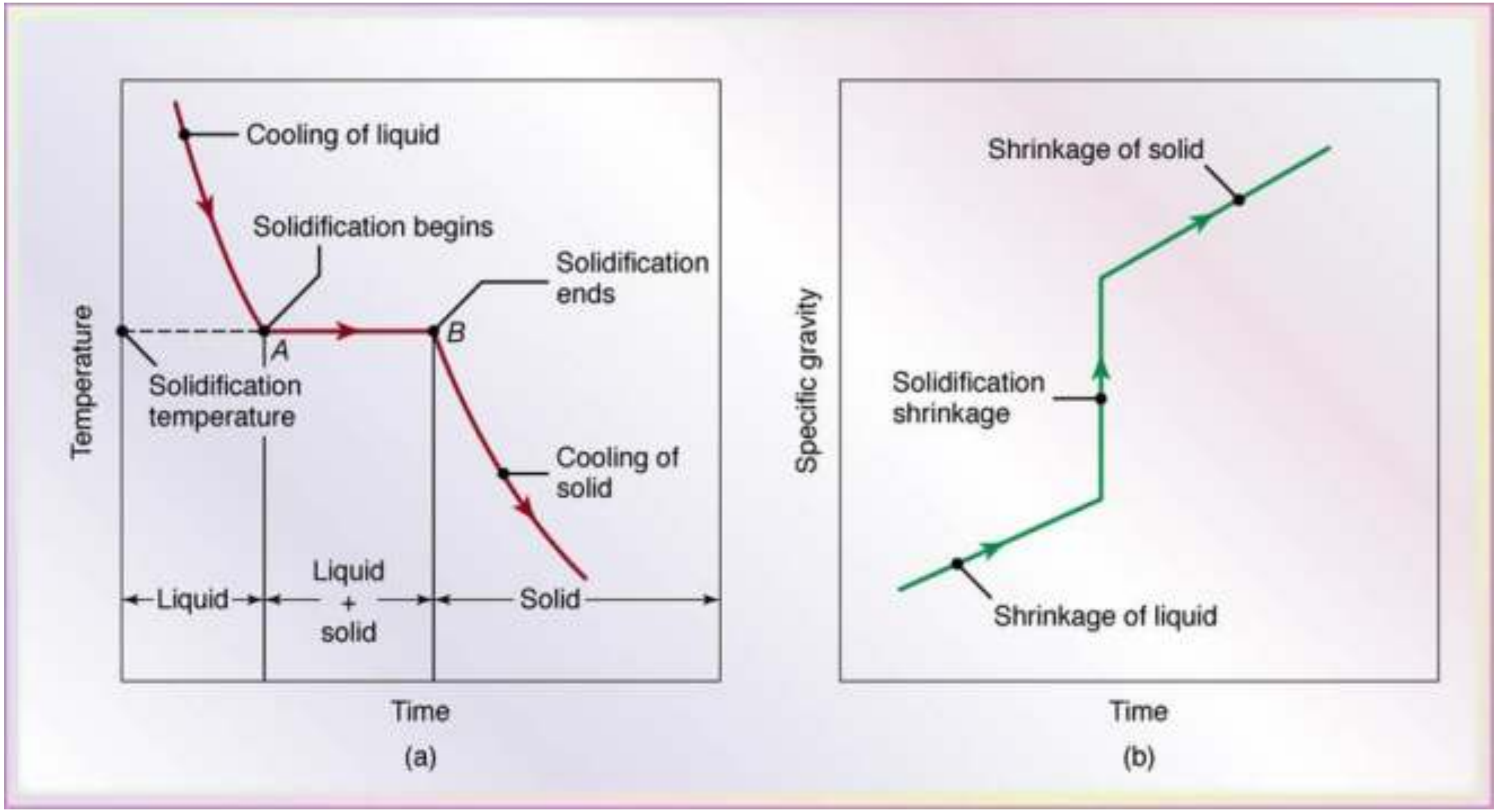


Match plate pattern



GATED PATTERN

SOLIDIFICATION OF PURE METALS



(a) Temperature as a function of time for the solidification of pure metals. Note that the freezing takes place at a constant temperature. (b) Density as a function of time

- **The Liquid Molten metals contracts or shrink in three stages,**
- Stage(1)- Liquid Contraction
  - When temperature of liquid metal drops from Pouring to Freezing temperature.
- Stage(2)- Phase Transition Contraction
  - When the metal changes from liquid to solid state.
- Stage(3)- Solid Shrinkage
  - When the temperature of solid phase drops from freezing to room temperature .

1. The **shrinkage for stage 3** is compensated by **providing shrinkage allowance** on pattern, while the shrinkage during **stages 1 and 2** are compensated by **providing risers.**
2. **Al has the highest liquid shrinkage, Brass –highest solid shrinkage & Steel- highest total shrinkage.**
3. **Risers are not used for grey cast iron casting due to the presence of carbon in the forms of graphite lakes which contracts in stage 1 cooling and expands in stage 2.**

PATTERN ALLOWANCES

Short note or SA

PATTERN SIZE = CASTING SIZE ± ALLOWANCES

i. Shrinkage/Contraction Allowance

– All metals shrink volumetrically after solidification. Hence for obtaining particular sized casting , the pattern is made oversized by an amount equal to that of shrinkage or contraction.

– Shrinkage allowances of different metals are given below:

a) Grey Cast Iron:6.95-10.4 mm/m

b) Malleable Cast Iron:10.4 mm/m

c) **Steel: 20.8 mm/m**

d) Aluminium:17 mm/m

e) Brass: 15.3 mm/m

f) Bronze: 10.4-20.8 mm/m

ii. Machining/Finish Allowances:

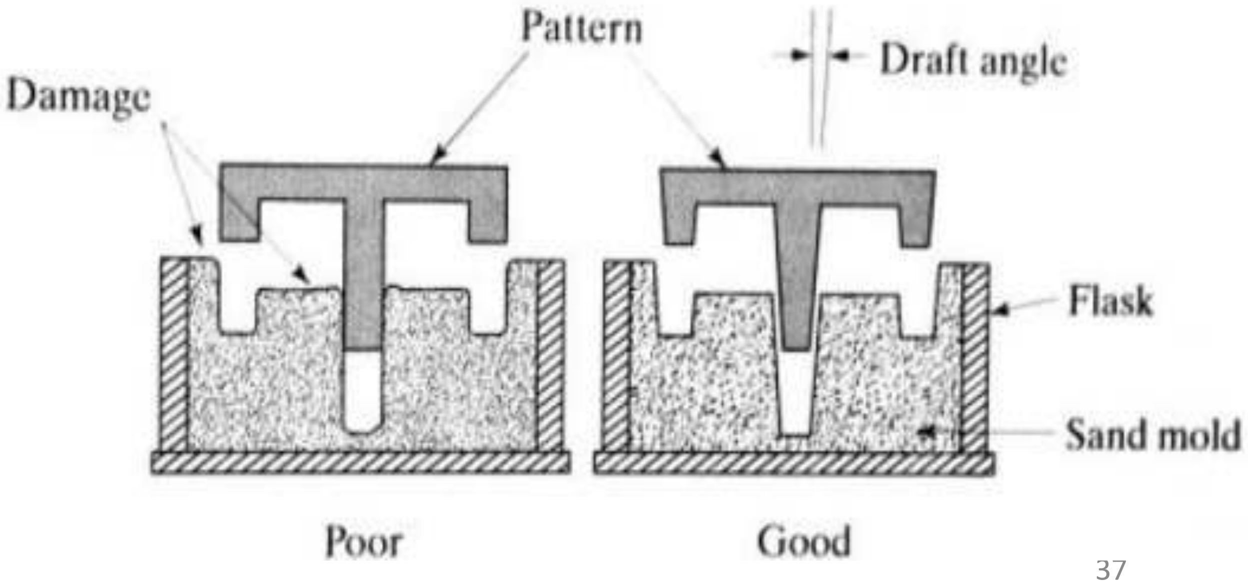
- Machining Allowances are provided for the following reasons:
  - During the heat treatment process, Castings get oxidized and scales formed need to be removed.
  - To remove surface roughness and other imperfections.
  - To achieve exact casting dimension and finish.

- Factors depending on which the machining allowances should be provided:
  - Nature of the metals.
  - Size and shape of the castings
  - Degree of surface finish on the finished part.
  - Molding process employed.

iii. Draft/Taper Allowances:

- Draft allowances are provided so that pattern can be easily removed from the mold.
- Provided to all surfaces perpendicular to parting line.

- The amount of taper depends on
  - Nature of the mold materials.
  - Size and shape of the pattern
  - Molding process employed.



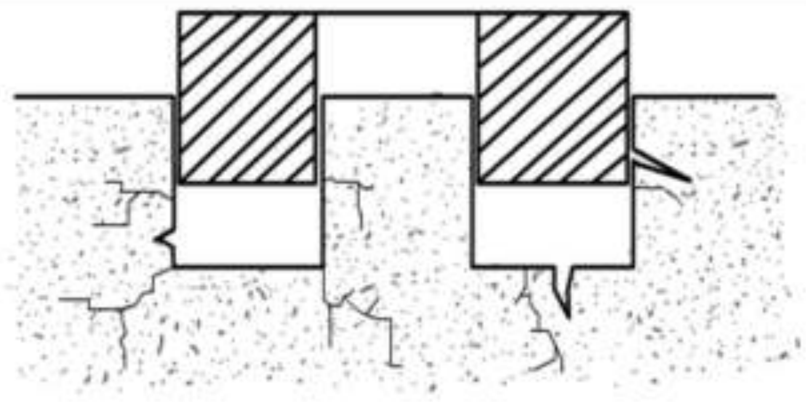


Figure 3 (a) Pattern Having No Draft on Vertical Edges

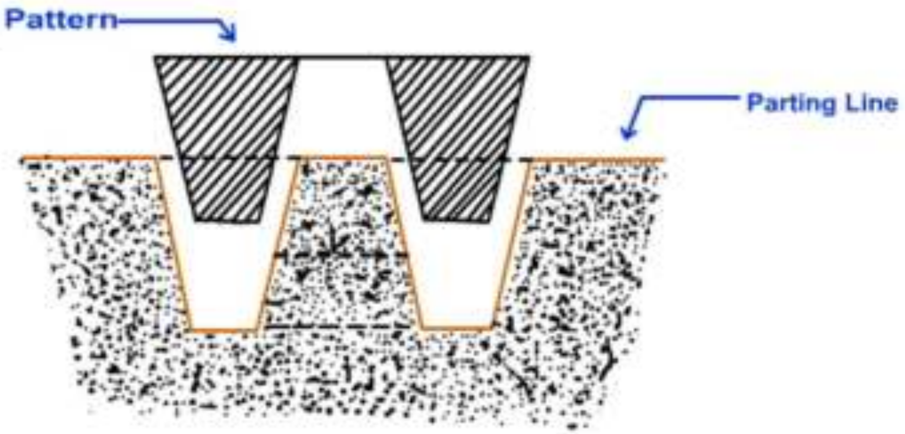


Figure 3 (b) Pattern Having Draft on Vertical Edges

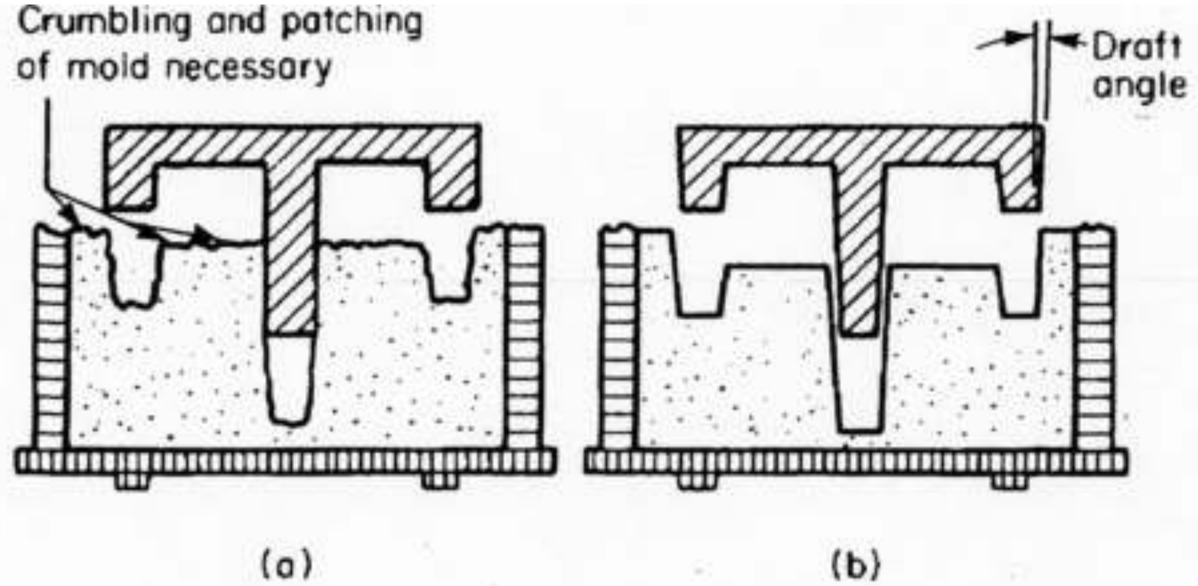
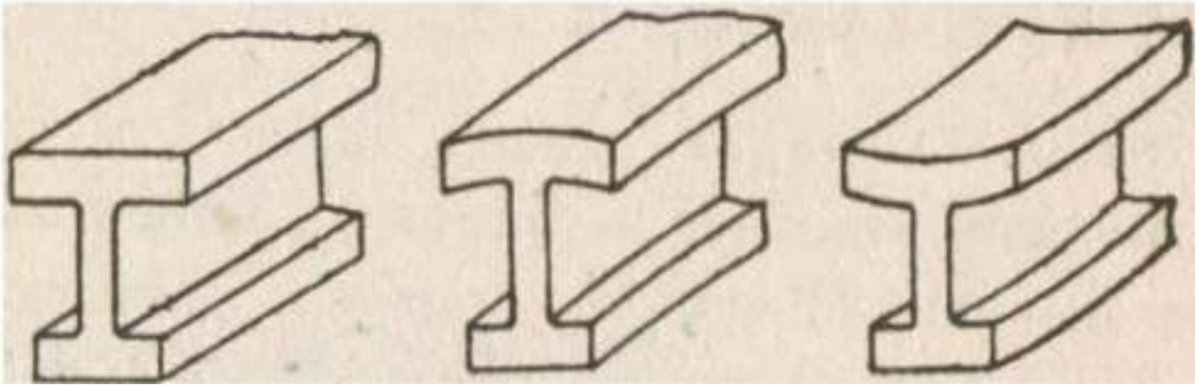


FIGURE 5.1.6 (*a*) Poor stripping from the mold results when no allowance is made for draft. (*b*) Ample draft permits easy and safe stripping.

iv. **Distortion/Camber Allowances:**

- Camber Allowances are provided to account for the following reasons:
  - Irregular shaped castings.
  - Non uniform shrinkage due to unequal arm thickness.
  - One portion of the casting cools at a faster rate as compared to the other



- Distortion can be practically eliminated by providing an allowance
- Generally varies from 2-20 mm depending upon the size, shape and material of the castings.

- **Shake/Rapping Allowances:**
  - Negative allowance provided to compensate for the enlargement in the mold cavity due to loosing of the pattern for easy removal by striking or rapping the pattern.
  - Provided on large castings .
- A pattern is shaken or rapped by striking the same with a wooden piece from side to side. This is done so that the pattern is little loosened in the mold cavity and can be easily removed.
- In turn, therefore, rapping enlarges the mould cavity which results in a bigger sized casting.
- Hence, a –ve allowance is provided on the pattern i.e., the pattern dimensions are kept smaller in order to compensate the enlargement of mould cavity due to rapping.

Pattern color codes

- Patterns are giving colors and shades in order to,
  - Identify quickly the main parts of the pattern and different parts of the pattern
  - Indicate the type of metal to be cast
  - Identify loose piece, core prints etc…
  - Identify the surface to be machined

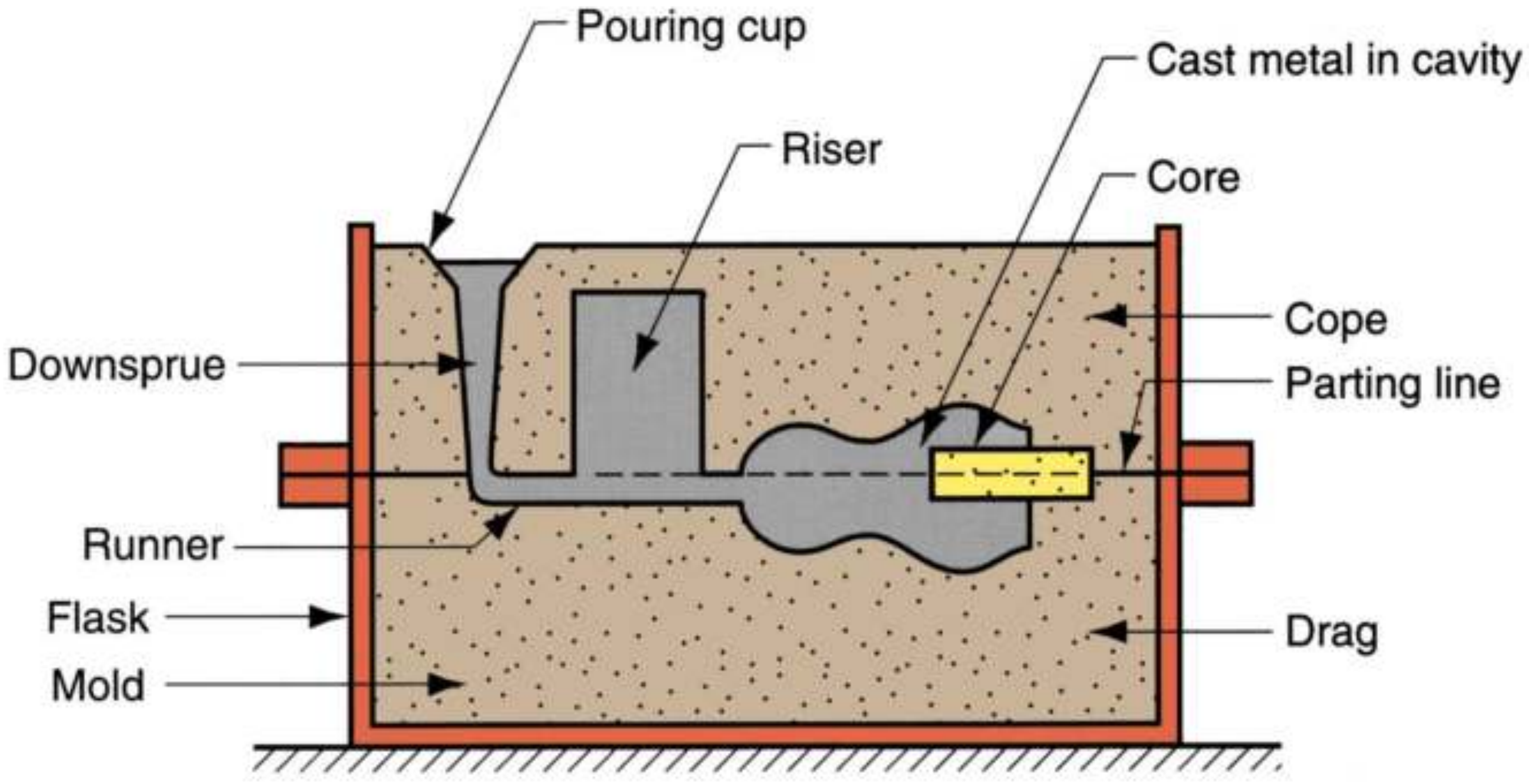
- **Black:** Cast surface to be left unmachined.
- **Red:** Cast surface to be machined.
- **Red Stripes on Yellow Base**: Loose Pieces
- **Black stripes on a yellow** background: Stop-offs or supports
- Yellow Stripes on **Black Background**: Core pints
- No color: Parting Surface.

DIFFERENCE BETWEEN PATTERN AND CASTING

- The main difference between a pattern and the casting is as regards their dimensions
- A pattern is slightly larger in size as compared to the casting, because a pattern,
- Carries Shrinkage allowances, it may be of the order of 1 to 2 mm/100mm
- Given a Machining allowances to clean and finish the required surfaces

- A pattern mat not have all holes and slots which a casting will have. Such holes unnecessarily complicate a pattern and therefore can be drilled in the casting after it has been made
- A pattern may be in two or three pieces whereas casting is in one piece
- A pattern and the casting also differ as regards the material out of which they are made

SAND CASTING-Nomenclature



Sand casting mold

Mould

..\..\Manufacturing Process\btech MP\for CASTING students\Die Casting Animation.WebM

- It's a cavity from which the casting is prepared.
- Castings made in two types of mould:
  - Permanent Mould- (Made of Steel or Grey Cast iron)
    - Reusable Mould generally used in die castings and centrifugal casting process.
    - Used for small intricate complex shapes due to low rate of cooling.
  - Expendable/Disposable/Sand Molds:
    - the mold is used for single casting, is made of sand, plaster, ceramics, and similar materials. After the casting, the mould is destroyed and the sand / core reclaimed for later use.

Types of Moulding

1. **Green Sand Mould-**
   - Most widely used moulding process.
   - Green sand is a sand which contains water
   - Small and medium sized castings.
2. **Dry Sand Molds-**
   - It contains binders like clay, molasses etc
   - harden when the mold is heated or dried.
   - Molded with green sand and afterwards heated.
   - Consist of
   - 70-75% Silica sand ,
   - 15-20% Clay,
   - 5-8% Sodium Silicate and
   - 2-4% Additives.

3) **Air dried Moulds-**
   - Moulding sand in green condition and then it is kept open to the atmospheric air for a certain period of time

4) **Skin dried moulding**

- Moulding with green sand and then the skin of the mold cavity is dried up with help of gas torches or radiant heating lamps.

5) **Core Sand Mould.**

- Made by assembling a number of cores made individually in separate core boxes and baked.

6) **Shell Moulds.**

- Produced with the help of heated iron or steel patterns.
- Exceptionally good surface finish and accuracy.

7) **Loam Moulds**

- No Pattern is needed to make a loam mold.
- Uses a moulding sand containing about 50 percent sand grains and 50 per cent clay . Consist of

49-50% Silica sand ,

49-50% Clay

and 1-2% Additives.

It is used for grey cast iron castings.

MOULDING SANDS

Ingredients/ Constituents of moulding Sand are:

1. **Silica**

2. Binders

2. Water

3. Additives

1. SILICA

- It is in the form of granular quartz, itself a sand, is the chief constituent of moulding sand.
- Silica contains **80-90** percent of silicon dioxide and is characterized by a high softening temperature and thermal stability.
- It is a product of the breaking up of quartz rocks or the decomposition of granite.
- Silica sand grains impart
  - refractoriness,
  - chemical resistivity,
  - and permeability to the sand.
  - They are specified according to their average size and shape.

2. Moulding Sand Binders

- Binders are used to improve cohesion between the moulding sand ingredients in the green or dry state.
- Gives strength to the moulding sand.
- Increasing the binder content reduces the permeability of moulding sand.
- **Clays are used as binders**.
- Fire Clay, Bentonite, Illite and Kaolinite

3. Additives

- Basic constituents of moulding sand mixture are- sand, binder and water.
- Materials other than basic ingredients are also added in the moulding mixture in order to
  - Enhance the existing properties.
  - To develop certain properties.

Some of the Additives used in moulding are given below.

- Facing Materials : used to obtain smoother surfaces of castings. e.g. Sea Coal, Graphite etc.
- Cushion Materials: used to prevent thermal expansion. E.g. Wood flour, perlite etc.
- Other special additives: e.g. fuel oil, iron oxide etc.

4. Water

- 1.5 to 8 percent.
- Activates the clay by developing plasticity and strength.
- Water in moulding sand is often referred to as "tempering water".
- Water in excess is called "free water",
- Free water makes the sand more plastic and more mouldable though the strength may be lowered.
- Control of water in sand (clay) is very important.

PROPERTIES OF MOULDING SANDS

- Flowability
- Green Strength
- Dry Strength
- Hot Strength
- Permeability
- Refractoriness
- Adhesiveness
- Collapsibility
- Fineness
- Coefficient of Expansion
- Durability

- **Flowability** : It is the ability of the moulding sand to get compacted to uniform density.

- **Cohesiveness or strength :** This is the ability of sand particles to stick together. Insufficient strength may lead to a collapse in the mould.
  - This property of a sand in its green or moist state is known as *green strength.* A mould having adequate green strength will retain its shape and will not distort or collapse even after the pattern is removed from the moulding box.
  - The strength of a sand that has been dried or baked is called *dry strength.*

- **Permeability** : It is the ability of a moulding sand to allow the passage of mould gases through them. Mould gases may be produced by the reaction of the molten metal with the moisture or binders.
  - The sand must, therefore, be sufficiently porous to removed evolved gases freely when the mould are poured.

- **Refractoriness** : It is the ability of the sand to withstand high temperature with out burn.
- **Adhesiveness** : It is the ability of the sand to stick on to the mould walls.
- **Collapsibility** : It is the ability of the sand to collapse after the casting solidifies.
- **Fineness** : It is the ability of the sand to produce smooth surfaced castings.
- **Coefficient of Expansion** : A good moulding sand should have less coefficient of expansion.
- **Durability** : It is the ability of the sand to be used again and again.

1. MOULDING SAND

For reference

- Moulding sand generally classified in to three types:
  - Natural Sands
  - Synthetic Sands
  - Special sands

Natural Sand

For reference

Characteristics :

- Contains 5-20% clay.
- Can maintain moisture content for a long time.
- Less refractory compared to synthetic sand.
- They are inexpensive.
- Contains organic matter.
- Can be easily repaired.
- Used for casting cast iron and non-ferrous metals.

Synthetic Sand

For reference

Synthetic Sand consists of :

- Natural Sand with or without clay.
- Binder
- Moisture.

Characteristics

- Have good permeability.
- Requires less proportion of binder.
- Greater refractoriness.
- More uniform grain size.
- Contains no organic materials.
- Used for casting steel, ferrous and non-ferrous metals.

Special sands

- They are ideal in getting special characteristics, which are not ordinarily obtained in other sands.
- Zircon, olivine, chamotte, chromite and chrome-magnesite are often used as special sand.

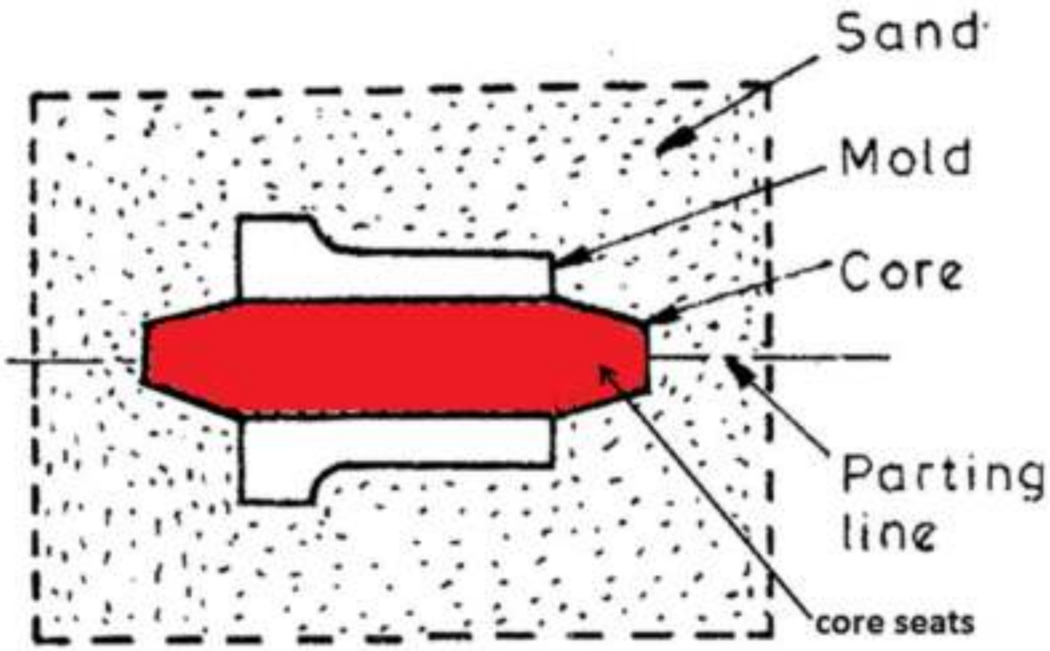
CORE

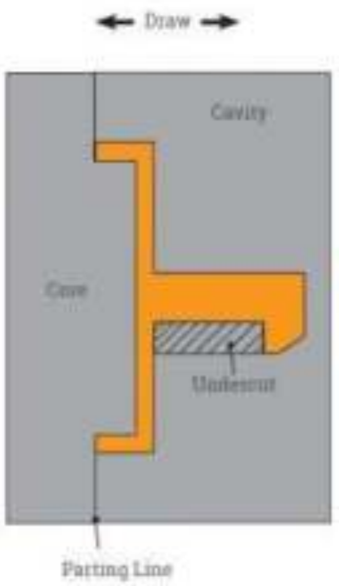
- **Core** is an obstruction which when positioned in the mould, naturally **does not permit the molten poured metal to fill up the space occupied by the core.**

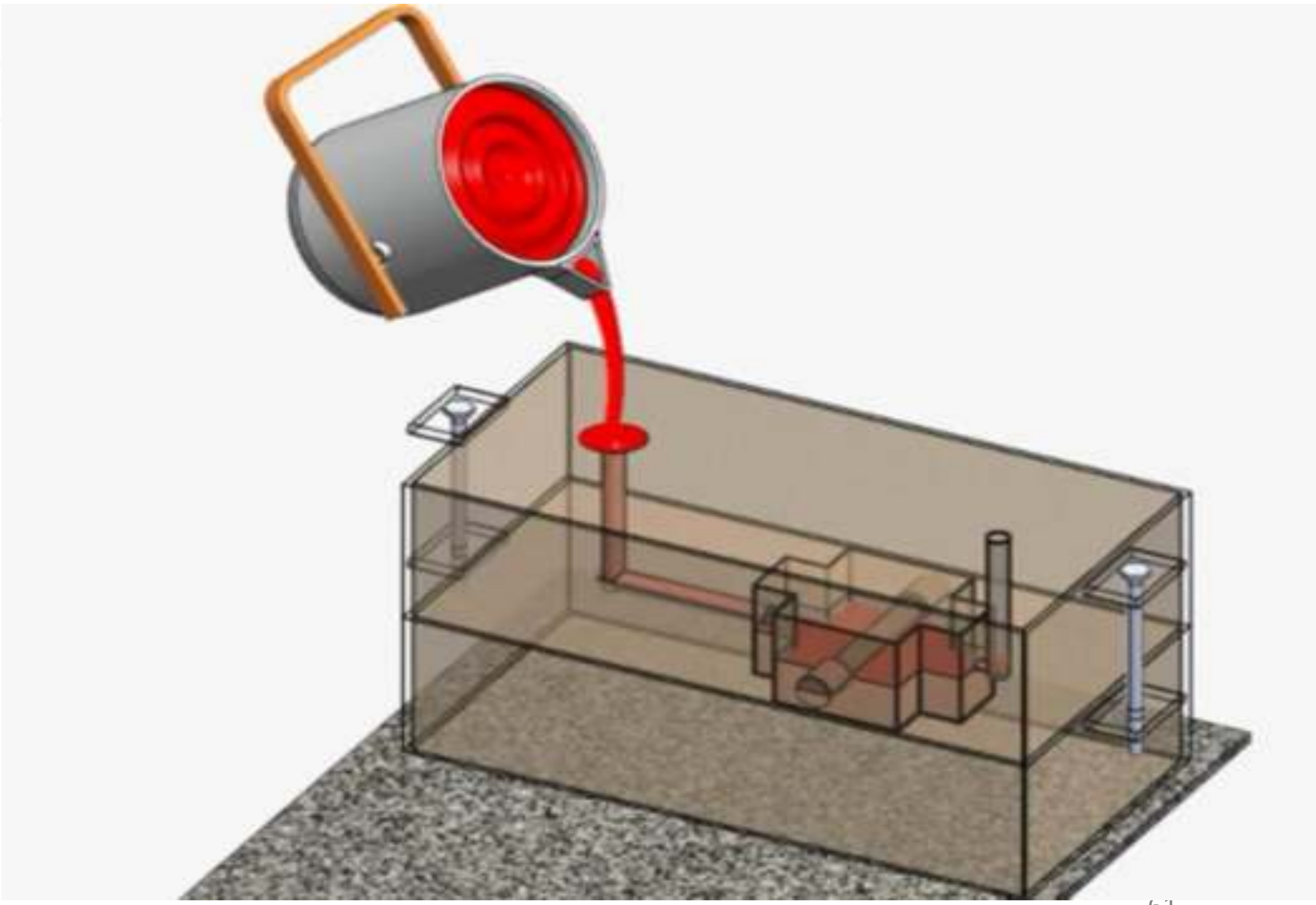
- In this way a core produces hollow casting.

- Cores are required to create undercuts and interior cavities that are often a part of castings.

- Cores are employed as inserts in moulds to form design features that are otherwise extremely difficult to produce by simple moulding.


Sand
Mold
Core
Parting
line
core seats


Draw
Cavity
Core
Undercut
Parting Line

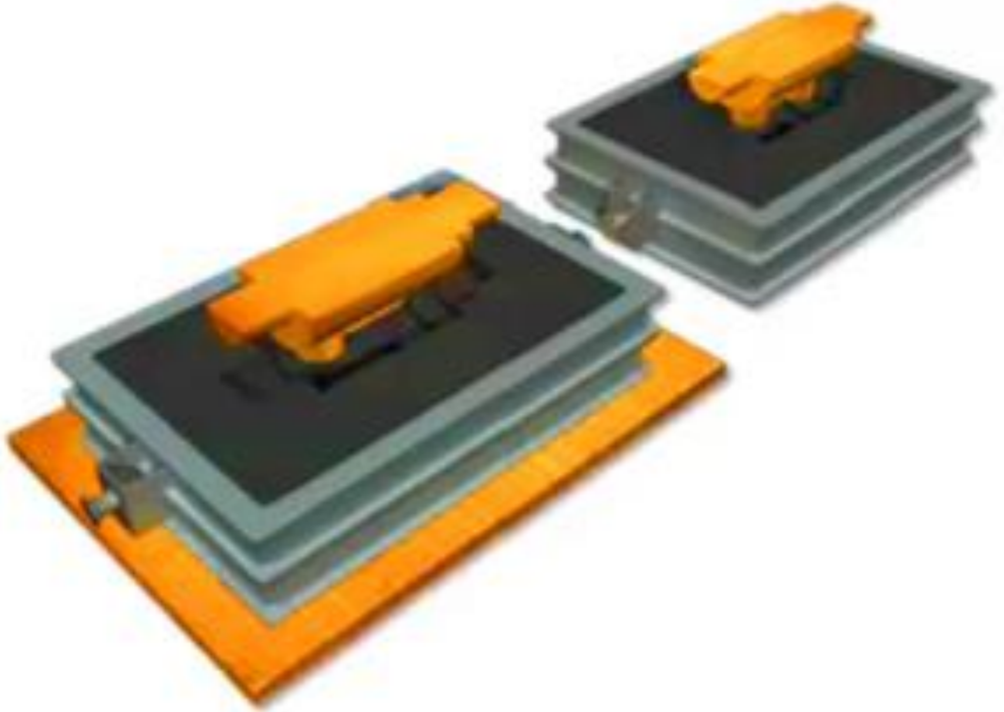


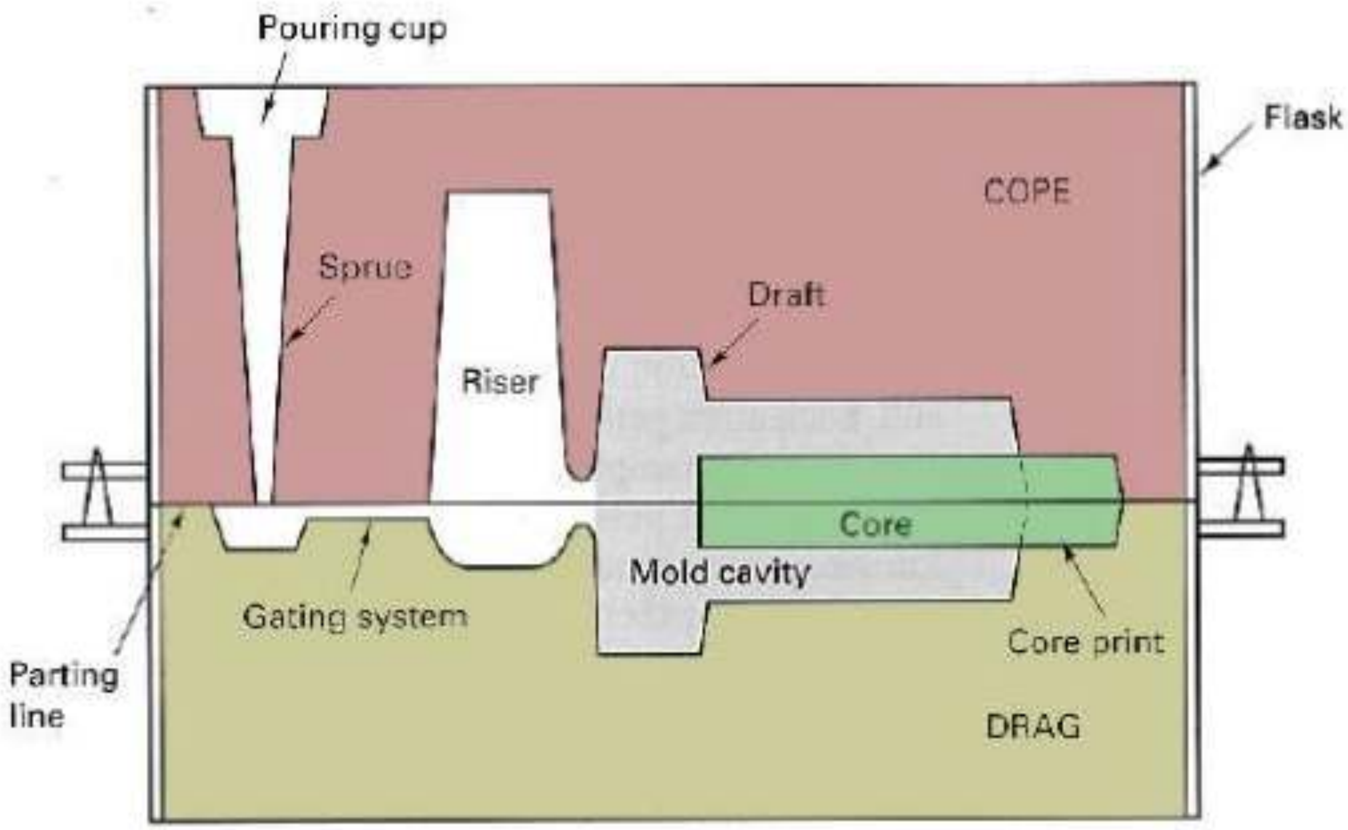
- Inserts employed as a part of the mold for obtaining hollow castings , undercuts, and interior cavities.

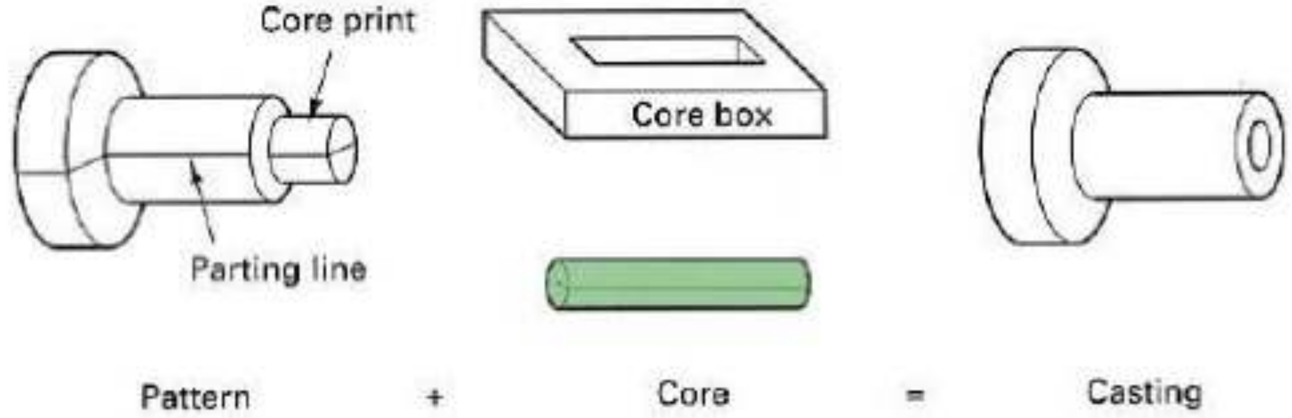
- Generally produced separately from the sand mold in the core boxes and is then hardened.

- For e.g.. Water cooling chamber in IC engine, Air space between cooling fins of an air cooled engine.
- Core is manufactured by dry sand with CO_2 Bonding
- *Essential properties core materials,*
  - *Non metal*
  - *Sufficient strength*
  - *Smooth surface*
  - *collapsibility*

INTRODUCTION TO CORE




Pouring cup
Flask
COPE
Sprue
Draft
Riser
Core
Mold cavity
Gating system
Core print
Parting line
DRAG


Core print
Core box
Parting line
Pattern
+
Core
=
Casting

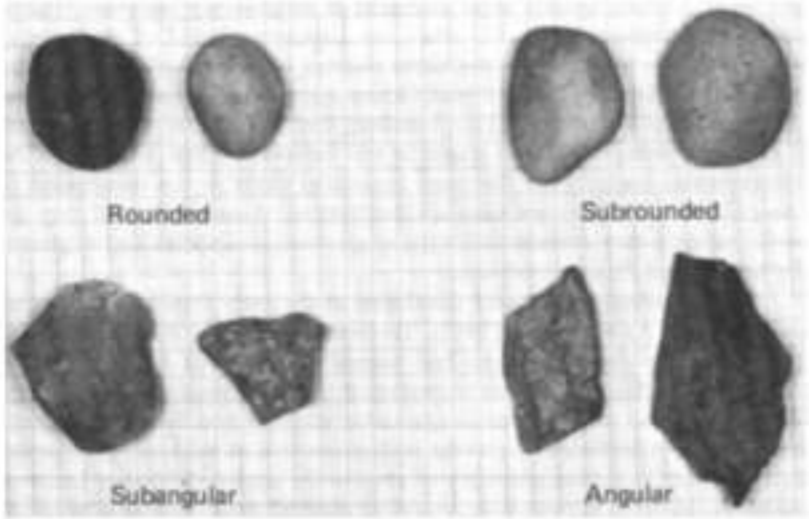
Core sand

- The ingredients of core sands are sand and binder
- Granular refractories
  - Usually Dry silica sand
  - Zircon
  - Olivin
  - Carbon sand
- Sand that contain more than

5% clay cannot be used for cores

- the important facts to be consider
  - Size
  - Shape
  - Distribution of sand grains
  - Clay content
  - Composition of clay particles
- Smaller grain size of sand – smooth surface casting
- Rounded grains sand for higher permeability

Shape of the Sand Grains



- Core sand has no natural bond formation ability
- **Core binders**
  - Used to hold sand grains together
  - Gives strength
  - Makes core resistant to breaking
- Core binders are generally 3 types
  - Binders that harden at room temperature
  - Binders that require baking to harden
  - clays
- 2 types:
  - Organic binders. Eg: Cereal binder, wood binder, veg. and animal oil
  - Inorganic binders. Eg: Bentonite, Iron oxide etc.
- **Water**
  - 2.5 to 5 % in green sand
  - Binders and additives work only in presence of moisture
- **Additives**
  - Used to enhance existing properties.
  - To add new properties.

- Sometimes oil sand is used for making cores .
- It is more popular and economical and produce better cores
- Commonly used material for manufacturing of core is dry sand with CO_2 bonding
- This is silica sand mixed with core oil which is composed of
  - linseed oil,
  - Corn oil,
  - light mineral oil and
  - other binding materials.
- Pitch or flours and water may be used in large cores for the sake of economy.

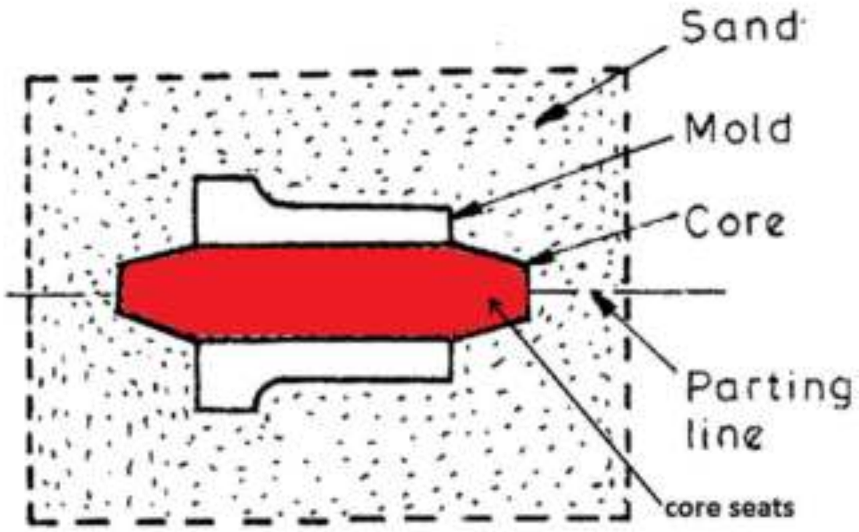
Essential Properties of Cores/ Core sand

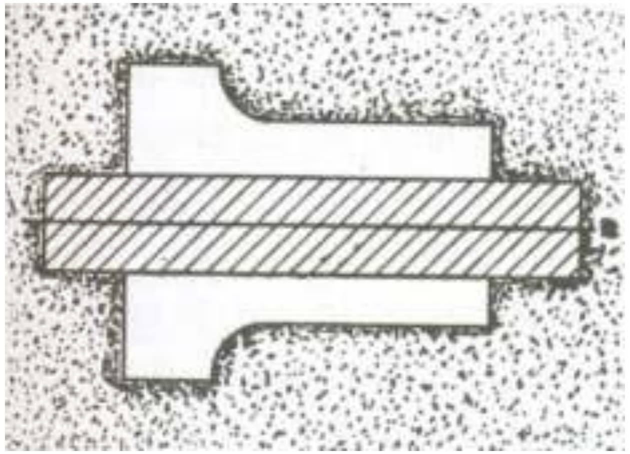
- Core must be strong.
- High Permeability to allow mould gases escape the mould walls.
- Smooth surface to ensure smooth castings.
- High refractiveness to withstand the high temperature of molten metal
- Collapsibility.
- Generate minimum amount of gases during pouring the molten metal.

Types of cores:

Horizontal Core

- Placed horizontally
- Usually cylindrical in form and is laid horizontally at the parting line of the mould.

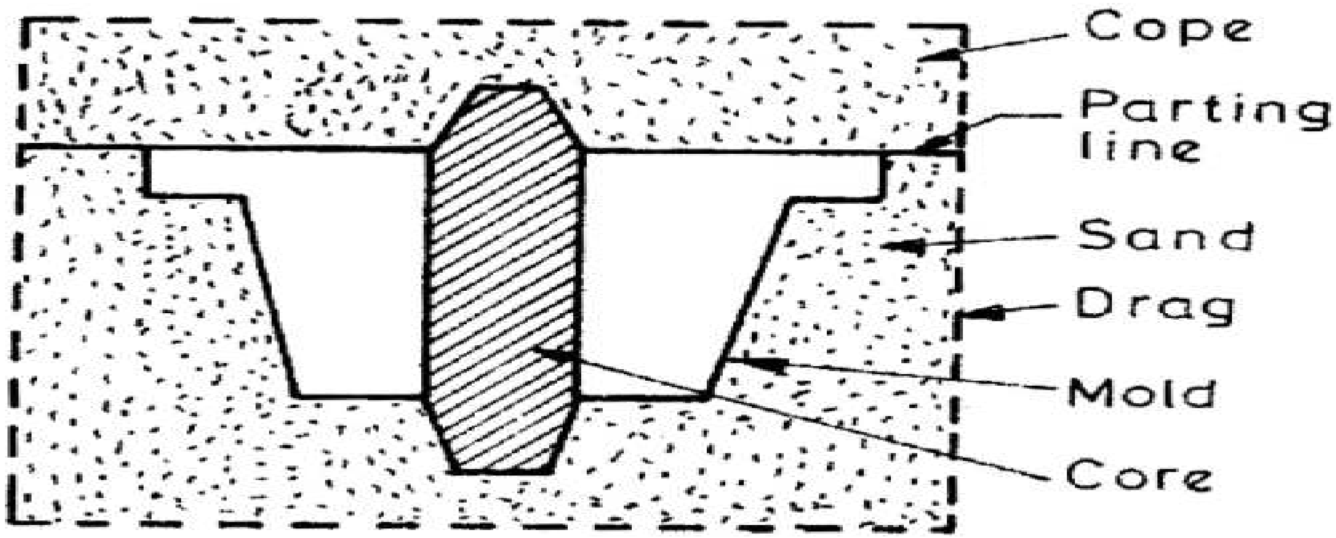




Vertical Core

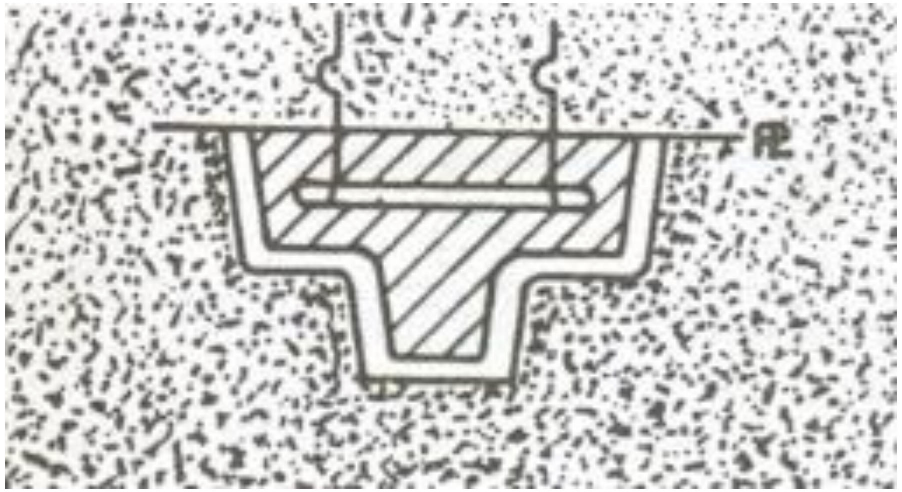
- Placed in a vertical position both in cope and drag halves of the mould are provided with a taper on the top and bottom of the core.

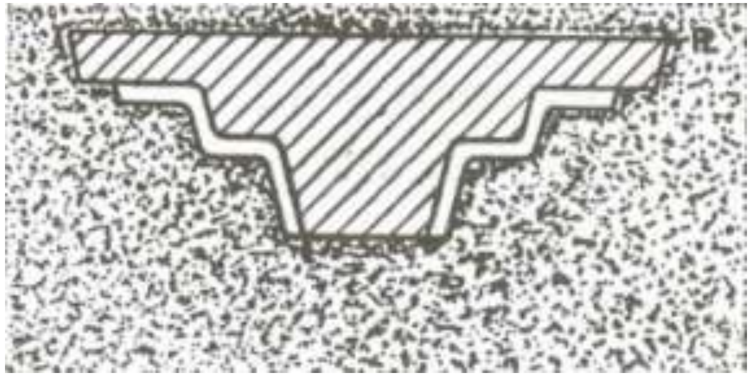
Note:-amount of taper on the top is greater than that at bottom.



Hanging or Cover Core

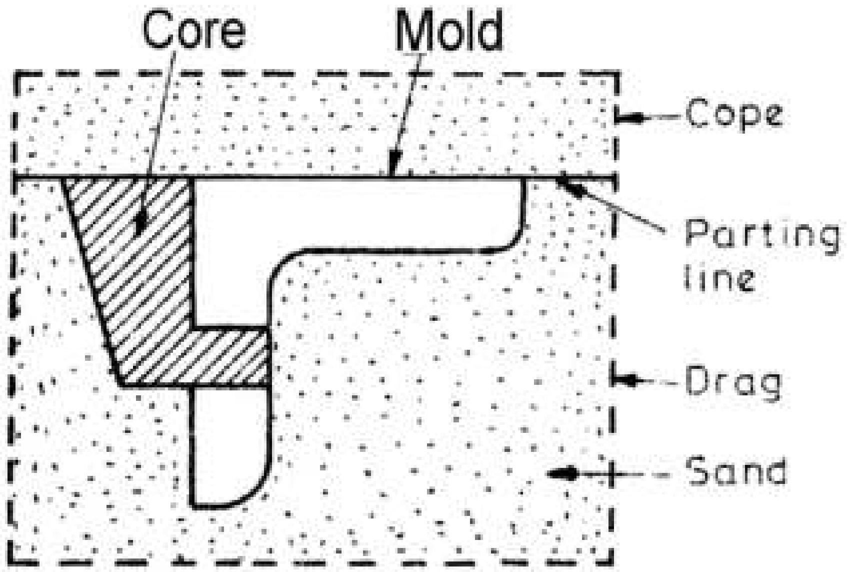
- If the core hangs from the cope and does not have any support at the bottom of the drag, it is referred to as a **hanging core**.
- if it has its support on the drag it is called **cover core**.





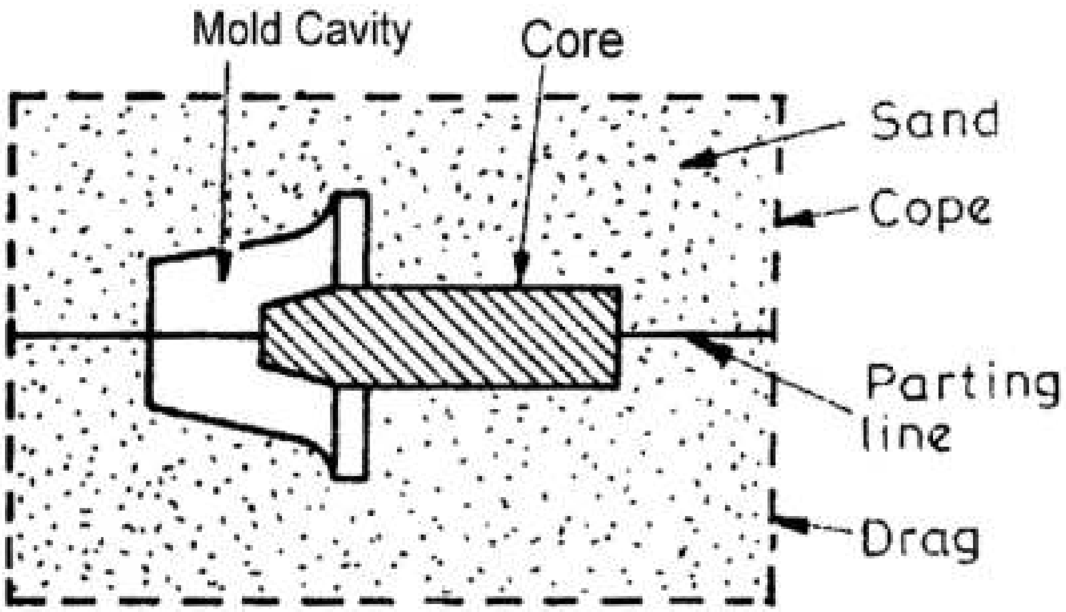
Wing Core

- Used when a hole or recess is to be obtained in the casting either above or below the parting line.
- The side of the core print is given sufficient amount of taper so that the core can be placed readily in the mould.
- Tapering is given to the core for easy location.
- Also known as drop core, tail core, chair core, and saddle core, according to its shape and position in the mould.



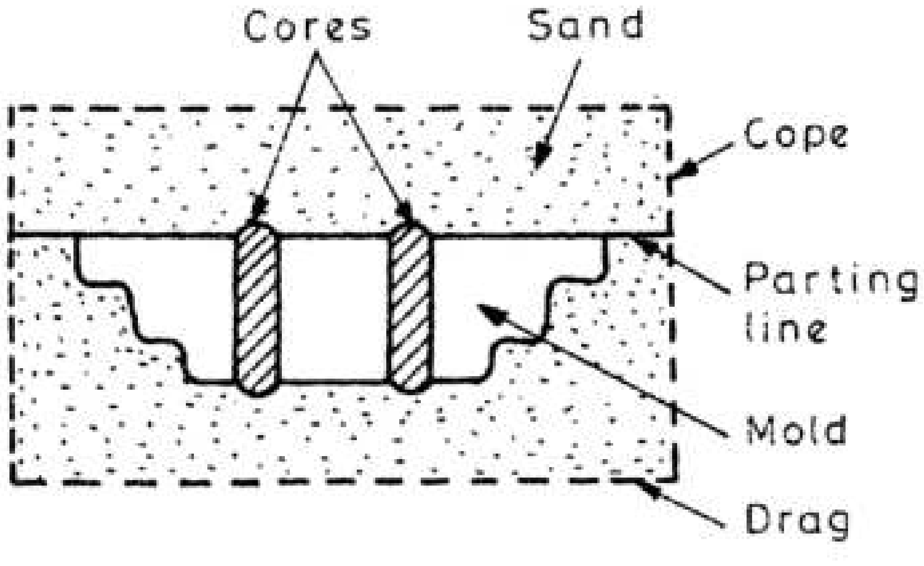
Balanced Core

- Supported in one end only.
- A Balanced Core requires a long core seat so that core does not sag or fall into the mould.
- It is used when the casting does not want a through cavity.



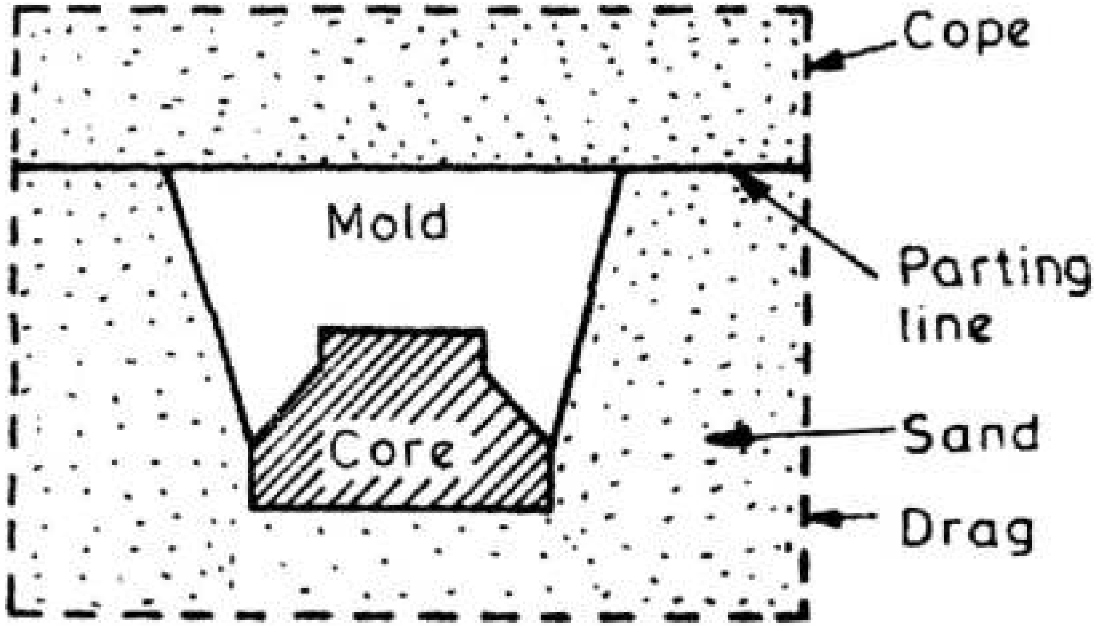
Kiss Core

- When the pattern is not provided with a core print and consequently no seat is available for the core,
- the core is held in position between the cope and drag simply by the pressure of the cope. This core is referred to as a kiss core.
- Suitable when a number of holes of less dimensional accuracy with regard to the relative position of the holes are required.



Ram Up Core

- It is sometimes necessary to set a core with the pattern before the mould is rammed up. Such a core is called ram-up core.
- Used when the core-detail is located in an inaccessible position in both interior and exterior portions of a casting



For reference

Forces acting on the mould

- As the mould fills it becomes exposed to high metallostatic pressures which tend to displace or distort the mould and cores
- The upward force acting on a flat mould surface is equal to

$$F= \rho * g * h * A$$

ρ = Density of the metal , h= head of metal, A=area

- The force is resisted by using box clamps and arrangements of plates and tie-bars to hold the mould parts tougher and by weighting the top part
- Cores too are exposed to an up-thrust
- The force is countered by high mechanical strength and rigidity in construction, enhanced by reinforcing grids and iron
- Chaplets are provided for support cores against the force

CORE PRINT

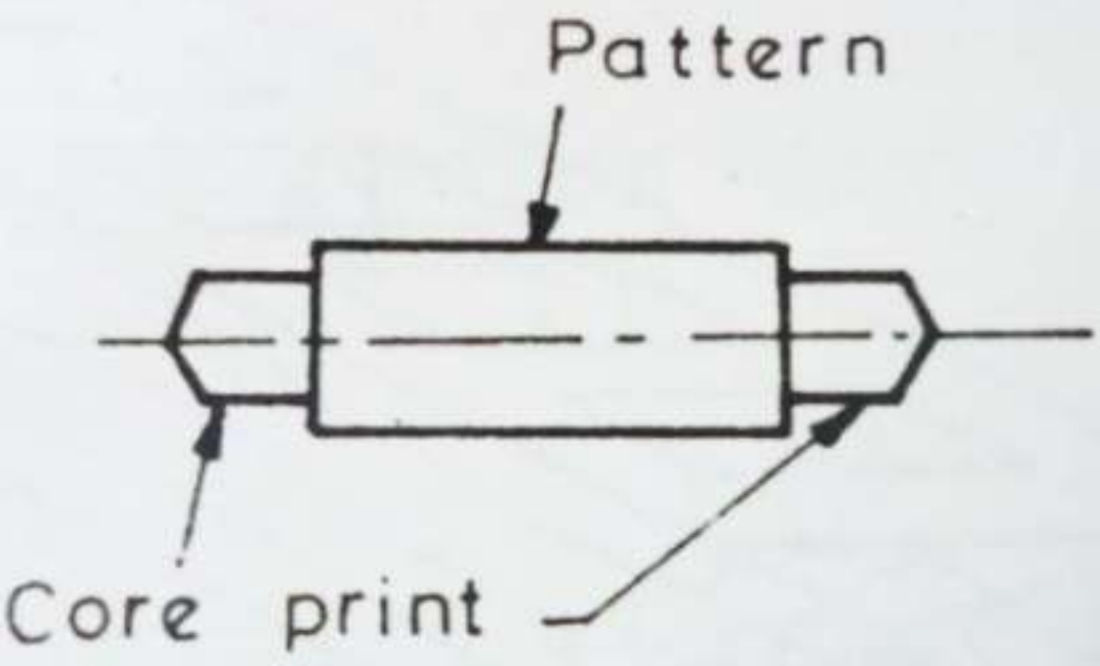


Fig. 10.24. Pattern and core prints

CORE PRINT

- Extra projections provided in the pattern.
- Impression in the form of a recess is made in the mould with the help of a projection suitably placed on the pattern. This projection on the pattern is, known as the coreprint
- Core prints form **core seats** in the mold when pattern is embedded in the sand.
- Core seat support the core against the buoyancy of the molten metal.
- Core print does not appear on the cast part.
- Classified into: cope print, drag print, parting line print.

TYPES OF CORE PRINTS

- **HORIZONTAL COREPRINT**
  - This is laid horizontally in the mould and is located at the parting line of the mould.
  - The coreprint is often found on the split or two-piece pattern. When it is important that certain core be located at a desired angular relationship with respect to the central axis, a flat portion at one end is made to coincide with a flat portion of the coreprint.

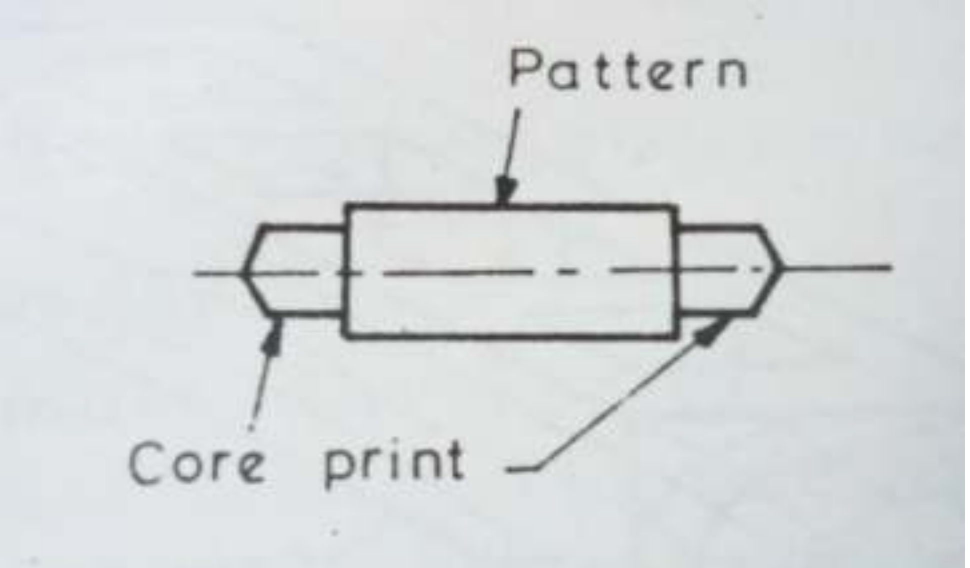


Fig. 10.24. Pattern and core prints

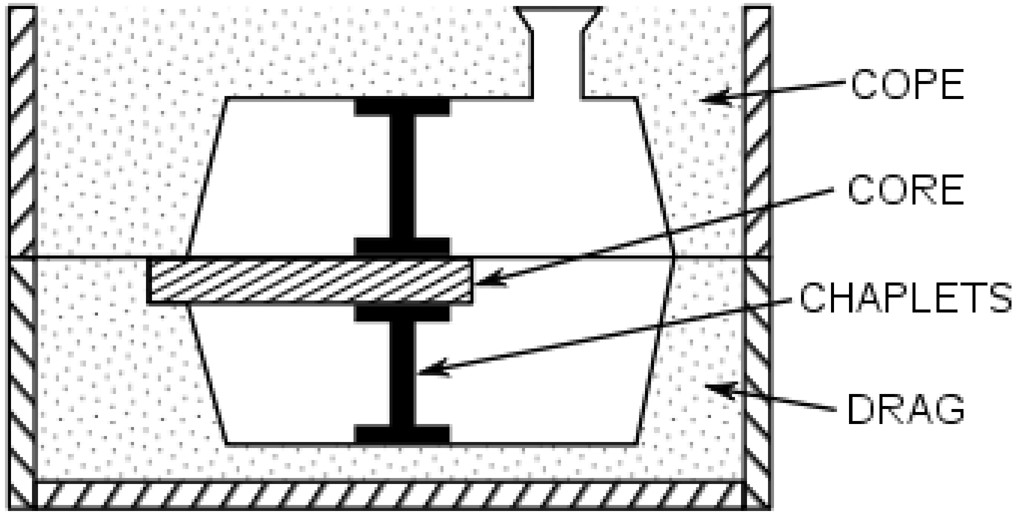
- **VERTICAL COREPRINT**
  - This stands vertically in the mould.
  - This is why this type of core is referred to as a vertical coreprint.
  - The coreprint is located on the cope and drag sides of a pattern and is constructed with considerable taper specially on the cope side (about 10-15°) so that they are moulded easily

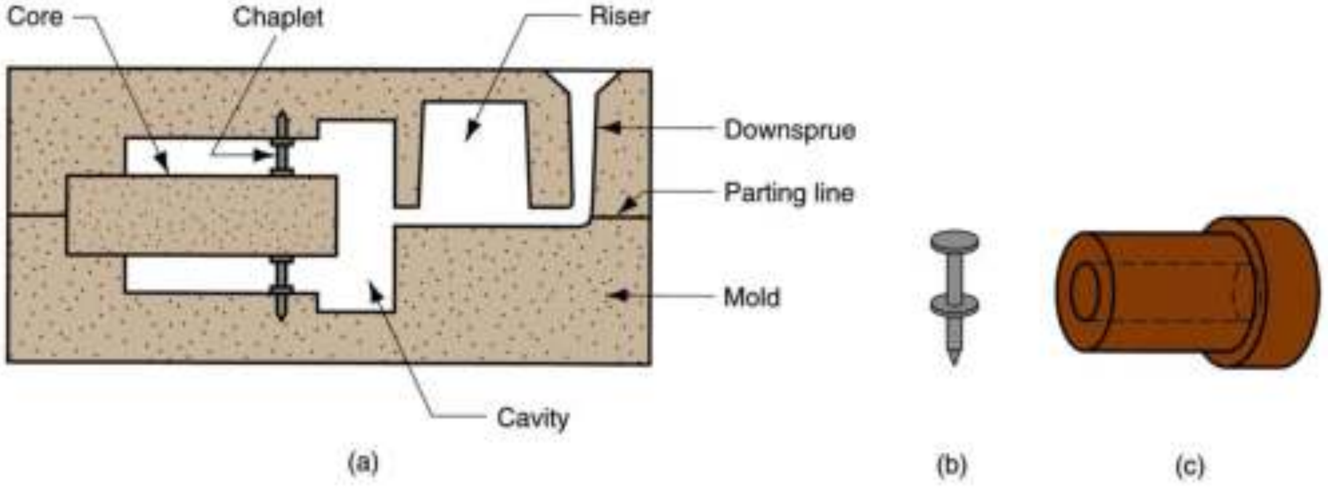
- **BALANCING COREPRINT**
  - This is used when a horizontal core does not extend entirely through the casting, and the core is supported at one end only.
  - An important feature of this coreprint is that the print of the core in the mould cavity should balance the part which rests in the core seat.

- **HANGING OR COVER CORE PRINT**
  - This is used when the entire pattern is rammed in the drag and the core is required to be suspended from top of the mould. In this case, the core serves as a cover for the mould, and also as a support for hanging the main body of a core.

- **WING OR DROP COREPRINT**
  - This is used when the cavity to be cored is above or below the parting line in the mould. Wing coreprints are also known as "chair", and "tail" coreprints

Chaplets



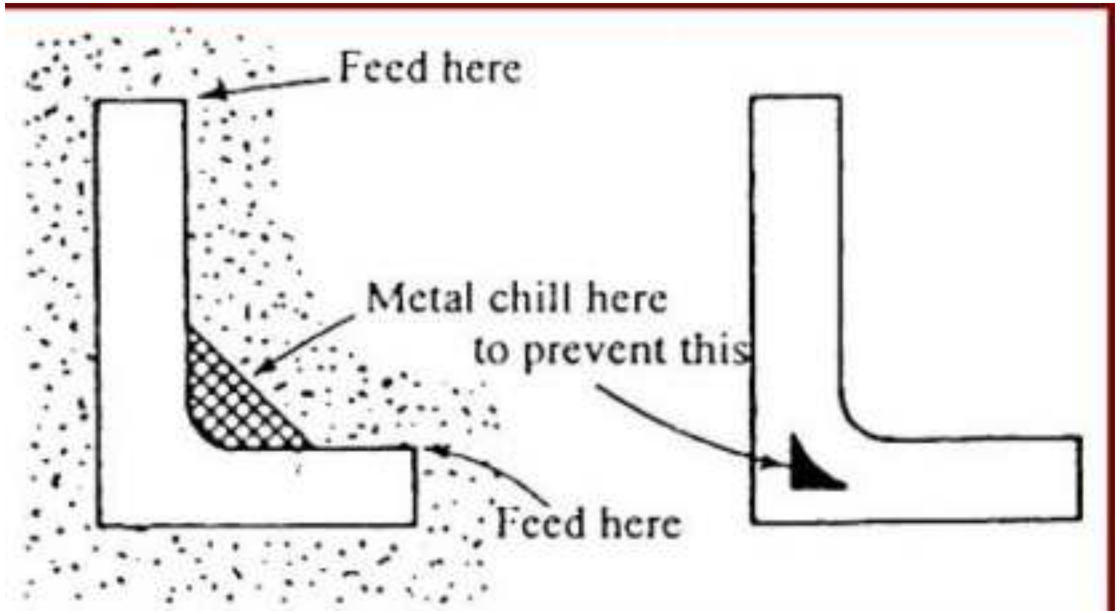


- Used to support the cores which tend to sag or sink in adequate core seats.
- Metal shapes located between the mold and the core surfaces.
- It melts as soon as the molten material is poured and will become an integral part of the castings.
- Hence, the material of chaplet is same as the molten metal.
- Directional solidification

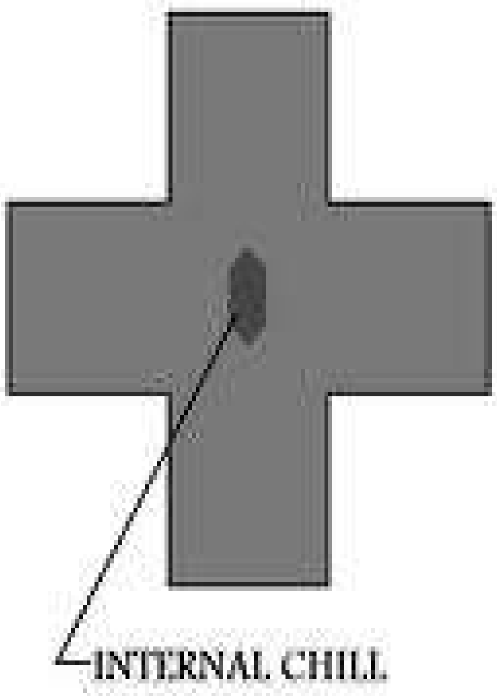
CHILLS

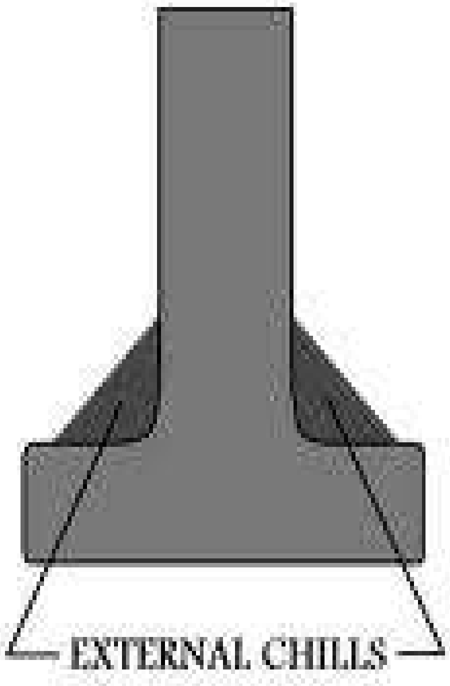
- Metallic pieces used to increase the heat transfer rate. (To accelerate the cooling rate).
- Directional solidification
- Considering the castings with different thick at different sections, thin section solidifies faster than thick sections. So, chills are inserted at thick sections to increase the cooling rate so that no internal stresses are developed due to difference in cooling rate.
- Commonly made of iron, which has higher density , higher thermal conductivity and higher thermal capacity compared to silica sand.
- Thus the heat of the molten metal is pulled from the metal faster than the other areas of the mould which contains the sand.
- Chills material-copper/bronze,Aluminium,graphite,silicon carbide

TYPES OF CHILLS



- External chills
- Internal chills





PADDING

- Loose sand particles at corner mould cavity
- When molten metal is poured into the cavity this loose sand particles at the corner gets eroded and enters into the cavity producing sand inclusion defects in the casting
- To avoid this L shaped metallic or non metallic piece will be placed at the corner of the pattern during moulding itself
- This L shaped pattern will not allow the molten metal to directly come in contact with loose sand particles
- Directional solidification

Mixing moulding sand
with binders & adhesives

Filling sand in
moulding flasks

Melting furnace

Pouring molten liquid

Knock out

Heat treatment

Machining

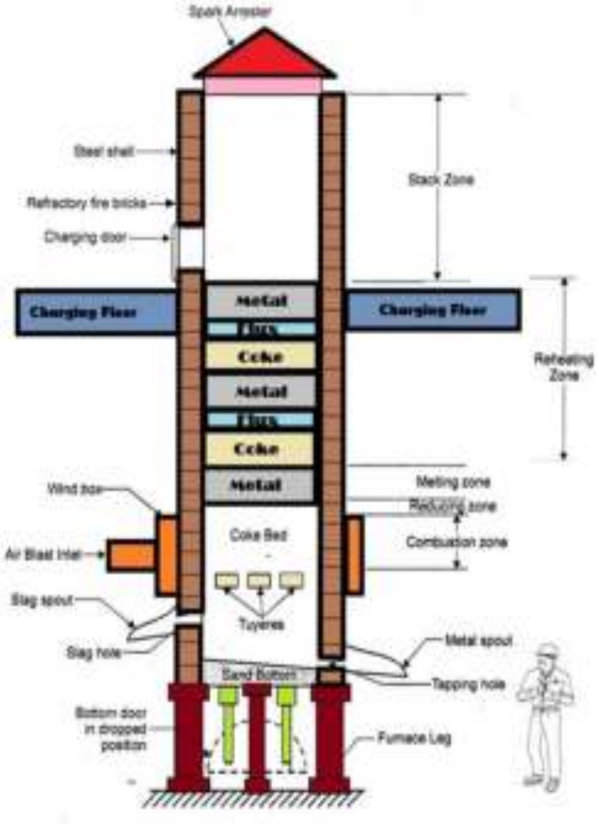
Final products of casting


Casting an Engine Cylinder.

For reference

CUPOLA FURNACE

- Cupola is employed for melting of scrap metal or (over 90%) of pig iron used in the production of Iron Castings.
- It is economical for the production of Grey Cast Iron, nodular cast iron, and some malleable iron castings.
- Cupola can be operated for long hours.
- Cupola does not produce metal of uniform quality.



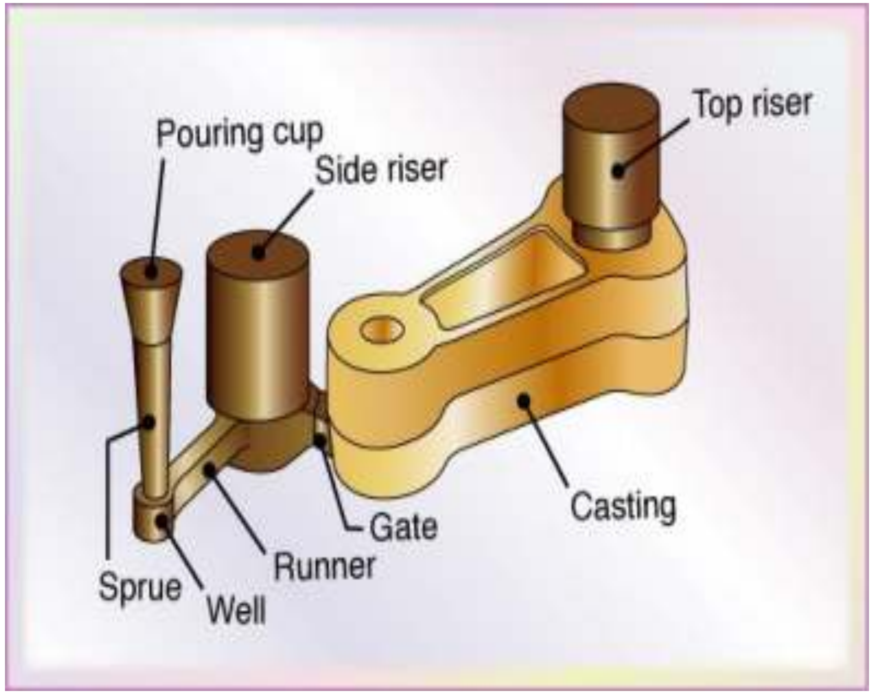
Cupola furnace

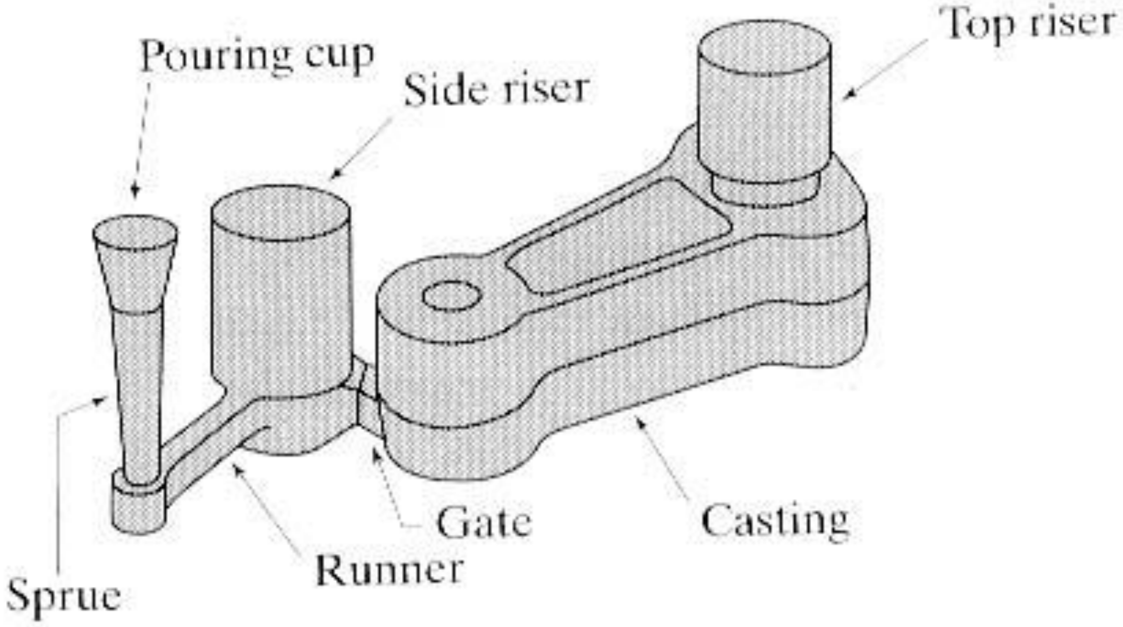
GATING SYSTEM

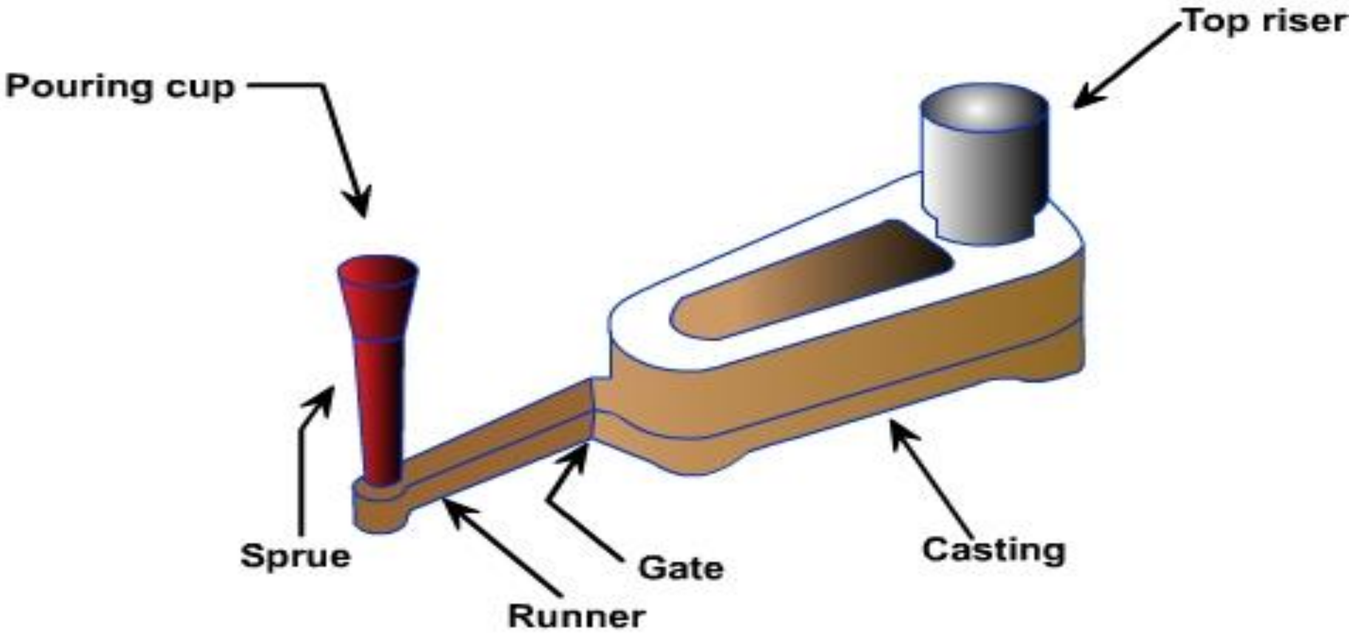
Gating System refers to all passageways through which the molten metal enters the mould cavity.

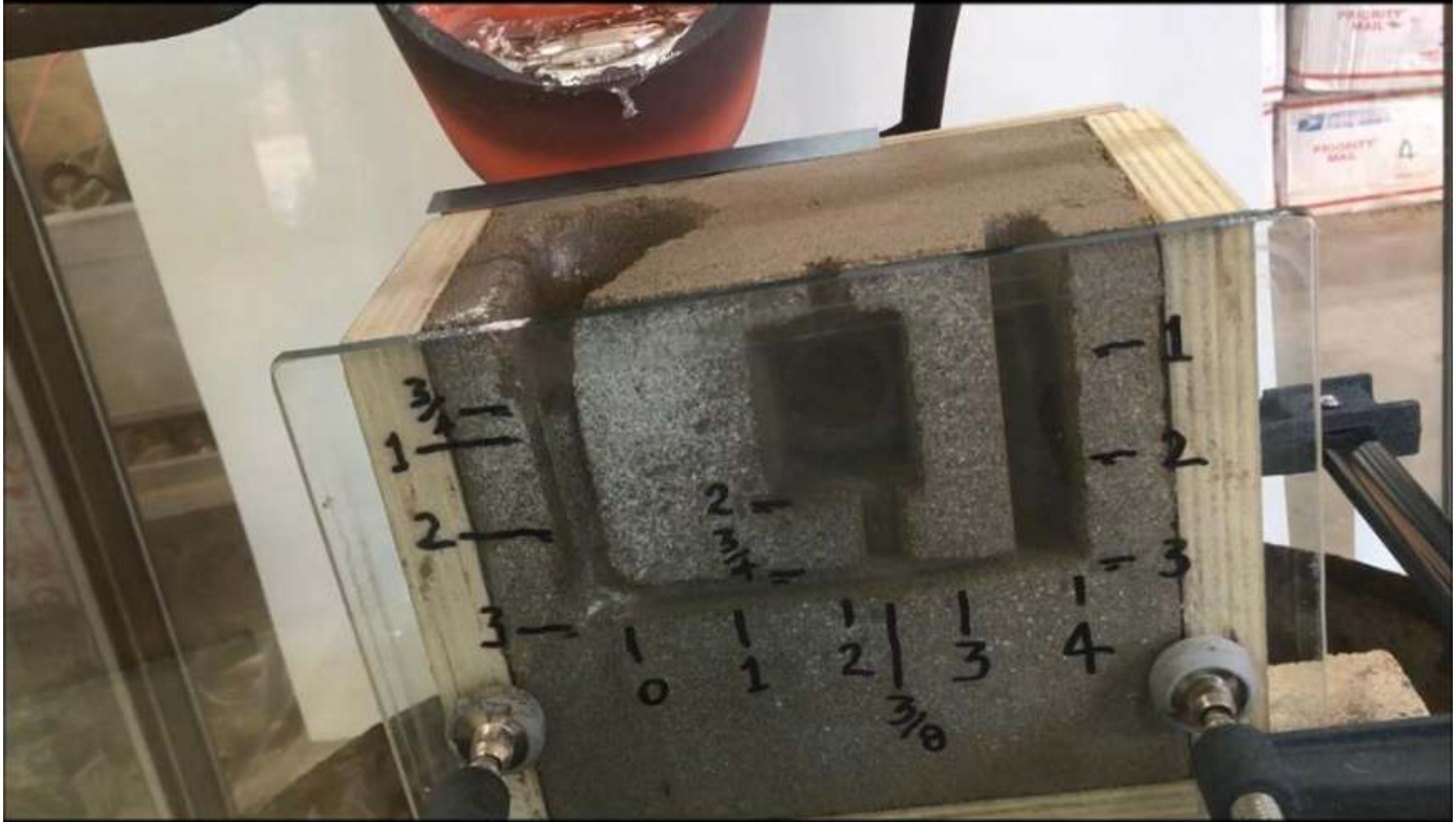
The gating system is composed of

- Pouring Cups
- Sprue
- Runner
- Gate
- Risers




Pouring cup
Side riser
Top riser
Sprue
Runner
Gate
Casting


Top riser
Pouring cup
Sprue
Runner
Gate
Casting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1
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2
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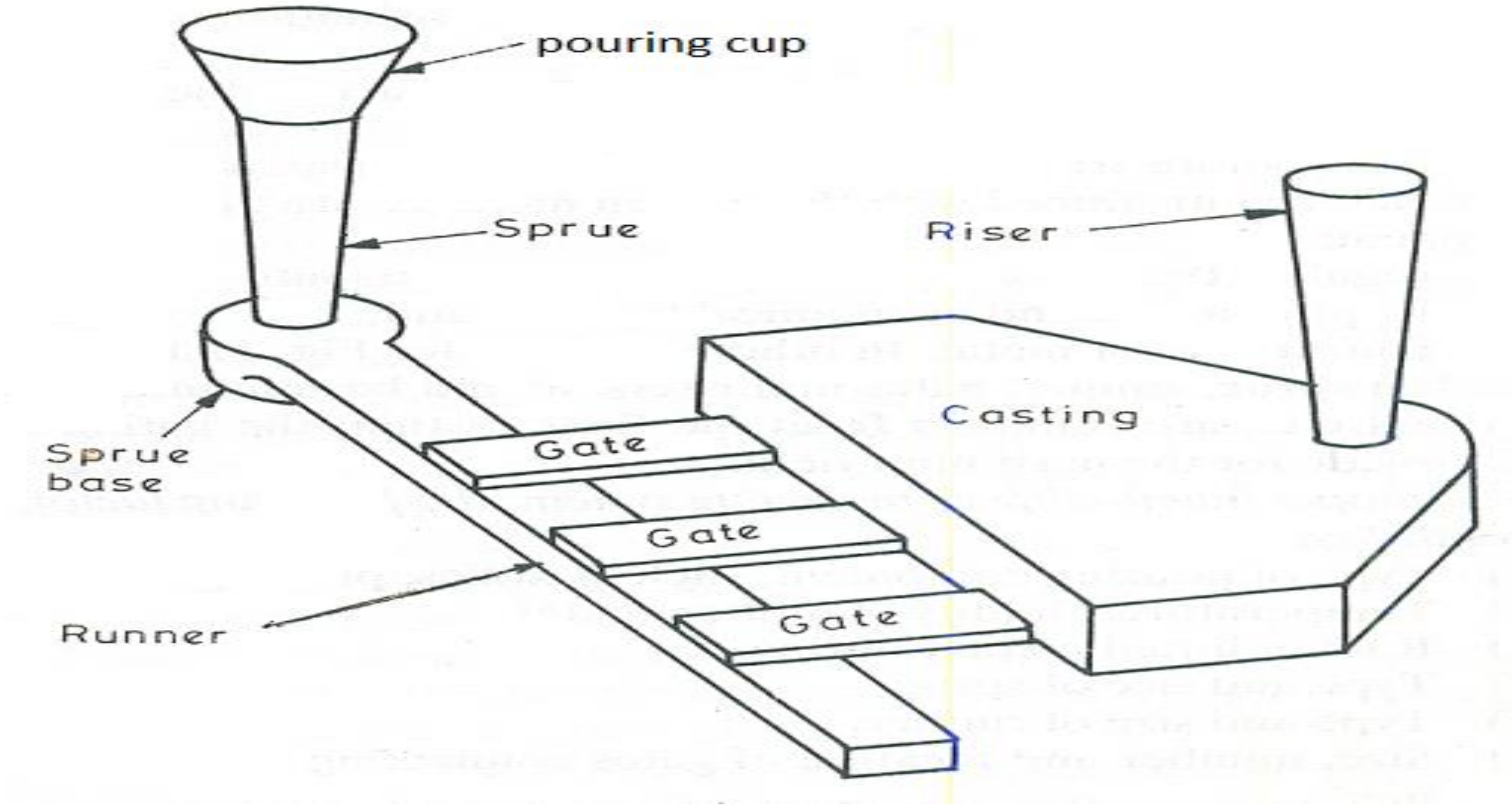
3/8
PRIORITY MAIL


pouring cup
Sprue
Riser
Casting
Sprue
base
Gate
Gate
Gate
Runner

FLUID FLOW IN GATING SYSTEM

Pouring cup → sprue → runner → gate → mold cavity → riser.

- Two basic principles of fluid flow in gating system are:
  - Bernoulli's Theorem
  - Law of mass continuity.

DESIGN/FUNCTION of gating system

- The gating system must be designed such that the time taken for pouring or filling of molten metal into the cavity should be a minimum as possible
- This is due to no part of casting cavity should start to solidify before complete filling of casting cavity
- The time for complete filling of a mould is called pouring time
- Pouring Time = $\frac{\text{volume}}{\text{area x velocity}}$
- PT should be low
- No aspiration will take place during filling of molten metal

- Fill the mold cavity before solidifying.
- Introduce the molten metal with less speed and less turbulence so that mould erosion and metal oxidation is prevented.
- During filling of molten metal gating system should ensure full flow of molten metal.
- Regulate the rate at which the molten metal entering the mould cavity.
- To trap non metallic inclusions and other impurities from entering into the mould cavity.
- Should consume less metal. ie., less metal should be solidified in the gating system. It should be economical

1. BERNOULLI'S THEOREM

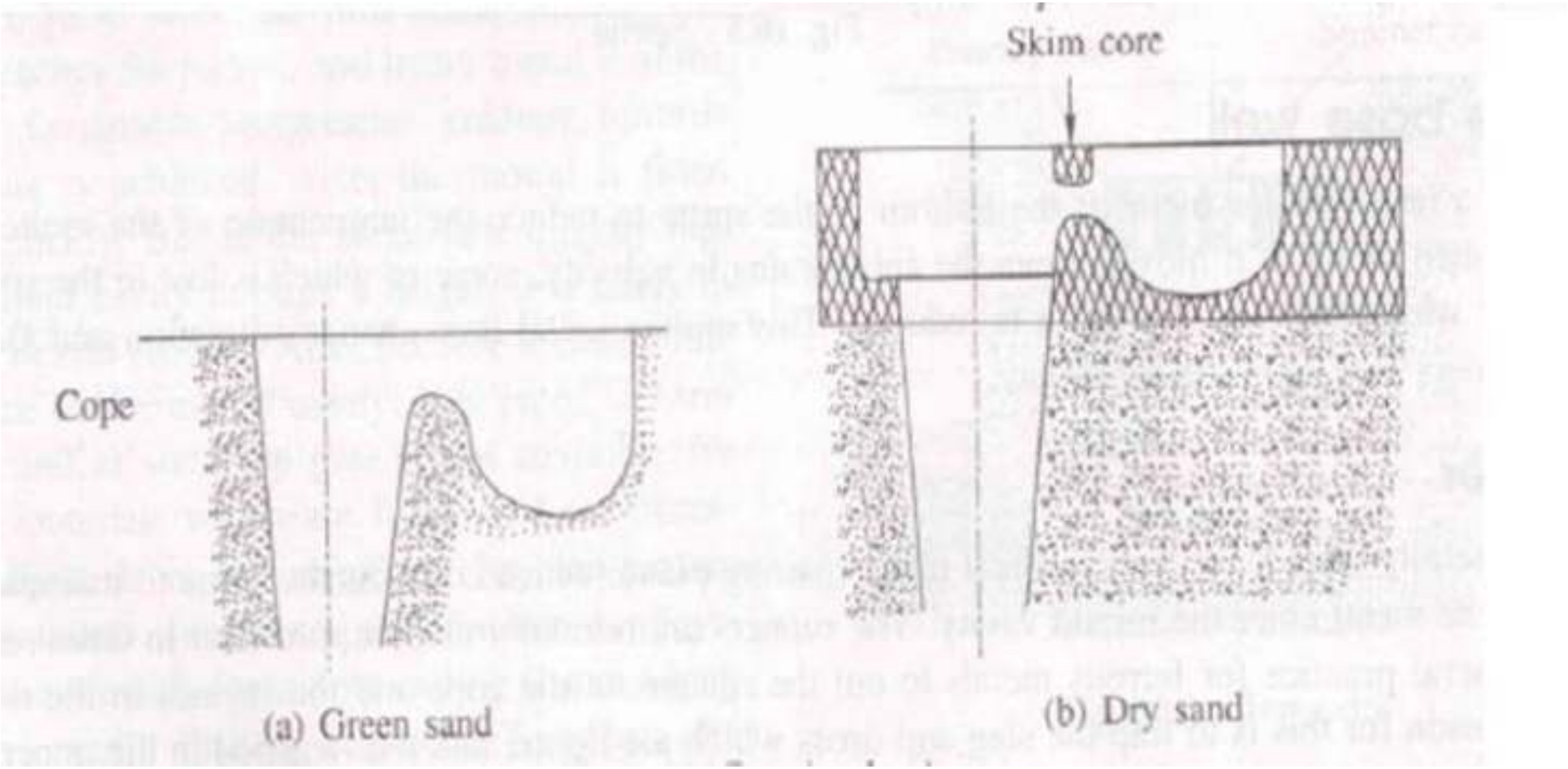
- The liquid metal that runs through the various channels in the mould obeys the Bernoulli's theorem
- Principle of conservation of energy.
- which states that the total energy head remains constant at any section
- Relates pressure (p), velocity (v), elevation/height of the fluid at any location in the system and frictional losses (f) in the system.
  - $h + \frac{p}{\rho g} + \frac{v^2}{2g}$ = constant
- At two different sections in the gating system,
  - $h_1 + \frac{p_1}{\rho g} + \frac{{v_1}^2}{2g} = h_2 + \frac{p_2}{\rho g} + \frac{{v_2}^2}{2g} + f$

2. LAW OF MASS CONTINUITY

- For incompressible liquid in a system with impermeable walls, the rate of flow is constant.
- If the flow channel narrows down to half its original cross-section, the metal velocity would be double, and vice versa.
- $Q = A_1 v_1 = A_2 v_2$
  - Where, Q= rate of flow in m^3/s
  - A = cross sectional area of liquid stream
  - V = average velocity of liquid in that cross section
- Incompressible flow refers to a flow in which the material density is constant
- Impermeable means nothing can get through it.

- **Pouring Cups / basins**
  - Is a funnel shaped cup which forms the top portion of the sprue.
  - It is used to direct the flow of molten metal to the sprue
  - In order that vortex is not formed during pouring, it is necessary that the pouring basin be kept full and constant conditions of flow are established.
  - This can be achieved by using a delay screen. A delay screen is a small piece metal sheet placed in the pouring basin at the top of the down sprue

- This screen usually melts because of the heat from the metal and in the process delays the entrance of metal into the sprue thus filling the pouring basin fully. This ensures a constant flow and full flow of metal.



Sprue

- Sprue feeds the molten metal to the runner.
- Sprue has its bigger end at the top end to receive the molten metal. The smaller end is connected to the runner.

Sprue design

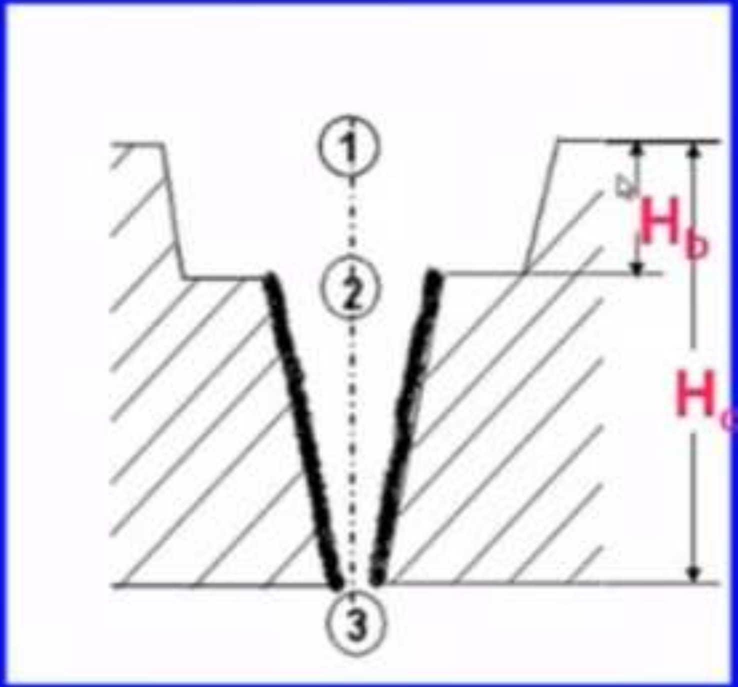
$$\frac{A_1}{A_2} = \sqrt{\frac{h_2}{h_1}}$$

- The provision of a sprue base well at the bottom of the sprue helps in reducing the velocity of the incoming metal and also the mould erosion.
- Aspiration effect/ inhalation effect
- Parabolic taper sprue can use to avoid Aspiration effect
- All along the length of the sprue the pressure is equal to zero gauge pressure or atmospheric pressure
- Manufacturing of parabolic sprue is difficult so we use straight tapered cylindrical sprue

$$Q = A_1V_1 = A_2V_2 = = A_3V_3$$

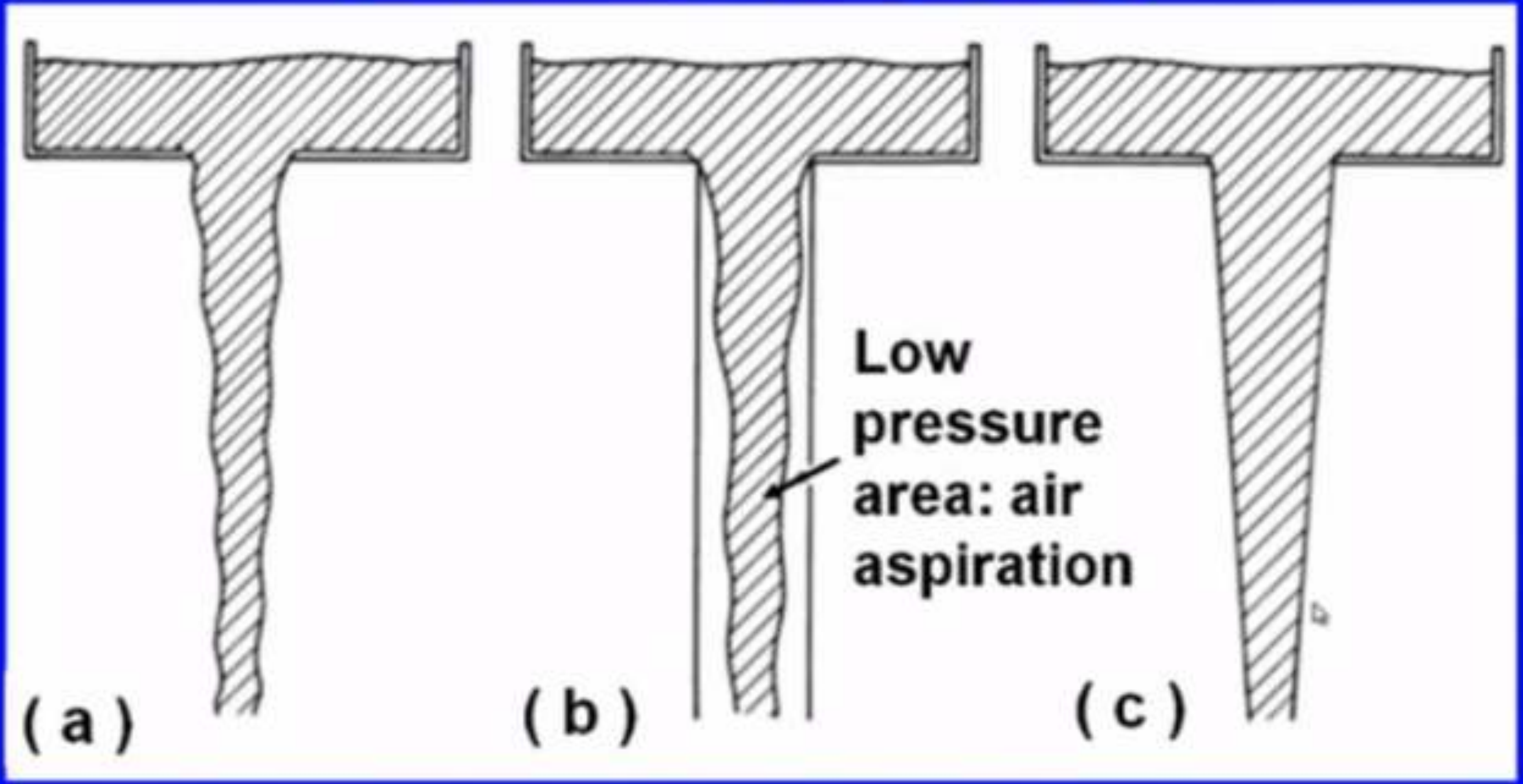
$$V_2 = \sqrt{2gH_b} \text{ and } V_3 = \sqrt{2gH_c}$$

$$\frac{A_2}{A_3} = \frac{\sqrt{H_c}}{\sqrt{H_b}}$$



- As the liquid flows down, the cross section of the fluid decreases. So the taper is provided in the sprue.
- Liquid loses contact if the sprue is straight which could cause '**aspiration**'.

ASPIRATION IN SPRUE



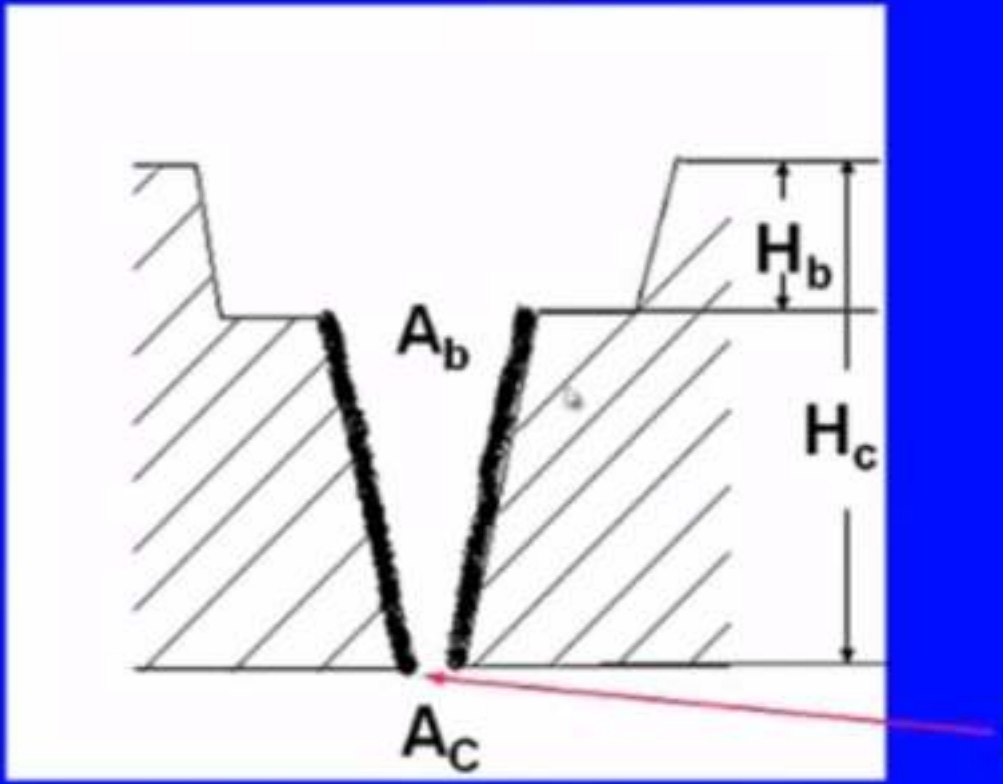
(a) Natural flow of a free-falling liquid.

(b) Air aspiration induced by liquid flow in a straight sprue.

(c) Liquid flow in a tapered sprue.

CHOKE AREA

The smallest area that occurs at the bottom of the sprue is known as '**Choke area**'.



Let

A_b = Cross-sectional area of sprue at its top

A_c = Cross-sectional area of sprue at the choke

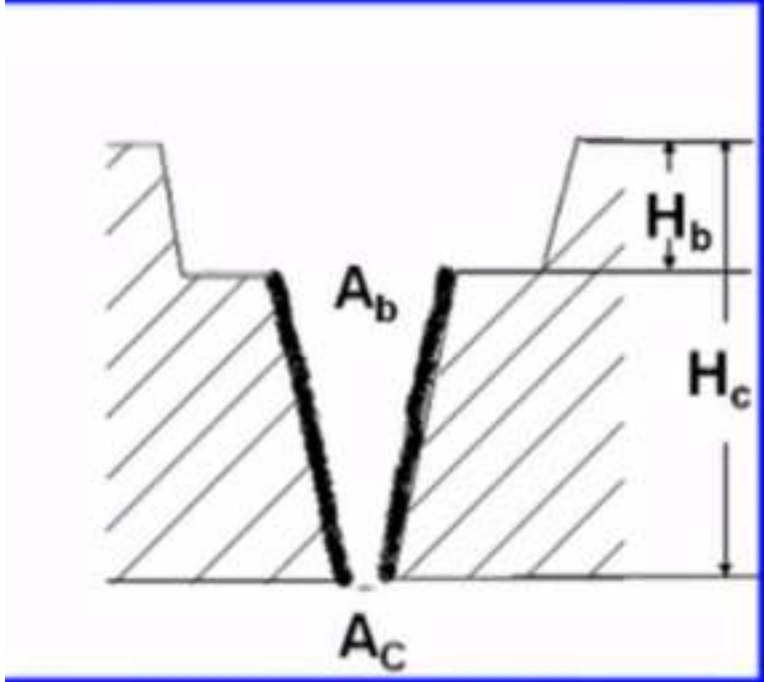
V_b = Velocity of liquid metal at the top of sprue

V_c = Velocity of liquid metal at the bottom of sprue (choke)

H_b = Height of pouring basin

H_c = Height of total metal head above the choke

Choke area is designed based on Bernoulli's theorem.



According to the Bernoulli's theorem, velocity of liquid metal at the top of sprue is given by:

$$V_b = \sqrt{2 . g . H_b}$$

Similarly, velocity at the bottom of sprue (choke) is given by:

$$V_c = \sqrt{2 . g . H_c}$$

Volume of flow at choke in a given time = $A_c . V_c . t$

$= W / \rho$

Where,

W = weight of poured metal

ρ = density of liquid metal

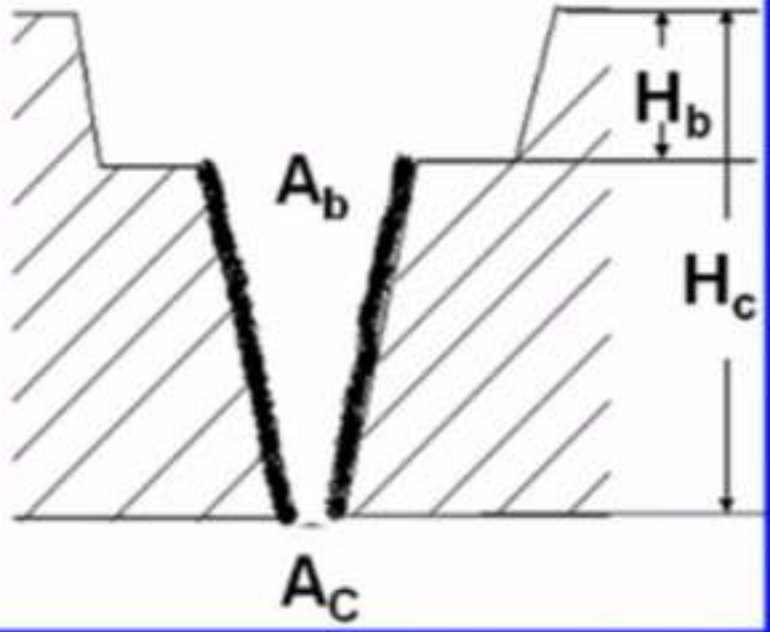
Thus, $A_c = \dfrac{W}{c . \rho . t . V_c}$

c = coefficient of discharge

But $V_c = \sqrt{2 . g . H_c}$

Hence, the choke area is given by:

$$A_c = \frac{W}{c \cdot \rho \cdot t\sqrt{2 \cdot g \cdot H_c}}$$



Where,

W= Wt. of poured metal (kg)

c = coefficient of discharge

ρ = density of liquid metal, (kg/cm^3) .

t = pouring time (seconds)

g = acceleration due to gravity (981 cm/sec^2)

H_c = height of total metal head above choke (cm)

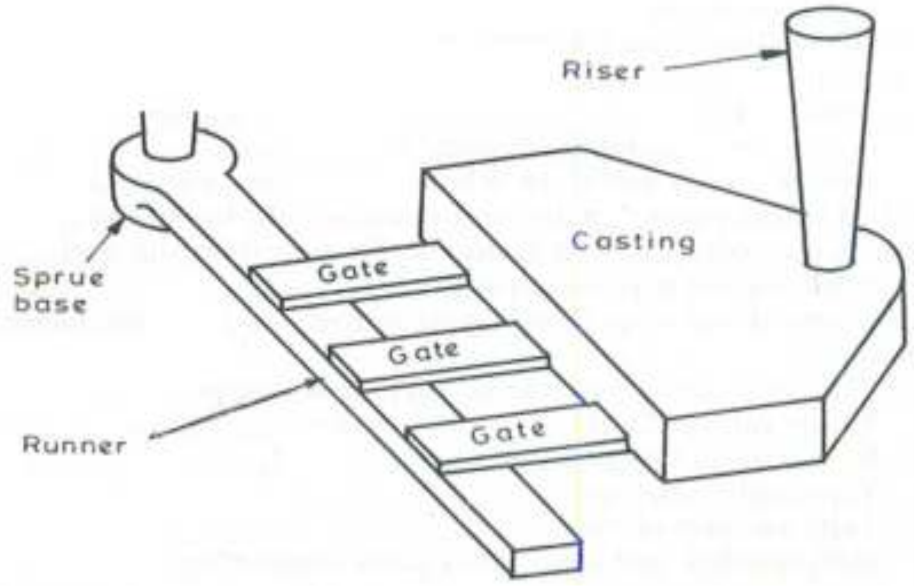
Sprue Base Well

- The provision of a sprue base well at the bottom of the sprue helps in reducing the velocity of the incoming metal and also the mould erosion

- A general guide line could be that the sprue base well area should be two to three times that of the sprue choke area and the well depth should be approximately equal to that of the runner

Runner

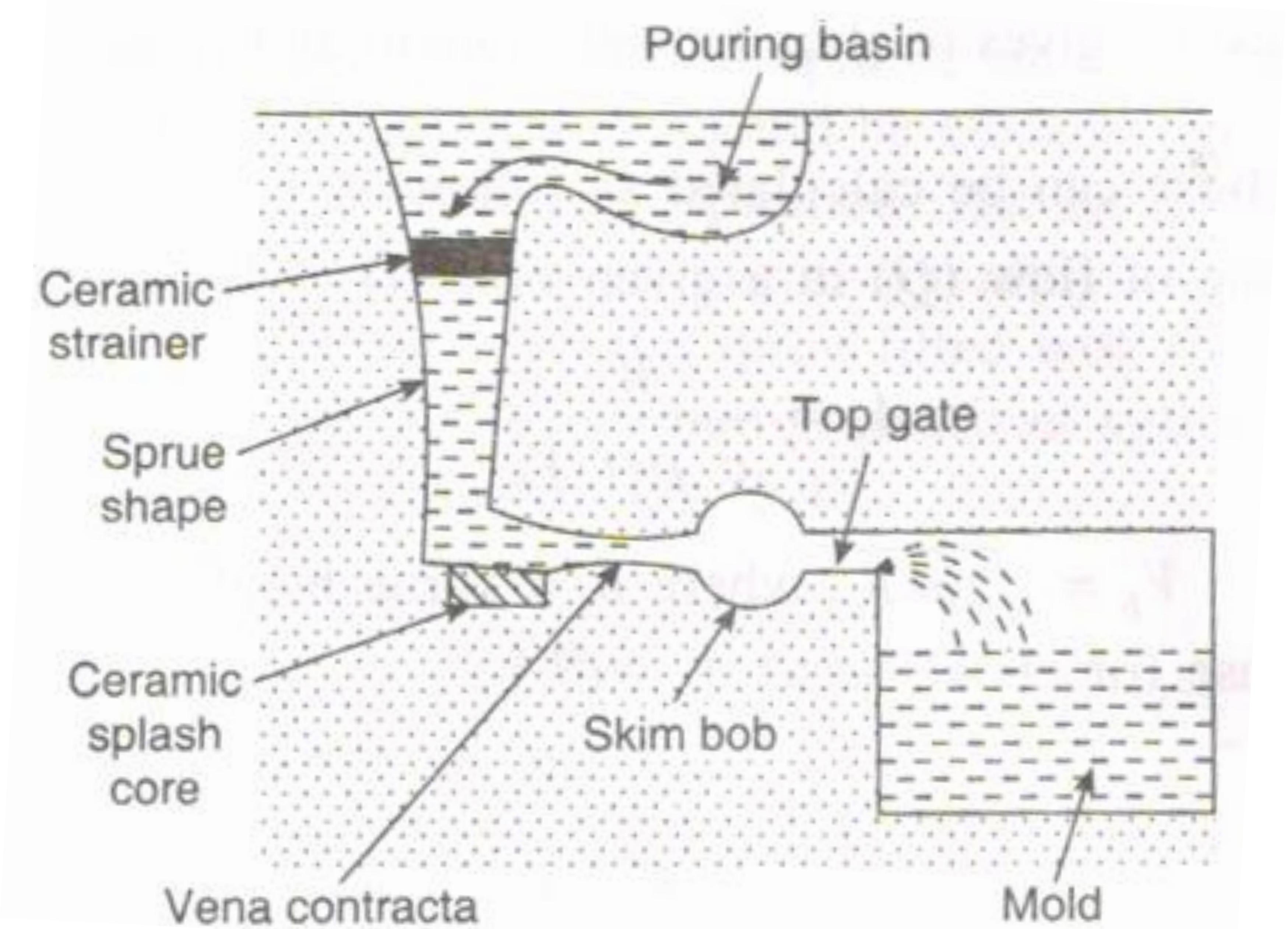
- Entry into runners from sprue base well should be made as smooth as possible in such castings, otherwise the direction of flow would tend to be turbulent.
- Though from heat loss factor circular cross section runners are preferable.
- But traditionally square or uniform trapezoidal runner sections are employed to reduce the turbulence.

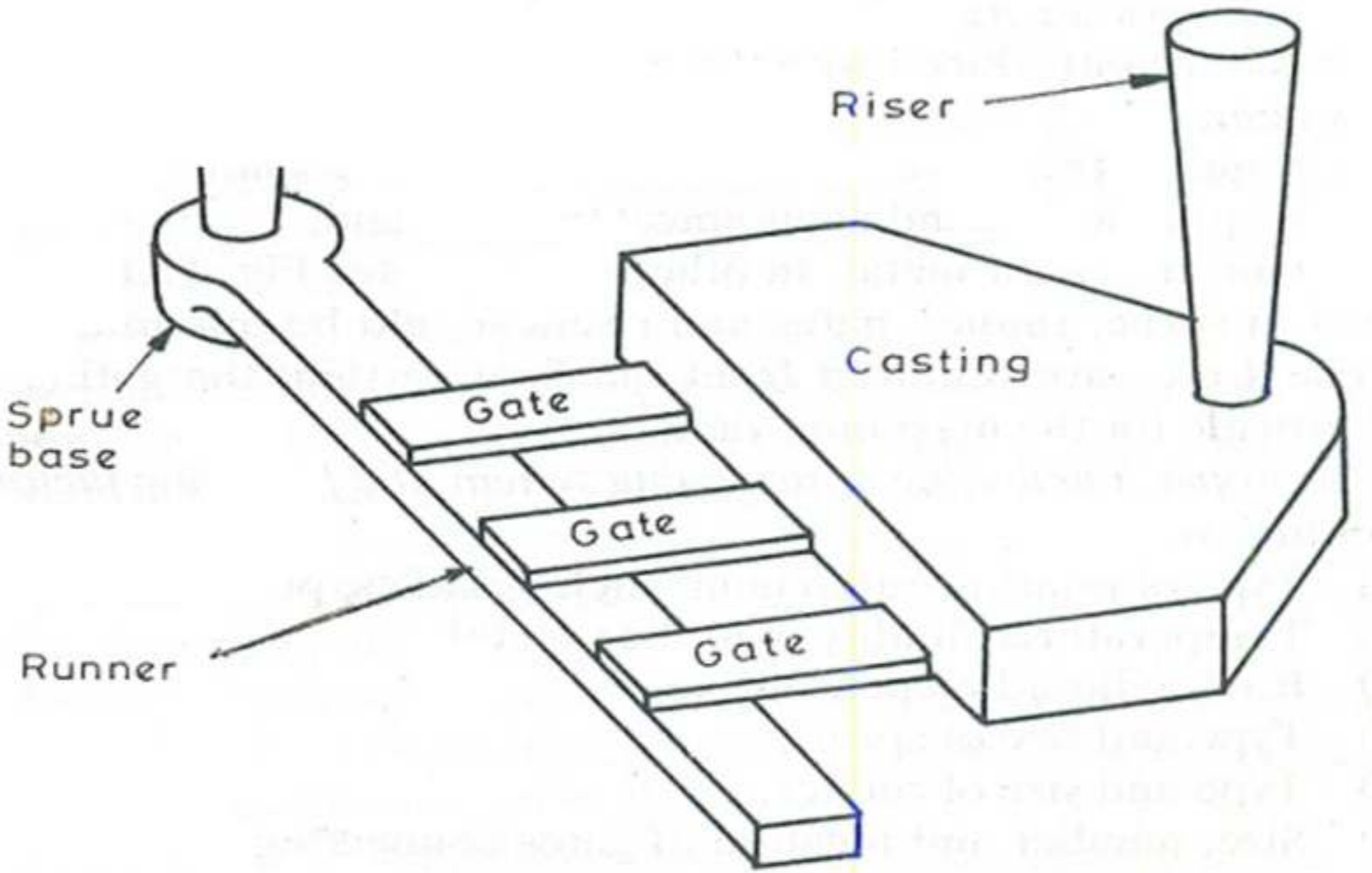


Ingate

– Is a channel which connects runner with mould cavity.
– It also horizontal and uniform trapezoidal cross section

- **Additional accessories**
  - **Strainer**
    - **Used for separating or filtering of impurities**
    - **Made with ceramic material with high porosity**
  - **Splash core**
    - **Used for avoiding the sand erosion in the bottom of the sprue**
    - **Made with ceramic material with high porosity**
  - **Skim bob**
    - **It is a semicircular cut given in runner**
    - **It is used for separating the impurities present in the molten metal**


Pouring basin
Ceramic strainer
Sprue shape
Top gate
Ceramic splash core
Skim bob
Vena contracta
Mold


Riser
Casting
Gate
Gate
Gate
Sprue
base
Runner

Gating ratio

- The rate of flow of metal through the mould cavity is a function of the c/s area of sprue, runner and ingates
- It is used to describe the relative c/s areas of the components of a gating system taking the sprue base area as unity
- It refers to the proportion of the cross sectional areas between the sprue, runner and ingates and is generally denoted as
- SPRUE AREA: RUNNER AREA: INGATE AREA.
- A_S : A_R : A_G

Classification of gating system

- **Based on the pressure above molten metal in pouring basin**
  - Non pressured gating system
  - pressured gating system

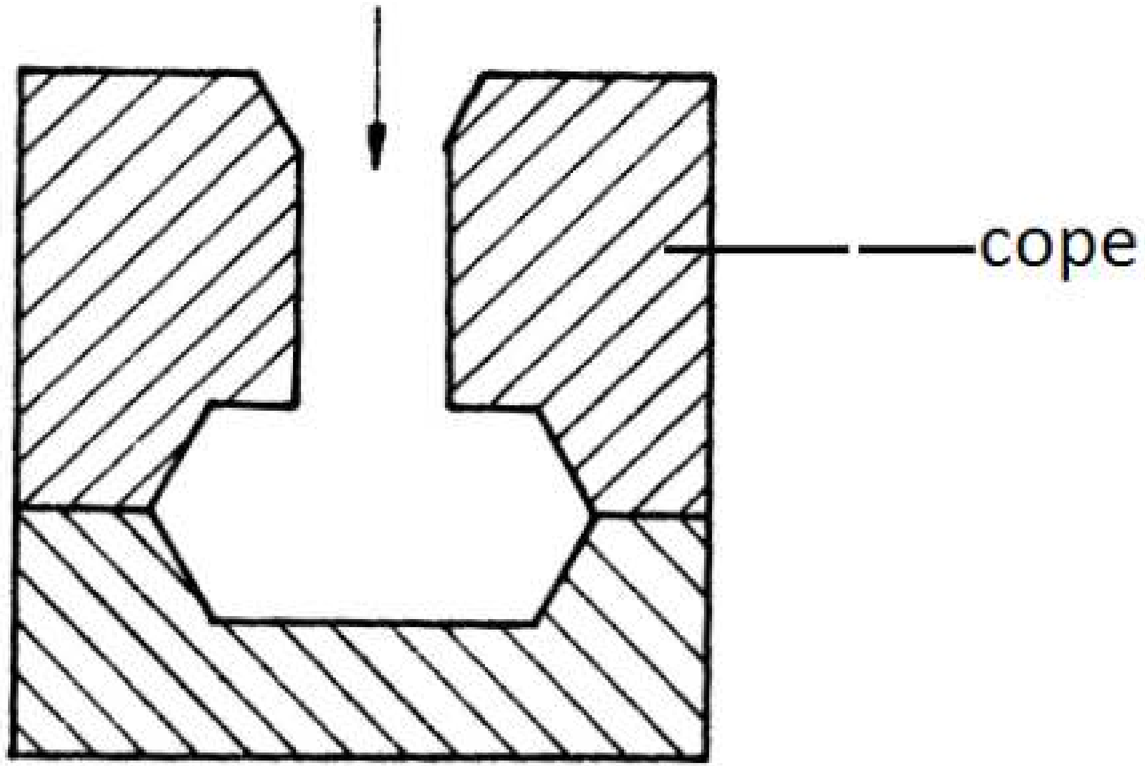
- **Based on the position of gate**
  - Top Gates or drop gate
  - Bottom Gate
  - Parting Line Side Gate
  - Step gating system (more than one ingate for large casting)

- Non pressured gating system
  - Pressure act on molten metal in pouring basin is Atmospheric pressure
  - Open the pouring basin to atmosphere
  - Gating ratio is $A_S : A_R : A_G = \mathbf{1 : 2 : 2}$
  - Not suitable for high reactive metal e.g.. Al, Mg

- Pressured gating system
  - Pressure act on molten metal in pouring basin is grater than Atmospheric pressure
  - Gating ratio is $A_S : A_R : A_G = \mathbf{1 : 2 : 1}$

1. Top Gates

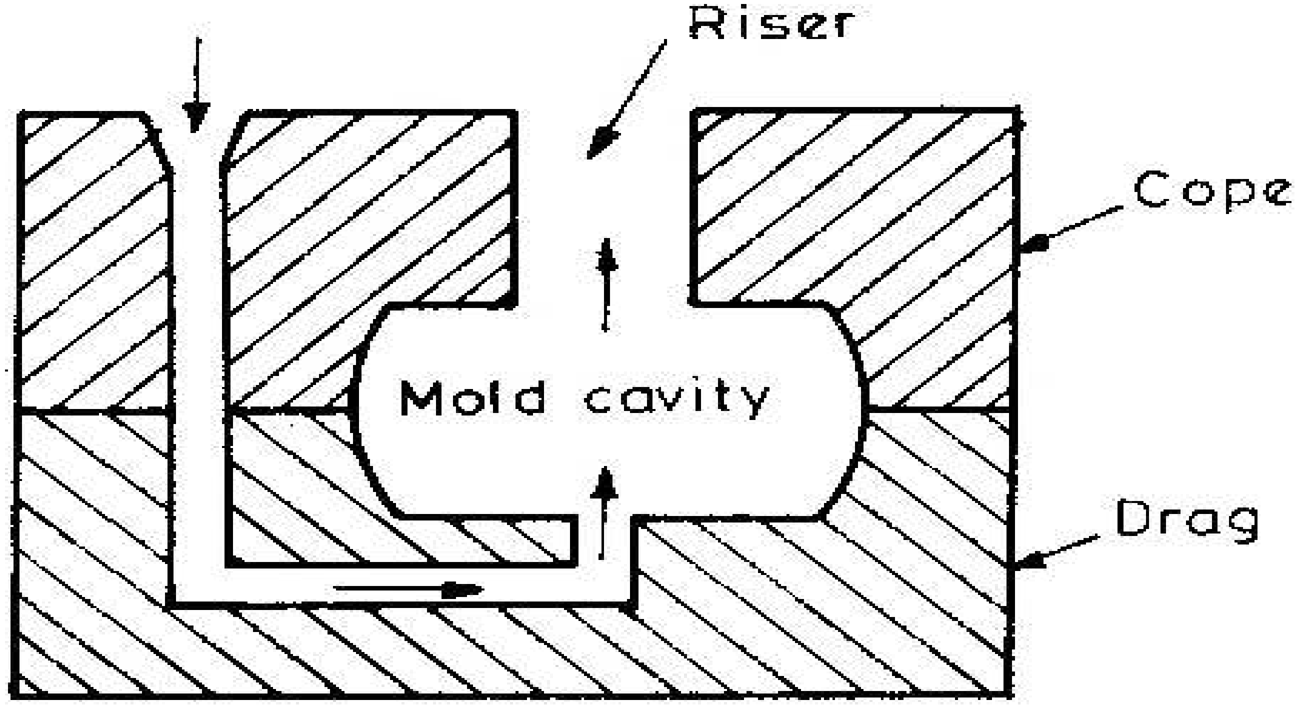
Made in the cope portion of mould. Metal enters from the top portion of the mould into the mold cavity.
This is applied in tall castings were high-pressure sand mould, shell mould and die-casting processes are done



2. Bottom Gate:

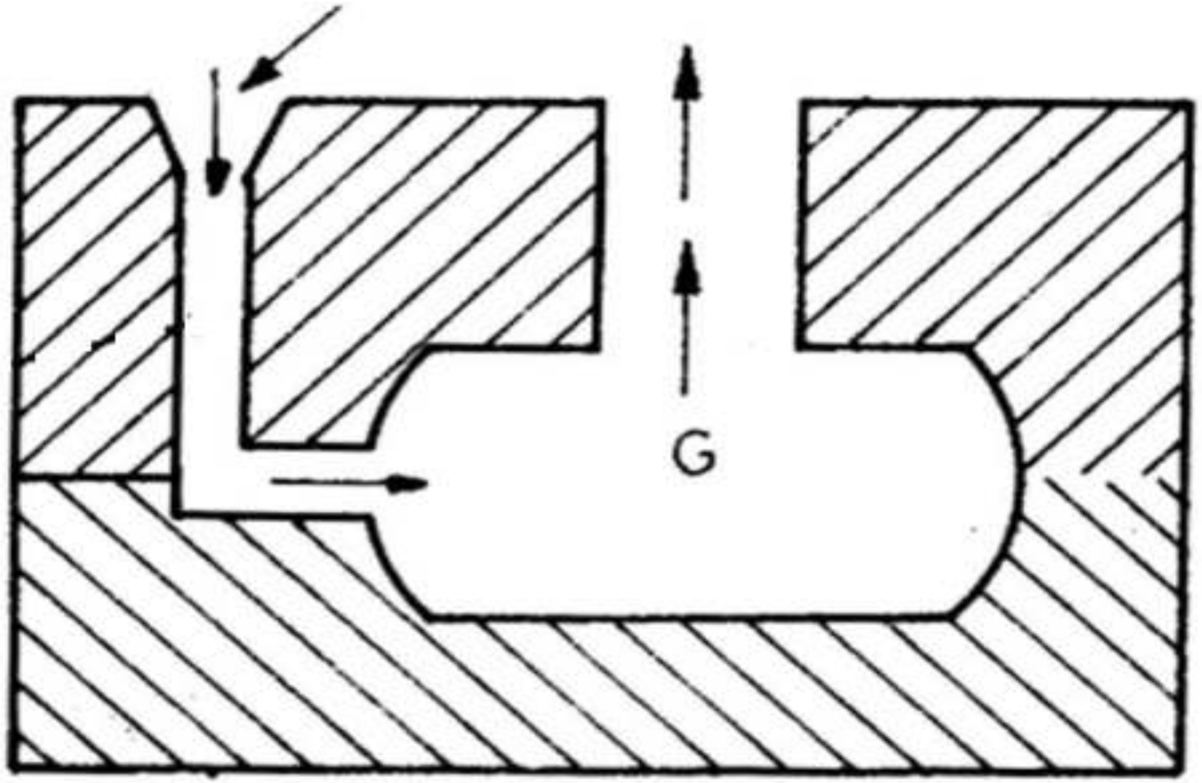
Made in the drag portion. The liquid metal rapidly fills the bottom portion of mould cavity and rises up gently.

This type is normally applied in ferrous metal's sand casting and gravity die-casting of non-ferrous metals. They are used for flat casting, which are filled under gravity.



3.Parting Line Side Gate

Liquid metal enters from the side of the mould.
(At the parting line separating cope and drag).



HEAT TRANSFER IN METAL CASTING

– Heat to be removed to convert liquid molten metal to solid cast

– Heat transfer from molten metal to surroundings through the mould will be taking place by unsteady state heat conduction

- 1) Solidification time

  - During solidification, a thin, solidified skin begins to form at the mould walls and thickens as time passes.
  - For flat mould walls, the thickness is proportional to square root of time.
  - Chvorinov's Rule: Solidification time is a function of the volume of casting and its surface area.
    - Solidification time = C $\left(\frac{Volume}{Surface\ Area}\right)^n$
    - C is a constant which depends on mold material, metal properties etc.
    - n=2
  - Thus a large solid sphere solidifies and cools at a slower rate than a small sphere.

CHVORINOV'S RULE

$$TST = C_m\left(\frac{V}{A}\right)^n$$

Where,

TST = total solidification time

V = volume of the casting

A = surface area of casting

n = exponent usually taken as 2

C_m is a constant which depends upon mould material

- $\frac{V}{A}$ Ratio also called modulus.

- A casting with a higher modulus (volume-to-surface area ratio) cools and solidifies more slowly than the one with a lower modulus.
- To feed molten metal to the casting, ***TST*** of the **riser** must be greater than ***TST*** of the **casting**.
- Since the mould constants of riser and casting will be equal, riser should be designed to have a larger modulus so that the main casting solidifies first.
- Ideal shape of a riser is a **sphere.**

Temperature Distribution during Metal Solidification

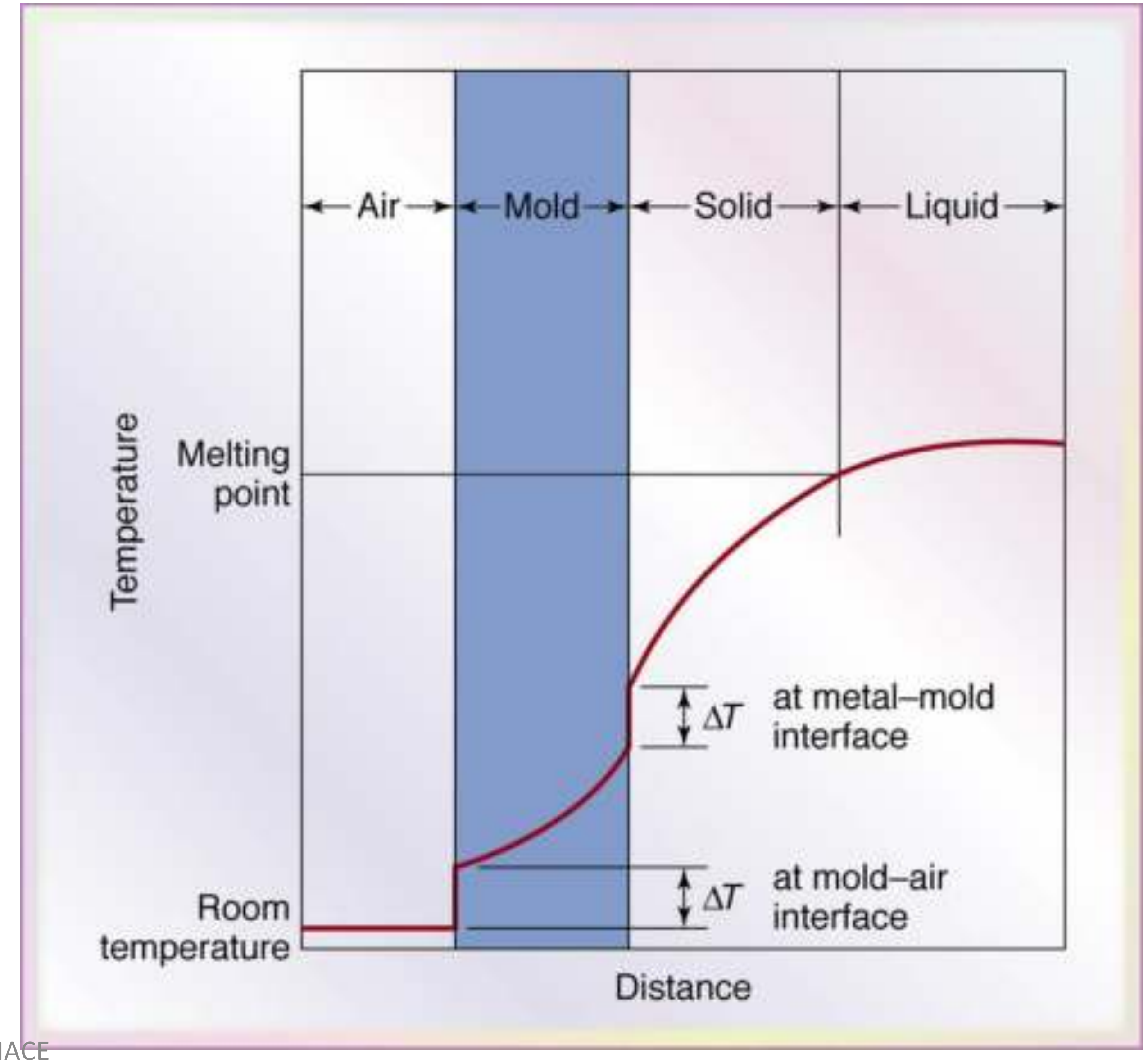


Figure 10.10 Temperature distribution at the interface of the mold wall and the liquid metal during the solidification of metals in casting

RISER

- Molten metal reservoir to compensate the shrinkage of metal during liquid and phase transition contraction stages. Hence, ensures the entire mold cavity is filled up.

- Allows the passage of gases which are released during initial stages of pouring.

- Functions of riser:
  - It should compensate the casting liquid shrinkages during cooling.
  - Escape of mould gases and air.
  - Indicate whether the mould cavity is filled or not.
  - Promotes directional solidification.

- **<u>Condition to be satisfied for design riser (shrinkage volume case)</u>**
  1. **V_R >= 3 V_S**
     - Volume of raiser should be at least 3 times the shrinkage volume of casting
  2. **T_R >= Tcast**
     - The solidification time of molten metal in the riser must be at least equal to the solidification time of molten metal in the casting
  3. **Location of raiser**
     - The spacing of risers in the casting must be considered by effectively calculating the feeding distance of the risers

- The metal in the raiser should remain in the molten state for a longer time than in the mould cavity
- The heat loss in the raiser should therefore be kept to a minimum or solidification time should be high
- Thus raiser shape should be such as to give volume to surface area ratio a maximum value
- For a constant volume among different shape for raiser we can select cylinder shape which has lower surface area also easy to manufacture

Risering Caine's method (method of riser design)

J.B.Caines develop a term freezing ratio,

Freezing ratio (X) = $\frac{cooling\ charecteristics\ of\ Casting}{cooling\ charecteristics\ of Riser} = \frac{\frac{Surface\ area\ of casting}{Volume of\ casting}}{\frac{Surface\ area\ of Riser}{Volume\ of Riser}}$ >1

Freezing ratio (X) of cylindrical shape = $\frac{a}{y-b} - c$

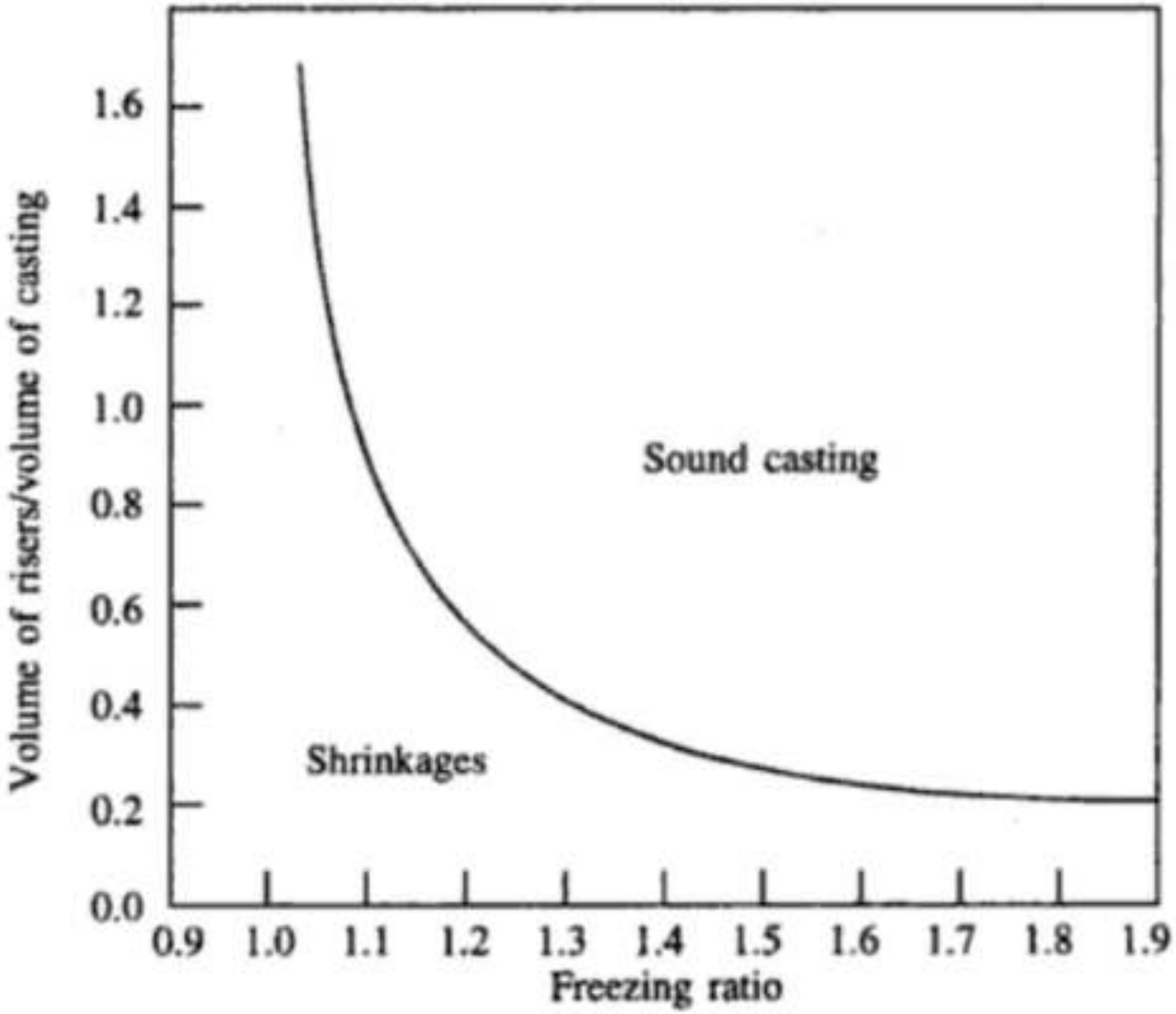
a,b,c are the constants taken from casting table corresponding to metal to be casted

Y= ratio of riser volume to casting volume= $\frac{Vr}{Vc}$

- *Values of constants are given in table:*

	a	b	c
Steel	0.10	0.03	1.00
Aluminium	0.10	0.06	1.08
Cast iron, brass [12.2]	0.04	0.017	1.00
Grey cast iron [12.3]	0.33	0.030	1.00
Aluminium bronze	0.24	0.017	1.00
Silicon bronze	0.24	0.017	1.00

- A graph plotted by Caine predicts whether the casting would be sound or defective one



Example 12.1 Calculate the size of a cylindrical riser (height and diameter equal) necessary to feed a steel slab casting 25 × 25 × 5 cm with a side riser, casting poured horizontally into the mould.

$$\text{Volume of the casting} = 25 \times 25 \times 5 = 3125 \text{ cm}^3$$

$$\text{Surface area of the casting} = 2 \times 25 \times 25 + 4 \times 25 \times 5 = 1750 \text{ cm}^2$$

$$\text{Volume of the riser} = \frac{\pi \times D^3}{4} \quad (9)$$

where D is the riser diameter.

$$\text{Surface area of the riser} = \pi \times D^2 + \frac{\pi \times D^2}{4} \quad (10)$$

$$= 1.25\ \pi\ D^2 \quad (11)$$

$$\text{Freezing ratio, } X = \frac{1750 / 3125}{1.25\pi D^2 / 0.25\pi D^3} = 0.112\ D \quad (12)$$

$$Y = \frac{\text{Volume of riser}}{\text{volume of casting}} = \frac{0.25\pi D^3}{3125}$$

$$= 0.000251\ D^3$$

Substituting this in the Caines's equation for steels

$$0.112\ D = \frac{0.10}{0.000251 D^3 - 0.03} + 1.0$$

On simplification, we get

$D^4 - 8.9286\ D^3 - 119.52\ D = 2490$

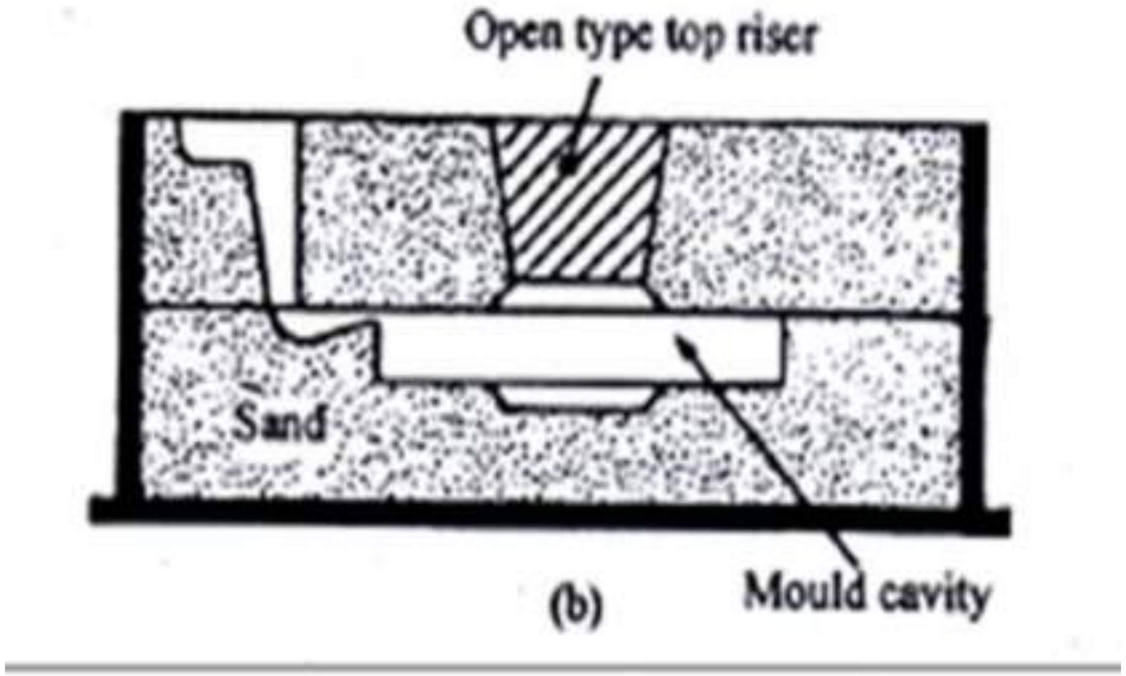
By trial and error, we get

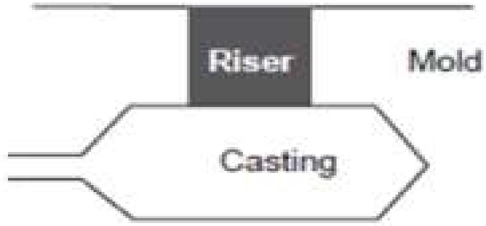
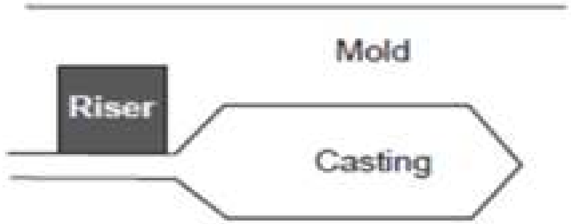
$D = 11.44 \text{ cm} \approx 12 \text{ cm}$

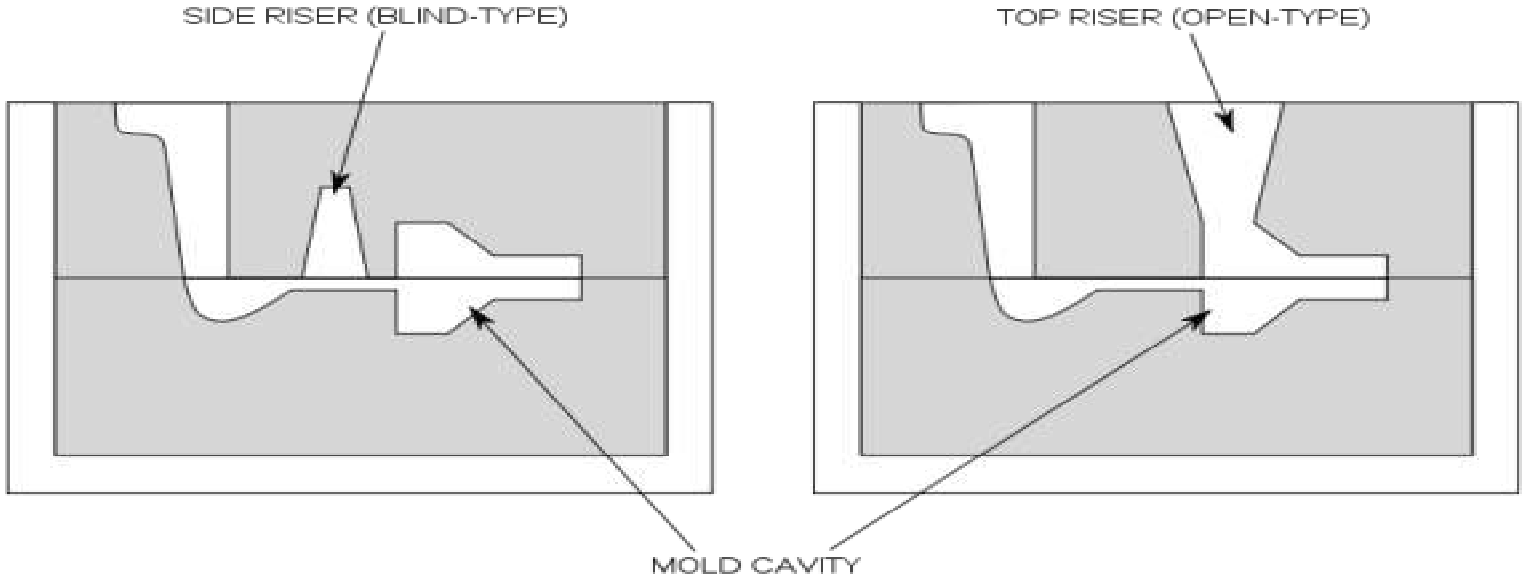
Eldho

1.OPEN RISER

- Top surface of the Open Riser is open to the atmosphere.
- It is usually provided at the top of cope or at the parting line.
- The liquid metal in the riser is fed to the mould cavity by atmospheric pressure and force due to gravity.
- Generally cylindrical in shape.

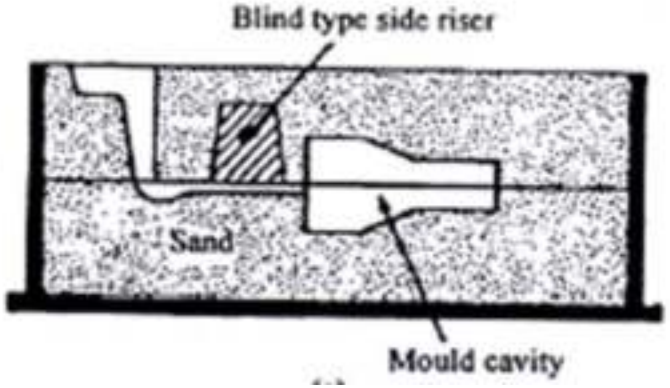


Riser design	Open	Blind
Top		
Side		



2.BLIND RISER

- A Blind Riser is not open to the atmosphere. It is surrounded in all sides by moulding material.
- Sometimes a vent may be provided at the top which is open to the atmosphere.
- Riser may be located in either cope or drag. or in the parting line.
- The feeding pressure is provided by mostly the force due to gravity.



Slag Trap System

- They remove slag, dross and other non metallic particles from the metal stream before the metal enters the mold cavity.
- Slags are due to:
  - Oxides formed during melting, metal transfer, and pouring.
  - Refractory particles from the furnace and ladle
  - Refractory particles present in the gating system or dislodged from the mold or cores during pouring
  - Reaction products from metallurgical operations
  - Undissolved metallic or non metallic particles made as additions to the molten metal for metallurgical modifications (inoculants).

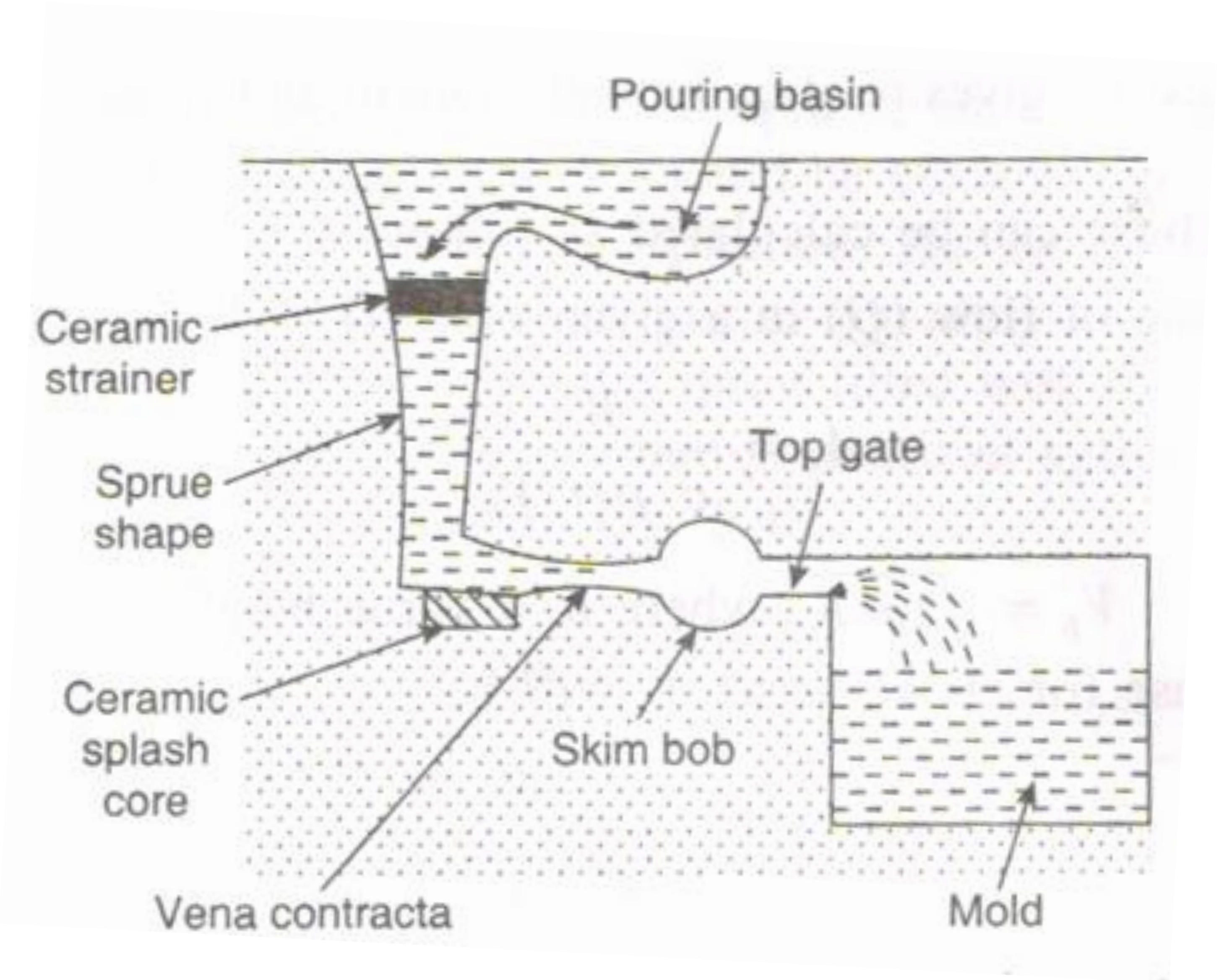
Slag trap system

In order to obtain sound casting quality, it is essential that the slag and other impurities be removed from the molten metal fully before it enters the mould cavity

Apart from the use of

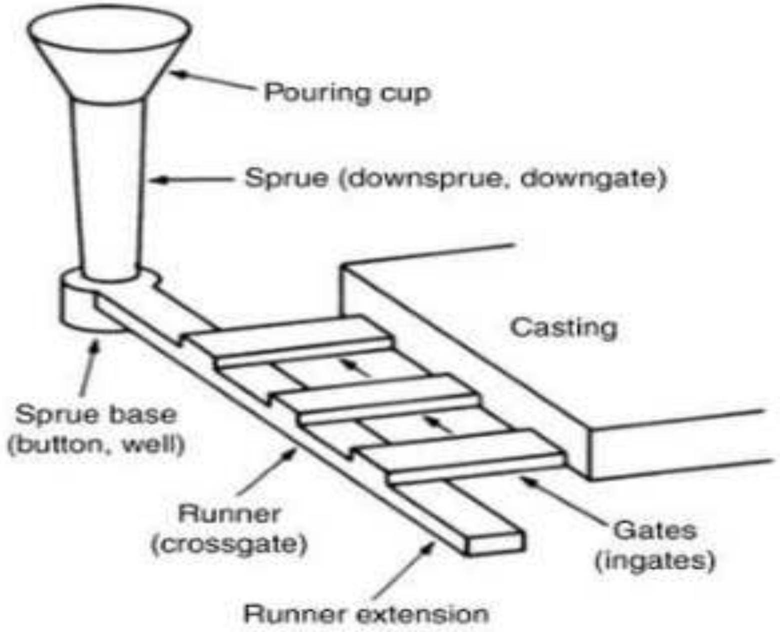
- Pouring basins
- strainer cores
- skim bob and
- Ingate slag trap , the following methods are also used

1. **Runner Extension**
2. **Whirl Gate**


Pouring basin
Ceramic strainer
Sprue shape
Top gate
Ceramic splash core
Skim bob
Vena contracta
Mold

Runner Extension

- Normally the metal which moves first into the gating system is likely to contain slag and dross which should not be allowed to get into the mould cavity
- This could be achieved by extending the runner beyond the ingates so that the momentum of the metal will carry slag past the gates and to a blind alley called runner extension
- A runner extension having a minimum of twice the runner width is desirable

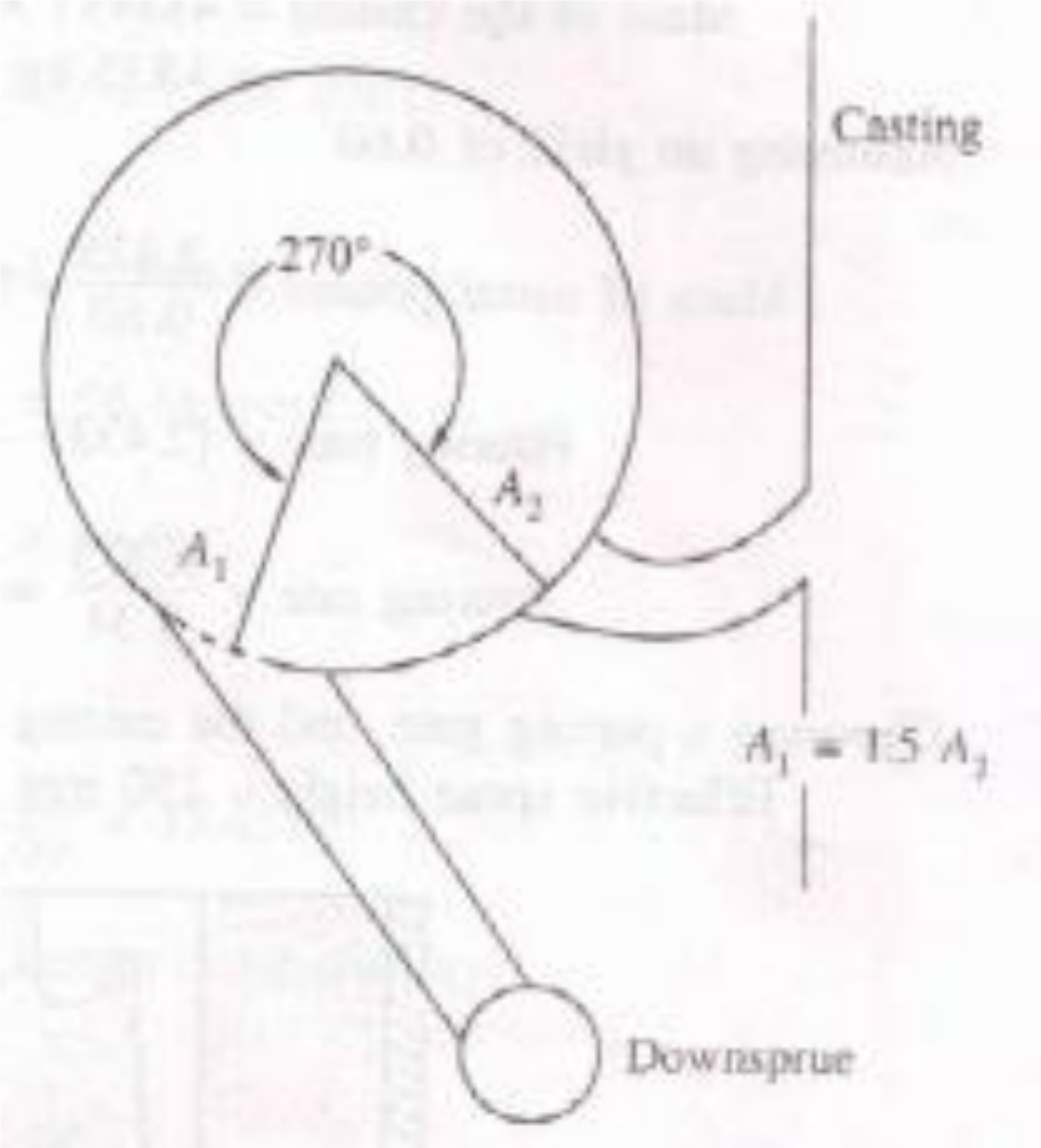


Whirl Gate

For reference

- Another method employed successfully to trap the slag from entering steel casting is a whirl gate.
- This utilizes the principle of centrifugal action to throw the dense metal to the periphery and retain the lighter slag at the centre.
- In order to achieve this action, it is necessary that entry area should be at least 1.5 times the exit area so that the metal is built up at the centre quickly
- Also the metal should revolve 270^0 before reaching the exit gate so as to gain enough time for separating the impurities

For reference



Fluid Flow and Solidification Time

Pouring Time $= \frac{\text{volume}}{\text{area x velocity}}$

Bernoulli's theorem $h + \frac{p}{\rho g} + \frac{v^2}{2g} = \text{constant}$

Mass continuity $Q = A_1 v_1 = A_2 v_2$

Sprue design $\frac{A_1}{A_2} = \sqrt{\frac{h_2}{h_1}}$

Reynolds number $\text{Re} = \frac{vD\rho}{\eta}$

Chvorinov's Rule $\text{Solidification time} = C\left(\frac{\text{Volume}}{\text{Surface Area}}\right)^n$

Should study formulas and problems corresponding to this

problem

Problems :

1. The flow rate of liquid metal into the downsprue of a mould is 1 *litre/s*. The cros sectional area at the top of the sprue is 800 mm^2 and its length 175 *mm*. What are should be used at the base of the sprue to avoid aspiration of the molten metal?

Solution :

Given, $Q = 1$ *litre/s* $= 0.001\ m^3/s$, height of sprue $= 175\ mm = 0.175\ m$

We know, $Q = A \times v$

$$\text{Velocity, } v = \sqrt{2 \times g \times h} = \sqrt{2 \times 9.81 \times 0.175} = 1.85\ m$$

$$\text{Area at base of sprue, } = A = \frac{Q}{v} = \frac{0.001}{1.854} = 0.54\ m^2$$

2. The downsprue leading into the runner of a certain mould has a length of 175 *mm*. The cross-sectional area at the base of the sprue is 400 mm^2. The mould cavity has a volume of 0.001 m^3. Determine: (a) the velocity of the molten metal flowing through the base of the downsprue, (b) the volume rate of flow, and (c) the time required to fill the mould cavity.

Solution :

Given, volume of mould cavity $= 0.001\ m^3/s$, height of sprue $= 175\ mm = 0.175\ m$ and area at the base of the sprue $= 400\ mm^2$

(a) Velocity, $v = \sqrt{2 \times g \times h} = \sqrt{2 \times 9.81 \times 0.175} = 1.85\ m$

(b) Volume flow rate, $Q = v \times A = 1.85 \times 0.004 = 0.00074\ m^3/s$

(c) Time to fill cavity $= \dfrac{V}{Q} = \dfrac{0.001}{0.00074} = 1.35\ s$

3. The total solidification times of three casting shapes are to be compared: (1) a sphere with diameter of 0.1 m, (2) a cube with each side of 0.1 m. The same casting alloy is used in the three cases. Determine the relative solidification times for each geometry.

Solution:

We know, by *Chvorinov's rule*, solidification time $= C \times \left(\dfrac{V}{A}\right)^2$

Sphere volume, $V = \dfrac{\pi \times D^3}{6} = \dfrac{\pi \times 0.1^3}{6}$; Sphere area, $A = \pi \times D^2 = \pi \times 0.1^2$

$$\frac{V}{A} = \frac{\dfrac{\pi \times 0.1^3}{6}}{\pi \times 0.1^2} = 0.01667\ m$$

Solidification time for sphere $= 0.01667^2 C = 0.000278\ m$

Cube volume, $V = L^3 = 0.1^3 = 0.001\ m^3$; Cube area, $A = 6 \times L^2 = 6 \times 0.1^2 = 0.06\ m^2$

$$\frac{V}{A} = \frac{0.001}{0.06} = 0.01667\ m$$

Solidification time for cube $= 0.01667^2 C = 0.000278\ m$

EXAMPLE 10.1 Solidification Times for Various Shapes

Three metal pieces being cast have the same volume, but different shapes: One is a sphere, one a cube, and the other a cylinder with its height equal to its diameter. Which piece will solidify the fastest, and which one the slowest? Assume that $n = 2$.

Solution The volume of the piece is taken as unity. Thus from Eq. (10.7),

$$\text{Solidification time} \propto \frac{1}{(\text{Surface area})^2}.$$

The respective surface areas are as follows:

Sphere:

$$V = \left(\frac{4}{3}\right)\pi r^3, \quad r = \left(\frac{3}{4\pi}\right)^{1/3}.$$

$$A = 4\pi r^2 = 4\pi\left(\frac{3}{4\pi}\right)^{2/3} = 4.84.$$

Cube:

$$V = a^3, \; a = 1, \text{ and } A = 6a^2 = 6.$$

Cylinder:

$$V = \pi r^2 h = 2\pi r^3, \quad r = \left(\frac{1}{2\pi}\right)^{1/3},$$

$$A = 2\pi r^2 + 2\pi r h = 6\pi r^2 = 6\pi\left(\frac{1}{2\pi}\right)^{2/3} = 5.54.$$

The respective solidification times are therefore

$$t_{sphere} = 0.043C, \; t_{cube} = 0.028C, \; t_{cylinder} = 0.033C.$$

Hence, the cube-shaped piece will solidify the fastest, and the spherical piece will solidify the slowest.

11. A mould has a down sprue whose length is 20 cm and the cross-sectional area at the base of down sprue is 1 cm^2. The down sprue feeds a horizontal runner leading into the mould cavity of volume 1000 cm^3. The time required to fill the mould cavity will be

(a) 4.05 sec
(b) **5.05 sec**
(c) 6.05 sec
(d) 7.25 sec

Solution: Time required to fill the mould cavity = t_m= Volume of mould cavity / Flow rate …. (1)

Volume of mould cavity = 1000 cm^3

Flow rate = $A_s \sqrt{2gh}$

A_s = Cross sectional area at the base of down sprue = 1 cm^2

h = length of down sprue

Putting the values in (1), we get that tm = 5.05 sec

13.A cylinder of 150 mm diameter & 200 mm height is to be cast without any riser. The cylinder is moulded entirely in the drag of a green sand flask & top gated. The cope of the flask is 200 mm height & the height of metal during pouring is 50 mm above the cope. A tapered sprue is employed & the gating ratio is 1: 1.5:2. The time taken (in seconds) to fill the casting cavity neglecting energy losses, if the in-gate area is 400 mm^2

(a) 2
(b) 4
(c) **8**
(d) 15

Solution: Pouring time = V/Q .... (1)

V = Volume of mould = $[(\pi \times 150^2)/4] \times 200\ mm^3$

Q = Flow rate = $(200) \times \sqrt{2 \times 9.81 \times 1000 \times (200 + 50)}\ mm^3/sec$

Here area of sprue is half of gate area, according to the gating ratio

Putting all values in equation (1) we get that pouring time = 8 sec

15. A mould having dimensions 100 mm × 90 mm × 20 mm is filled with molten metal through a gate with height 'h' and cross-sectional area A, the mould filling time is t_1. The height is now quadrupled and the cross-sectional area is halved. The corresponding filling time is t_2. The ratio t_2/t_1 is

(a) 3
(b) **1**
(c) 4
(d) 5

Solution: $T_1 = (V) / (A \times \sqrt{2gh})$

Now, for T_2 we have $h_2 = 4$ h, $A_2 = A/2$

$T_2 = (V) / [(A/2) \times \sqrt{2g \times 4h}]$

So $T_2 / T_1 = 1$

12. In a sand casting process, a sprue of 10 mm base diameter and 250 mm height leads to a runner which fills a cubical mould cavity of 100 mm size. The volume flow rate (in mm^3/sec) and the mould filling time (in second) are

(a) 0.8×10^5, 2.8
(b) 1.1×10^5, 7.54
(c) 1.7×10^5, 5.78
(d) 2.3×10^5, 8.41

Solution: Given, D = 10 mm, h = 250 mm

Velocity of molten metal at the sprue end = $V_1 = \sqrt{2gh}$

Cross sectional area of sprue = $A_1 = (\pi d^2/4)$

Where d = diameter of sprue base

Flow rate = A_1V_1 = 173942.13 mm^3/ sec

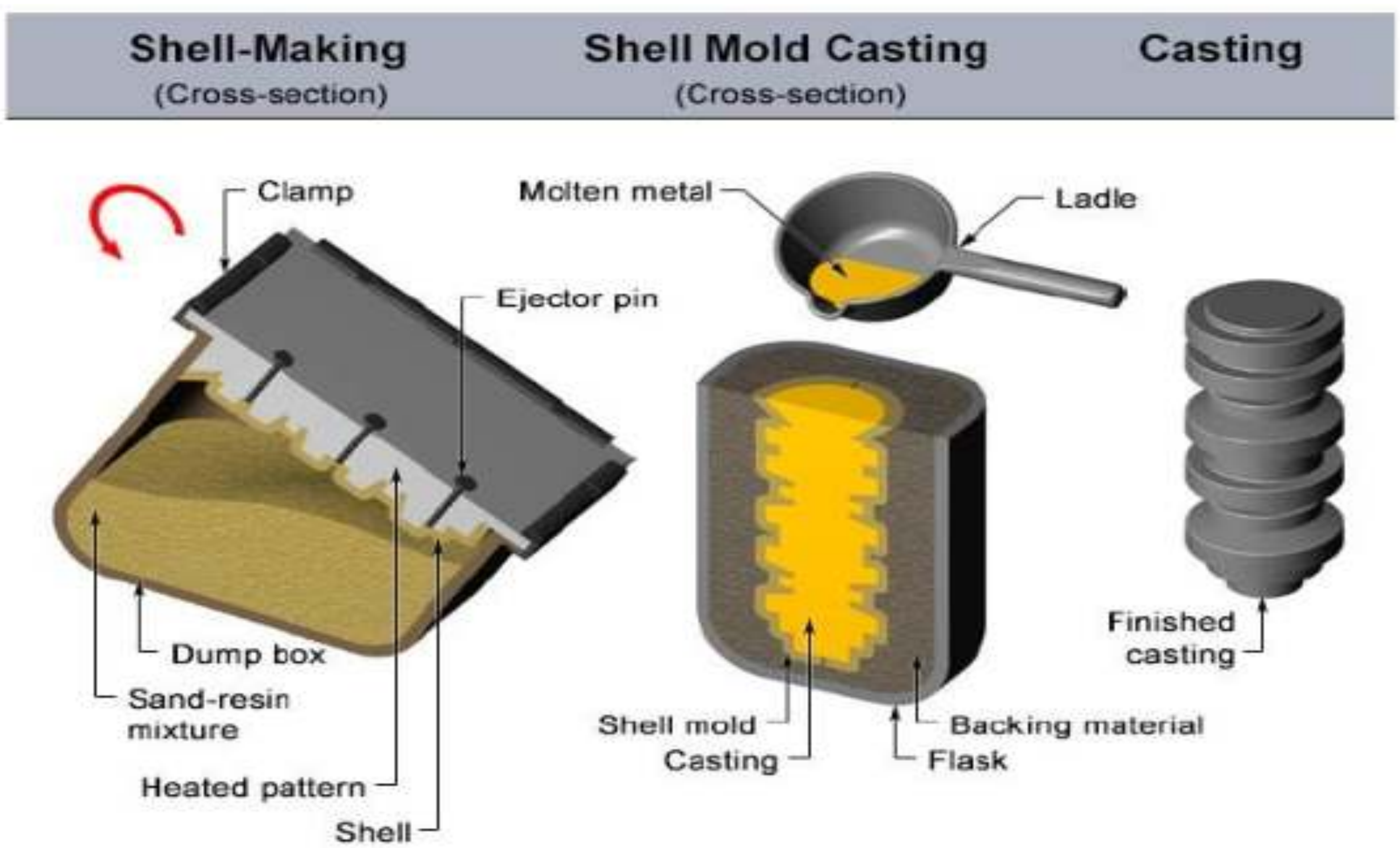
Volume of mould = $100\times100\times100$ mm^3

Mould filling time = Volume of mould / Flow rate = 5.75 sec

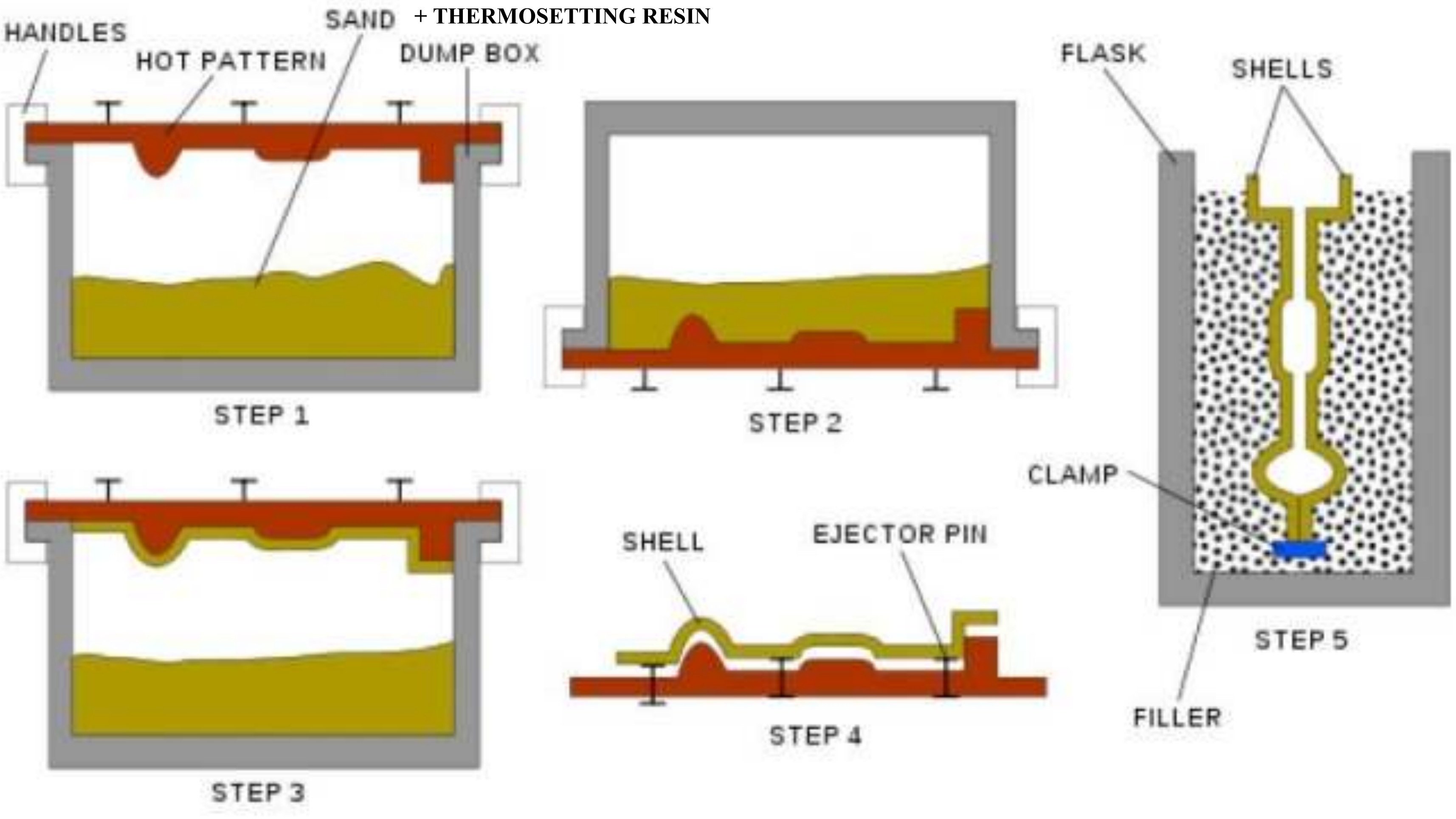
Special casting process

1. Shell Molding: (shell casting)

- Produced with the help of heated iron or steel patterns.
- Fine sand+ Resin is used to produce shell halves which are assembled to form the mold.
- Produces exceptionally good surface finish and dimensional accuracy.
- Also known as Croning or C process.



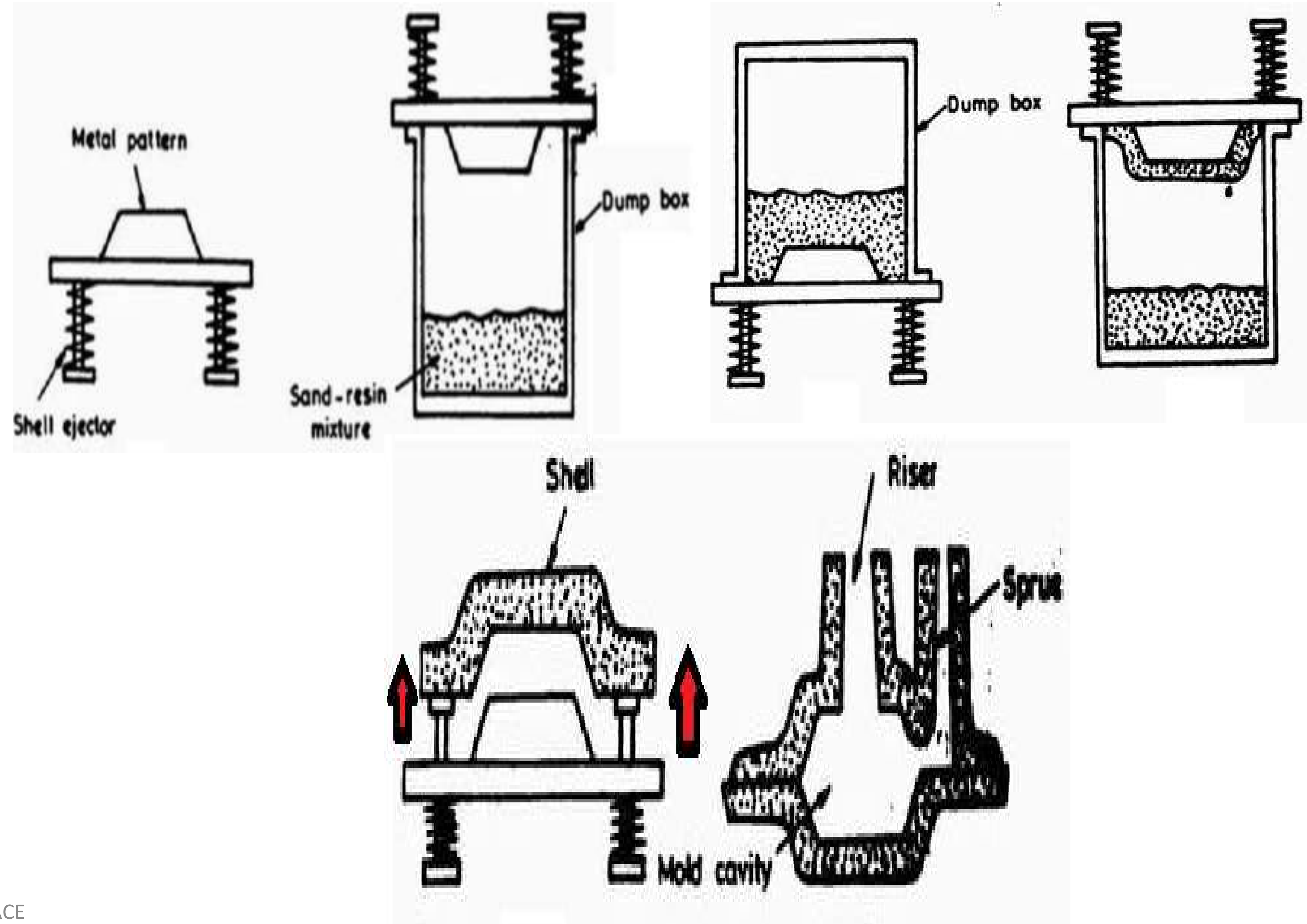
Shell molding-steps



Step 1. Preheated pattern clamped over dump box
Step 2. Dump Box inverted over hot pattern.
Step 3. Dump Box turned to original position.
Step 4. Shell stripped from the pattern.
Step 5. Shell Assembly.

- A match plate or cope-drag **metal pattern** having the profile of the required casting is heated.
- Pattern after being heated is taken out of the oven and sprayed with a solution of a lubricating agent to prevent the shell from sticking to the metal pattern.
- Metal pattern (made up of iron or steel) is then turned face down and clamped over the open end of the dump box. The dump box contains sand resin mixture.
- The dump box is inverted so that dry sand-resin mixture falls on to the face of hot metal pattern.
- The resin sand mixture in contact with the pattern gets heated up, the resin softens and fuses to form a soft and uniform shell of about 6 mm thickness on the surface of pattern.

- As the dump box is turned to its original position, excess sand-resin mixture falls back into the dump box leaving a shell adhering closely to the pattern.
- The pattern along with the shell adhering to it is passed directly into an oven and due to that the shell acquires rigidity.
- The shell is then stripped from the pattern plate with the help of ejector pins.
- After the shells so obtained have cooled
- Two halves of the shell mould are assembled, supported by sand or metal shot in a box, and pouring is accomplished. The finished casting with sprue is removed.


Metal pattern
Shell ejector
Dump box
Sand-resin mixture
Dump box
Shell
Riser
Sprue
Mold cavity

SHELL MOLDING

ADVANTAGES

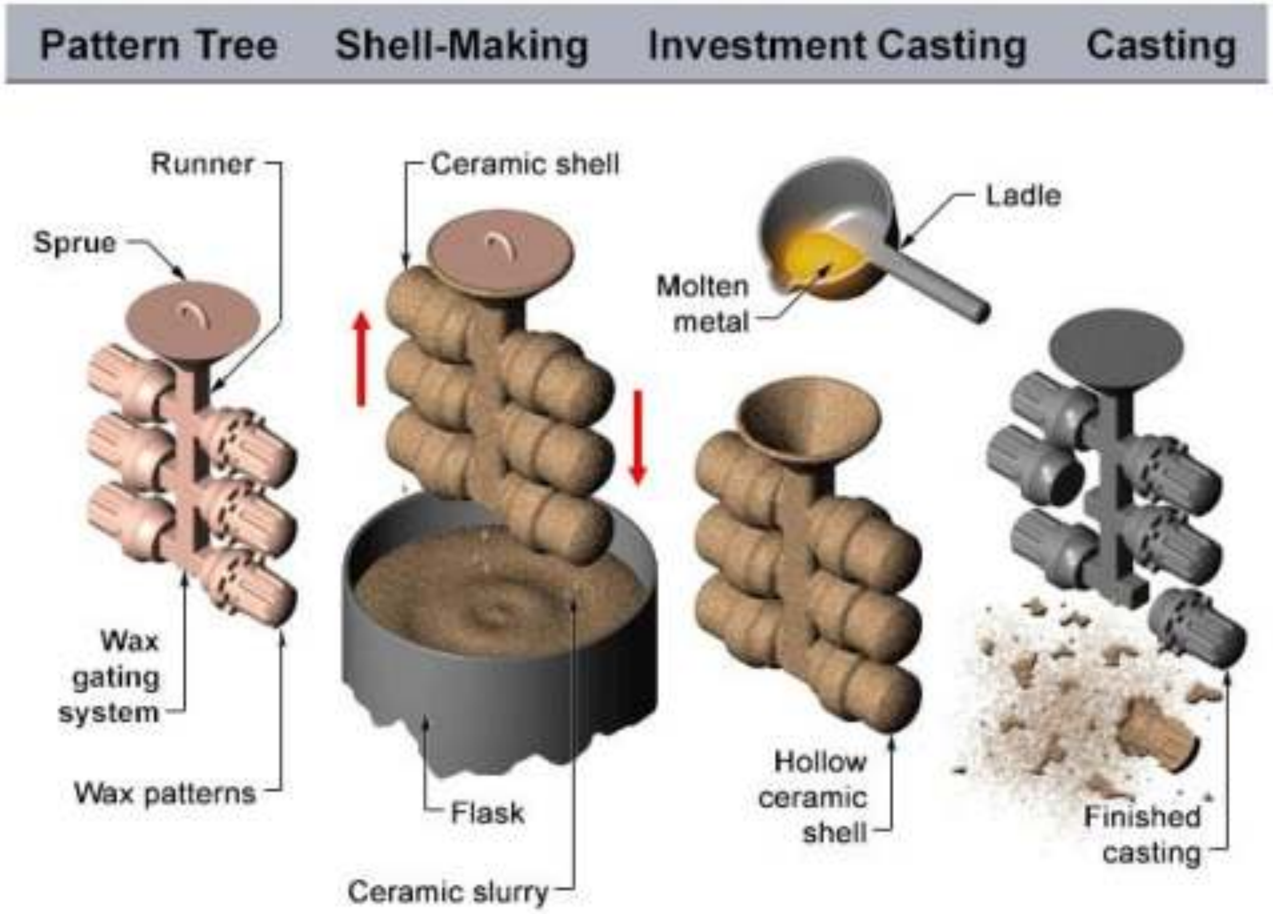
- Shell thickness typically 9 mm is used
- Surface of shell mold cavity is smoother than sand mold.
- Easy flow of molten metal, good surface quality
- Finish is of the order of 2.5 micrometer.
- Good dimensional accuracy
- Can be mechanized for mass production and is very economical
- Gears, valve bodies, bushings, and cam shafts are typical products

DISADVANTAGES

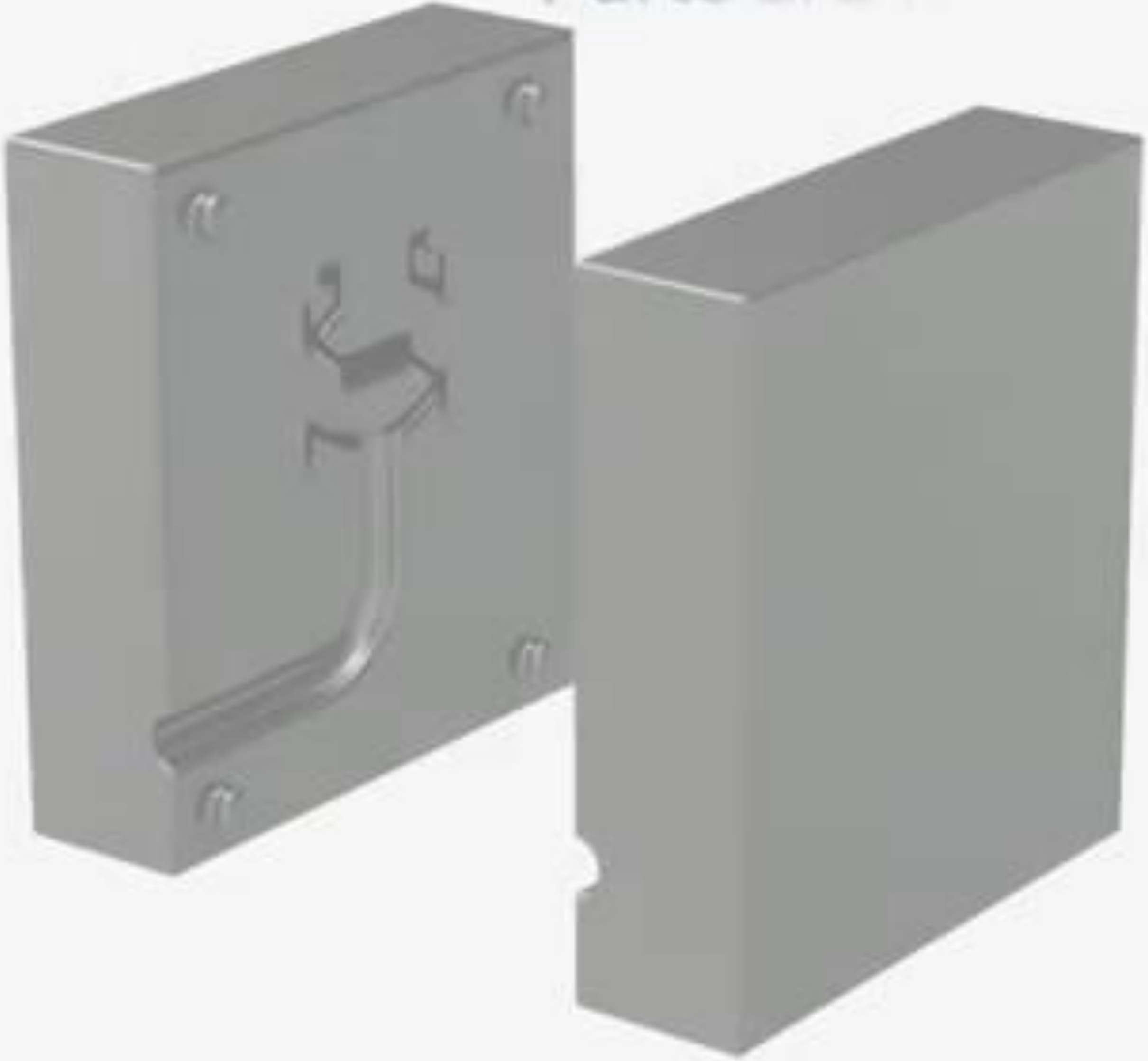
- Expensive metal pattern as compared to sand casting
- Difficult to justify for small quantities manufacturing
- Possible on small to medium size parts
- Suitable for steel castings less than 10 kg.
- Resin Costs-comparatively higher.

2.Investment moulding (or Casting)

- Term “Investment” stand for cloak which is refractory mold that surrounds the pre-coated wax pattern.
- Produces casting with good surface finish and dimensional accuracy.

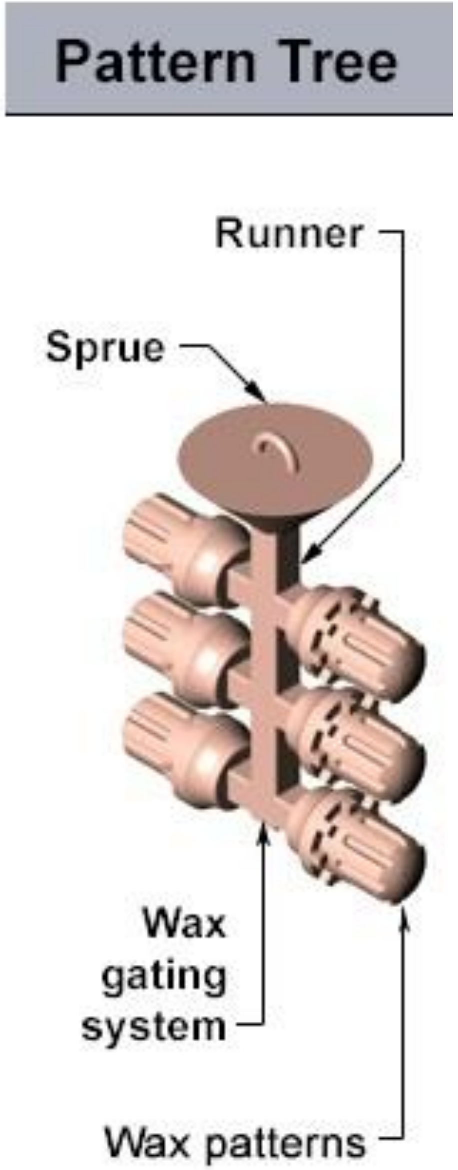


Parts are

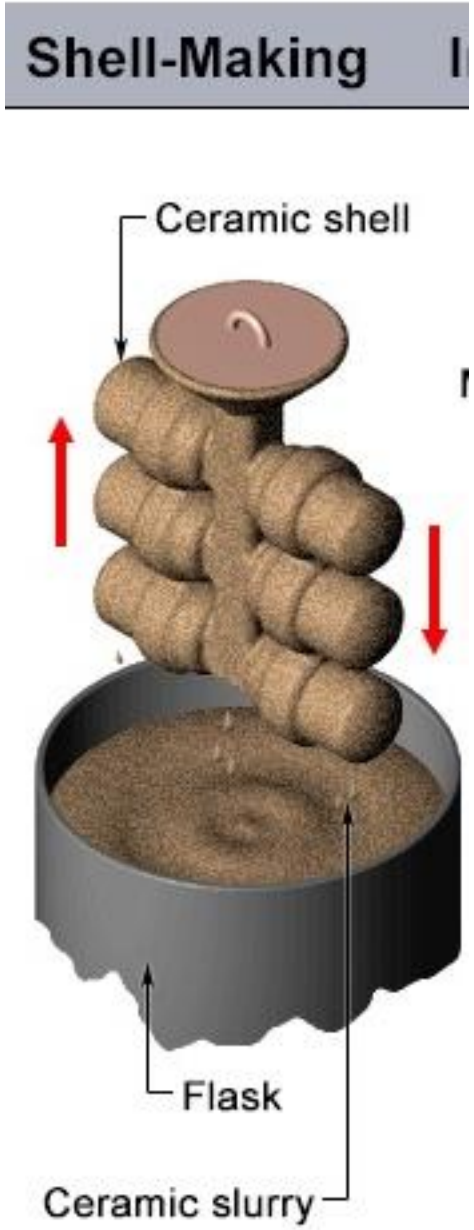


Investm

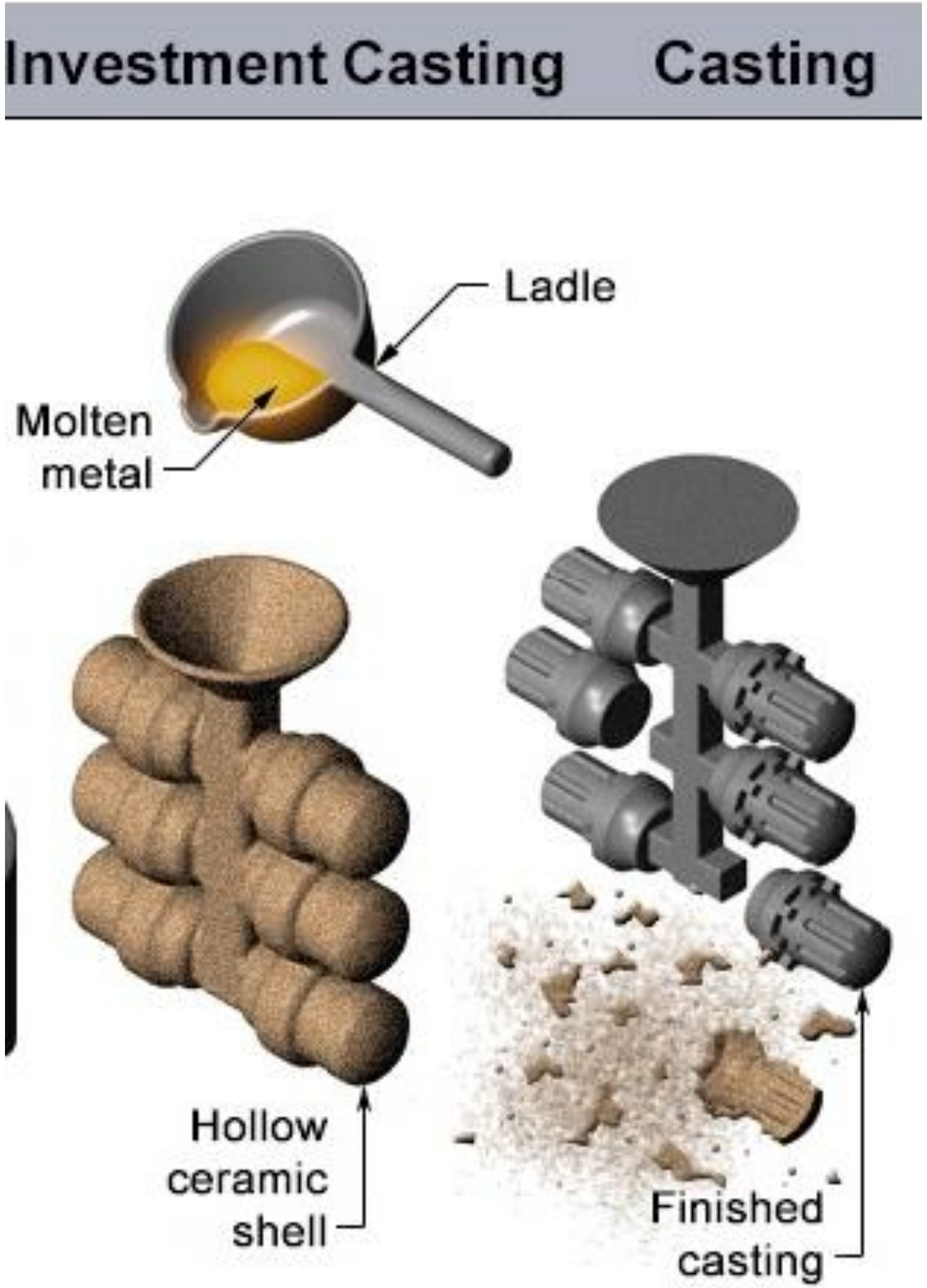
Process steps



- **Pattern creation** –
  - The wax patterns are typically injection moulded into a metal die and are formed as one piece.
  - Several of these patterns are attached to a central wax gating system (sprue, runners, and risers), to form a tree-like assembly.
  - The gating system forms the channels through which the molten metal will flow to the mould cavity.

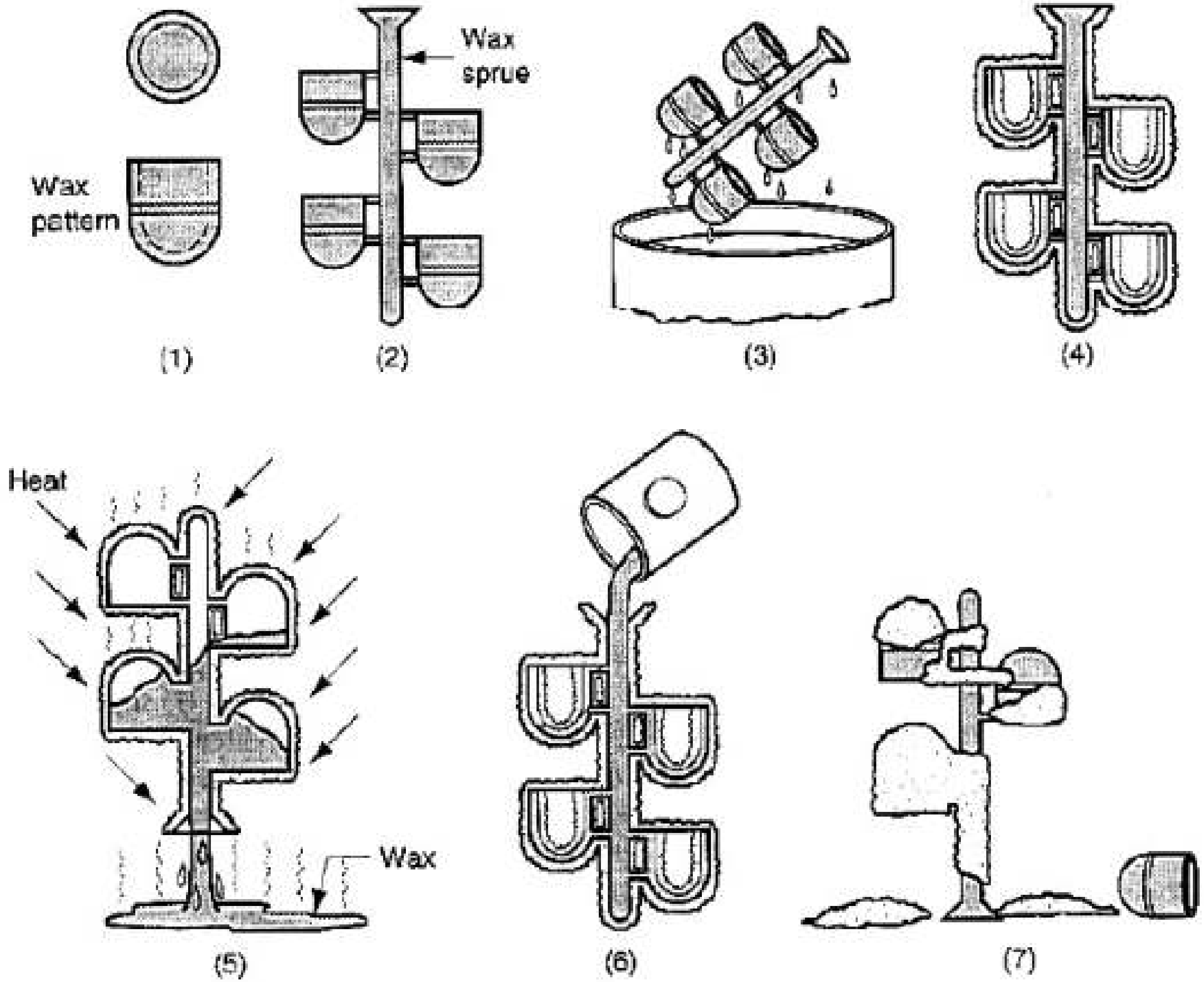


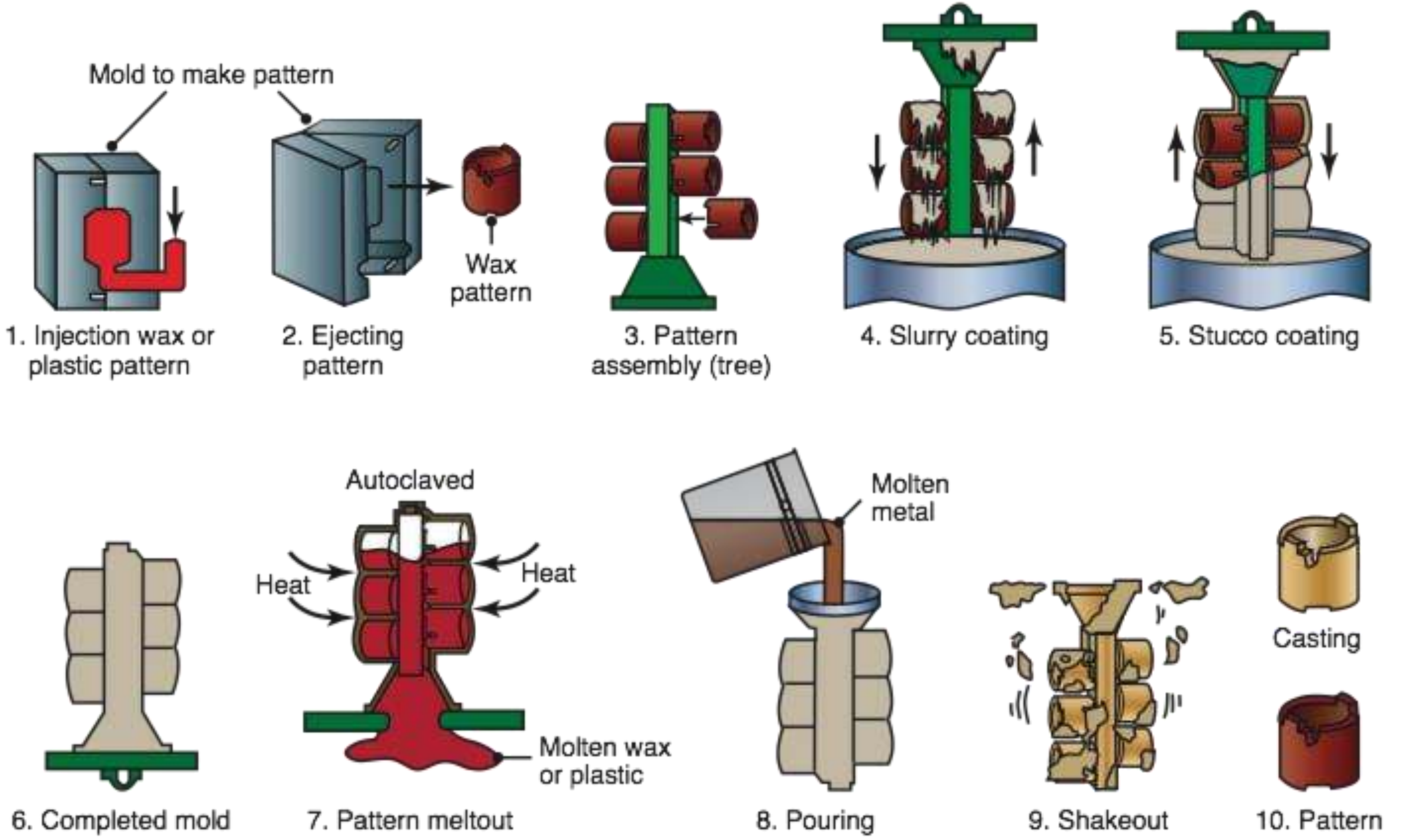
- **Mould creation –**
  - This "pattern tree" is dipped into a slurry of fine refractory particles, such as very fine silica and binders, ethyl silicate and acids. After the initial coating is dried the pattern is coated repeatedly to increase its thickness
  - This process is repeated until the shell is thick enough to withstand the molten metal it will encounter.
  - The shell is then placed into an oven and the wax is melted out leaving a hollow ceramic shell that acts as a one-piece mould, hence the name "lost wax" casting.



- **Pouring –**
  - The mould is preheated in a furnace to approximately 1000°C (1832°F) and the molten metal is poured from a ladle into the gating system of the mould, filling the mould cavity.
  - Pouring is typically achieved manually under the force of gravity, but other methods such as vacuum or pressure are sometimes used.
- **Cooling –**
  - After the mould has been filled, the molten metal is allowed to cool and solidify into the shape of the final casting.
  - Cooling time depends on the thickness of the part, thickness of the mould, and the material used.

- **Casting removal –**
  - After the molten metal has cooled, the mould can be broken and the casting removed.
  - The ceramic mould is typically broken using water jets, but several other methods exist.
  - Once removed, the parts are separated from the gating system by either sawing or cold breaking (using liquid nitrogen).
- **Finishing –**
  - Often times, finishing operations such as grinding or sandblasting are used to smooth the part at the gates.
  - Heat treatment is also sometimes used to harden the final part.


Wax pattern
(1)
Wax sprue
(2)
(3)
(4)
Heat
Wax
(5)
(6)
(7)


Mold to make pattern
Wax
pattern
1. Injection wax or
plastic pattern
2. Ejecting
pattern
3. Pattern
assembly (tree)
4. Slurry coating
5. Stucco coating
Autoclaved
Heat
Heat
Molten
metal
Casting
Molten wax
or plastic
6. Completed mold
7. Pattern meltout
8. Pouring
9. Shakeout
10. Pattern

Automated Shell Production

Figure 12.5 A robot generates a ceramic shell on wax patterns (trees) for investment casting. The robot is programmed to dip the trees and then place them in an automated drying system. With many layers, a thick ceramic shell suitable for investment casting is formed. *Source*: Courtesy of Wisconsin Precision Casting Corporation

3.CENTRIFUGAL CASTING

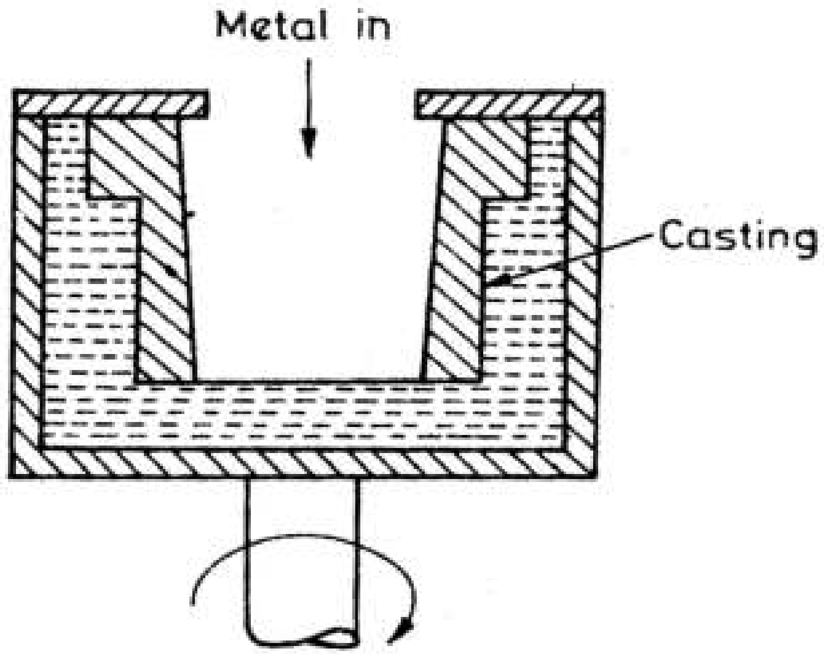
Principle of Centrifugal Casting

- In Centrifugal Casting liquid metal is introduced into a rotating mould so that metal being poured is thrown to the outer surface of the mould cavity. Casting cools and solidifies from outside towards the axis of rotation.

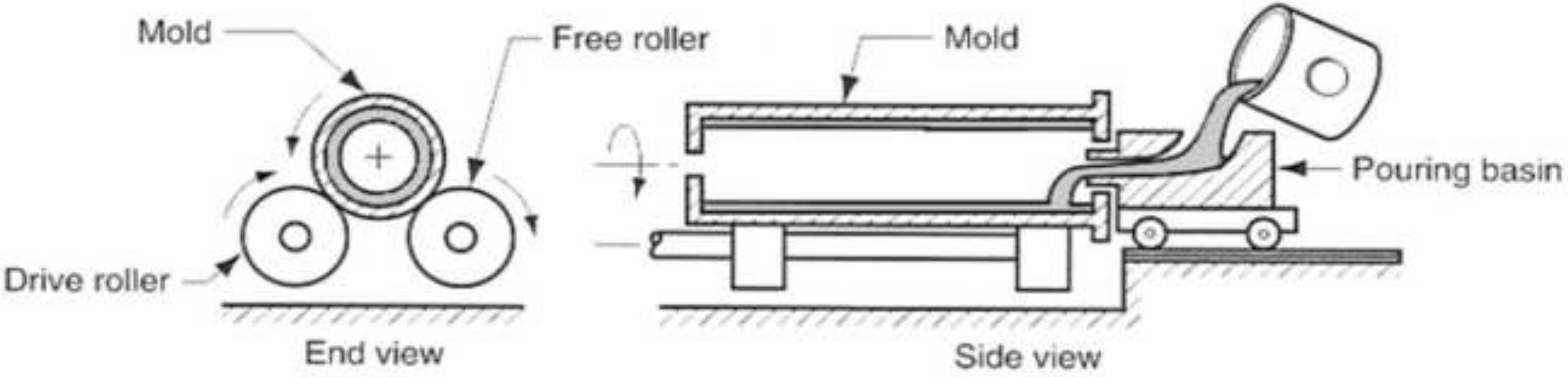
Types of Centrifugal Castings

- True Centrifugal Casting.
- Semi-Centrifugal Casting.
- Centrifuge Casting.

True Centrifugal Casting



True centrifugal casting



Setup for true horizontal centrifugal casting

CENTRIFUGAL CASTING

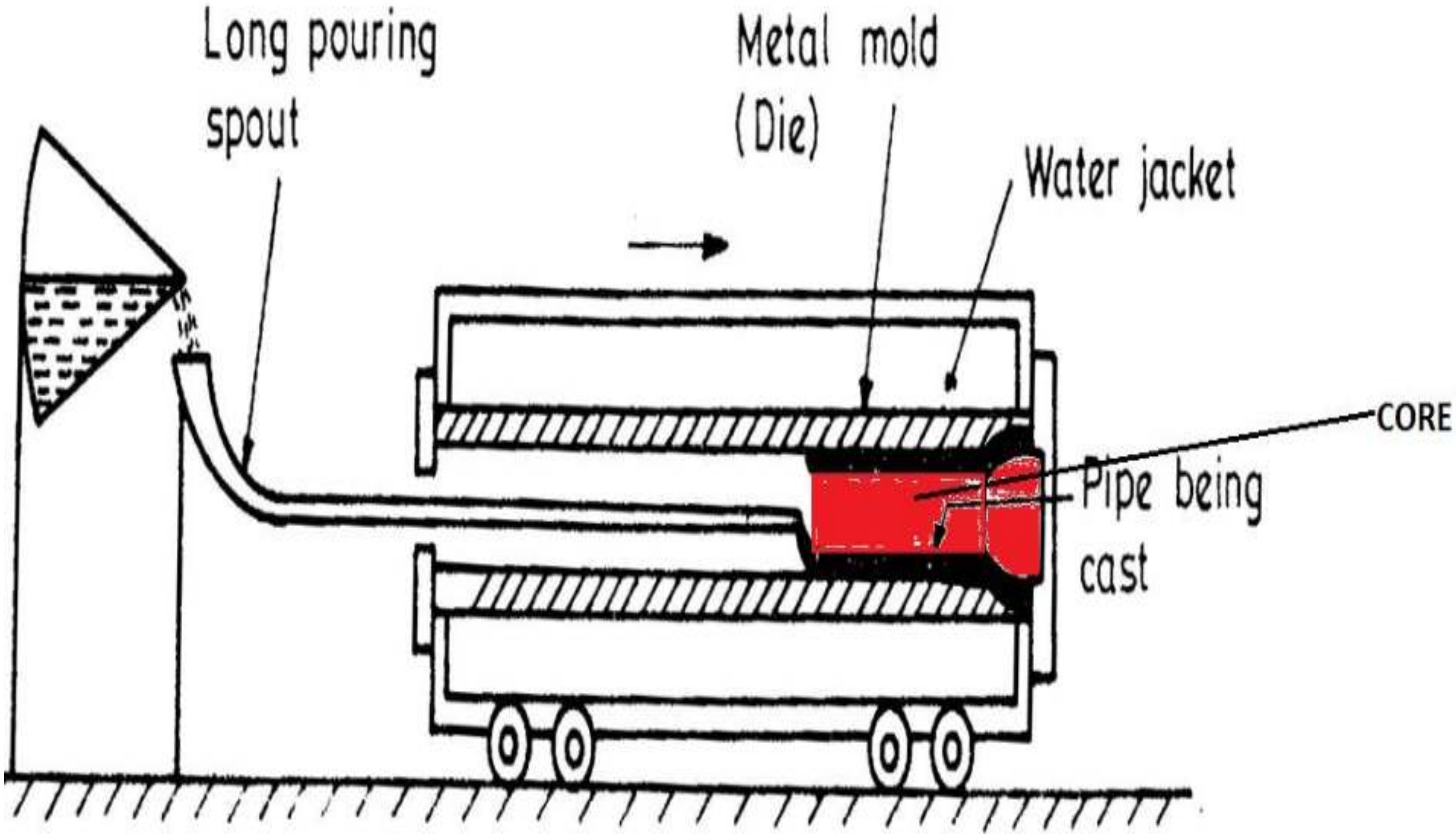
- Used for making castings having more or less outer symmetrical shape (round, square).
- In this molten metal is poured in to a rotating mould
- The axis of rotation is horizontal, but can be vertical for short work piece
- Mold surface can be any shape
- But the surface of the casting remains cylindrical because the molten metal is uniformly distributed by centrifugal force
- Because of difference in density, lighter particles such as dross, impurities, slag are collected at the inner surface of the casting

- Cylindrical mould rotated about an axis common to both casting and mould
- Casting cools and solidifies from outside towards the axis of rotation ; so it results in good directional solidification. Hence casting are free from shrinkage
- To cast a hollow cylinder.

❖ For example a cylindrical mould is made to rotate about its own axis at a speed such that the metal being poured is thrown to the outer surface of the mould cavity. The metal solidifies in the form of a hollow cylinder. The cylinder wall thickness is controlled by the amount of liquid metal poured.

- Used for making gun barrels, cast iron pipes etc.

De Lavaud Process



- Consists of an accurately machined metal mould(die), entirely surrounded by cooling water.
- The machine is mounted on wheel so that it can be moved lengthwise on a slightly inclined track.
- At one end of a track there is a ladle containing liquid metal which flows along a long pouring spout.
- Mould can be rotated about its axis.
- As the pouring proceeds, the casting machine is moved slowly down the track so that metal being poured fills the mould cavity following a helical path.
- Rate of pouring, speed of the casting machine and rotation of mould is controlled.
- After completion of pouring the machine will be at the lower end of its track.
- The pipe after it has solidified is taken out from the mould.

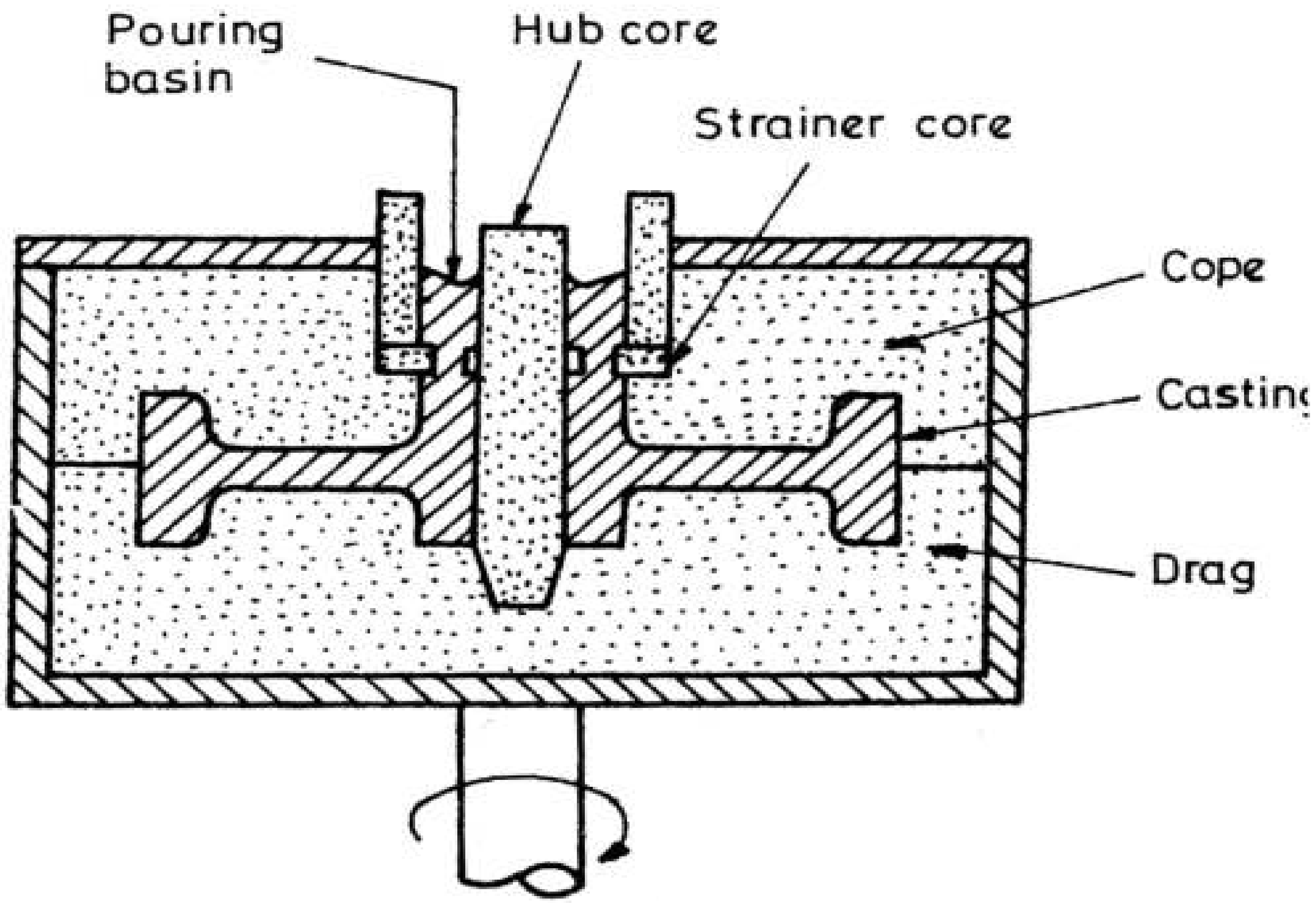
Advantages of Centrifugal Castings

- Castings produced are sound.
- Rejection is less.
- Production rate is sufficiently high.
- Thin and intricate shapes can be cast.
- Directional solidification is obtained.

Disadvantages

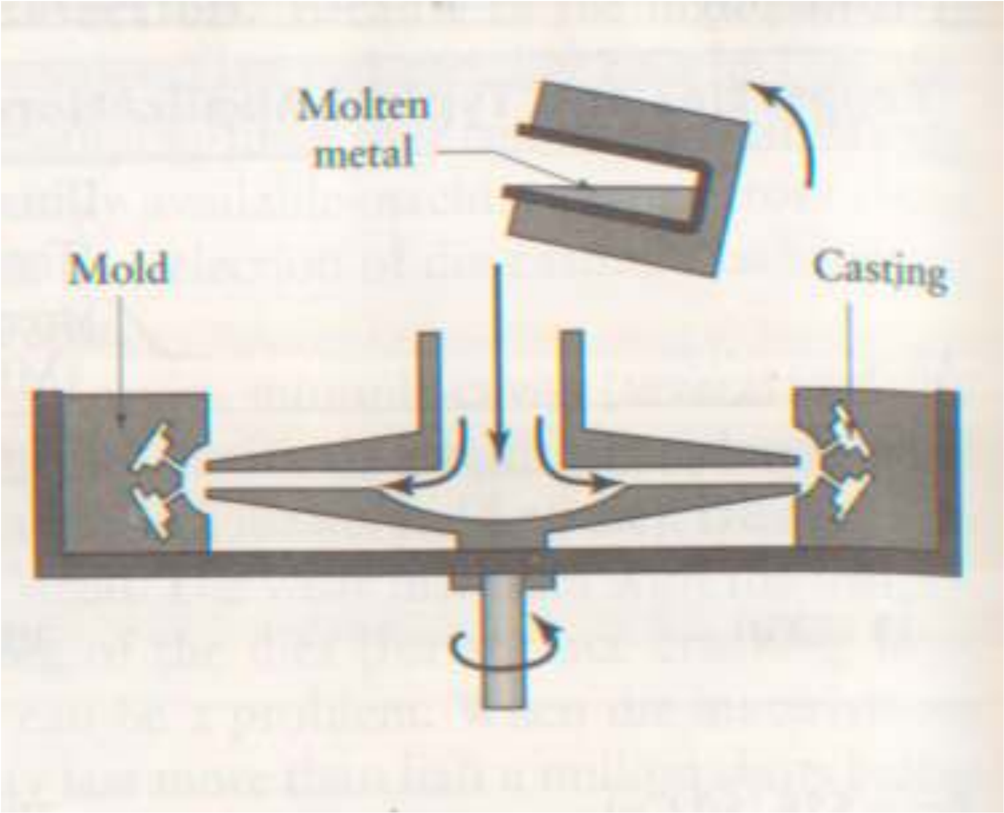
- All shapes cannot be cast.
- Initial investment is more.

Semi-Centrifugal Casting



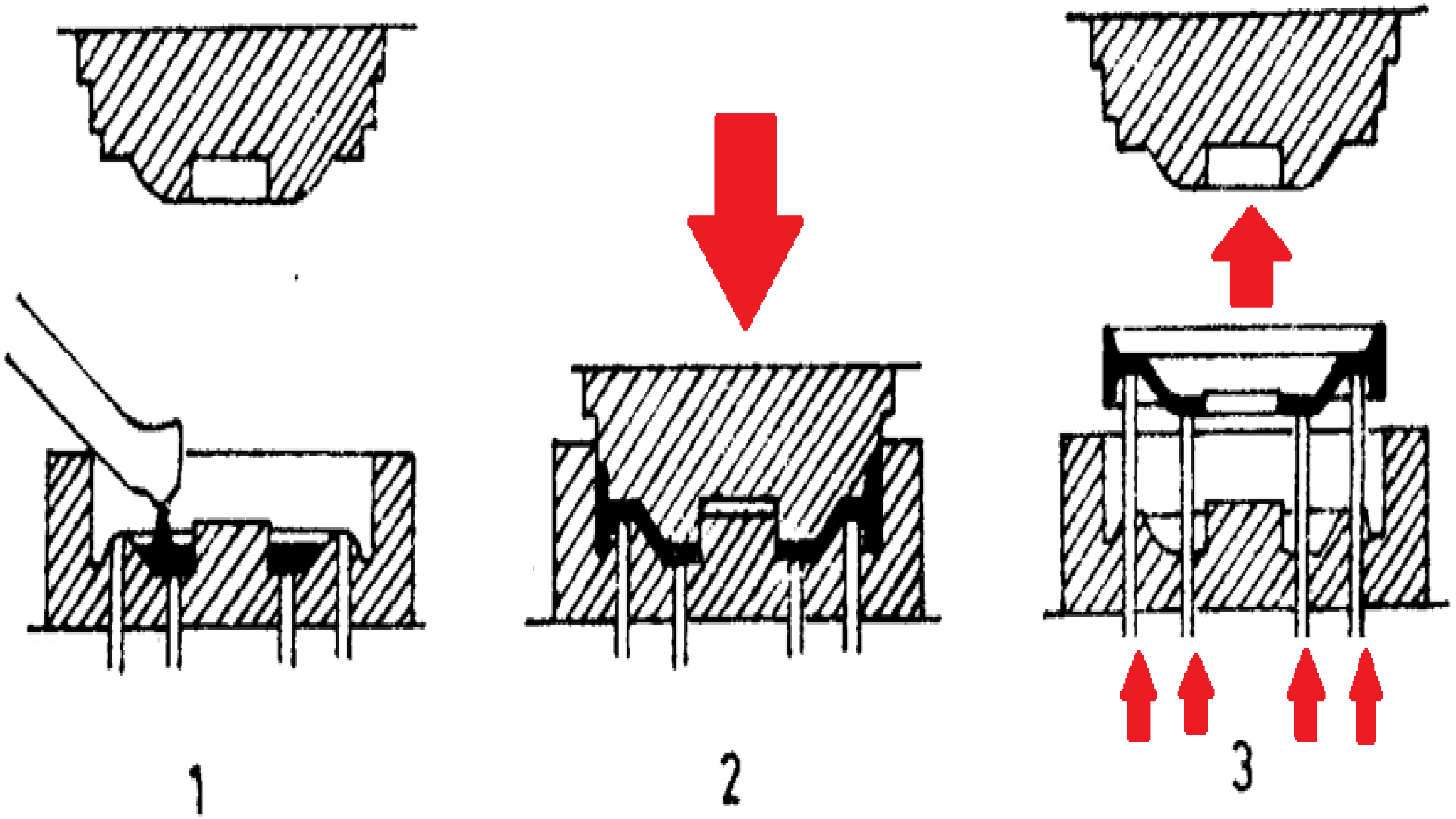
- Like Centrifugal castings, Semi-centrifugal castings also uses the rotation of the mould about its axis.
- **Unlike True Centrifugal Casting, a core is used to form a central cavity**, for producing internal shapes that could not be formed by any other method.
- Semi-Centrifugal Casting technique is used to produce castings which are symmetric about the axis of rotation.
- Rotating speed is less than true centrifugal casting.
- Gear blanks, wheels are produced using Semi-Centrifugal castings.

Centrifuge Casting

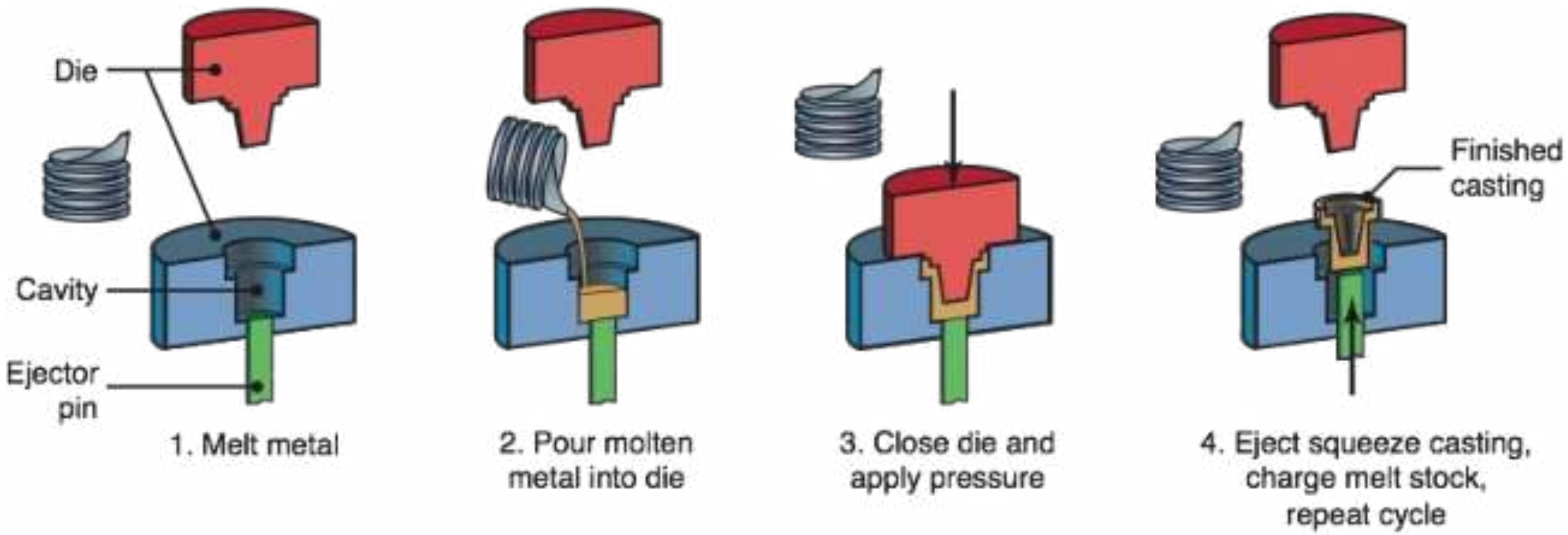


- Mould cavities of any shape are placed at a certain distance from the axis of rotation
- The molten metal is poured at the center and is forced into the mould by centrifugal force
- The properties with in the castings vary by the distance from the axis of rotation

4 .SQUEEZE CASTING



- Involves solidification of the molten metal under high pressure
- Hence the process is a combination of casting and forging
- Steps involved in Squeeze Casting :
  - Pouring measured quantity molten metal into the lower die.
  - Exerting load using a punch or upper die through out solidification. Force exerted is between 31-108 MN/m^2)
  - After solidification cast is taken out.

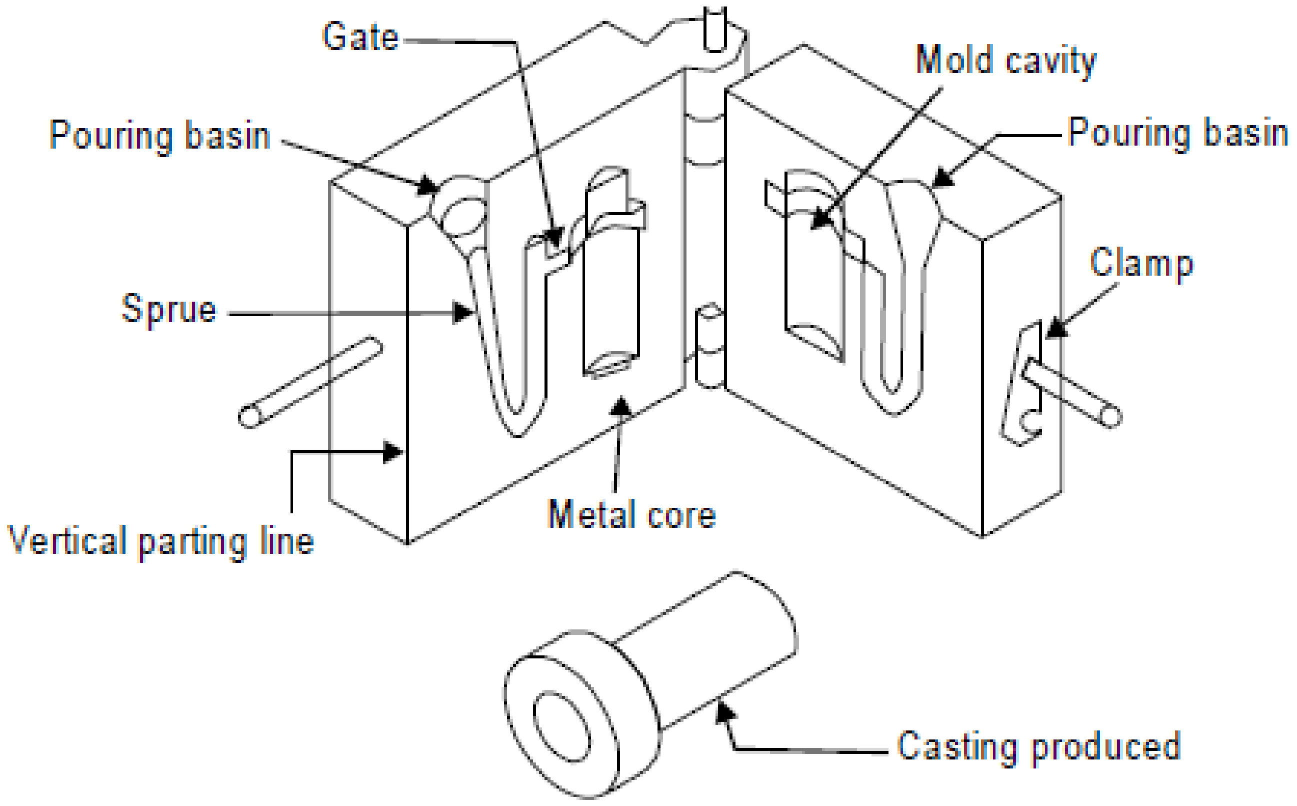


- The high pressure contact at the die-metal interface promotes heat transfer resulting in a fine microstructure with good mechanical properties and limited microporosity
- Part with near net shape can produce
- Pressure applied higher than pressure die casting and lower than the hot or cold forging
- Advantages :
  - Faster solidification.
  - Solidification under load eliminates shrinkage.
  - The microstructure is isotropic. Thus the properties are uniform through the component. This in turn allow the components to be designed with less metal.

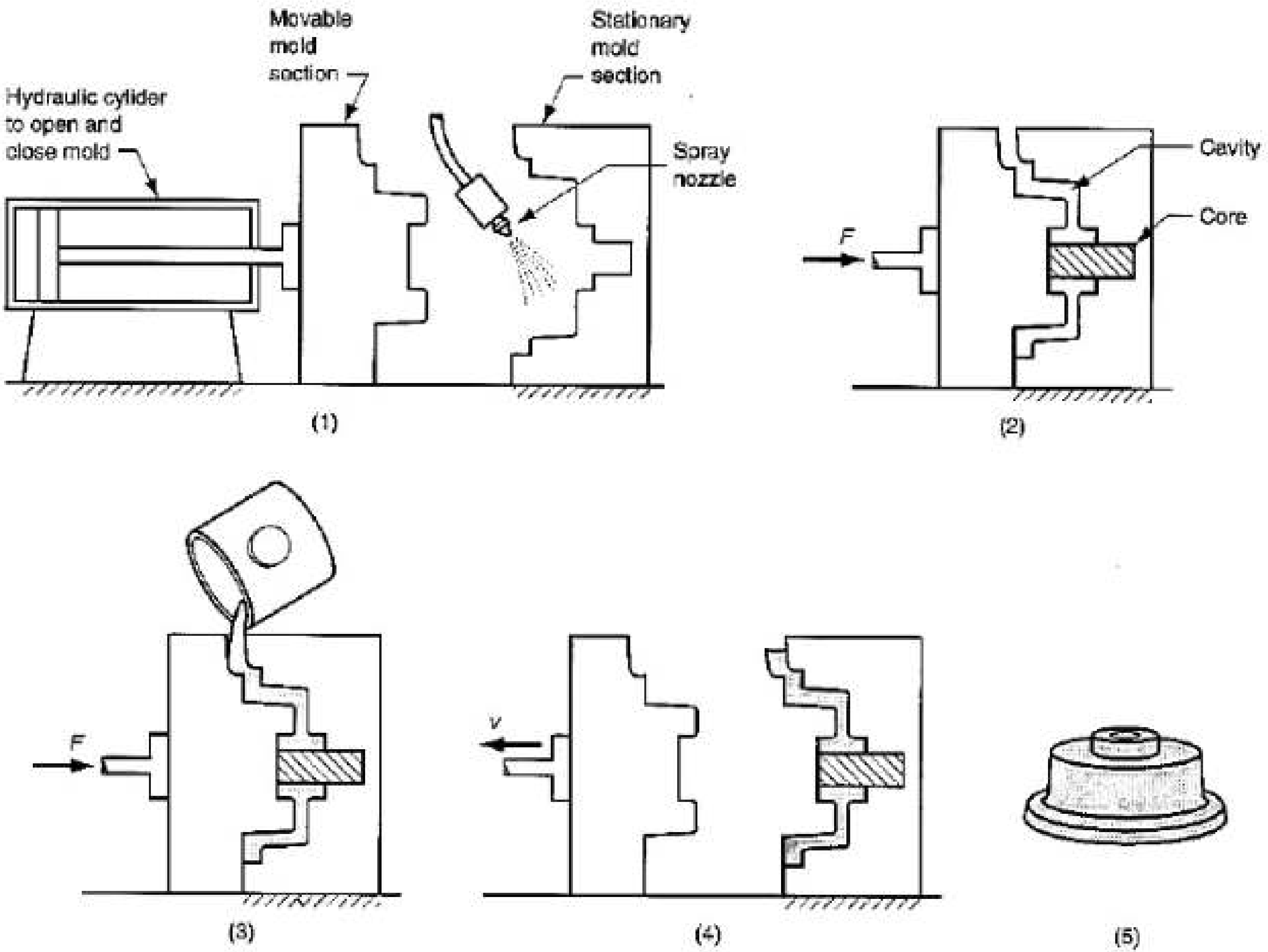
5. DIE OR PERMANENT MOLD CASTING

1. GRAVITY DIE OR PERMANENT MOLD CASTING:

– Molten metal is poured into the mould under gravity only and no external pressure is applied to force the liquid metal into the mould cavity.



Steps in permanent mold casting



- The metallic mould can be reused many times before it is discarded or rebuilt. These moulds are made of dense, fine grained, heat resistant cast iron, steel, bronze, anodized aluminium, graphite or other suitable refractoriness.
- The mould is made in two halves in order to facilitate the removal of casting from the mould. The mould walls of a permanent mould have thickness from 15 mm to 50 mm.
- For faster cooling, fins or projections may be provided on the outside of the permanent mould. This provides the desirable chilling effect.
- Permanent Molds are used to make the casting of Aluminium Alloys, Magnesium Alloys, Zinc Base, Lead, Copper Base etc.,

Advantages

(*i*) Fine and dense grained structure is achieved in the casting.

(ii) No blow holes exist in castings produced by this method.

(iii) The process is economical for mass production.

(iv) Because of rapid rate of cooling, the castings possess fine grain structure.

(v) Close dimensional tolerance or job accuracy is possible to achieve on the cast product.

(vi) Good surface finish and surface details are obtained.

(vii) Casting defects observed in sand castings are eliminated.

(viii) Fast rate of production can be attained.

(ix) The process requires less labour

Disadvantages

(*i*) The cost of metallic mould is higher than the sand mould. The process is impractical for large castings.

(ii) The surface of casting becomes hard due to chilling effect.

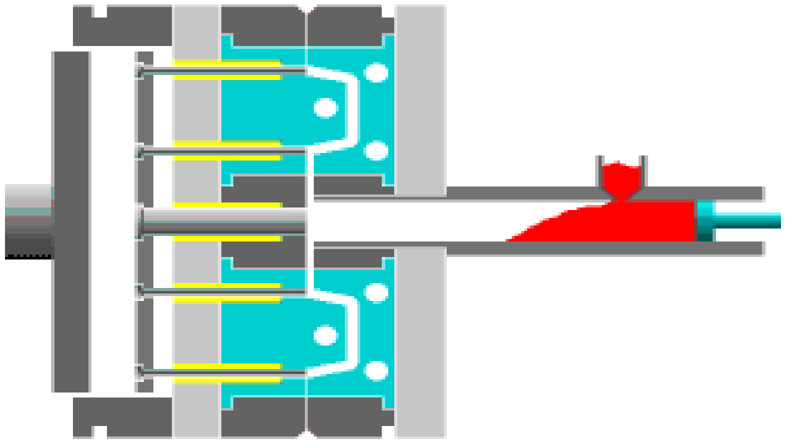
(iii) Refractoriness of the high melting point alloys.

Application

i) This method is suitable for small and medium sized casting such as carburettor
bodies, oil pump bodies, connecting rods, pistons etc.
(ii) It is widely suitable for non-ferrous casting.

2. PRESSURE DIE CASTINGS OR DIE CASTINGS

- In Pressure Die Casting, the molten metal is forced into permanent mould cavity made of reusable steel very quickly under pressure.
- The pressure varies from **0.7 to 700 Mpa** and is maintained while the casting solidifies.
- The pressure is maintained until the metal has completely solidified in the mould
- Used for producing castings having intricate shapes.
- Process is suitable for lead, magnesium, tin and zinc alloys.



Die Casting Machines:

A Die Casting Machine performs the following operations :

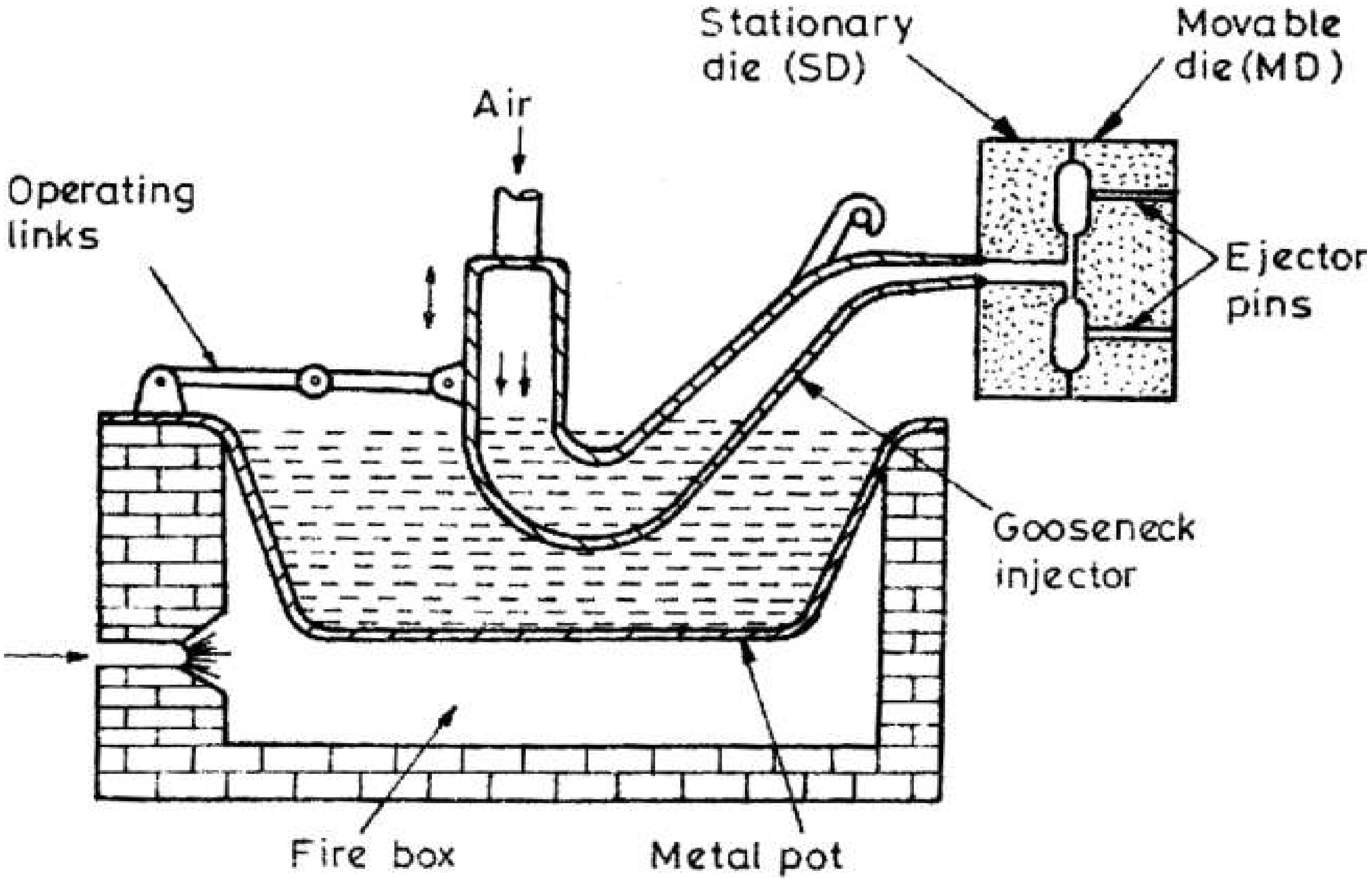
- Holding the two halves of the die together.
- Closing the die.
- Injecting molten metal into the die.
- Opening the die.
- Ejecting the casting out of the die.

A Die Casting Machine consist of four basic elements namely:

1. Frame
2. Source of Molten Metal
3. Die Casting Die
4. Metal Injecting Mechanism

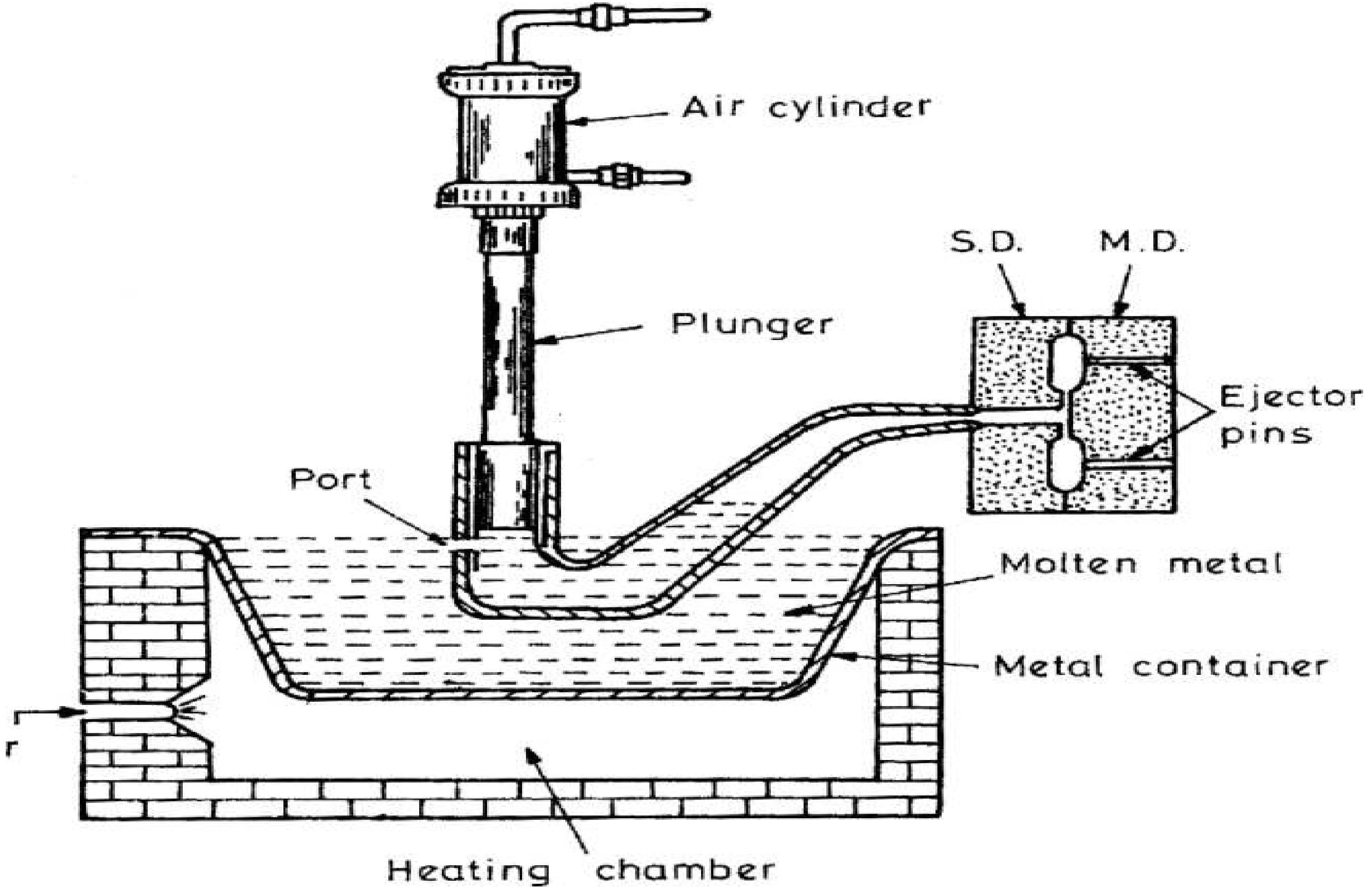
- Two general types of molten metal injection mechanisms for die castings or two main types of machines used for producing Die castings are :-
  1. Hot Chamber Die casting
     a) Goose Neck or Air Injection Type
     b) Submerged Plunger Type
  2. Cold Chamber Die casting

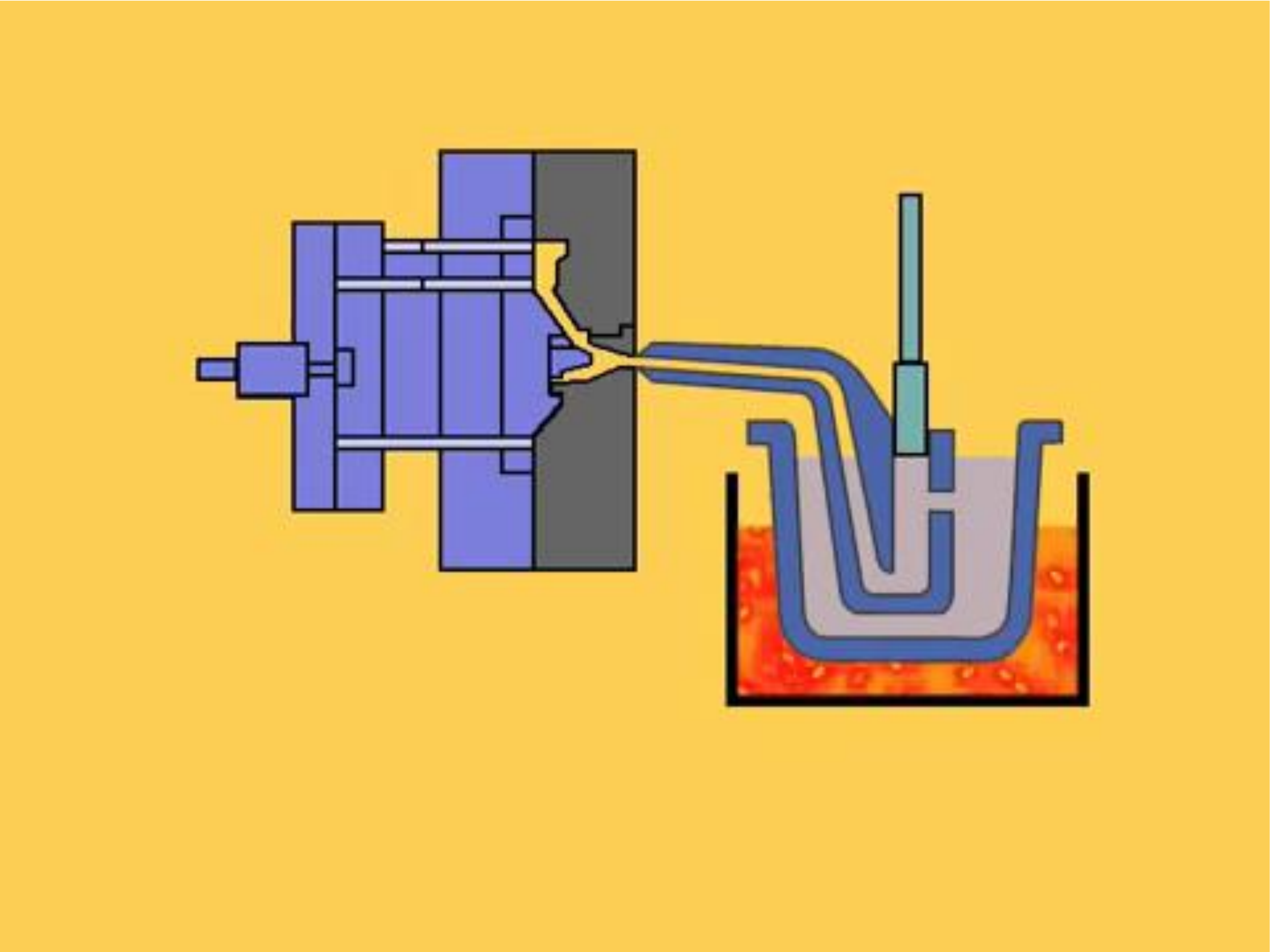
GOOSE NECK OR AIR INJECTION TYPE

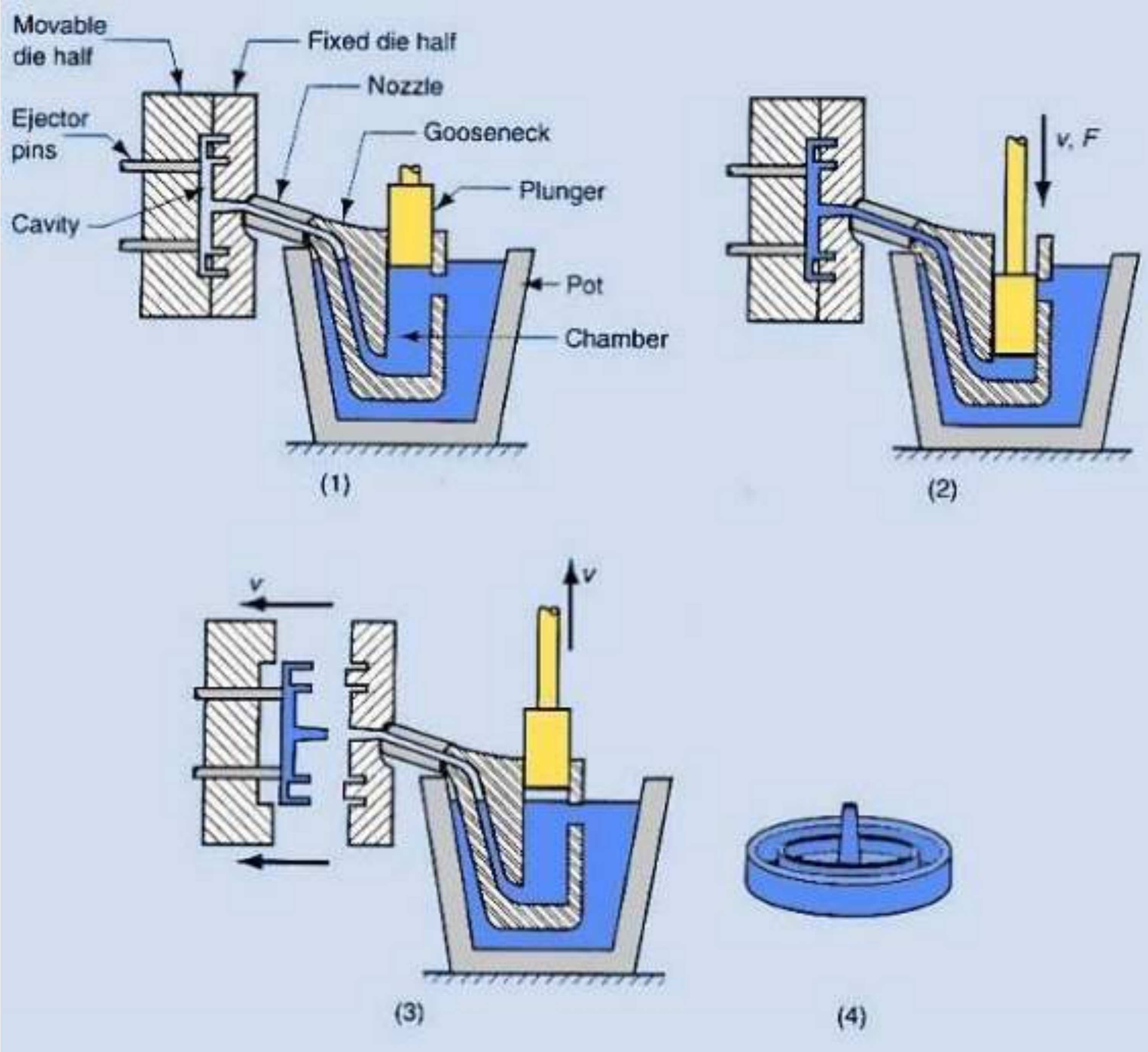


- The Cast Iron Goose Neck is pivoted so that it can be dipped in the molten metal to collect the molten metal when needed.
- Molten metal fills the cylindrical portion and the curved passageways of the gooseneck.
- Gooseneck is then raised and connected to an air line which supplies air to force the molten metal into the closed die.
- Air pressure is of the order of **30 to 45kg/cm^2**.
- The pressure is maintained until the metal has completely solidified in the mould
- When the metal has solidified, die is opened and the casting is ejected.
- Advantage: Simple, no plunger.
- Disadvantage: Production rate low, low pressure exerted on the molten metal.

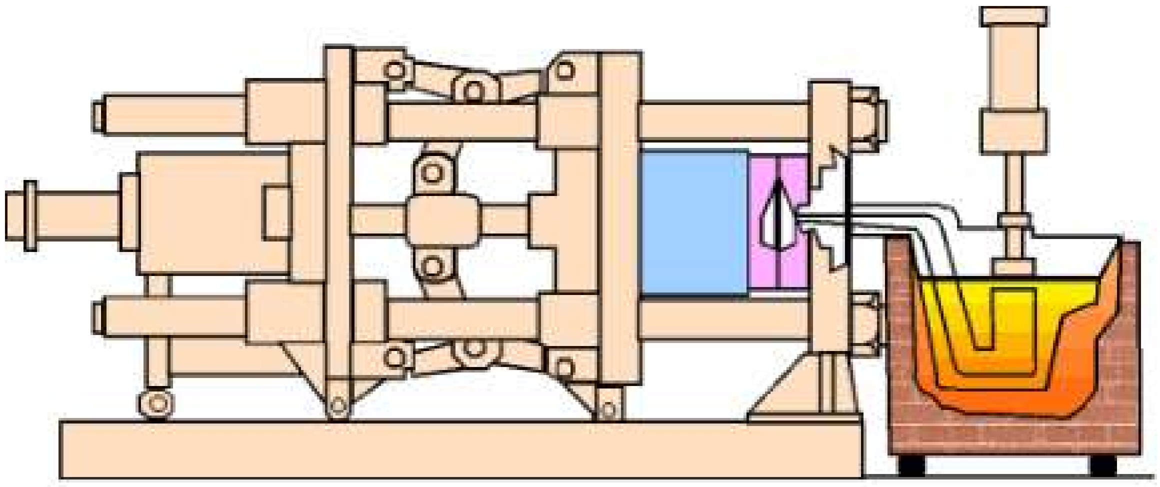
SUBMERGED PLUNGER TYPE



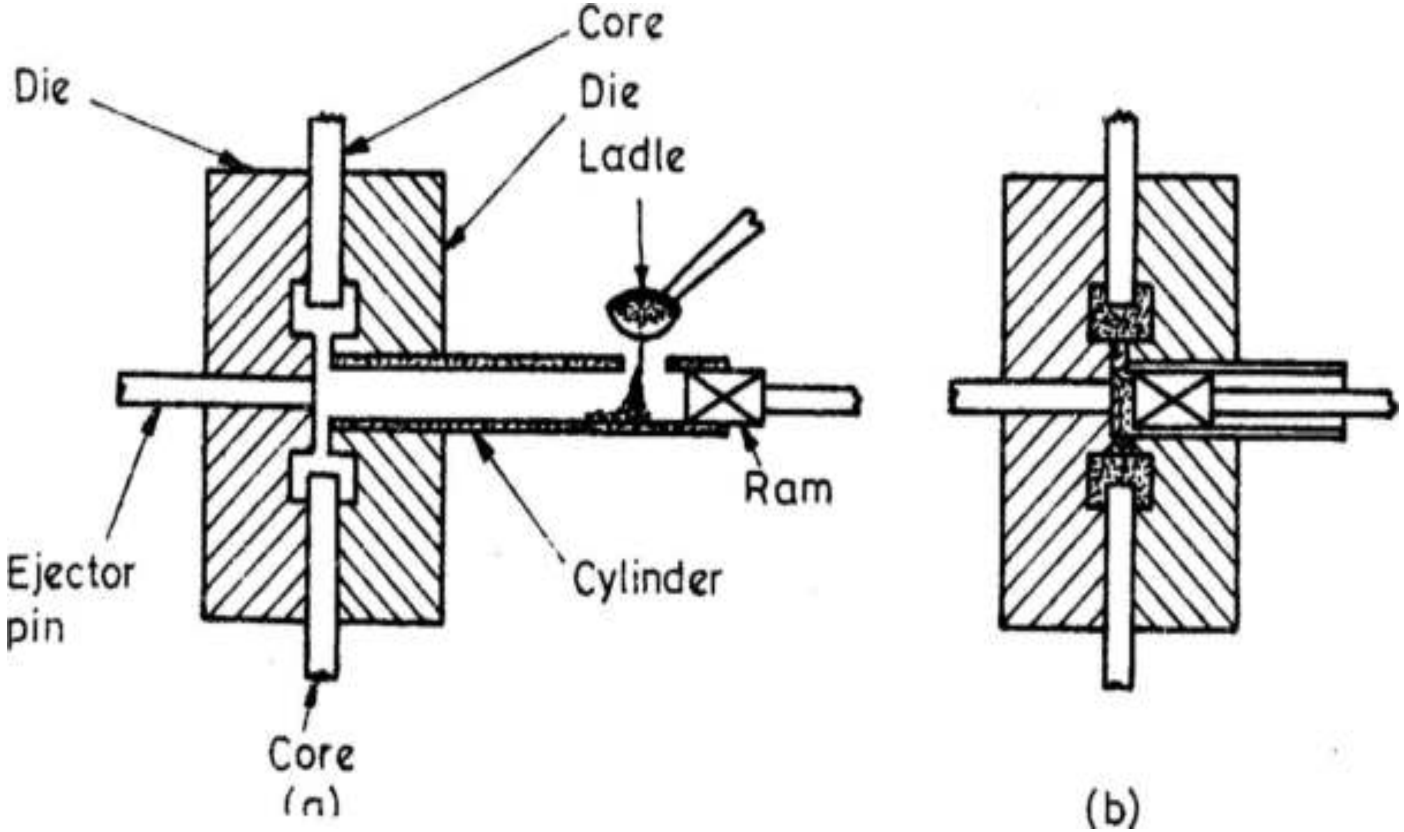


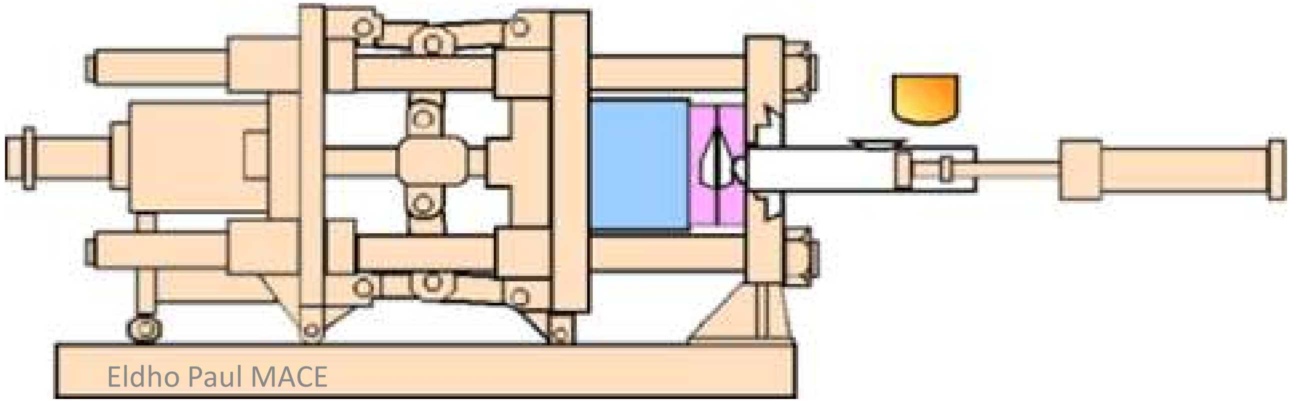

Movable die half
Fixed die half
Nozzle
Ejector pins
Gooseneck
Plunger
Cavity
Pot
Chamber
(1)
v, F
(2)
v
v
(3)
(4)

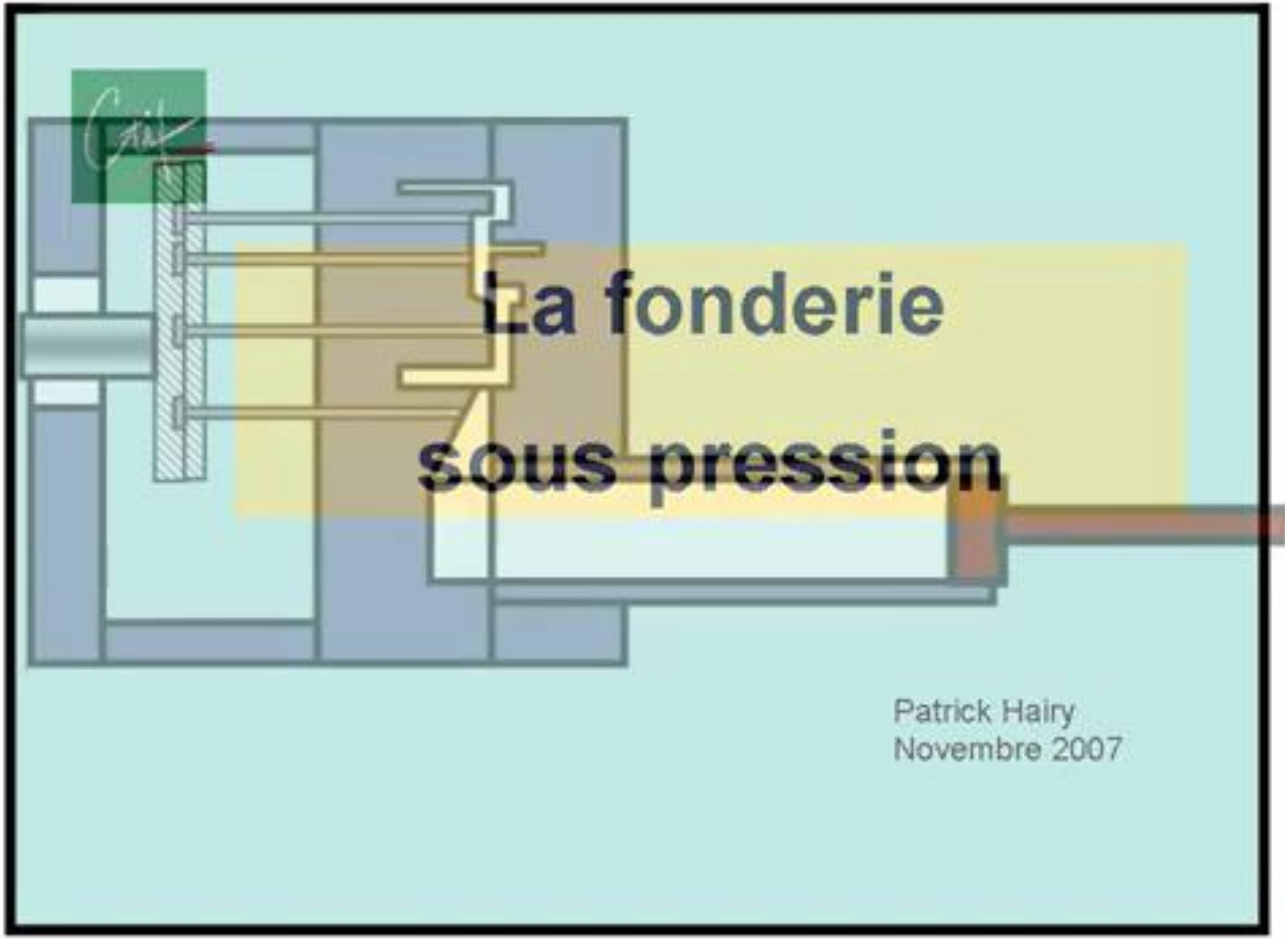
- Consists of an injection cylinder which is partially submerged in the pot containing molten metal.
- When the plunger is in the up position, it clears the port in the cylinder and through it the molten metal fills the cylinder.
- As the plunger moves down, the molten metal is forced through the nozzle into the die.
- Pressure exerted on the molten metal is of the order **140 to 200 kg/cm^2**.
- When the metal has solidified, die is opened and the casting is ejected.



COLD CHAMBER DIE CASTING






La fonderie
sous pression
Patrick Hairy
Novembre 2007

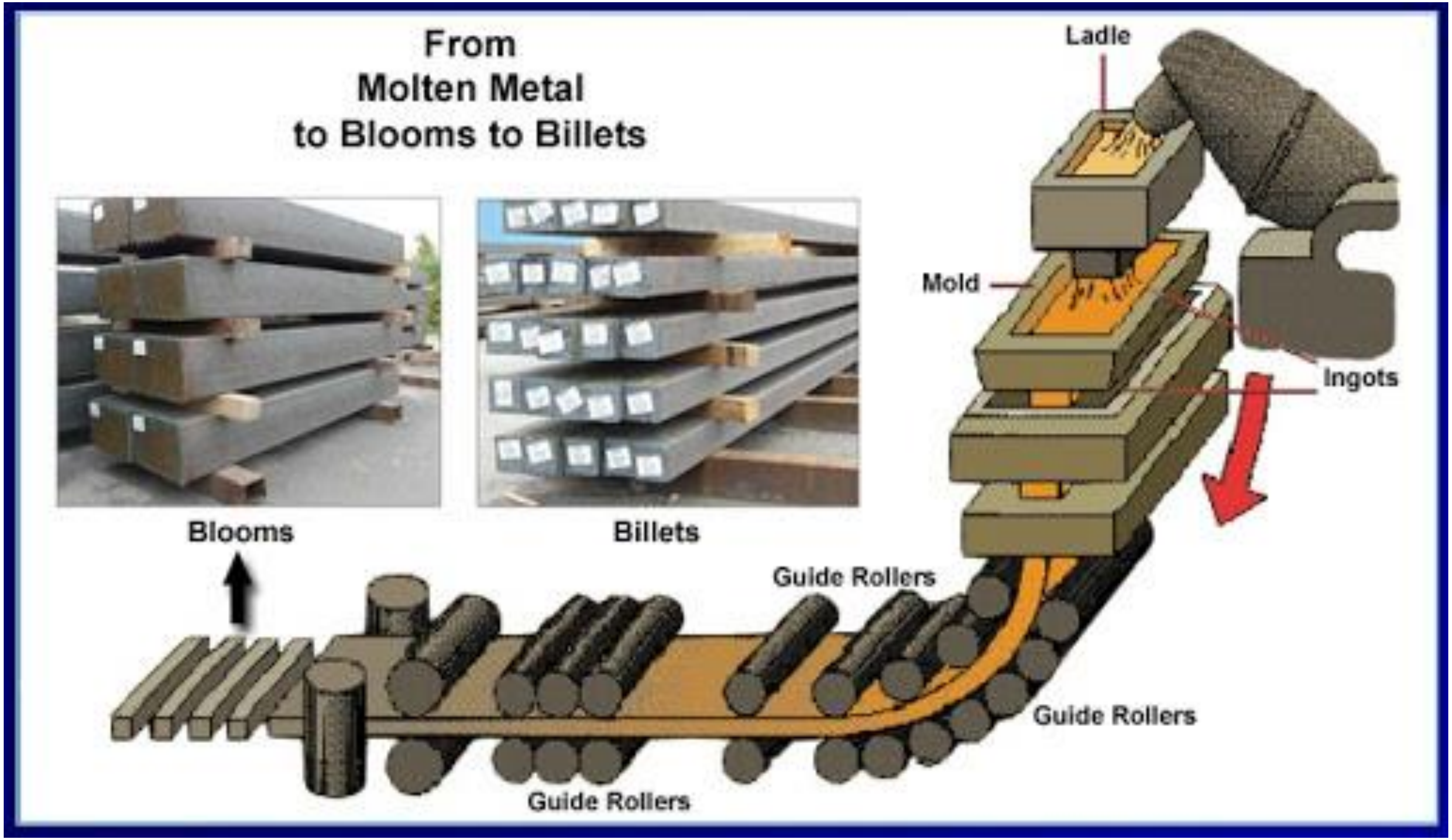
- Consists of a pressure chamber of cylindrical shape (injection cylinder) fitted with a ram or piston usually operated by hydraulic pressure.
- Injection cylinder is not heated hence the name cold chamber casting
- Molten metal (low temperature when compared to hot chamber die casting) is brought in a ladle(serving spoon) and poured into the cold chamber after that the die is closed.
- Ram forces the molten metal into the die.
- The pressure exerted is of the order **20 to 70 MPa.**
- When the molten metal is solidified, the casting is ejected out.
- Advantage: Castings have high dimensional accuracy and greater density.
- Disadvantage: Dies should be made stronger.

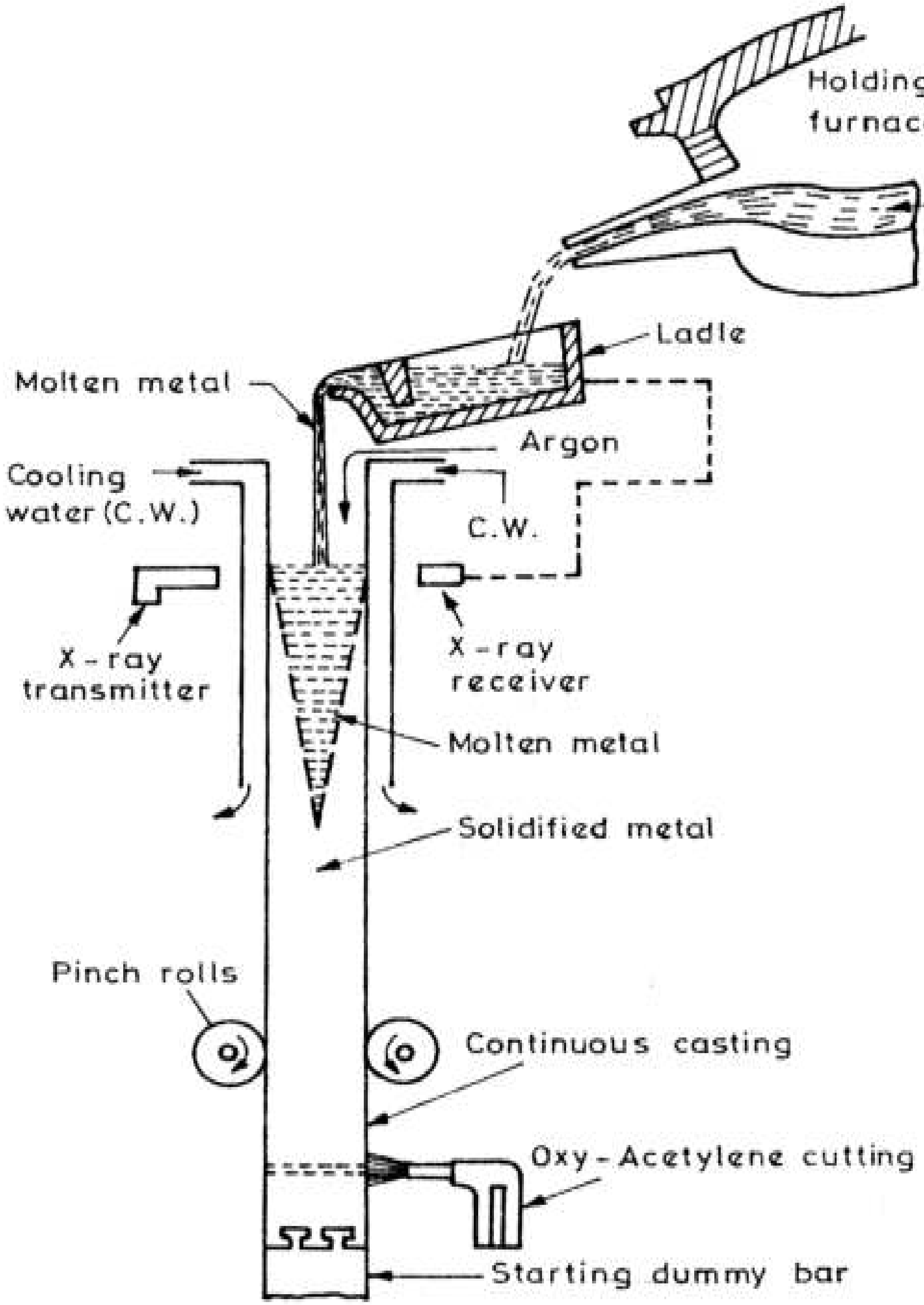
Die Casting Applications:

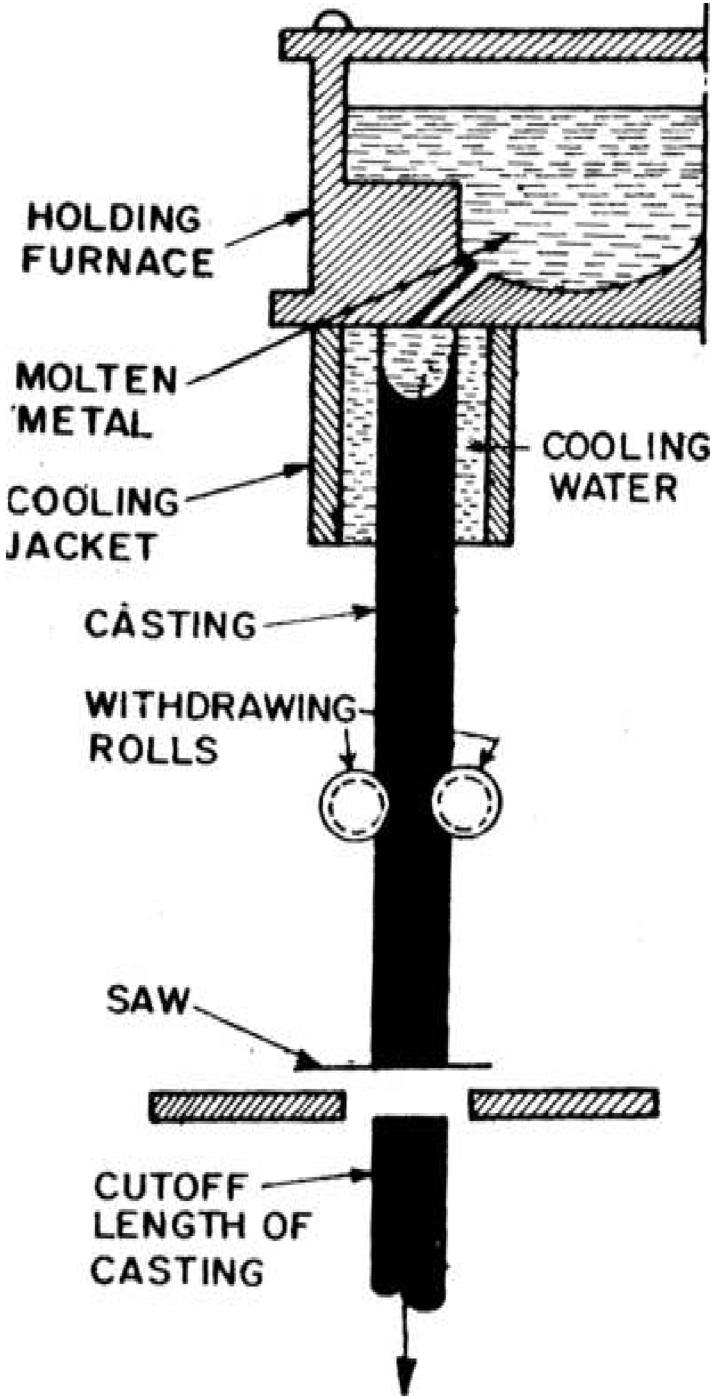
- Die casting is most suitable for casting medium sized parts with complex details.
- Die-casting is the largest casting technique that is used to manufacture consumer, commercial and industrial products like automobiles, toys, parts of sink faucet, connector housing, gears, etc.
- Most die castings are done from non-ferrous metals like aluminum, magnesium, etc.

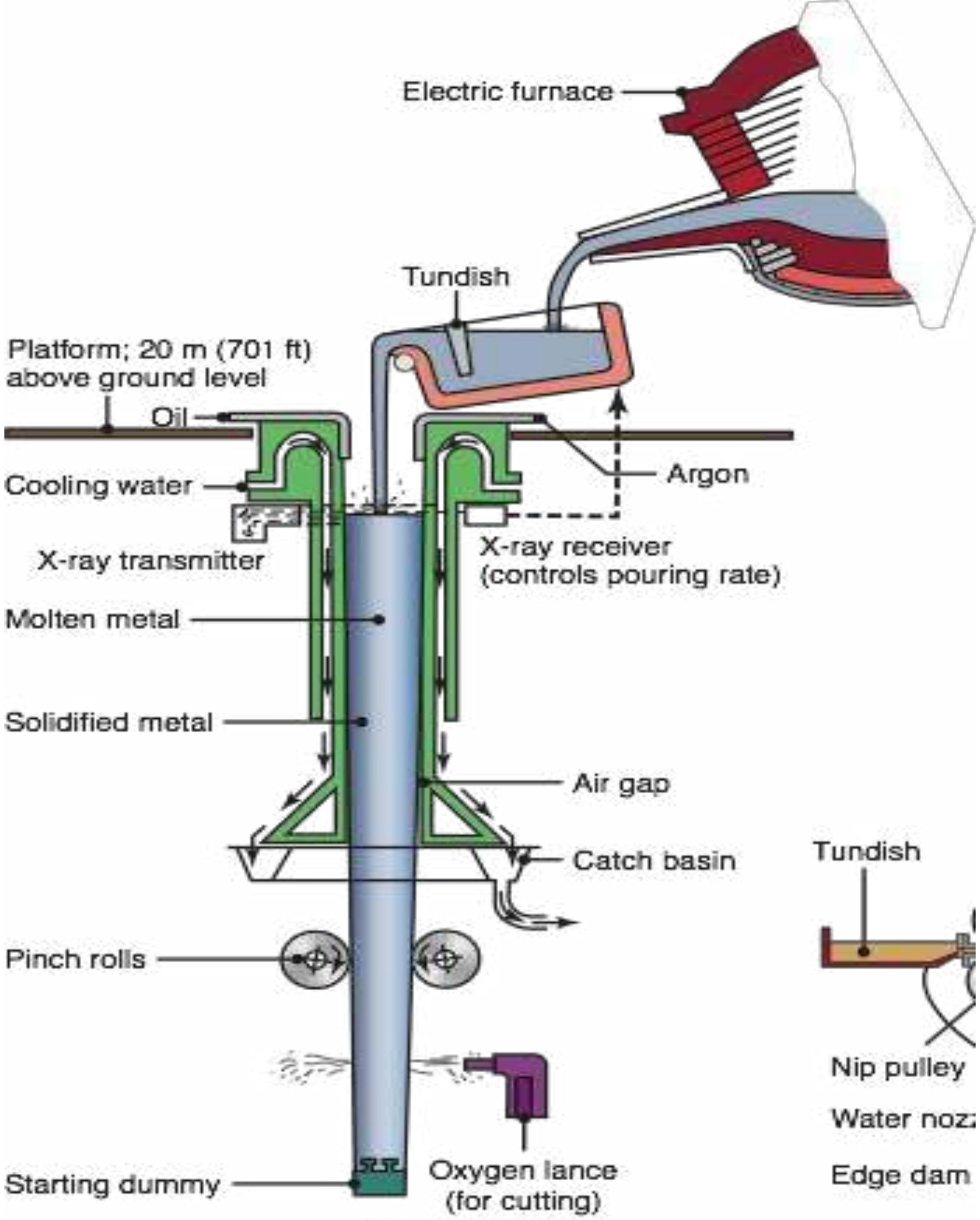
6.CONTINUOUS CASTING

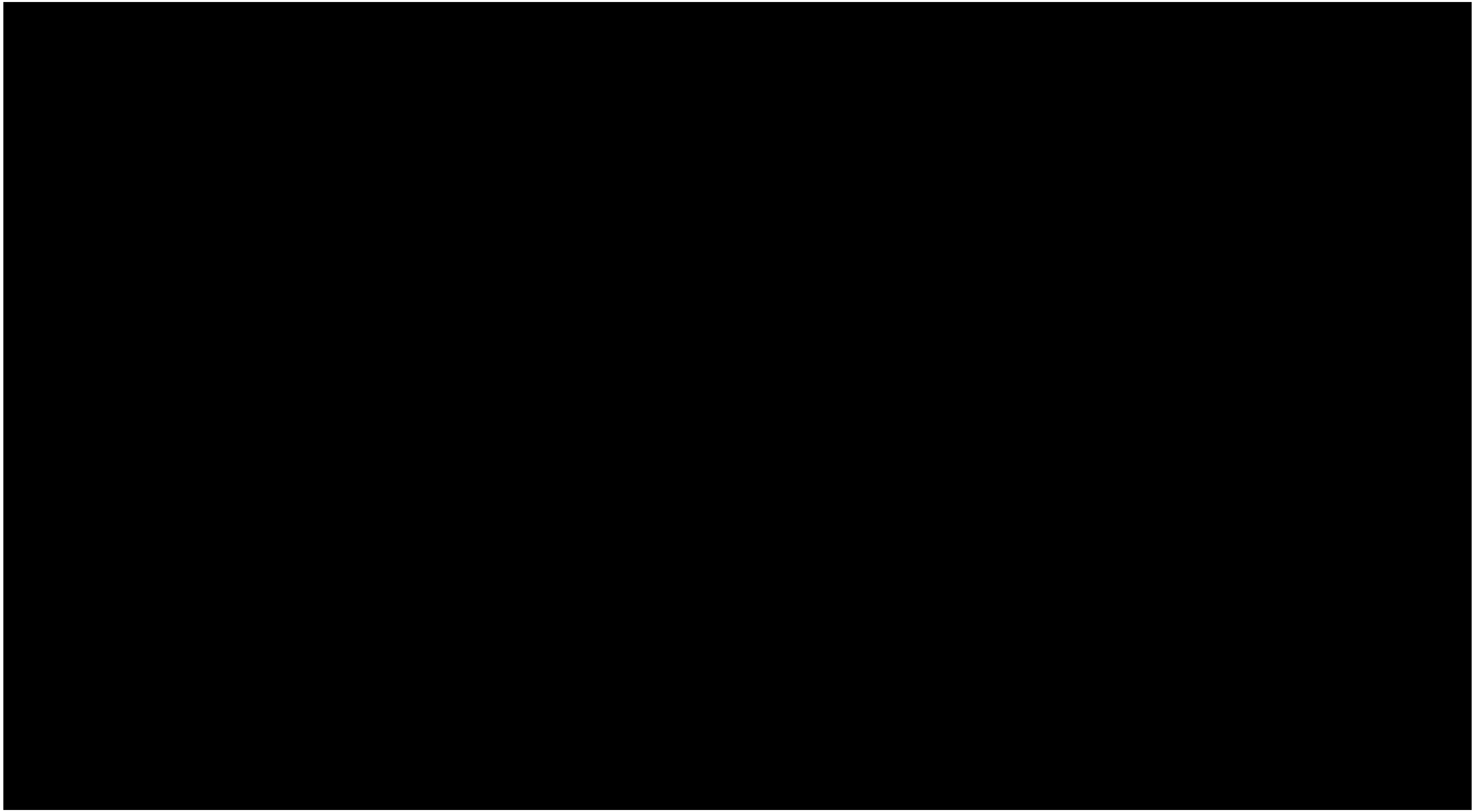
- Round ingots, slabs, square billets and sheets can be cast Continuous process directly from the molten metal.
- Continuous replaces the casting of ingots. Ingot is produced by pouring molten metal into different molds. Ingot is allowed to cool to remove the mold. Ingot is then reheated and put between the rolls. Ingots are then machined and used for fabrication.
- Continuous process eliminates the various stages involved in the production of ingots.


From
Molten Metal
to Blooms to Billets
Ladle
Mold
Ingots
Blooms
Billets
Guide Rollers
Guide Rollers
Guide Rollers


Holding furnace
Molter metal
Ladle
Molten metal
Argon
Cooling water (C.W.)
C.W.
X - ray transmitter
X - ray receiver
Molten metal
Solidified metal
Pinch rolls
Continuous casting
Oxy - Acetylene cutting
Starting dummy bar


HOLDING FURNACE
MOLTEN METAL
COOLING WATER
COOLING JACKET
CASTING
WITHDRAWING ROLLS
SAW
CUTOFF LENGTH OF CASTING


Electric furnace
Tundish
Platform; 20 m (701 ft) above ground level
Oil
Argon
Cooling water
X-ray transmitter
X-ray receiver (controls pouring rate)
Molten metal
Solidified metal
Air gap
Catch basin
Tundish
Pinch rolls
Nip pulley
Water noz
Edge dam
Oxygen lance (for cutting)
Starting dummy
(a)



STEPS INVOLVED IN CONTINUOUS CASTING

- Molten metal is transferred from the furnace into a special ladle called a **TUNDISH**.
- Molten metal is then poured into a bottom less mould of desired shape, which is cooled by water.
- Due to the cooling water supply, molten metal get cooled and starts to shrink. (***The shrinking effect provides a small gap between the mould and the metal, helping the cast shape to be removed continuously from the mould.)***
- Metal is pulled using **Pinch Rolls**.
- Metal passing out of the **Pinch Rolls** is then cut to desired length by a saw or Oxyacetylene Torch.

- Argon provides an inert free atmosphere to avoid the contamination of the molten metal.
- X-Ray unit control the pouring of molten metal from the ladle.
- Al and Cu are continuously cast.

- **Advantages**
- Cheaper than rolling from ingots.
- Surfaces are better than got from ingots.
- Improved quality.

Applications

- Production of billets, slabs and sheets.
- Brass, Copper and its alloys, Aluminum Alloys, Magnesium, carbon and alloy steels may be cast using this technique.

APPLICATION OF CONTINUOUS CASTING

- A great tonnage of continuous casting is done using cast steel.
- Other metals that are continuous casting are copper, aluminum, grey cast iron s, white cast irons, aluminum bronzes, oxygen-free copper, etc.
- Metals are cast as ingot for rolling, extrusion, or forging, and long shapes of simple cross section are cast as round, square, hexagonal rods, etc.


CONTINUOUS CASTING MACHINE

QUALITY CONTROL OF CASTING

- Casting Inspection provides the necessary information for Quality Control of Castings.
- Quality Control is aimed at producing castings which meet the specifications and reduce the Inspection needed.
- For economic production of castings Quality Control should be carried out in various stages of Casting such as
  - Pattern Making,
  - Mold Making,
  - Melting,
  - Metal pouring
  - Heat Treatment,
  - Fettling etc.

CASTING DEFECTS

Text Book reference: Peter Beeley, Foundry Technology, Butterworth-Heinemann

- Imperfections in the castings is called as Defects or Flaws in castings.
- The following are the major defects which are likely to occur in sand castings:

  (i) Gas defects

  (ii) Shrinkage cavities

  (iii) Moulding material defects

  (iv) Shaping faults arising in pouring

  (v) Inclusions and sand defects

  (vi) Contraction defects

  (vii) Dimensional errors

  (vii) Compositional errors and segregation

1. Gas Defects

- All these defects are caused to a great extent by the lower gas passing tendency of the mould which may be due to lower venting, lower permeability of the mould and/or improper design of the casting.
- The lower permeability of the mould is, in turn caused by finer grain size of the sand, higher clay, higher moisture, or by excessive ramming of the moulds.

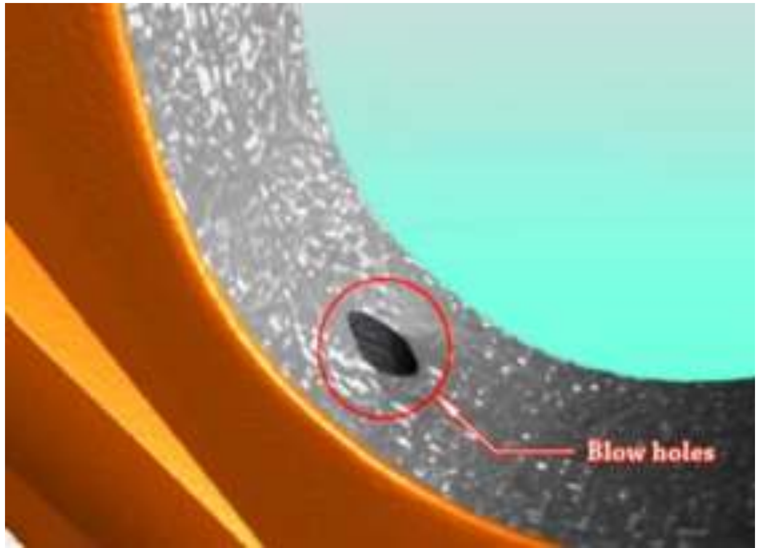
- The defects in this category can be classified into,

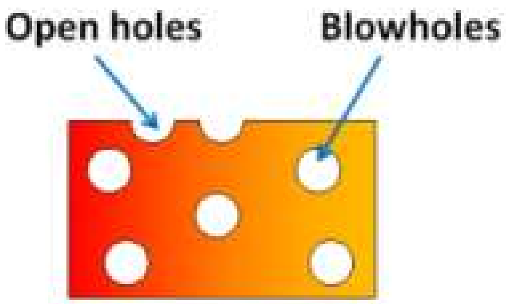
  1. Blow holes and open blows
  2. Air inclusions
  3. Pin hole porosity

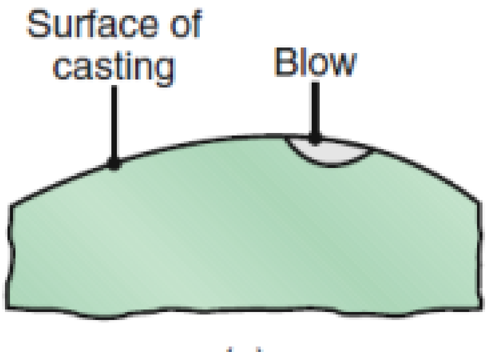
1. Blow holes and open blows

- These are the spherical, flattened or elongated cavities present inside the casting or on the surface.
- On the surface they are called open blows and inside, they are called blow holes. These are caused by the moisture left in the mould and the core.
- Because of the heat in the molten metal, the moisture is converted into steam, part of which when entrapped in the casting ends up as blow hole or ends up as open blow when it reaches the surface.

- Causes : Excess moisture, less permeability of sand , insufficient venting practice. fine sand grains, higher amount of binder or over ramming of the mould. etc.

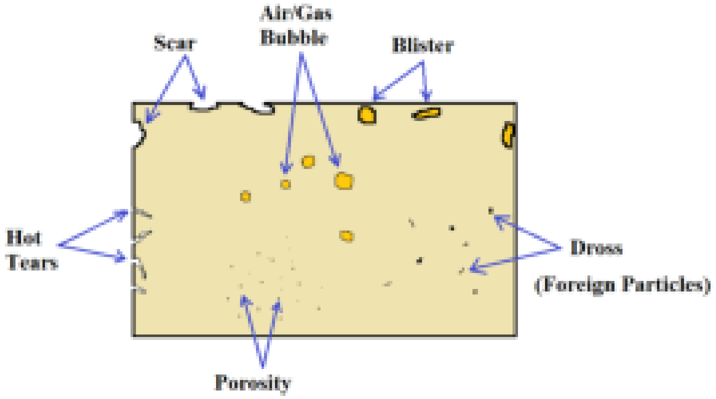






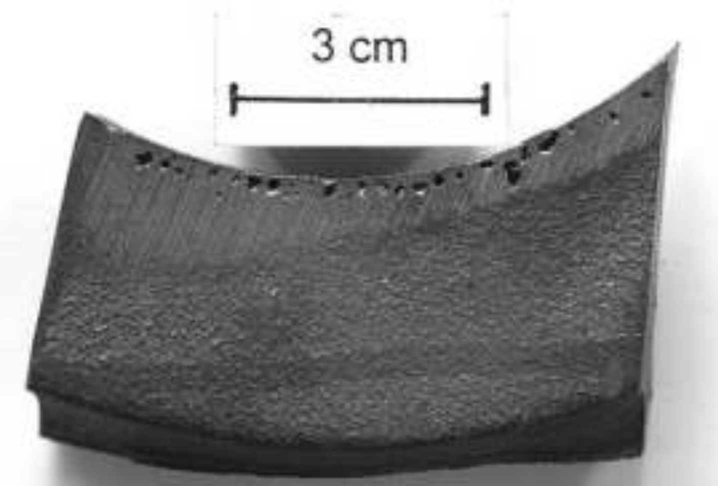
2. Air inclusions

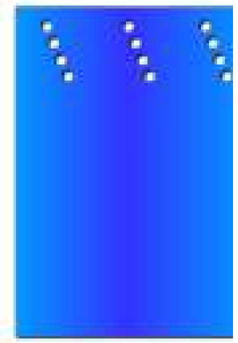
- The atmospheric and other gases absorbed by the molten metal in the furnace, in the ladle, and during the flow in the mould, when not allowed to escape, would be trapped inside the casting and weaken it.
- The main reasons for this defect are:
  - The higher pouring temperatures, which increase the amount of gas absorbed,Poor gating design such as straight sprues in unpressurised gating, abrupt bends and other turbulence causing practices in the gating and increasing the air aspiration and finally the low permeability of the mould itself.
- The remedies would be to choose the appropriate pouring temperature and improve gating practices by reducing the turbulence.



3. Pin hole porosity

- This is caused by hydrogen in the molten metal. This could have been picked up in the furnace or by the dissociation of water inside the mould cavity. As the molten metal gets solidified, it loses the temperature which decreases the solubility of gases and there by expelling the dissolved gases.
- The hydrogen while leaving the solidifying metal would cause very small diameter and long pin holes showing the path of escape. These series of pin holes cause leakage of fluids under high operating pressures.
- The main reason for this is the high pouring temperature which increases the gas pick up. This is particularly severe in aluminium alloys or steels and irons having aluminium.

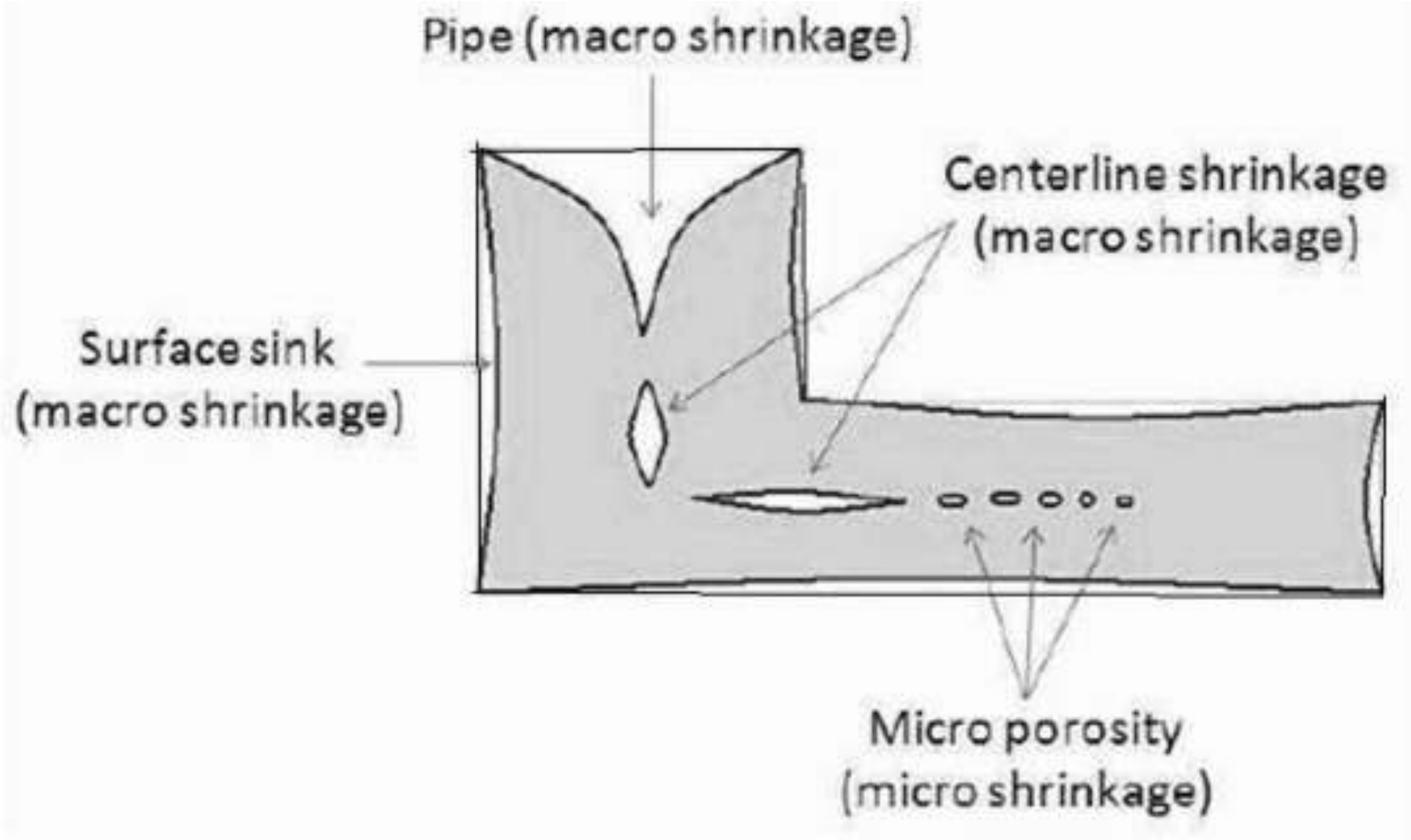




Pinholes

2. Shrinkage cavities

- These are caused by the liquid shrinkage occurring during the solidification of the casting.
- To compensate this, proper feeding of liquid metal is required as also proper casting design.



3. Moulding Material Defects

- Under this category are those defects which are caused because of the characteristics of the moulding materials.
- The defects that can be put in this category are:
  - Cuts and washes
  - Metal penetration
  - Fusion
  - Run out
  - Rat tails and buckles
  - Swell
  - Drop
- These defects occur essentially because the moulding materials are not of requisite properties or due to improper ramming.

1. Cuts and washes

These appear as rough spots and areas of excess metal, and are caused by the erosion of moulding sand by the flowing molten metal. This may be caused by the moulding sand not having enough strength or the molten metal flowing at high velocity. The former can be remedied by proper choice of moulding sand and using ap propriate moulding method. The latter can be taken care of by altering the gating design to reduce the turbulence in the metal, by increasing the size of gates or by using multiple in-gates.

2. Metal penetration

When the molten metal enters the gaps between the sand grains, the result would be a rough casting surface. The main reason for this is that, either the grain size of the sand is too coarse or no mould wash has been applied to the mould cavity. This can also be caused by higher pouring temperatures. Choosing appropriate grain size, together with a proper mould wash should be able to eliminate this defect.

3. Fusion

This is caused by the fusion of sand grains with the molten metal, giving a brittle, glassy appearance on the casting surface. The main reason for this defect is that the clay in the moulding sand is of lower refractoriness or that the pouring temperature is too high. The choice of an appropriate type and amount of bentonite would cure this defect.

4. Run out

A run out is caused when the molten metal leaks out of the mould. This may be caused either due to faulty mould making or because of the faulty moulding flask.

5. Rat tails and buckles

Rat tail is caused by the compression failure of the skin of the mould cavity because of the excessive heat in the molten metal. Under the influence of the heat, the sand expands, thereby moving the mould wall backwards and in the process when the wall gives away, the casting surface may have this marked as a small line. With a number of such failures, the casting surface may have a number of criss crossing small lines. Buckles are the rat tails which are severe.

- The main cause for these defects are: the moulding sand has got poor expansion properties and hot strength or the heat in the pouring metal is too high.

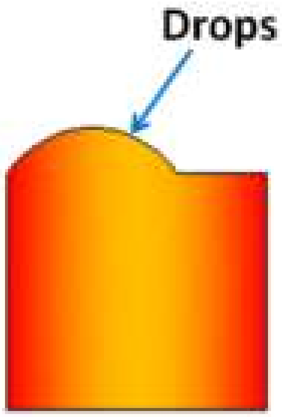
6. Swell

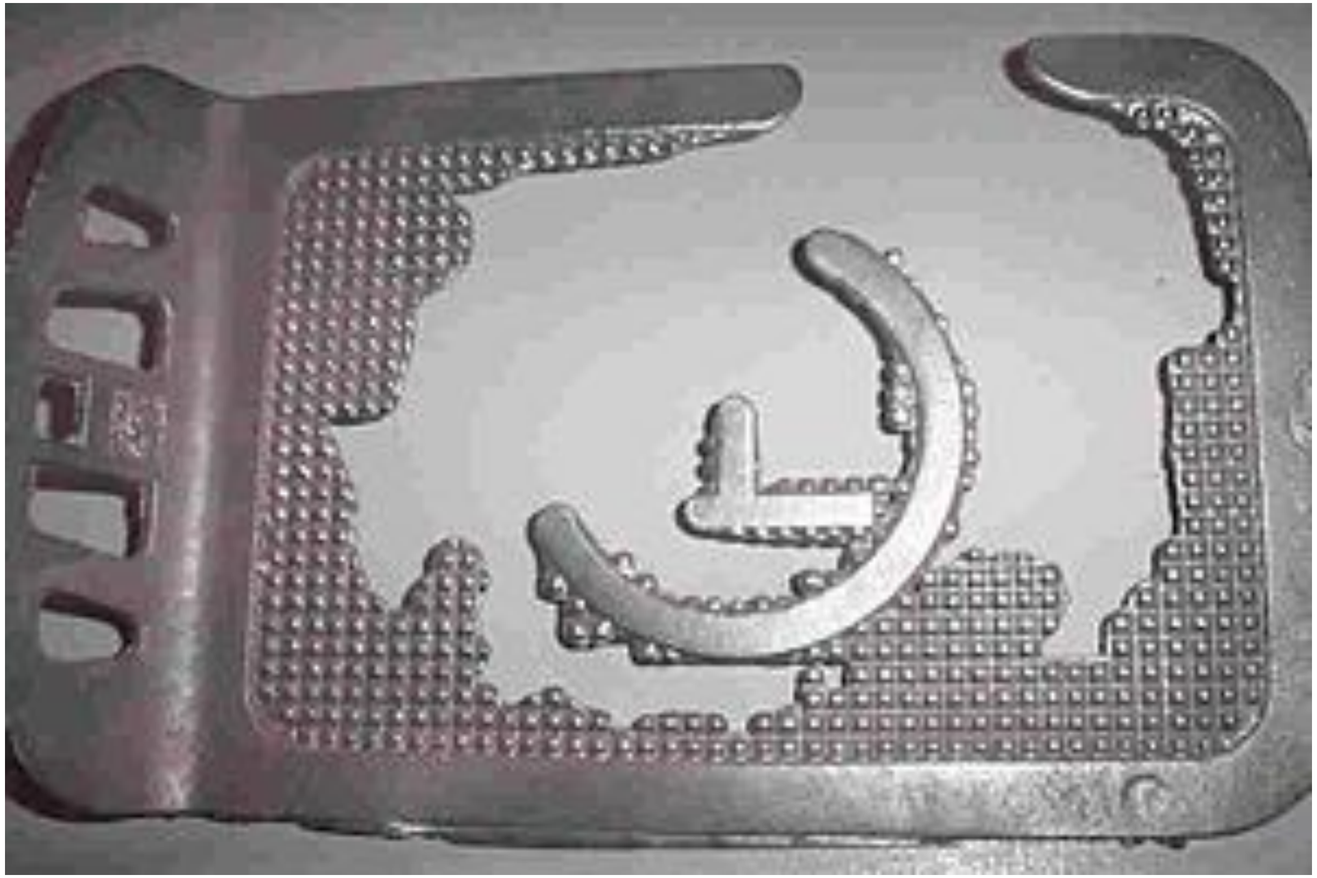
Under the influence of the metallostatic forces, the mould wall may move back causing a swell in the dimensions of the casting. As a result of the swell, the feeding requirements of castings increase which should be taken care of by the proper choice of risering. The main cause of this is the faulty mould making procedure adopted. A proper ramming of the mould should correct this defect

7. Drop

- The dropping of loose moulding sand or lumps normally from the cope surface into the mould cavity is responsible for this defect. This is essentially due to improper ramming of the cope flask.

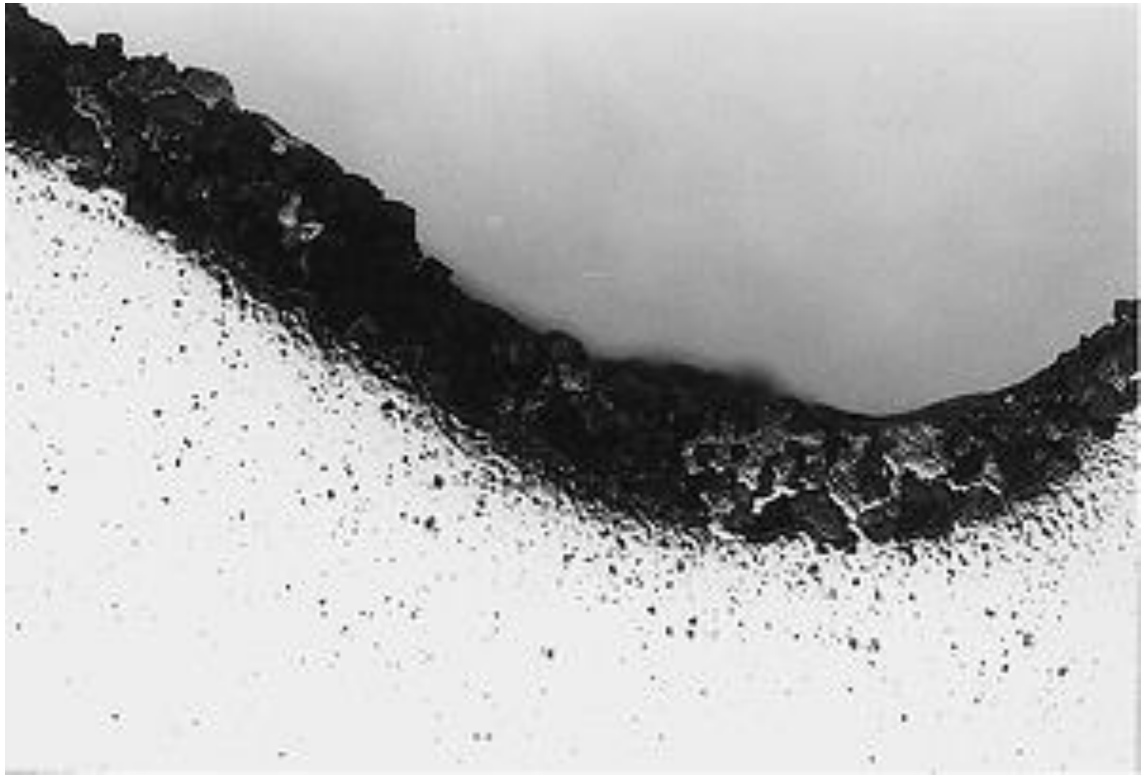
Swell





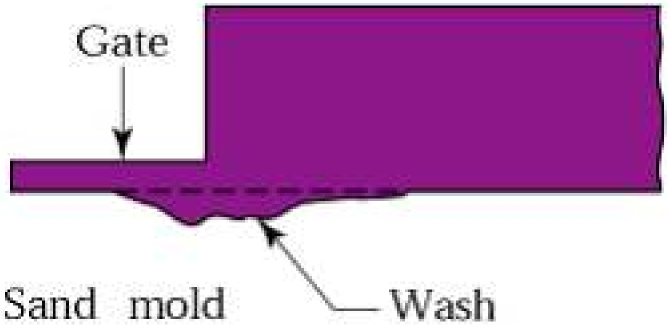
Run out

Rat tails



Metal penetration

Fusion



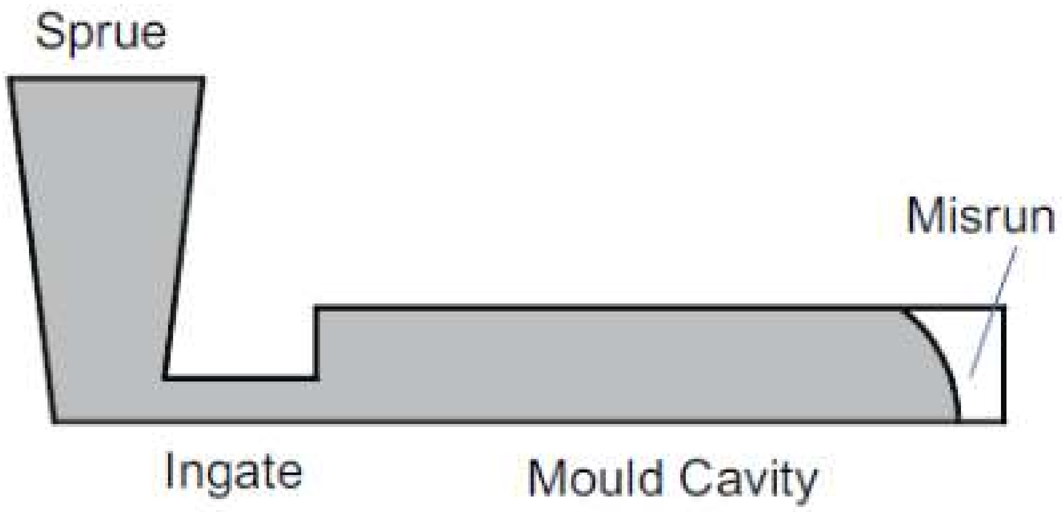
Cuts and washes

4. Shaping faults arising in pouring

- When the liquid metal enters the mould, the first requirement is that it should satisfactorily fill the mould cavity and develop a smooth skin through intimate contact with the mould surface.
- Failure to meet these conditions produce different defects like,
  - Misrun or short run casting
  - Cold laps
  - Cold shuts

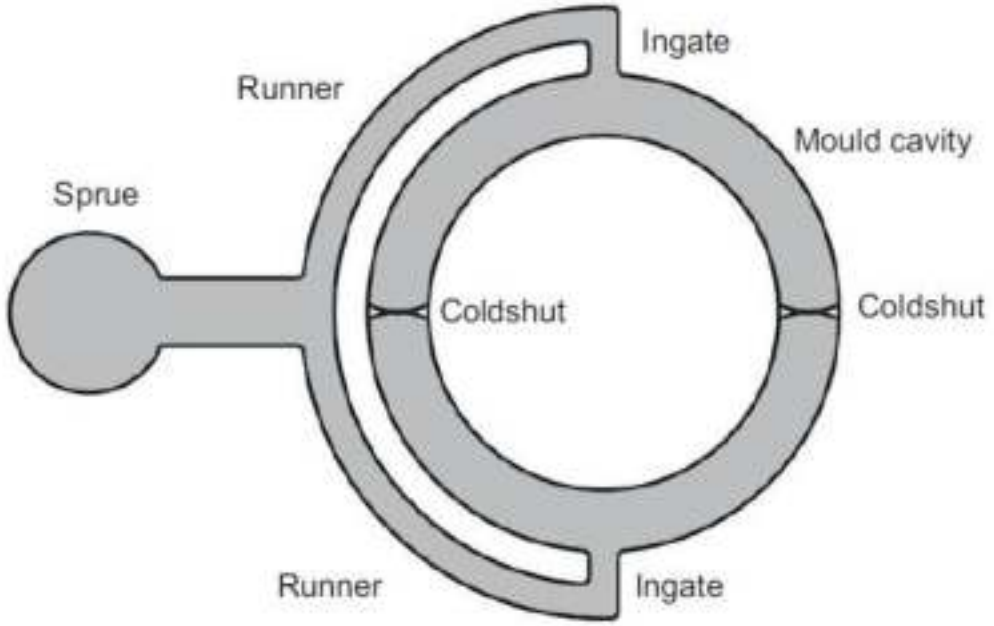
1. Misrun or short run casting

- If the molten metal is too cold or casting section is too thin, entire mold cavity may not be filled during pouring and the result is Misrun.
- Misrun is caused when the metal is unable to fill the mould cavity completely and thus leaving unfilled cavities
- The defect may appear like a crack
- Metal solidifies prematurely and some limb or section of the casting is omitted



2. Cold Shut/lap

- Cold shut is caused when two metal streams, while meeting in the mould cavity, do not fuse together properly thus causing a discontinuity or weak spot in the casting.
- Low temperatures can prevent fusion at the junction
- Crack with a round edge on the casting surface.
- Cold shut is usually a result of a lack of fluidity of the molten metal, or a poor design of the gating system.



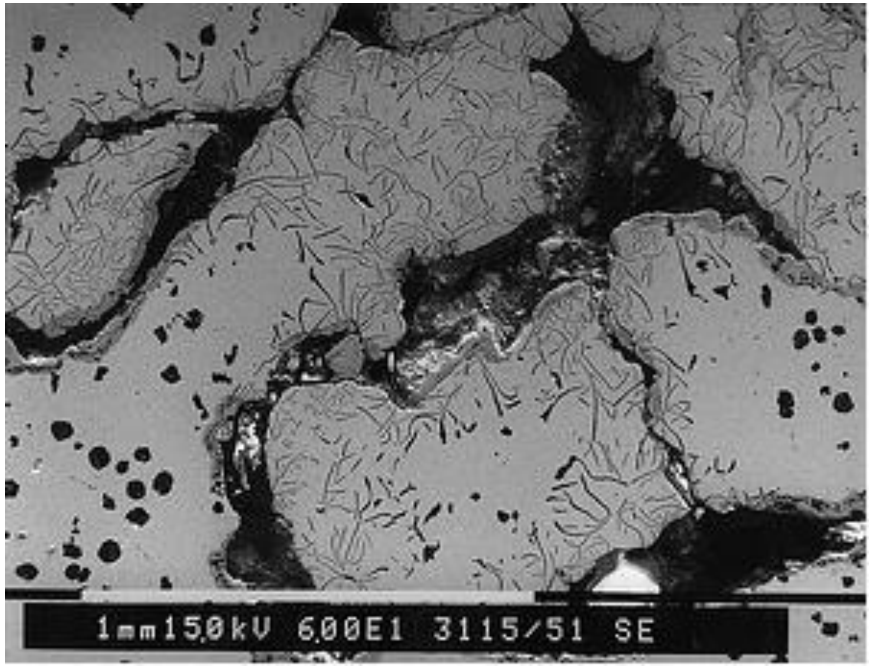
5. Inclusions and sand defects

- Inclusions in castings which result from entrainment of non-metallics during pouring.
  - Dross
  - Slag
  - Flux residues
  - Moulding material/Sand inclusions

- Such inclusions can best be prevented by retention in the furnace and by careful skimming at the pouring stage. Clean and well maintained teapot or bottom pouring ladles give a high degree of protection.
- They are regarded as harmful because they act as stress raisers and thus reduce the strength of the casting.

1. Slag inclusions (scab)

- During the melting process, flux is added to remove the undesirable oxides and impurities present in the metal.
- Slag is the waste material which is removed. Slag is impure residue that contains large amount of calcium, magnesium silicate, iron, aluminium etc derived during the process of pig iron and steel production and during the smelting of metals such as copper, lead and nickel.
- At the time of tapping, the slag should be properly removed from the ladle before pouring the metal into the mould.
- Otherwise any slag entering the mould cavity will weaken the casting and also spoil the surface of the casting. This can be eliminated by some of the slag trapping methods.

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2. Moulding material/Sand inclusions

- Sand inclusions can originate as loose material in the mould cavity, so careful closing is essential.
- Moulding material can also be eroded during pouring, leading either to massive inclusions or to a widespread distribution of separate grains.

6. Contraction defects

- The cooling of cast metal from the solidus to room temperature is accompanied by considerable further contraction.
- Unlike the liquid and solidification shrinkages, which can be compensated by an influx of liquid, solid contraction affects all linear dimensions of the casting, hence the need for standard pattern allowances in accordance with the expected contraction behavior of the alloy.
- Castings never contract completely freely and the metal must develop sufficient cohesive strength to overcome significant resistance.
- Hindrance to contraction may be offered by the mould, by hydrostatic pressure of residual liquid and by other parts of the casting itself due to differential cooling.
- Stresses can thus arise either from external restraint or from thermal conditions alone.

- The individual types of defects associated with contraction are,
  - Hot Tears
  - Cracking, distortion and residual stress

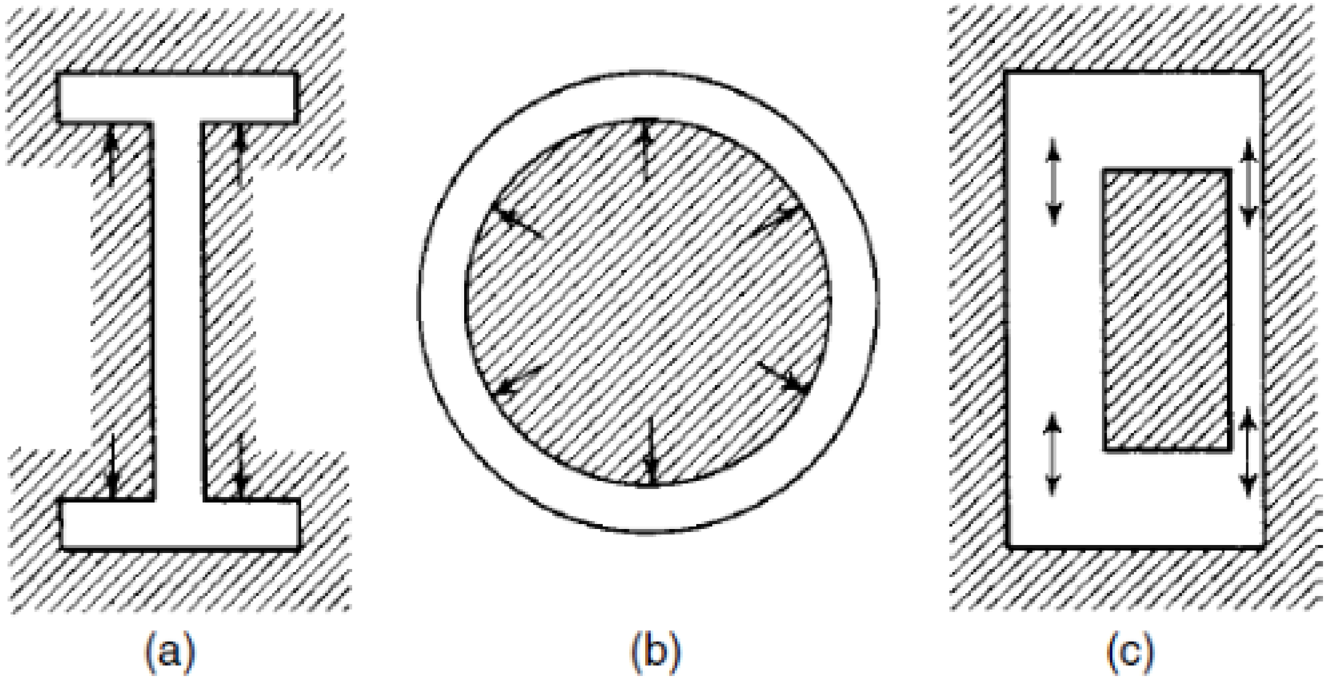
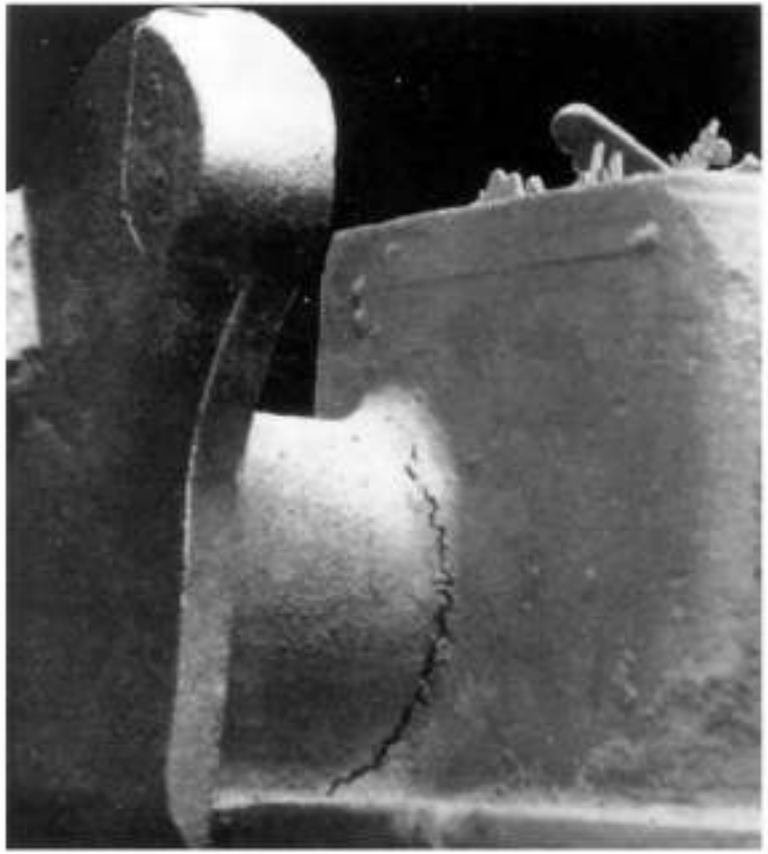


Figure 5.22 Typical design features giving rise to contraction stresses. (a) Mould restraint, (b) core restraint, (c) differential contraction of casting members

1. Hot Tears

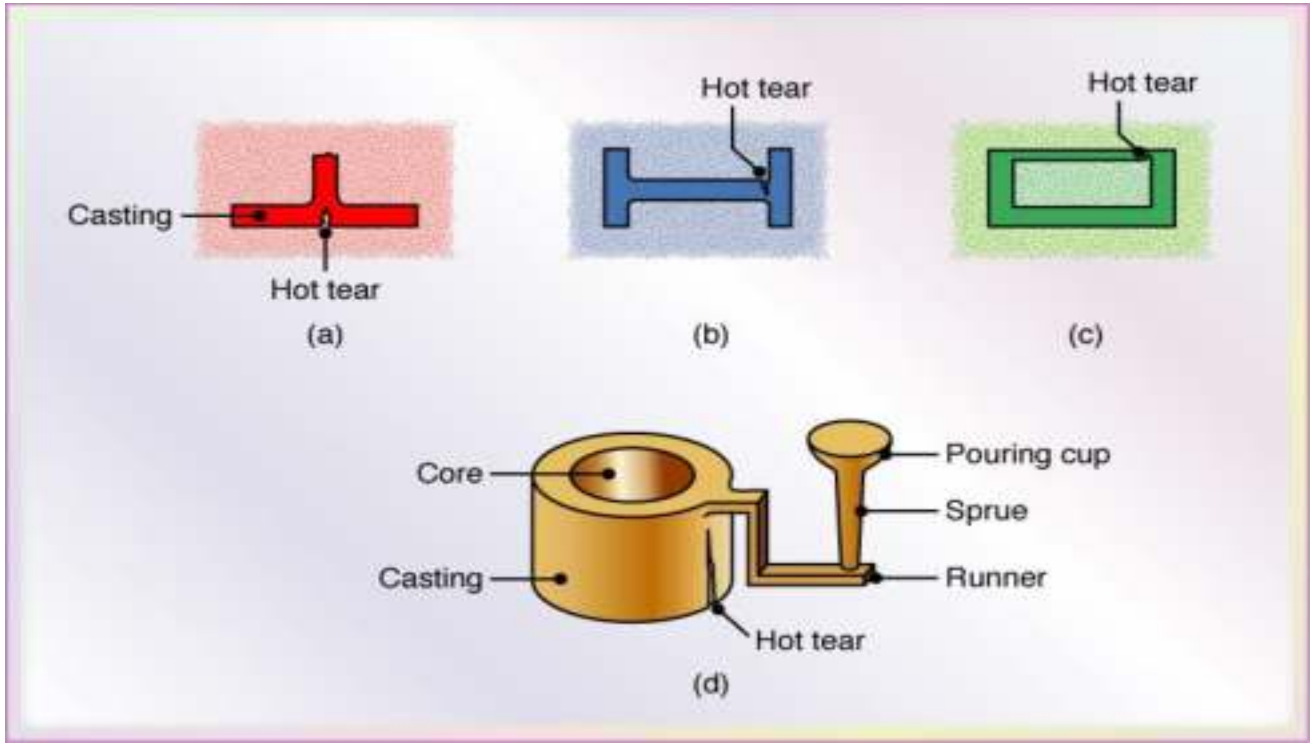
- Hot tears or 'pulls' are characterized by irregular form, partial or complete fracture following an intergranular path.
- Tears are often located at changes in section, where stress concentration is associated with locally delayed cooling.
- Since metal has low strength at higher temperature, any unwanted cooling stress may cause the rupture of the casting.
- The occurrence of hot tears is influenced by three factors, namely alloy composition, the design of the individual casting and foundry technique.



24 Typical hot tear at change of section (courtesy of Edit
s Industries de la Fonderie)

- Susceptibility to tearing is closely associated with the mode of freezing and thus with alloy constitution.
- Design and production conditions influence hot tearing mainly through effects upon temperature distribution and resistance to contraction.
- Temperature distribution and hot spot intensity are influenced by design, by gating technique, and by selection of pouring speed and temperature, all of which can be used to reduce the strain concentration.

Examples of hot tears in castings. These defects occur because the casting cannot shrink freely during cooling, owing to constraints in various portions of the molds and cores. Exothermic (heat-producing) compounds may be used (as exothermic padding) to control cooling at critical sections to avoid hot tearing



2. Cracking, distortion and residual stress

- At lower temperatures through the interaction of members cooling at different rates, residual stress may develop.
- A casting in a state of residual stress exhibits elastic distortion and is dimensionally unstable: its dimensions may change either spontaneously on ageing or if heating occurs in service.

- Very high stresses can be developed, especially where sections are of widely varying thickness. The stresses can exceed the elastic limit of the material in extreme cases. If the alloy has poor ductility, fracture can then occur during the late stages of cooling: the typical cold crack or 'clink'

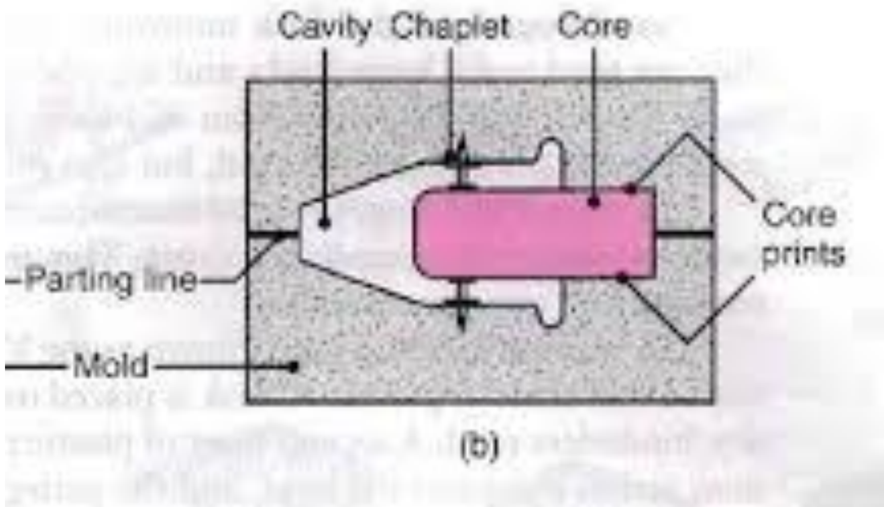
Figure 5.29 Typical cold crack or 'clink' in a casting (from Reference 2) (courtesy of Editions Techniques des Industries de la Fonderie)

6. Dimensional errors

- The dimensions of a casting are subject to variation from minor changes in production conditions within the limits of normal working practice.
- Individual errors may result from specific faults in equipment and practice; such errors, can occur in patternmaking, moulding and casting, or fettling.
- Patternmaking and fettling errors are relatively uncommon and most dimensional faults originate during mould production or in casting. Principal causes are misalignment of mould parts and cores, mould distortion, anomalous contraction and distortion in cooling.
- Major errors are due to,
  - Alignment faults
  - Mould distortion

1. Alignment faults

- Misplaced cores arising mainly from deterioration of pattern equipment and moulding tackle.
- Defects from misplaced or ill fitting cores can be avoided by attention to core print design and clearances



2. Mould distortion

- At the moulding stage the mould cavity can be enlarged by excessive rapping in pattern withdrawal

7. Compositional errors and segregation

- Most compositional errors arise from simple causes, for example melting losses of reactive elements or the use of incorrect furnace charges. Such errors can be avoided by careful melting practice.
- Segregation may occur with respect either to alloying or impurity elements, the final casting being seen either as a compositional gradient in a single phase or as a local concentration of a second phase.
- Constitutional factors which produce a strong segregation tendency are long freezing range, gentle liquidus slope and low solid solubility.
- Segregation occurs in two types of distribution. Compositional differences may be on a microscopic scale, extending over dimensions of the order of a single grain or less, or there may be major zonal segregation between one part of a casting and another; these are referred to as micro and macro segregation respectively.

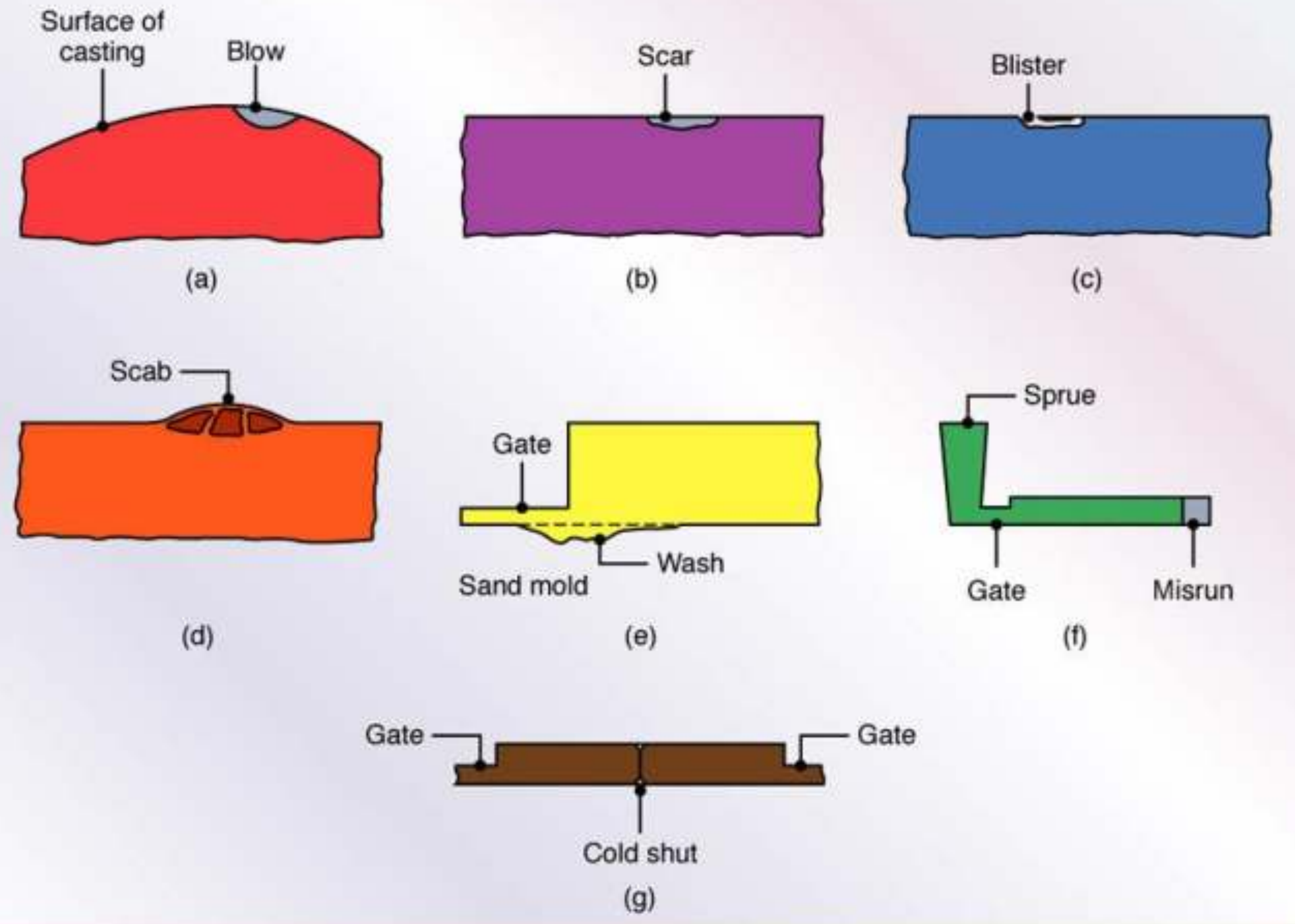
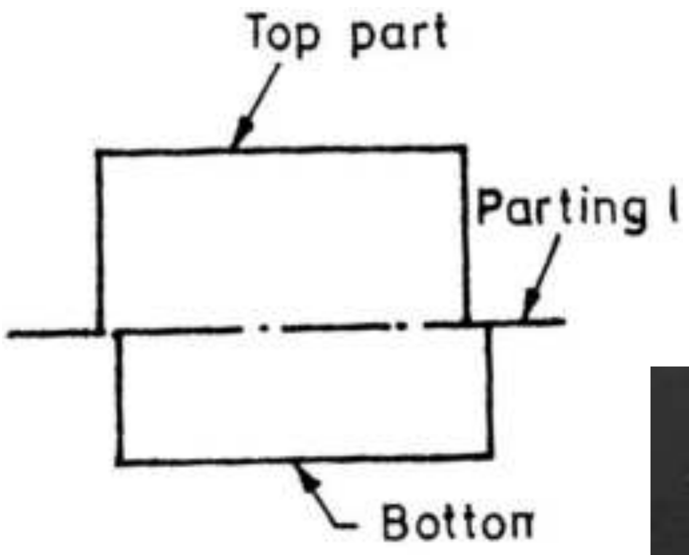


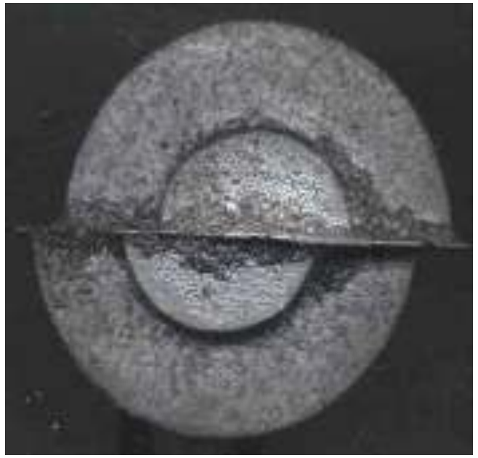
Figure 10.13 Examples of common defects in castings. These defects can be minimized or eliminated by proper design and preparation of molds and control of pouring procedures.

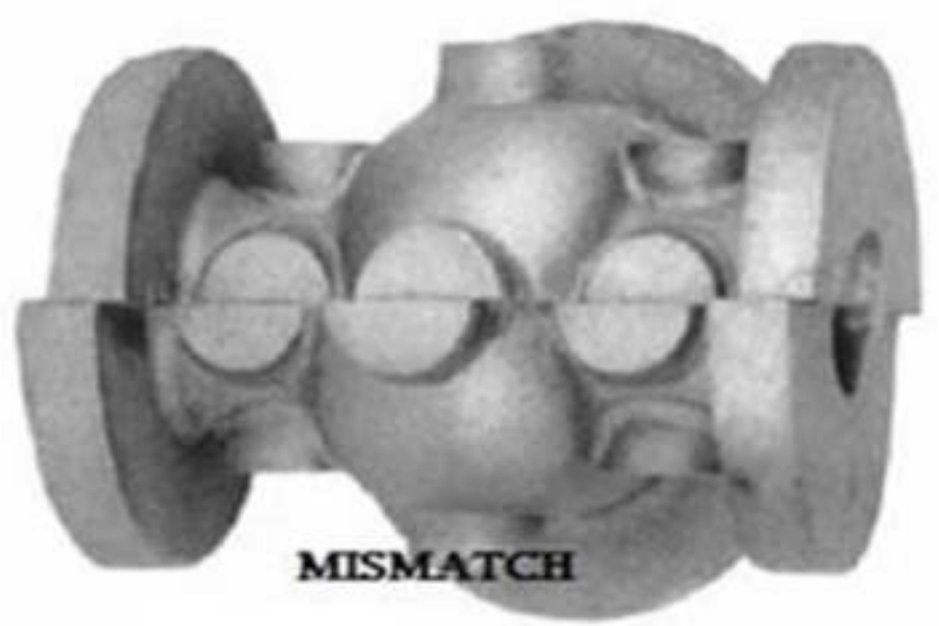
8. CASTING SHAPE DEFECTS

a) **Mismatch or Mold Shift** : Castings does not match at the parting line. There is a mismatch of the top and bottom parts of the casting.

- Causes : Loose Dowels.

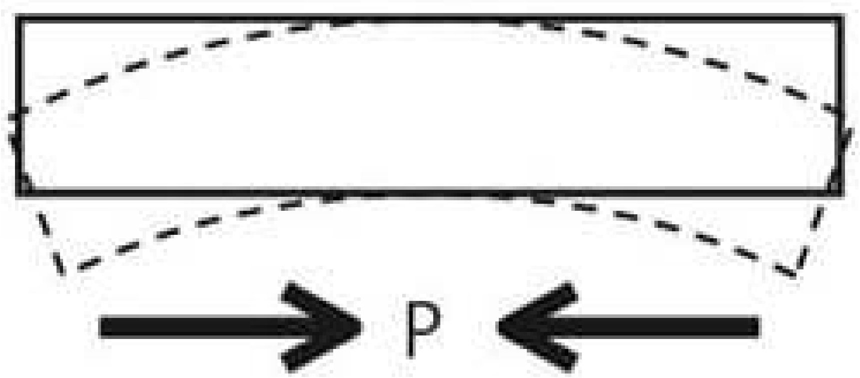






b. Warping

- Warping is an unwanted casting deformity that can occur over time, which results in a change in the dimensions of the final product. It can happen during or after solidification.
- Warping is typically a result of different rates of solidifications of different sections, which causes stress in adjoining walls. Large and flat sections are more prone to warping.
- Normalizing heat treatment can remove residual stress in iron casting. A straightening between quench and aging processes might also be required for aluminum casting.



Economics And Surface Finish Obtainable

For reference

TABLE 12.6

General Cost Characteristics of Casting Processes

Casting process	Cost*			Production rate (pieces/hr)
	Die	Equipment	Labor	
Sand	L	L	L-M	<20
Shell mold	L-M	M-H	L-M	<50
Plaster	L-M	M	M-H	<10
Investment	M-H	L-M	H	<1000
Permanent mold	M	M	L-M	<60
Die	H	H	L-M	<200
Centrifugal	M	H	L-M	<50

*L = low; M = medium; H = high.

Economics of Casting

For reference

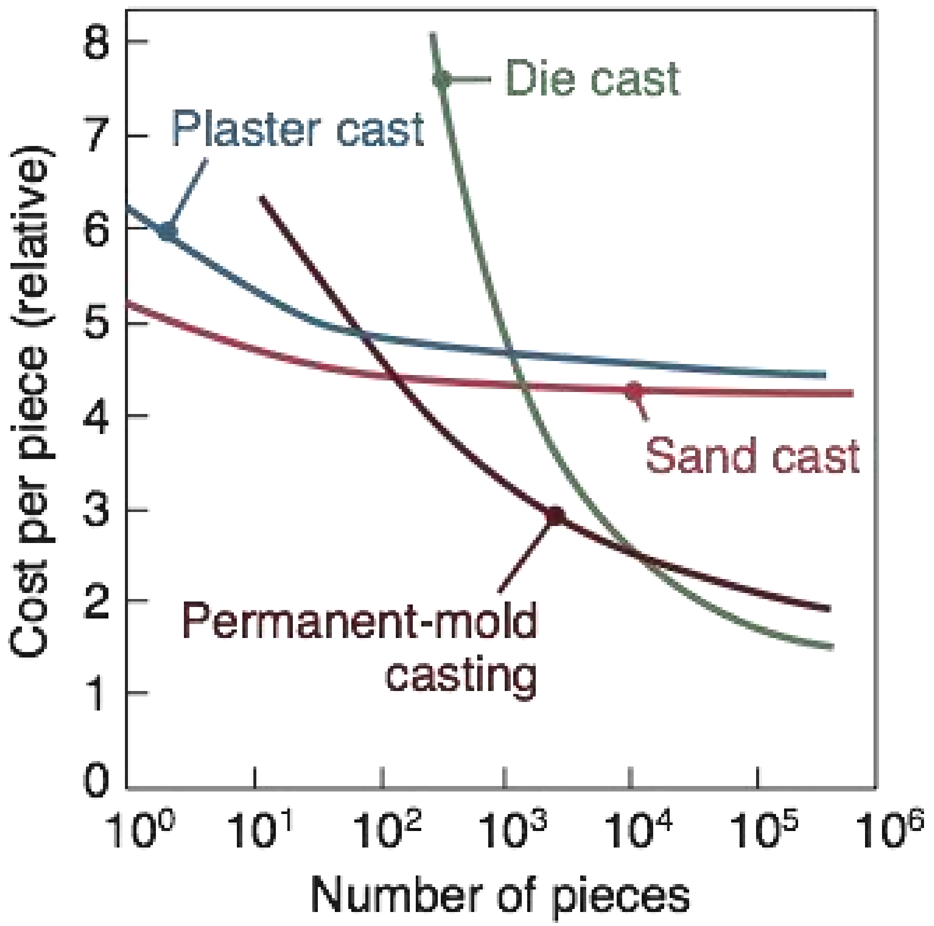


FIGURE 5.39 Economic comparison of making a part by two different casting processes. Note that because of the high cost of equipment, die casting is economical mainly for large production runs. *Source:* The North American Die Casting Association.

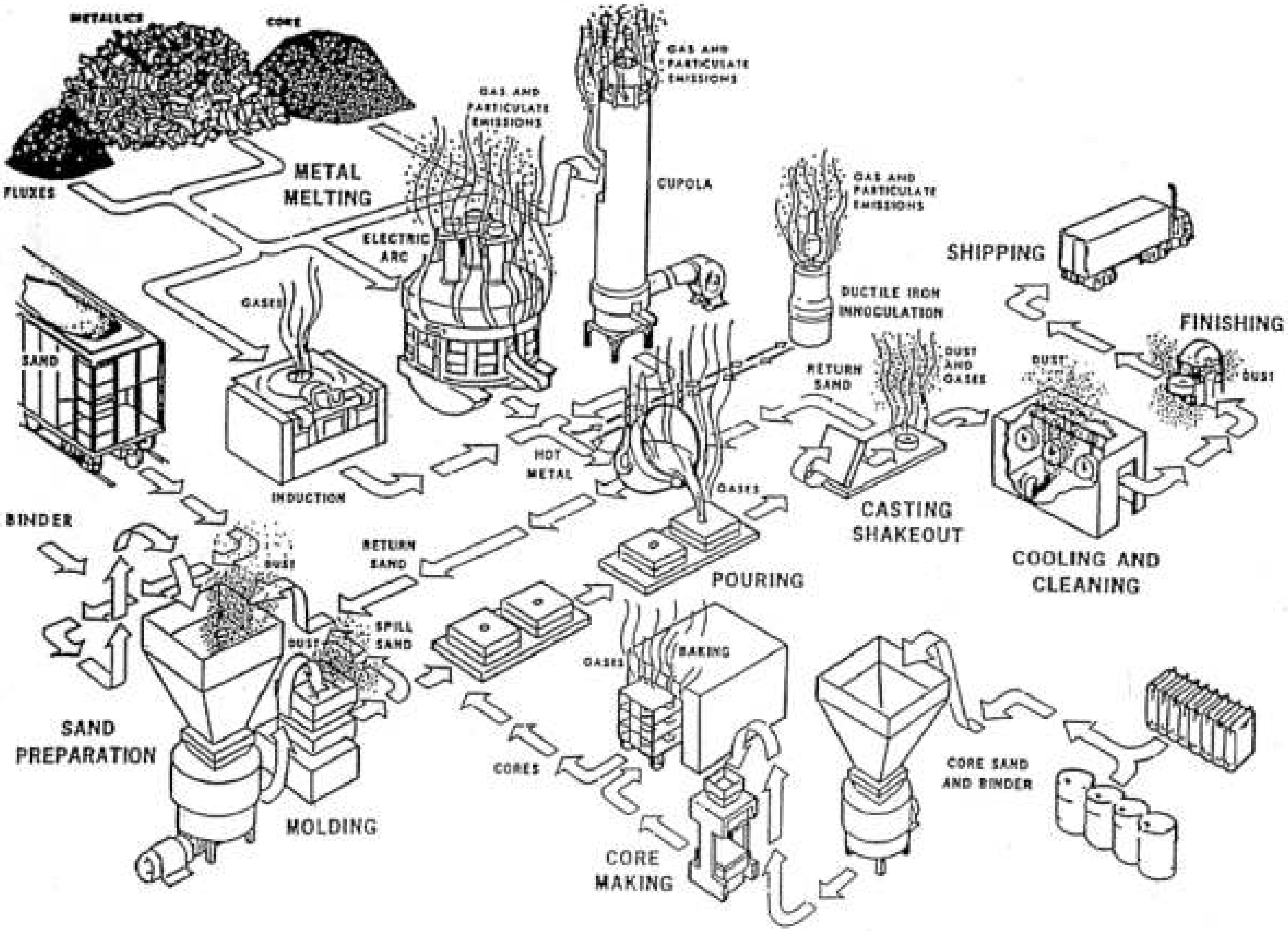
Cost - Casting

- Sand casting
  - Tooling and equipment costs are low
  - Direct labor costs are high
  - Material utilization is low
  - Finishing costs can be high
- Investment casting
  - Tooling costs are moderate depending on the complexity
  - Equipment costs are low
  - Direct labor costs are high
  - Material costs are low
- Die casting
  - Tooling and equipment costs are high
  - Direct labor costs are low to moderate
  - Material utilization is high

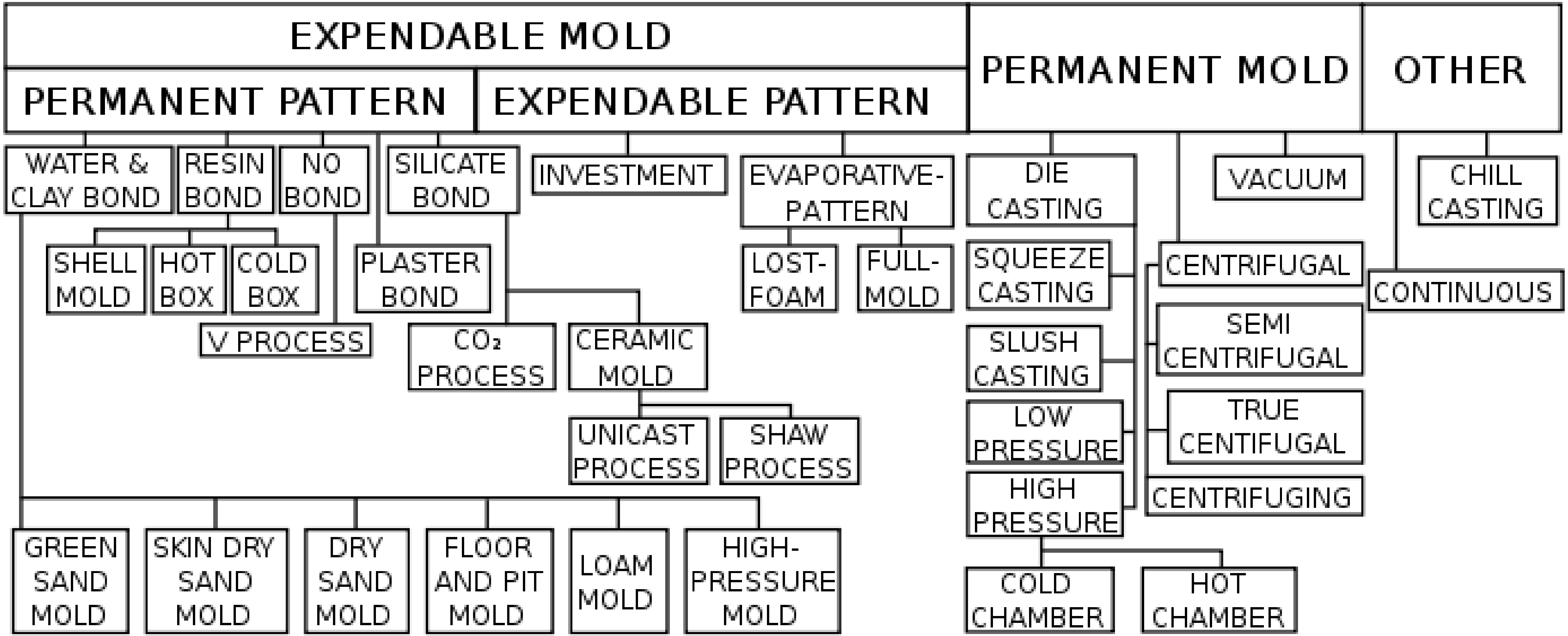
Casting Processes Comparison

Process	Advantages	Limitations
Sand	Almost any metal is cast; no limit to size, shape or weight; low tooling cost.	Some finishing required; somewhat coarse finish; wide tolerances.
Shell mold	Good dimensional accuracy and surface finish; high production rate.	Part size limited; expensive patterns and equipment required.
Expendable pattern	Most metals cast with no limit to size; complex shapes	Patterns have low strength and can be costly for low quantities.
Plaster mold	Intricate shapes; good dimensional accuracy and finish; low porosity.	Limited to nonferrous metals; limited size and volume of production; mold making time relatively long.
Ceramic mold	Intricate shapes; close tolerance parts; good surface finish.	Limited size.
Investment	Intricate shapes; excellent surface finish and accuracy; almost any metal cast.	Part size limited; expensive patterns, molds, and labor.
Permanent mold	Good surface finish and dimensional accuracy; low porosity; high production rate.	High mold cost; limited shape and intricacy; not suitable for high-melting-point metals.
Die	Excellent dimensional accuracy and surface finish; high production rate.	Die cost is high; part size limited; usually limited to nonferrous metals; long lead time.
Centrifugal	Large cylindrical parts with good quality; high production rate.	Equipment is expensive; part shape limited.

Summary



METAL
MELTING
FLUXES
ELECTRIC
ARC
CUPOLA
SAND
GASES
INDUCTION
HOT
METAL
SHIPPING
DUCTILE IRON
INNOCULATION
FINISHING
RETURN
SAND
CASTING
SHAKEOUT
COOLING AND
CLEANING
POURING
BINDER
RETURN
SAND
SPILL
SAND
SAND
PREPARATION
MOLDING
BAKING
CORES
CORE
MAKING
CORE SAND
AND BINDER

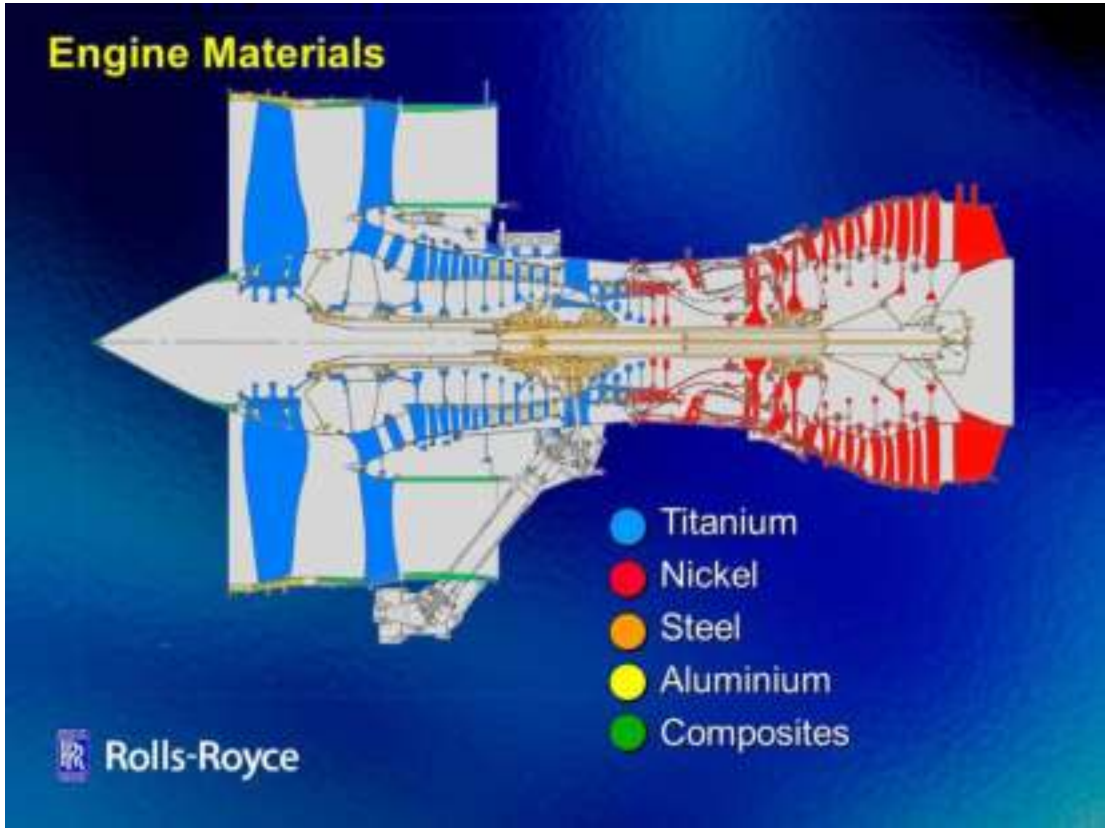

EXPENDABLE MOLD
PERMANENT PATTERN
EXPENDABLE PATTERN
PERMANENT MOLD
OTHER
WATER & CLAY BOND
RESIN BOND
NO BOND
SILICATE BOND
INVESTMENT
EVAPORATIVE-PATTERN
DIE CASTING
VACUUM
CHILL CASTING
SHELL MOLD
HOT BOX
COLD BOX
PLASTER BOND
LOST-FOAM
FULL-MOLD
SQUEEZE CASTING
CENTRIFUGAL
CONTINUOUS
V PROCESS
CO₂ PROCESS
CERAMIC MOLD
SLUSH CASTING
SEMI CENTRIFUGAL
UNICAST PROCESS
SHAW PROCESS
LOW PRESSURE
TRUE CENTIFUGAL
HIGH PRESSURE
CENTRIFUGING
GREEN SAND MOLD
SKIN DRY SAND MOLD
DRY SAND MOLD
FLOOR AND PIT MOLD
LOAM MOLD
HIGH-PRESSURE MOLD
COLD CHAMBER
HOT CHAMBER

Superalloy

Reference text book: SUPERALLOYS A Technical Guide Matthew J. Donachie, Stephen J. Donachie

- **Superalloys** are unique high temperature materials used in gas turbine engines, which display excellent resistance to mechanical and chemical degradation.
- Based upon nickel, but containing significant amounts of at least ten other elements including chromium and aluminium, the superalloys are high-temperature materials which display excellent resistance to mechanical and chemical degradation at temperatures close to their melting points.
- Superalloys are an important group of high-temperature materials used in the hottest sections of jet and rocket engines where temperatures reach 1200–1400 °C. Superalloys are based on nickel, cobalt or iron with large additions of alloying elements to provide strength, toughness and durability at high temperature.
- Certain classes of material possess a remarkable ability to maintain their properties at elevated temperatures. These are the high-temperature materials. Their uses are many and varied, but good examples include the components for turbines, rockets and heat exchangers.

- Figure 1.4 illustrates the different materials used in the various parts of the Trent 800 aeroengine.
- One sees that titanium alloys are chosen for the fan and compressor sections, on account of their low density, good specific strength and fatigue resistance.
- However, in the **combustor and turbine arrangements, the nickel-based superalloys are used almost exclusively. Superalloys are used also in the final (high-pressure) stages of the compressor.**

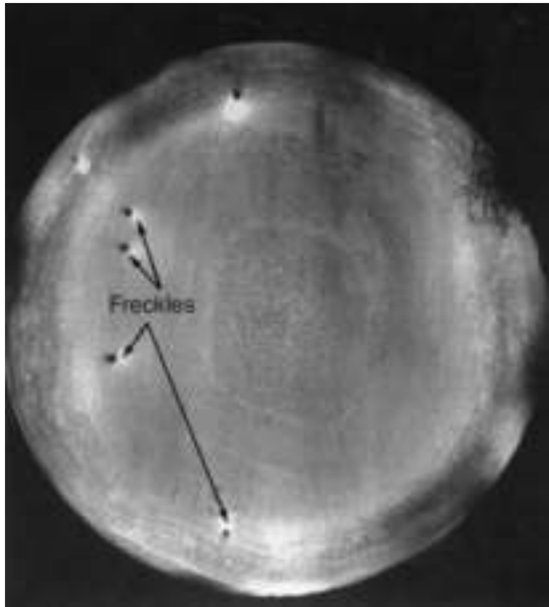


- In the combustor and turbine arrangements of in get engine, the nickel-based superalloys are used almost exclusively. Superalloys are used also in the final (high-pressure) stages of the compressor.
- When designing a gas turbine engine, great emphasis is placed on the choice of the turbine entry temperature (TET)
- The performance of the engine is greatly improved if the TET can be raised.

Superalloy Production Methods

- Superalloys must solidified under controlled conditions.
- When solidification rates are too slow, the solute rejected from the first dendrites formed (primary dendrites) may form continuous channels of very high solute content.
- When these channels solidify (as ''freckles''), they are too concentrated in solute to be dissolved by subsequent heat treatment, and thus form continuous hard defects.
- Freckled structures must be avoided in any superalloy that is intended for service where fatigue life is an important design criterion.

- For most commercially useful wrought superalloys, the solidification conditions of static casting will produce freckles. Thus, these alloys are normally static cast as electrodes, which are consumably remelted under controlled conditions. The consumable remelt processes, vacuum arc remelting (VAR) and electroslag remelting (ESR),



Vacuum Induction Melting(VIM)

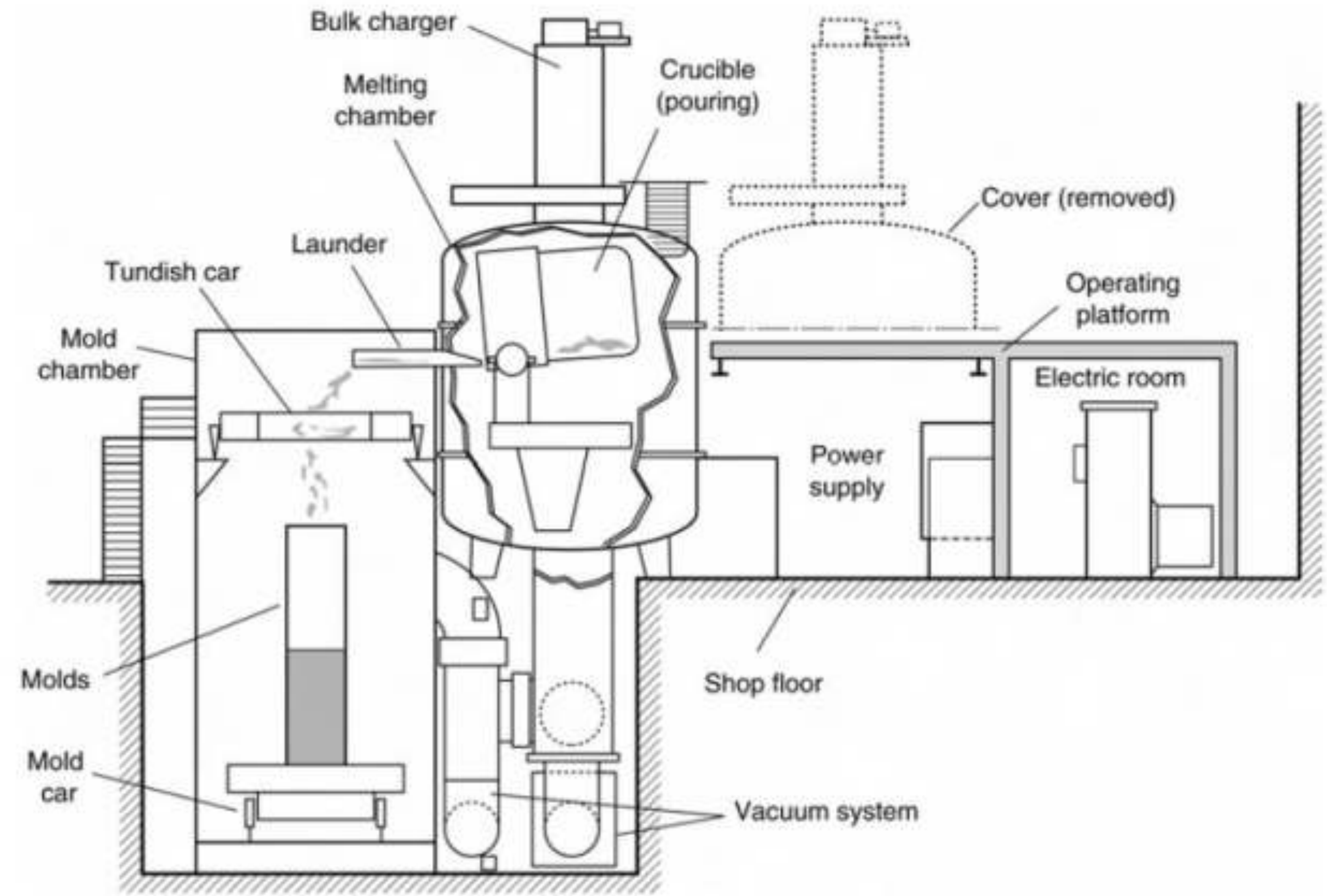
- Vacuum-induction-melted superalloys intended for wrought applications are seldom used in the as-cast condition.
- The vast majority of the ingots cast are intended for consumable remelting operations in order to improve the structure of the material and/or enhance the cleanliness further than may repeatedly be accomplished in VIM.
- Thus, VIM molds tend to be either tall, cylindrical molds that will be remelted into rounds in VAR or ESR, or to be rectangular (slab) molds destined for remelting by ESR.
- In all cases, the industry terminology is not to refer to these cast pieces as ''ingot'' but as ''electrode,' emphasizing their intended use as intermediate stock in a multiple-melting process.

Vacuum Induction Melting(VIM)

- A VIM furnace is simply a melting crucible inside a steel shell that is connected to a highspeed vacuum system
- The heart of the furnace is the crucible (The crucible is generally of a size (4500 to 22,750 kg capacity) with heating and cooling coils and refractory lining.
- Heating is done by electric current that passes through a set of induction coils.
- The coils are made from copper tubing that is cooled by water flowing through the tubing.
- The passage of current through the coils creates a magnetic field that induces a current in the charge inside the refractory.
- When the heating of the charge material is sufficient that the charge has become all molten, these magnetic fields cause stirring of the liquid charge.
- The optimal induction coil frequency for heating the charge varies with the charge shape, size. and melt status (liquid or solid).

Vacuum Induction Melting(VIM)

- The charge generally consists of three portions:
  - A virgin portion, which consists of material that has never been vacuum melted.
  - A refractory portion, which consists of those virgin elements that are strong oxide formers and have the tendency to increase the solubility of oxides and nitrides in the virgin charge.
  - A revert (or scrap) portion, which consists of both internal and external scrap that previously has been vacuum melted.



4.9 Schematic of double-chamber VIM

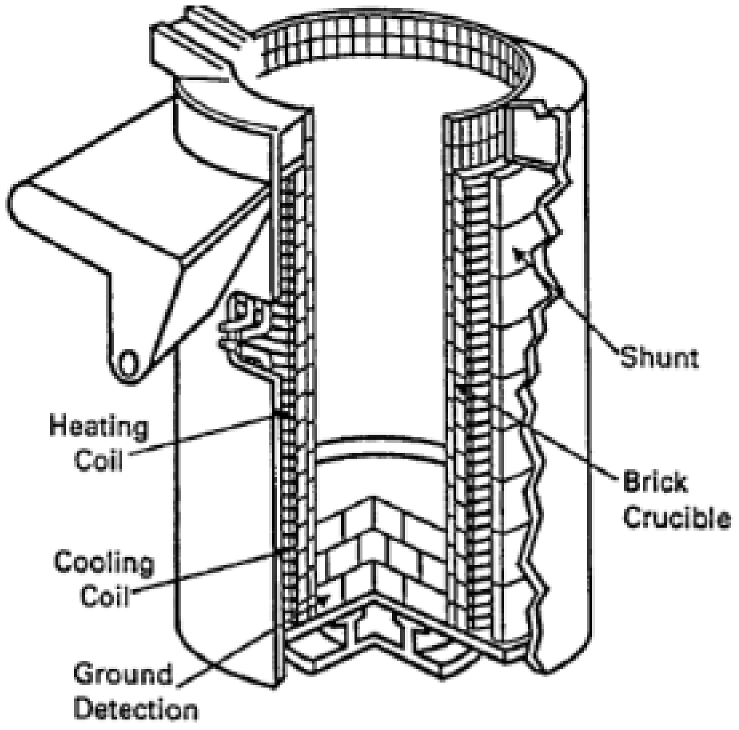


Fig. 4.8 Schematic of vacuum induction melting crucible (shell, coil stack, backup lining, and working lining)

Vacuum Induction Melting Furnace Operation.

- At the completion of the preceding heat, the melt chamber is isolated from the mold chamber.
- Immediately after ensuring that the furnace is vacuum-tight, the addition of the virgin portion of the heat will begin through the bulk charger.
- When all of the virgin portion of the charge has been added and the charge has become all molten.
- Outgassing of the virgin material will be taking place.
- The addition of the revert portion of the charge may begin after the outgassing is complete.
- The refractory elements, or a portion of the refractory elements, may now be added as well. The addition of aluminum serves to further lower the oxygen content of the melt by reacting to form alumina and floating to the top of the melt.
- It is common to add calcium to the melt to desulfurize the material.
- The molds for the heat will have been assembled, liquid run into the mold chamber, the chamber pumped down, the launder pass-through valve opened, and the launder extended into position in the mold chamber. The tundish will also be moved into position.

Electroslag Remelting

- Also called electro-flux remelting
- The electroslag remelting (ESR) process is used to remelt and refine steels and various super-alloys, resulting in high-quality ingots.
- This process can be started up through vacuum induction melting.
- The ESR process uses the as-cast alloy as a consumable electrode.
- In the ESR process, an electrode is prepared by casting or forging after the conventional melting, refining and casting process.
- The ESR equipment consists of a large capacity power supply and a water cooled crucible.
- The melting of the electrodes occurs in the mould by heating caused by the electric resistance of the slag.

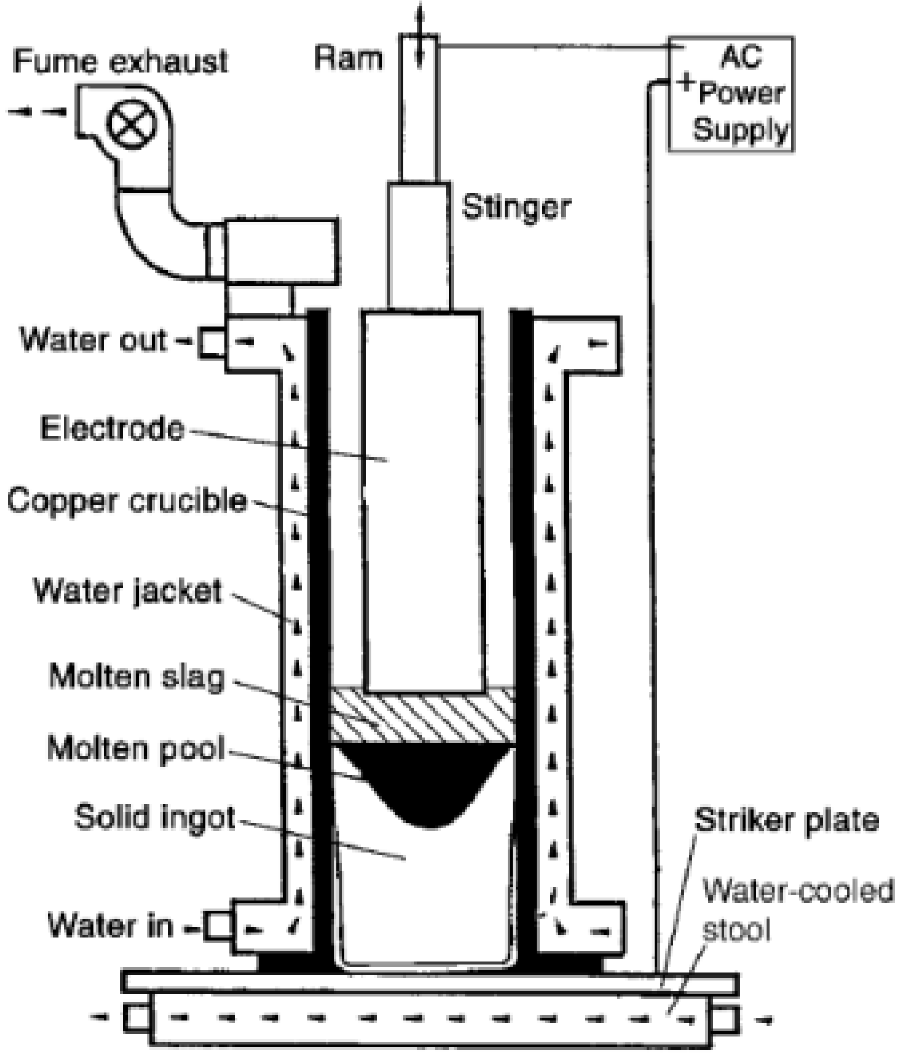


Fig. 4.21 Schematic of electroslag remelting

- A water-cooled stool is assembled to the shell to form the bottom of the crucible. A starter or striker plate is usually enclosed in the junction between the crucible shell and the crucible stool.
- For crucibles to be used with hot slag starts, the crucible may contain an opening at the bottom (a ''mouse hole'') through which the molten flux will be introduced.
- The top of the ESR furnace contains the ram drive and load cells. It is connected electrically to the crucible stool.
- Oxides on an electrode surface are incorporated into the slag.

- There are two possible start-up scenarios, cold start and hot start.

- In cold start, the slag and small particles of the alloy to be melted (usually machining chips) are placed on the starter plate. The electrode is touched into the slag-alloy mix and backed out to establish an arc. High melt power is used in this start-up phase. The arc melts down both the slag and the metal particles, at which point the electrode becomes immersed in the slag and the melt process shifts to melting of the electrode surface by the slag.

- In hot slag starts, the slag is melted externally by electric arc in graphite crucibles.The molten slag is introduced, generally through a bottom mouse hole, into the crucible. The electrode is lowered into the slag, and melting commences.

- Electric current (generally AC) is passed between the electrode and crucible stool. The new ingot is covered in an engineered slag that is superheated by the electric current.

- The electrode tip is slowly melted from contact with the slag. These metal droplets travel through the slag to the bottom of the water-cooled mold and slowly freeze as the ingot is directionally solidified upwards from the bottom of the mold.

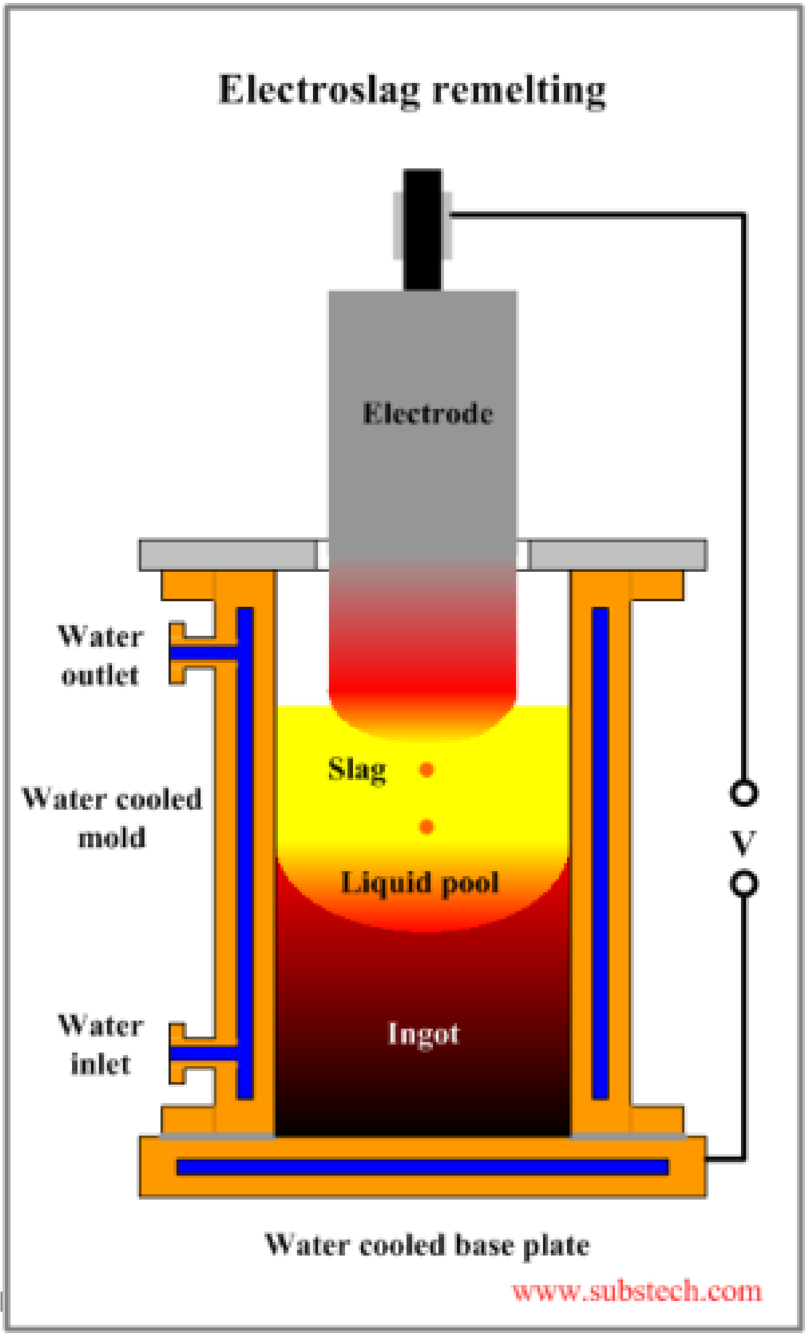
- As the droplets of electrode material fall, refining of the material proceeds. The material solidifies at the bottom of the molten material pool.

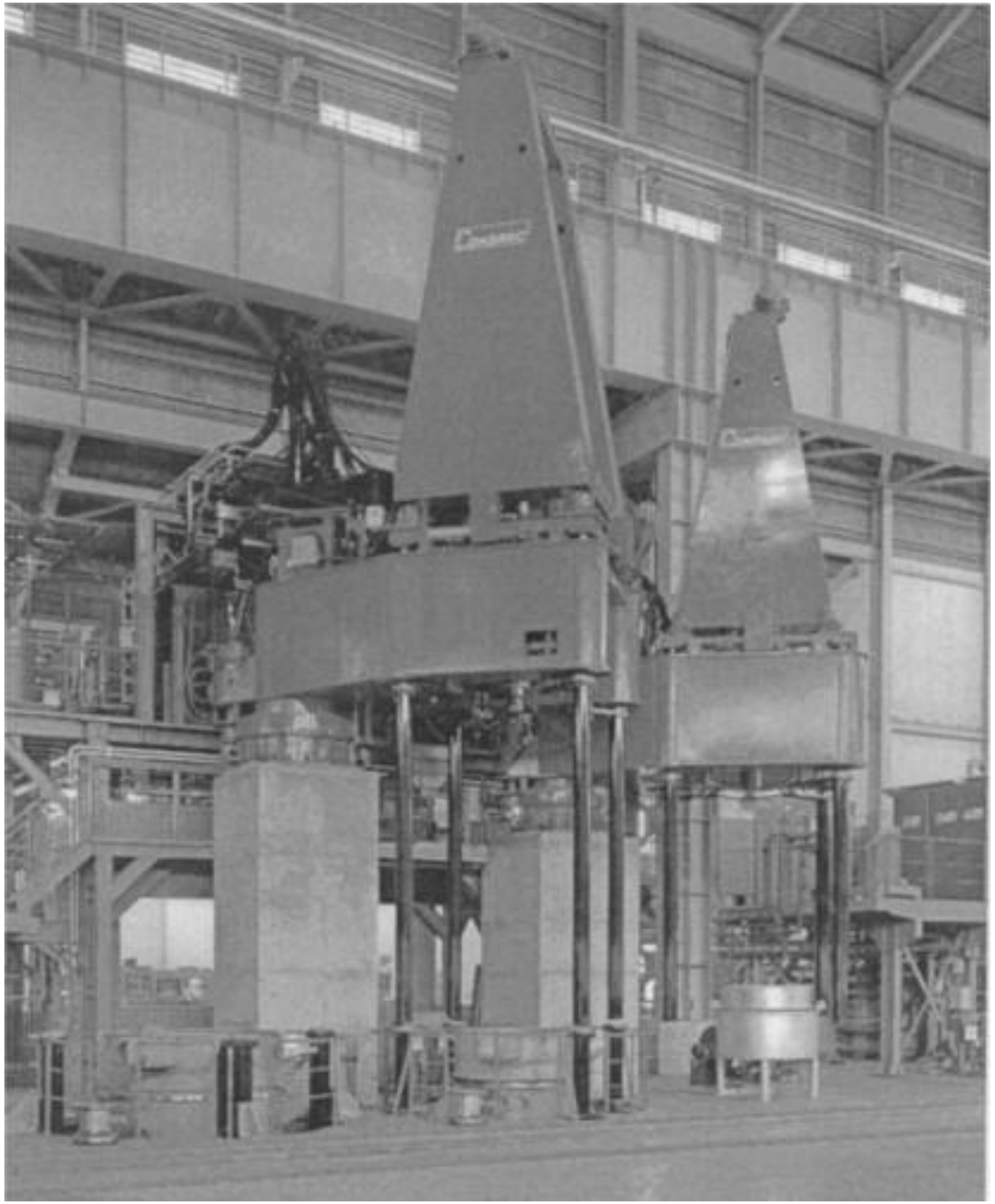
- The slag pool floats above the refined alloy, continuously floating upwards as the alloy solidifies.

- The molten metal is cleaned of impurities that chemically react with the slag or otherwise float to the top of the molten pool as the molten droplets pass through the slag

- Electroslag remelting uses highly reactive slags (calcium fluoride, lime, alumina, or other oxides are usually the main components) to reduce the amount of type-A sulfide present in biometal alloys.

- Formation of macro segregation is suppressed and the distribution of chemical elements becomes more uniform compared to ingots made by conventional casting.


Electroslag remelting
Electrode
Water
outlet
Slag
Water cooled
mold
V
Liquid pool
Water
inlet
Ingot
Water cooled base plate
www.substech.com



Eldho I


WACKER
ELECTROFLUX
The success factor

Vacuum arc remelting (VAR)

- In VAR, the electrode is remelted in a vacuum chamber, of which the water-cooled crucible is an integral part.
- A direct electric current (dc) is passed through the electrode to the bottom of the crucible (the stool) and the electrode withdrawn, so that an arc is formed between the stool and the electrode face.
- The heat generated by this arc melts the face of the electrode, and metal transfer onto the stool begins as the molten metal drips onto the stool and is solidified.
- As the volume of metal on the stool (the ingot) builds up, an equilibrium state is reached in which there is a solid ingot, a mushy zone of both liquid and solid above that, and then a zone that is totally liquid.
- Because the heat extraction in the steady-state condition of melting is fastest through the sidewalls and slower down the ingot and through the stool, the mushy zones and liquid zones are shallower near the sidewalls and deeper in the ingot center.

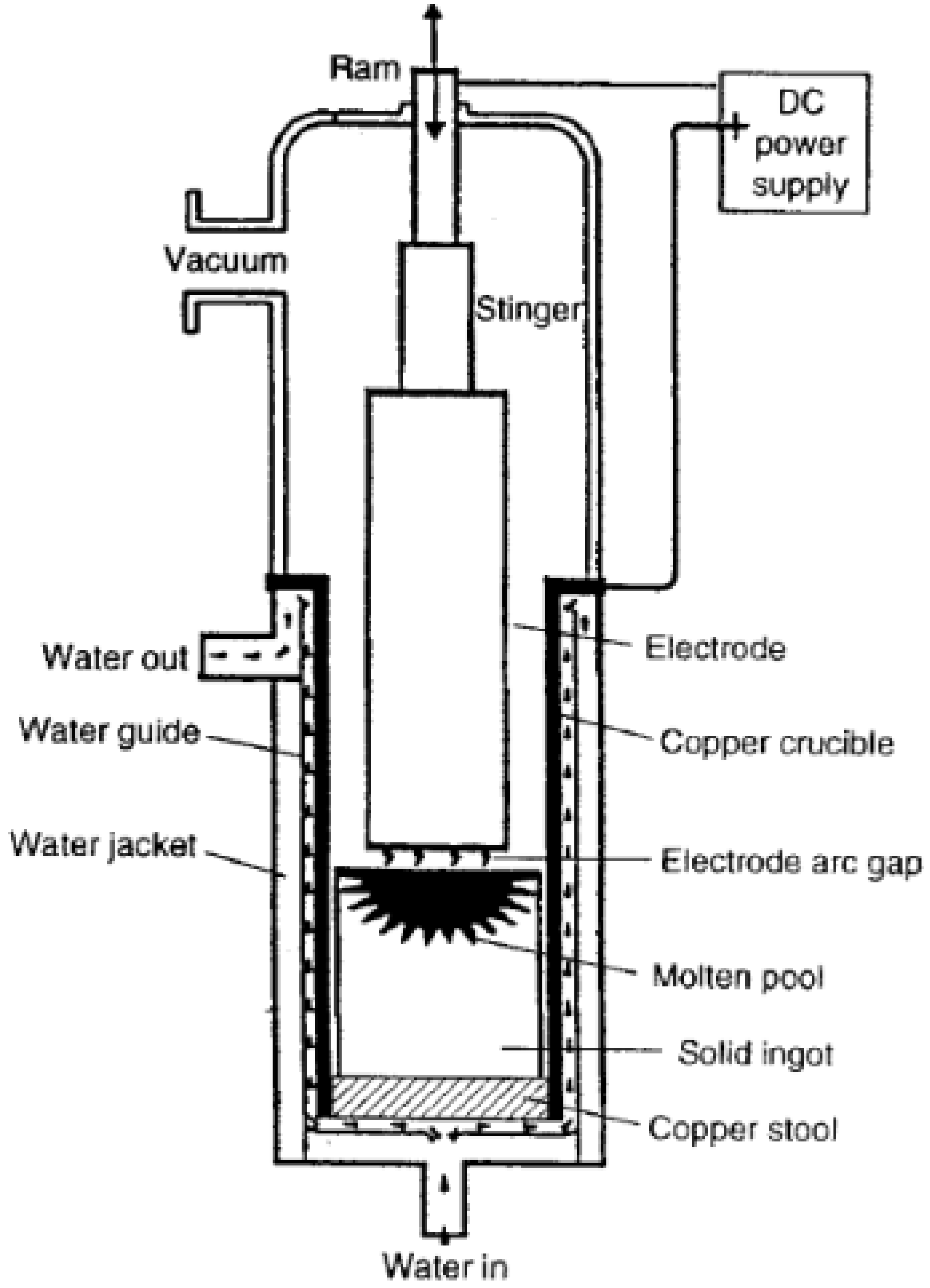


Fig. 4.10 Schematic of VAR furnace

- The thickness of the mushy zone at the center of a VAR ingot is controlled by the efficiency of heat extraction, the size (diameter) of the crucible, and the melt rate of the electrode face. The melt rate is controlled by the magnitude of current passed through the electrode.
- Other factors that are controlled so as to positively affect the solidifying structure are the distance of the melting face above the molten pool (arc gap) and the clearance of the sides of the electrode from the crucible (annulus).
- It should be recognized that, when the electrode face becomes molten, the metal droplets are immediately transferred by gravity into the molten pool. Thus, VAR is a process in which it is inherently impossible to superheat the metal.
- This, coupled with the very high heat-extractive capability of the process, makes VAR the choice for economic manufacture of the largest-diameter ingots of segregation-prone superalloys.
- Additionally, the exposure of small volumes of molten metal to high vacuum is capable of removing detrimental high-vapor-pressure elements

Vacuum arc remelting (VAR)

- g

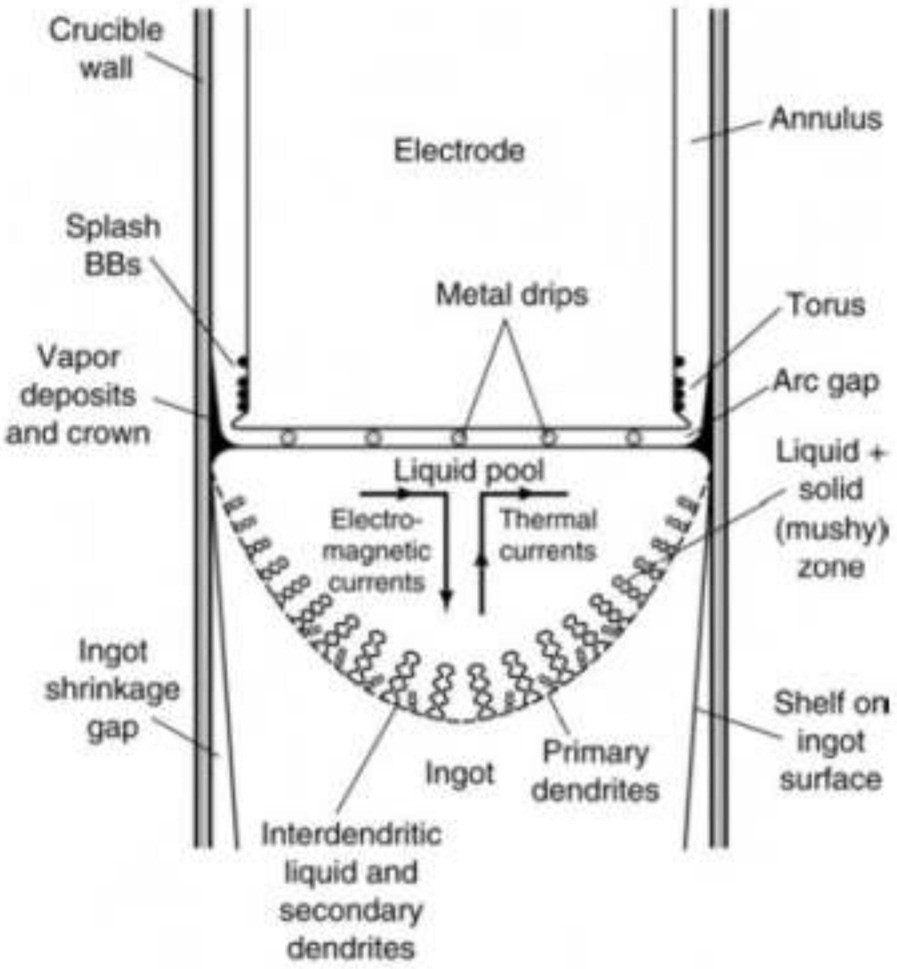
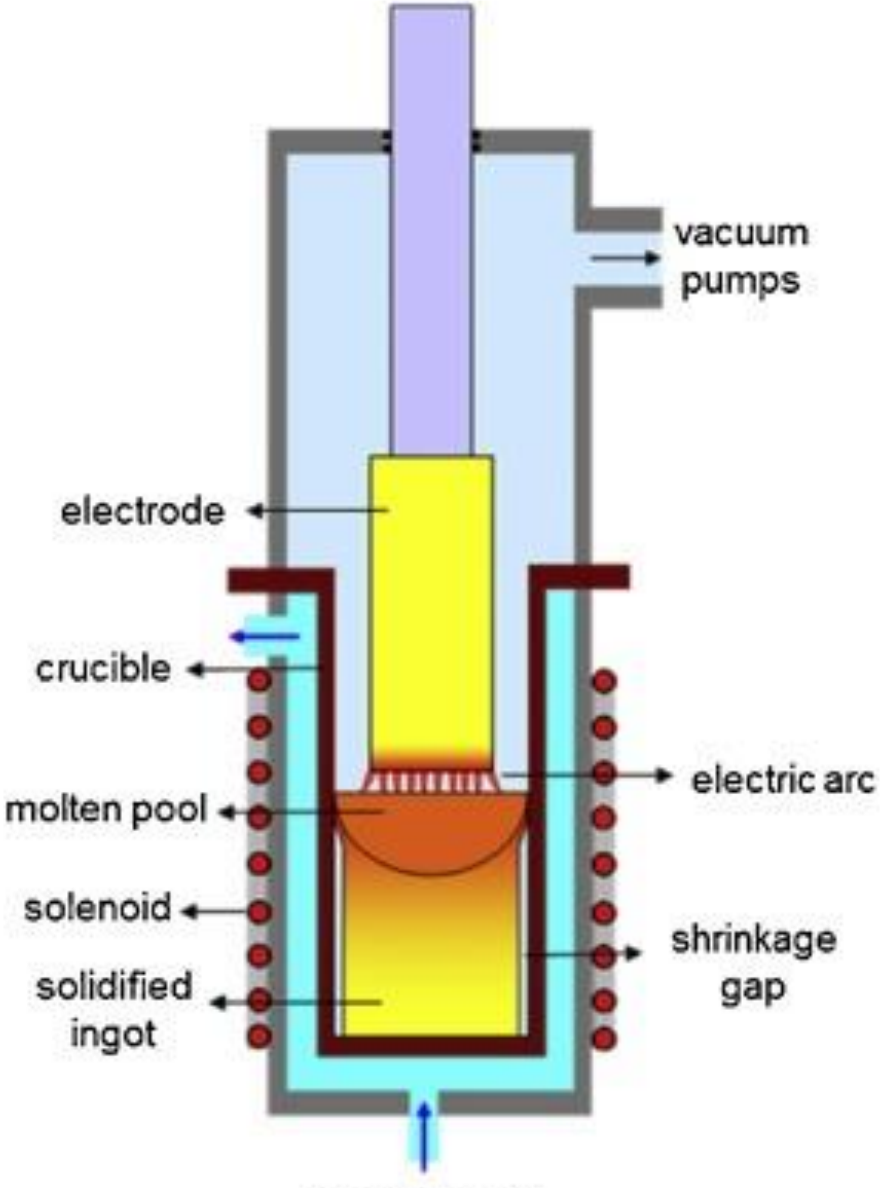


Fig. 4.14 Longitudinal schematic of the structure developed in a VAR ingot during melting

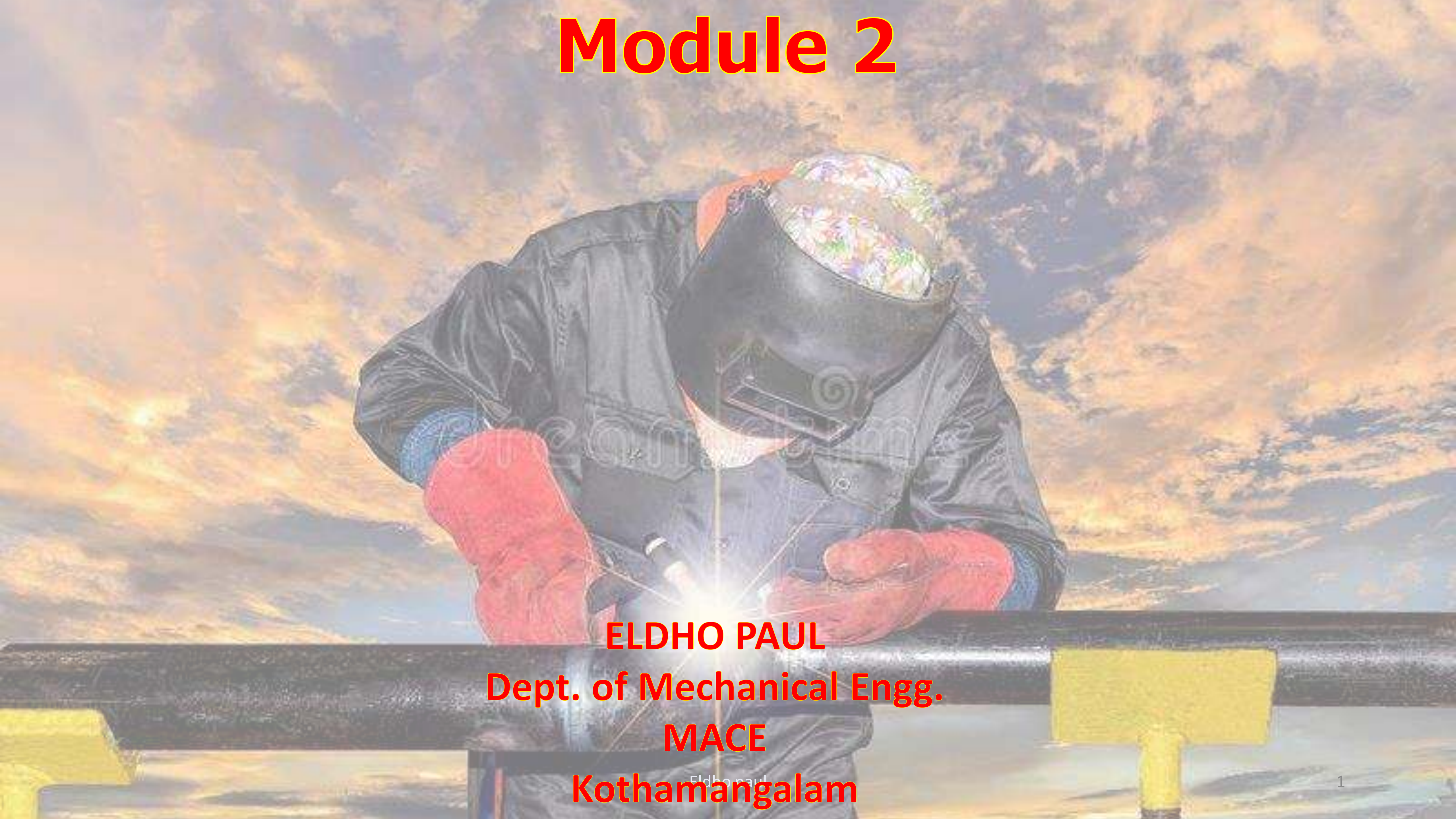


Vacuum arc remelting (VAR) operation

- The alloy to undergo VAR is formed into a cylinder(Electrode) typically by vacuum induction melting (VIM) or ladle refining (air melt).
- The VAR crucible is cooled using water jacket tubes are called water guides.
- The top of the crucible mates with the VAR head. The head contains the vacuum ports and the ram, which drives the electrode into the crucible as it is consumed.
- Electrode preparation is an important part of high-quality VAR operation. Oxides are not desired on a VAR electrode
- Electrode is then put into a large cylindrical enclosed crucible and brought to a metallurgical vacuum (0.001-0.1 mmHg or 0.1-13.3 Pa).

Vacuum arc remelting (VAR)

- At the bottom of the crucible is a small amount of the alloy to be remelted, which the top electrode is brought close to prior to starting the melt.
- Several kiloamperes of DC current arc used to start an arc between the two pieces, and from there, a continuous melt is derived.
- The arc is struck between the electrode and the stool
- The crucible (typically made of copper) is surrounded by a water jacket used to cool the melt and control the solidification rate.
- The three major parameters defining the melt process are ingot and electrode diameter, arc gap, and melt rate.



Module 2

ELDHO PAUL
Dept. of Mechanical Engg.
MACE
Kothamangalam

Course Outcomes

At the end of the course students will be able to,

- CO2. Categorize welding processes according to welding principle and material.
- CO3.Understand requirements to achieve sound welded joint while welding different similar and dissimilar engineering materials.
- CO5.Recommend appropriate part manufacturing processes when provided a set of functional requirements and product development constraints.

Course Outcome 2 (CO2):

Categorize welding processes according to welding principle and material

1. Why is the quality of welds produced by submerged arc welding very good?
2. What does the strength of a weld nugget in resistance spot welding depends on?
3. What is the strength of a welded joint is inferior or superior to the parent metal? Why?
4. Why some joints may have to be preheated prior to welding.

Course Outcome 3 (CO3): Understand requirements to achieve sound welded joint while welding different similar and dissimilar engineering materials.

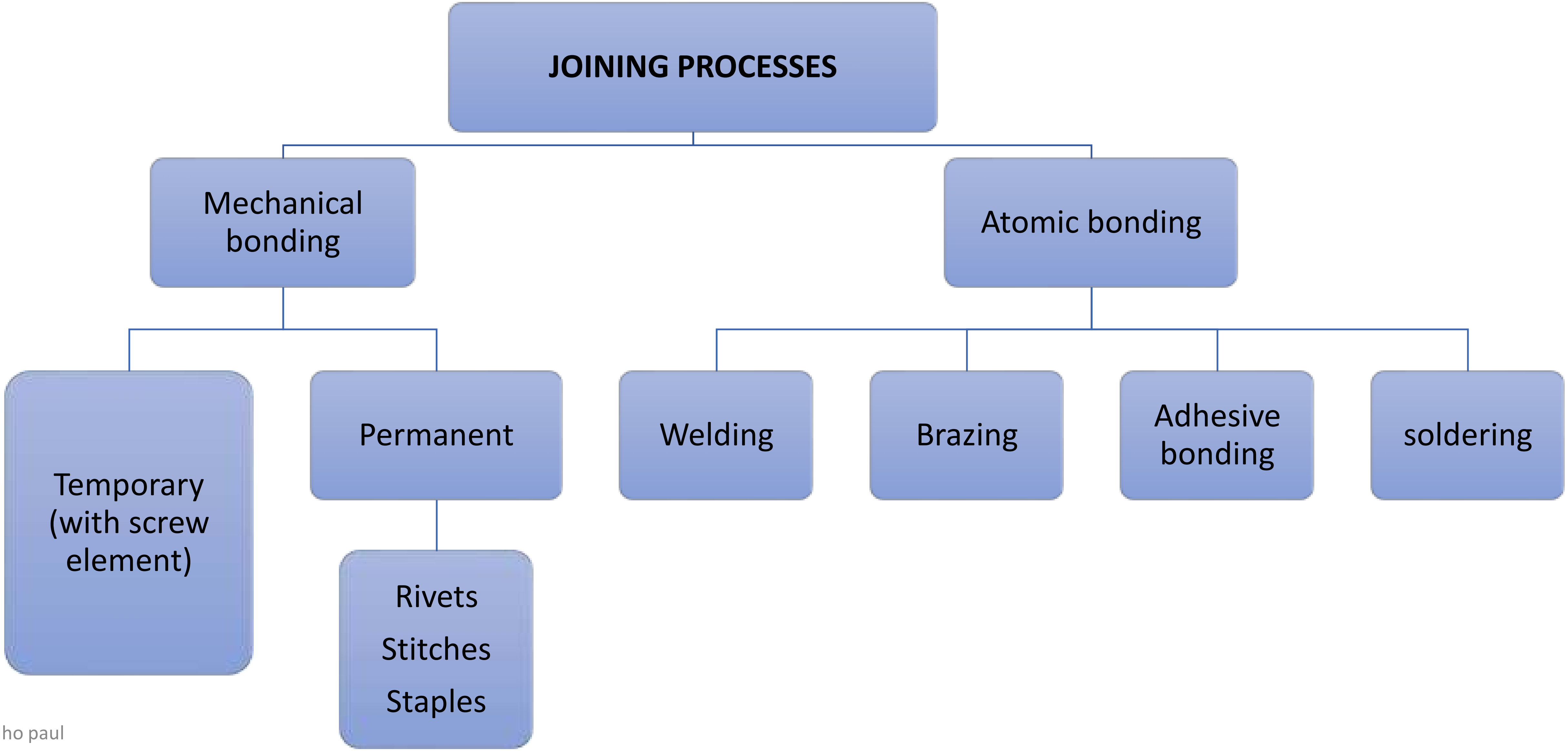
1. Assume that you are asked to inspect a weld for a critical application. Describe the procedure you would follow. If you find a flaw during your inspection, how would you go about determining whether or not this flaw is important for the particular application?
2. In the building of large ships, there is a need to weld large sections of steel together to form a hull, for this application, which welding process would you select? Why?

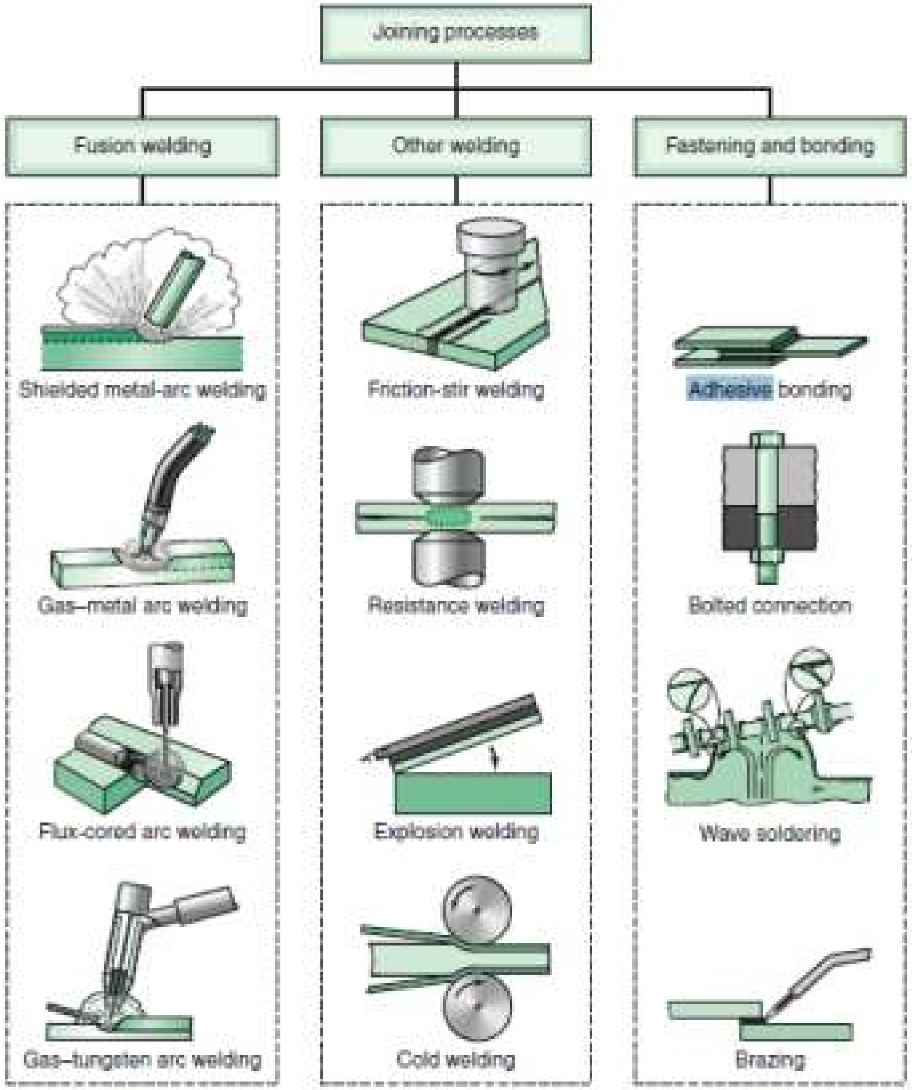
Syllabus

2.1	Welding:-welding metallurgy, diffusion, heat affected zone, driving force for grain growth, grain size and hardness- joint quality: porosity, slag inclusions, cracks, surface damage, residual stress lamellar tears, stress reliving, heat treatment of welded joints - weldability (Kalpakjian, Lindberg) - destructive and non destructive tests of welded joints (may be provided as class assignment - Lindberg).	2	CO2

2.2	Resistance welding: HAZ, process and correlation of process parameters with welded joints of spot, seam, projection, stud arc, percussion welding-applications of each welding process –simple problems. (Kalpakjian).	3	CO2 CO5
2.3	Arc welding:-HAZ, process and correlation of process parameters with welded joints of shielded metal arc, submerged, gas metal, flux cored, electrogas, electroslag, gas tungsten, plasma arc, electron beam, laser beam –simple problems - Thermit welding, friction welding- applications of each welding process. (Kalpakjian, Lindberg).	3	CO2
2.4	Oxyacetylene welding:-chemistry, types of flame and its applications - brazing- soldering - adhesive bonding.	1	

JOINING PROCESSES




Joining processes
Fusion welding
Other welding
Fastening and bonding
Shielded metal-arc welding
Friction-stir welding
Adhesive bonding
Gas–metal arc welding
Resistance welding
Bolted connection
Flux-cored arc welding
Explosion welding
Wave soldering
Gas–tungsten arc welding
Cold welding
Brazing
(f)

INTRODUCTION

- Welding is a materials joining process which produces coalescence of materials by heating them to suitable temperatures with or without the application of pressure or by the application of pressure alone, and with or without the use of filler material.
- Welding provides a permanent joint but it normally affects the metallurgy of the components
- Melting the work pieces and adding a filler material to form a pool of molten material (weld pool) that cools to become strong joint.

Basic Classification

- **Fusion Welding**

  In this type of welding no pressure is involved but a very high temperature is produced in or near to the joint. The metal at the joint is heated to the molten state and allowed to solidify. The heat may be generated by electric arc, combustion of gasses or chemical action.

  Welded joint undergoes metallurgical and physical change

  (Ex) Gas welding, Arc welding

- **Plastic Welding or Pressure Welding or Solid state welding**

  The metal to be joined are to be heated to the plastic state and then forced together by external pressure without the addition of filler material

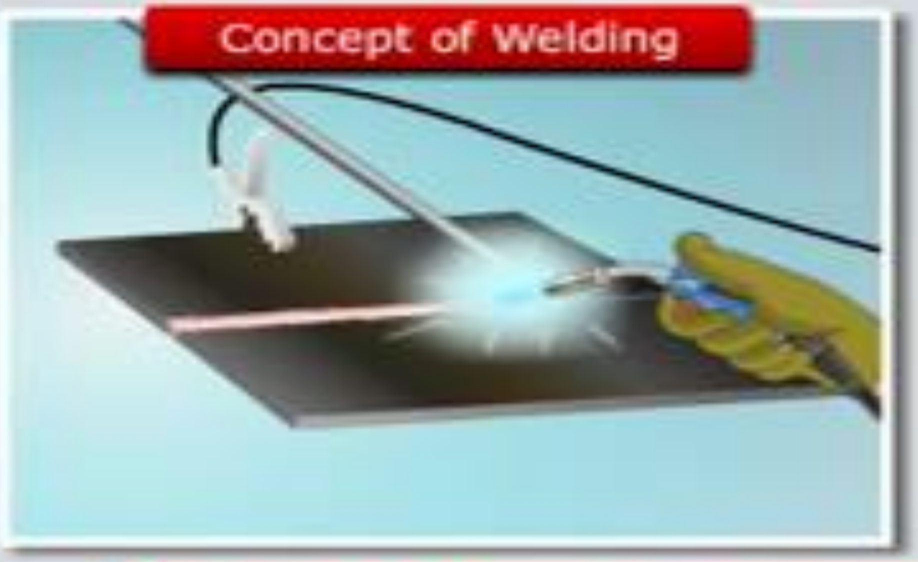
  (Ex) resistance welding, forged welding

Give the classification of **Welding Process**.

Keywords

- *Fusion Welding*
- *Pressure Welding*

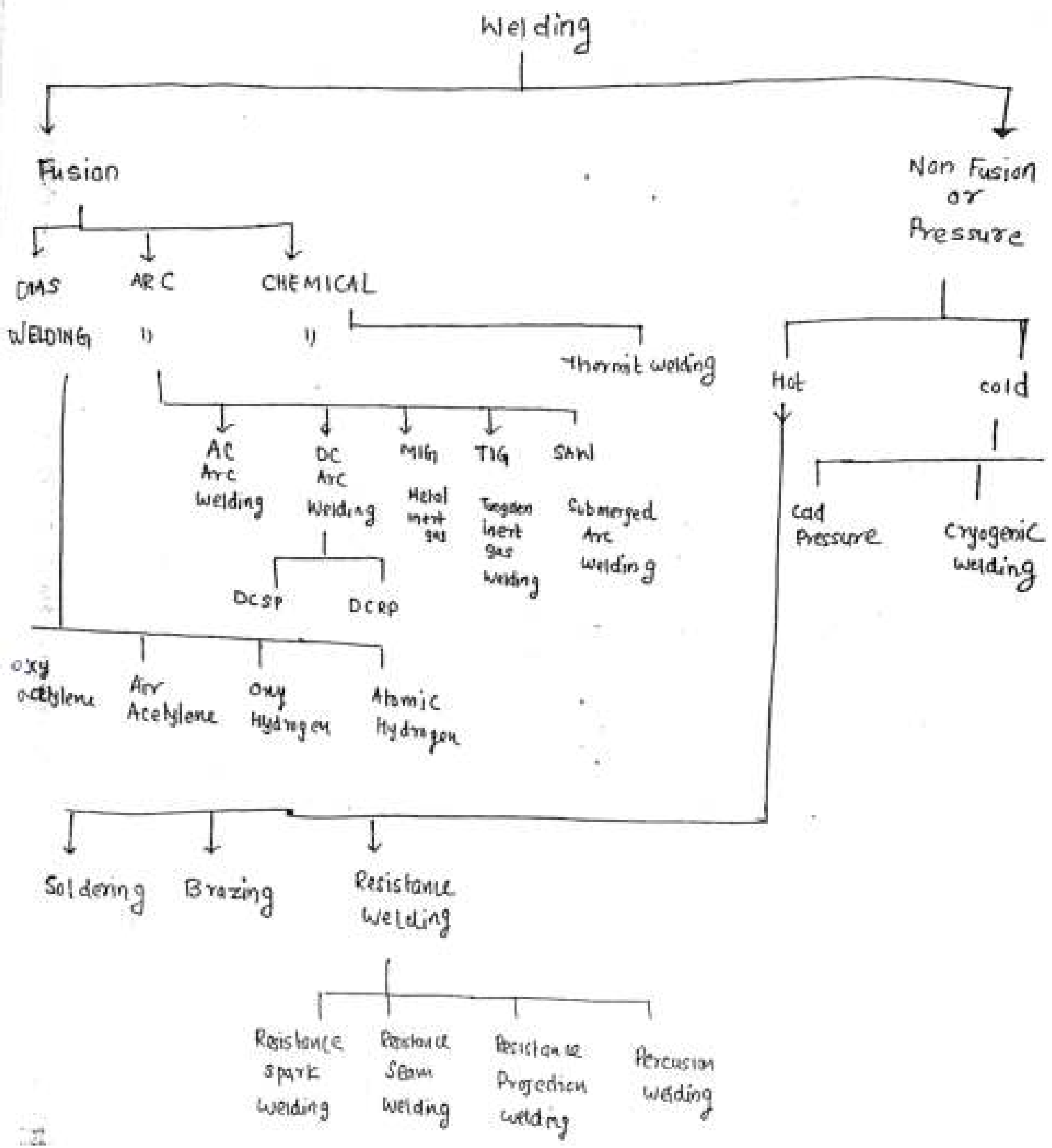
Concept of Welding

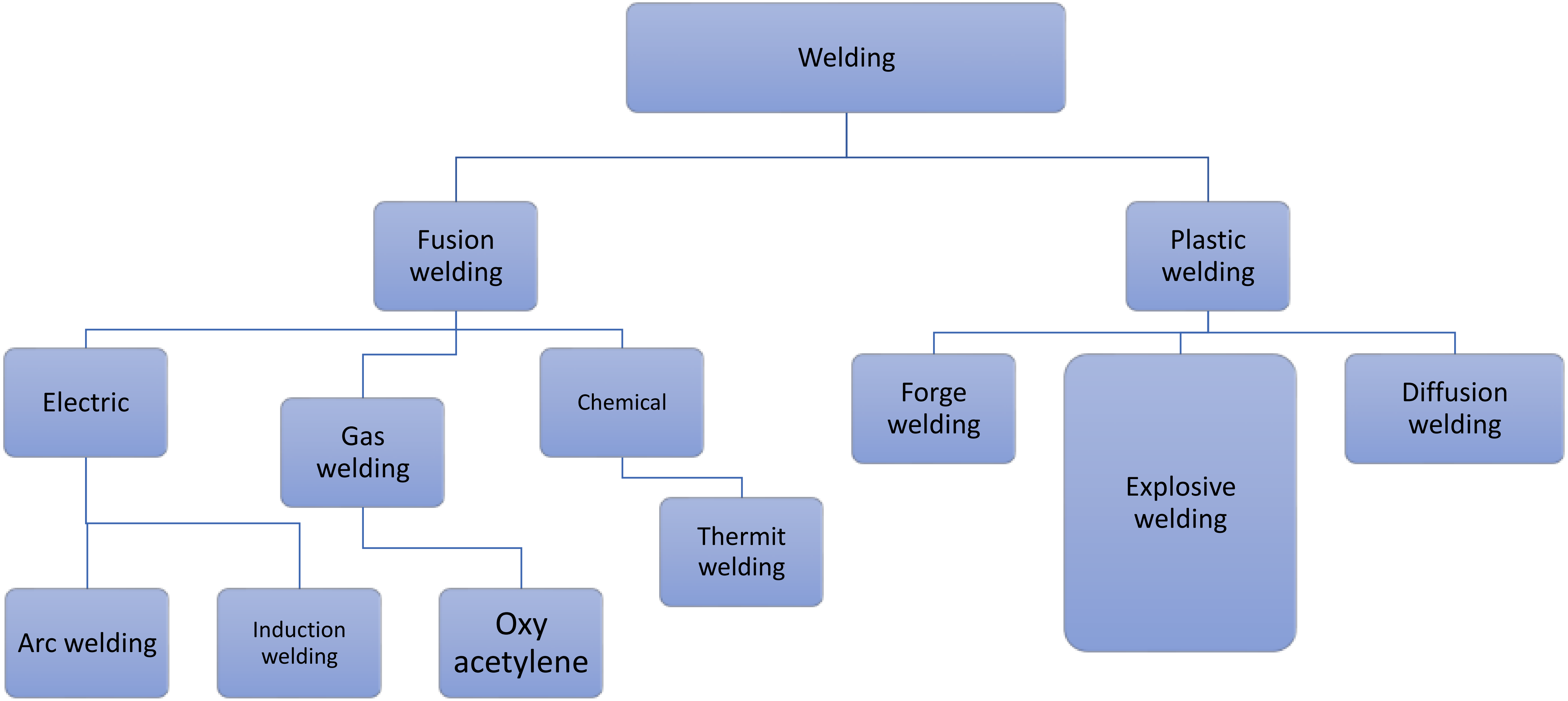


Types of Welding Process

- Fusion Welding
- Pressure Welding

WELDING PROCESS is classified as *Fusion Welding* and *Pressure Welding*.


Welding
Fusion
Non Fusion or Pressure
GAS WELDING
ARC
CHEMICAL
Thermit welding
Hot
cold
AC Arc welding
DC Arc Welding
MIG Metal inert gas
TIG Tungsten Inert gas Welding
SAW Submerged Arc welding
DCSP
DCRP
Cold Pressure
Cryogenic welding
oxy acetylene
Air Acetylene
Oxy Hydrogen
Atomic Hydrogen
Soldering
Brazing
Resistance Welding
Resistance spark welding
Resistance Seam Welding
Resistance Projection welding
Percussion welding


Welding
Fusion welding
Plastic welding
Electric
Gas welding
Chemical
Forge welding
Explosive welding
Diffusion welding
Thermit welding
Arc welding
Induction welding
Oxy acetylene

Types of welding

1. Gas welding

- Oxy-acetylene
- Air-acetylene
- Oxy-hydrogen welding

2. Arc welding

- Carbon arc
- Metal arc
- Plasma arc
- Electro-slag
- Submerged arc
- Flux-cored arc
- Gas metal arc (MIG)
- Gas tungsten arc (TIG)
- Atomic hydrogen arc

3. Resistance welding

- Butt
- Spot
- Projection
- Percussion

4. Thermit welding

5. Solid state welding

- Friction
- Ultrasonic
- Explosive
- Diffusion

6. Newer welding

- Electron-beam
- Laser

7. Related Processes

- Arc welding
- Brazing
- Soldering

Applications

- Aircraft construction
  - Welded engine mounts
  - Turbine frame for jet engine
  - Ducts and other fittings
  - Rocket motor fuel and oxidizer tanks
- Automobile construction
  - Arc welded car wheels
  - Steel rear axle housing
  - Frame side rails
  - Automobile frame, brackets

- Pressure vessels and tanks
  - Clad and lined steel plates
  - Shell construction
  - Joining of nozzle to the shell
  - Oil, gas and water storage tanks

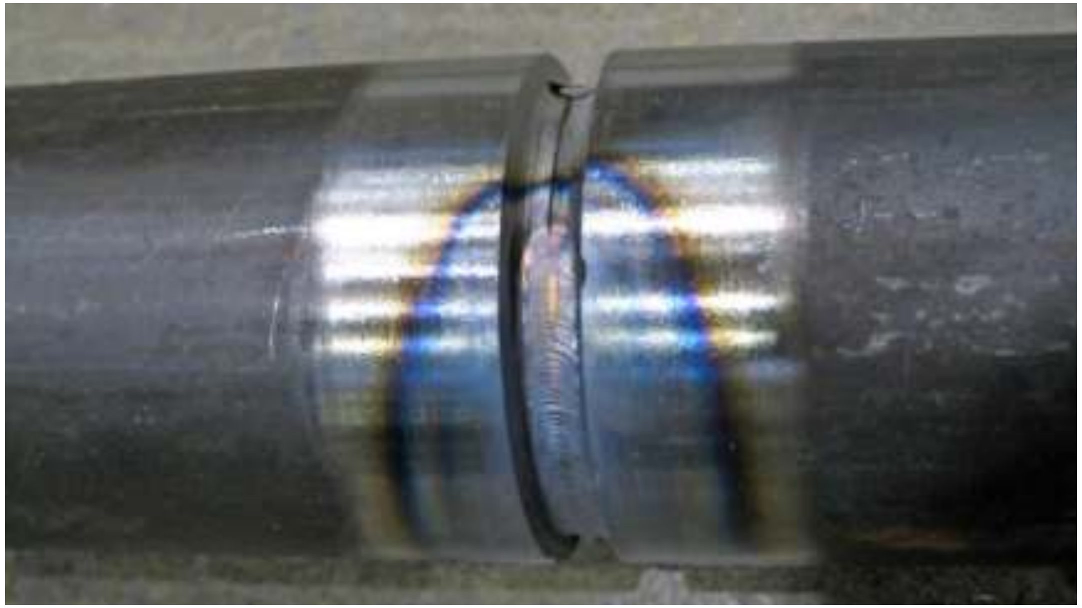
- Piping and pipeline
  - Rolled plate piping
  - Open pipe joints
  - Oil, gas and gasoline pipe lines

- Ship
  - Shell frames
  - Girders to shells
  - Bulkhead webs to plating
  - Deck beams and
  - bulkhead stiffeners
- Bridges
  - Pier construction
  - Section lengths

- Repair and maintenance works
  - Repair of broken and damaged components and machinery
  - such as tools, dies, gears, shears, press, and machine tool frames
  - Rebuilding of worn out or undersized parts rejected during inspection

Metallurgy Of Welding

- Three distinct zones for fusion weld joint,
  - Unaffected Base metal
    - Portion far away from the heat source
  - Heat affected zone HAZ
    - Region subjected to elevated temperature for period of time during welding
  - Weld metal zone or fusion zone
    - Composed of resolidified base metal and filler metal



METALLURGY OF WELD

- During Welding process the metals to be joined are heated over a range of temperatures and is followed by cooling to ambient temperatures.
- Peak temperature will be at the weld area resulting in complex mixture of microstructures especially in steel.
- Welding also produces internal stresses and plastic strain in the vicinity of the weld.
- If the welding atmosphere is also not proper, certain chemical changes also takes place.
- Thus, welding brings about thermal, structural and chemical changes takes place during welding.

Metallurgy Of Welding

- The metallurgy and properties of the HAZ and weld metal zone depends,
  - The type of metals joined,
  - Particular joining process,
  - Filler metals used (if any),
  - Welding process variables.

- A joint produced without a filler metal is called autogenous, and its weld zone is composed of the resolidified base metal.
- A joint made with a filler metal has a central zone called the weld metal and is composed of a mixture of the base and the filler metals.

- The heat-affected zone (HAZ) is within the base metal itself. It has a microstructure different from that of the base metal after the welding, because it has been temporarily subjected to elevated temperatures during welding.

- The portions of the base metal (Unaffected Base metal)that are far enough away from the heat source do not undergo any microstructural changes during welding because of the far lower temperature to which they are subjected.

- The properties and microstructure of the HAZ depend on,
  - Rate of heat input and cooling and
  - Temperature to which this zone was raised.
  - Metallurgical factors (such as the original grain size, grain orientation, and degree of prior cold work),
  - Physical properties (such as the specific heat and thermal conductivity of the
  - metals) influence the size and characteristics of the HAZ.

METALLURGY OF WELD

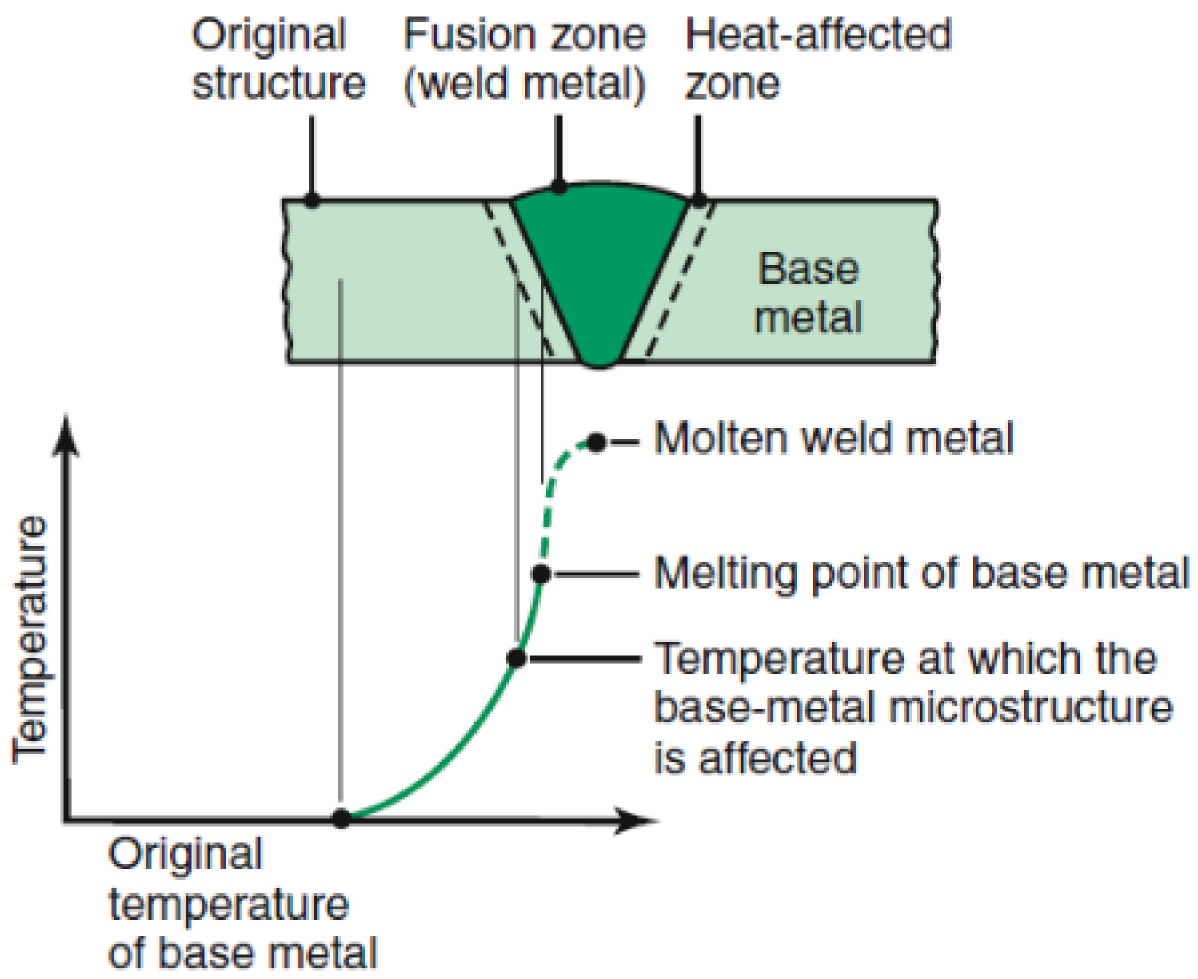
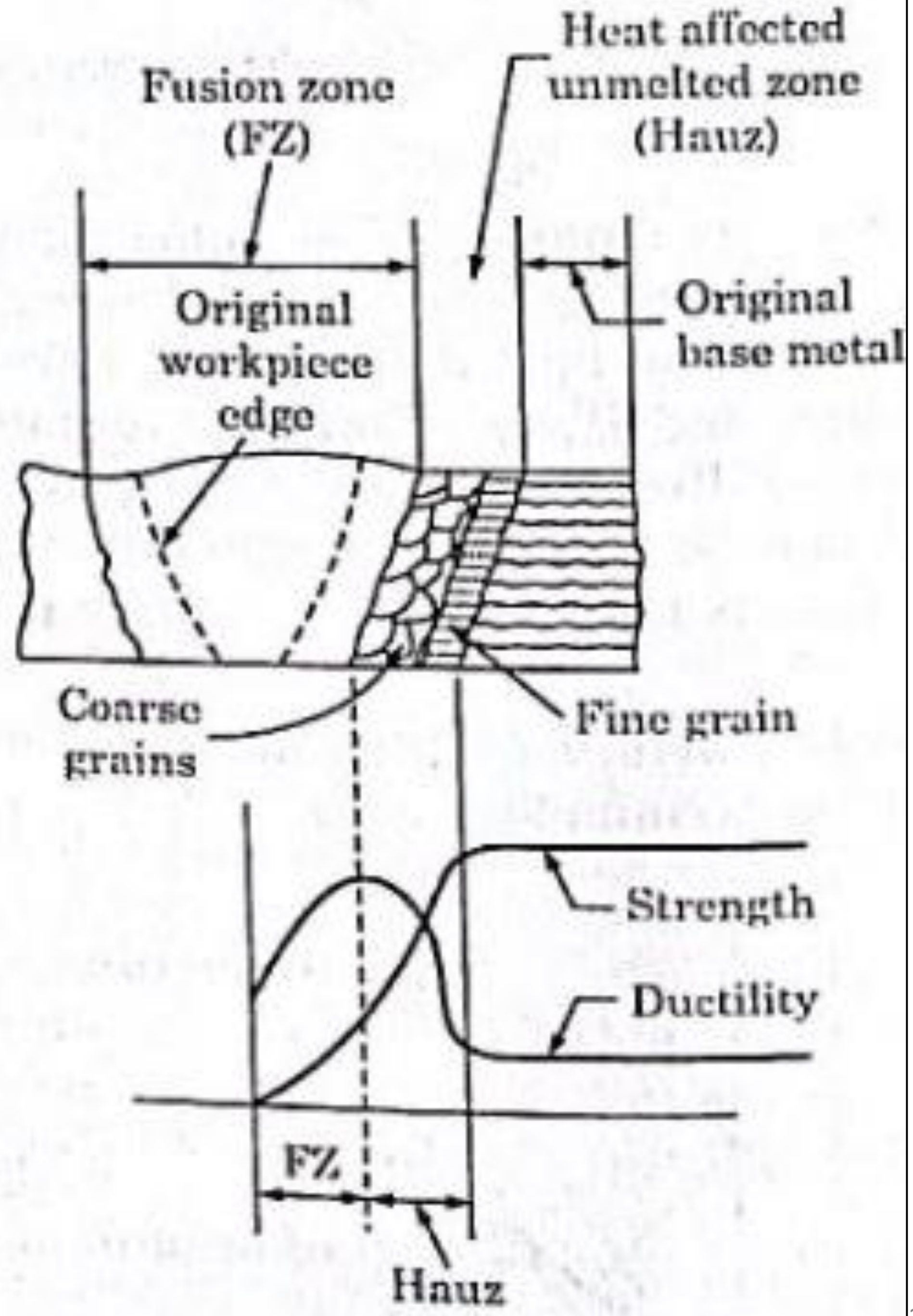


FIGURE 30.17 Characteristics of a typical fusion-weld zone in oxyfuel–gas and arc welding.



- The heat applied during welding *recrystallizes* the elongated grains of the coldworked base metal.
- Grains that are away from the weld metal will recrystallize into fine, equiaxed grains.
- Grains close to the weld metal have been subjected to elevated temperatures for a longer time.
- Consequently, the grains will grow in size (grain growth), and this region will be softer and have lower strength. Such a joint will be weakest at its HAZ.

METALLURGY OF WELD

Structure Of Weld Section

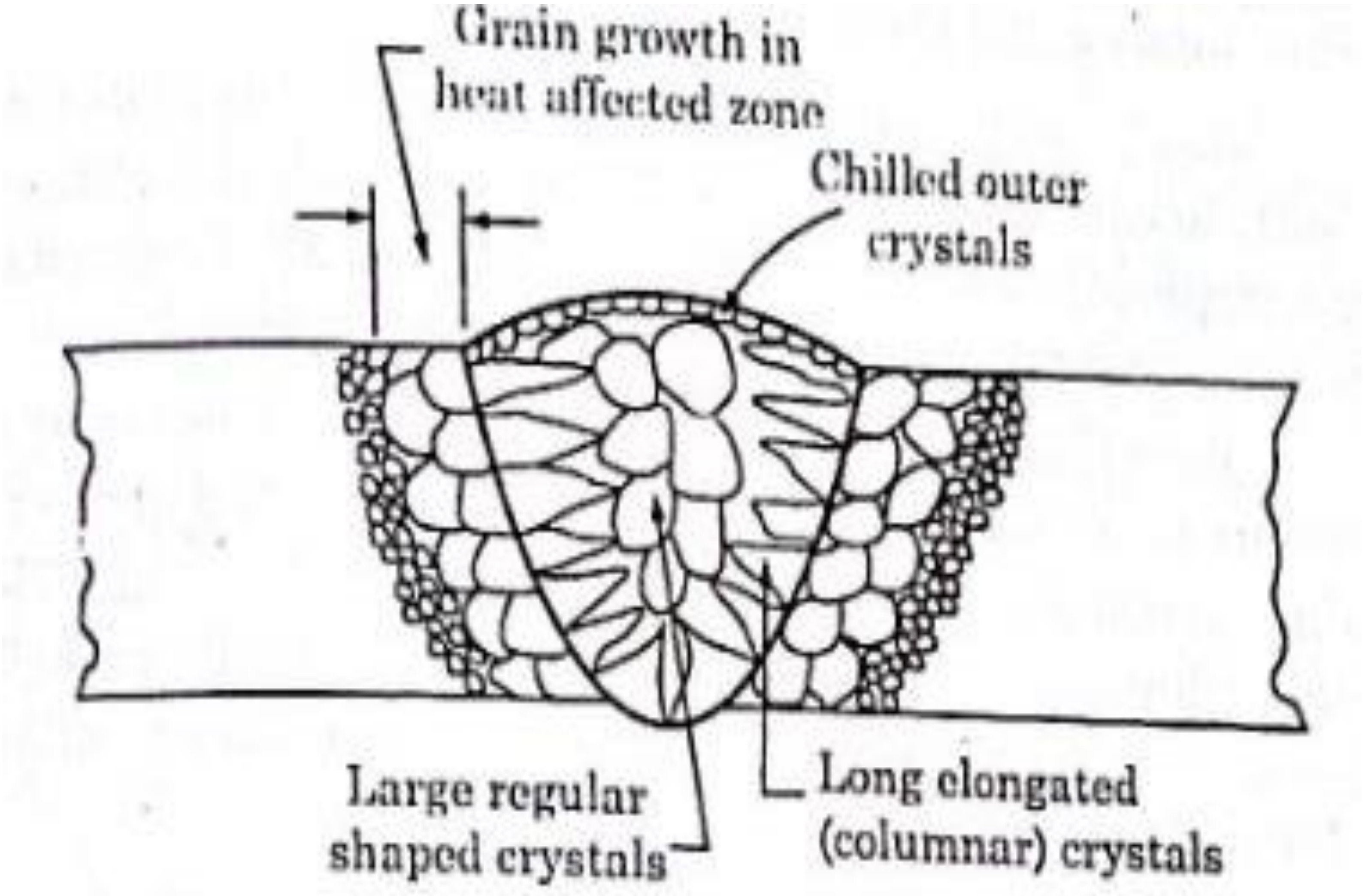
- Columnar (long elongated) crystals are formed near the fusion face due to directional cooling of the weld.

- Since the inner part of the weld cools more uniformly, it result in an enlarged but regular crystal structure.

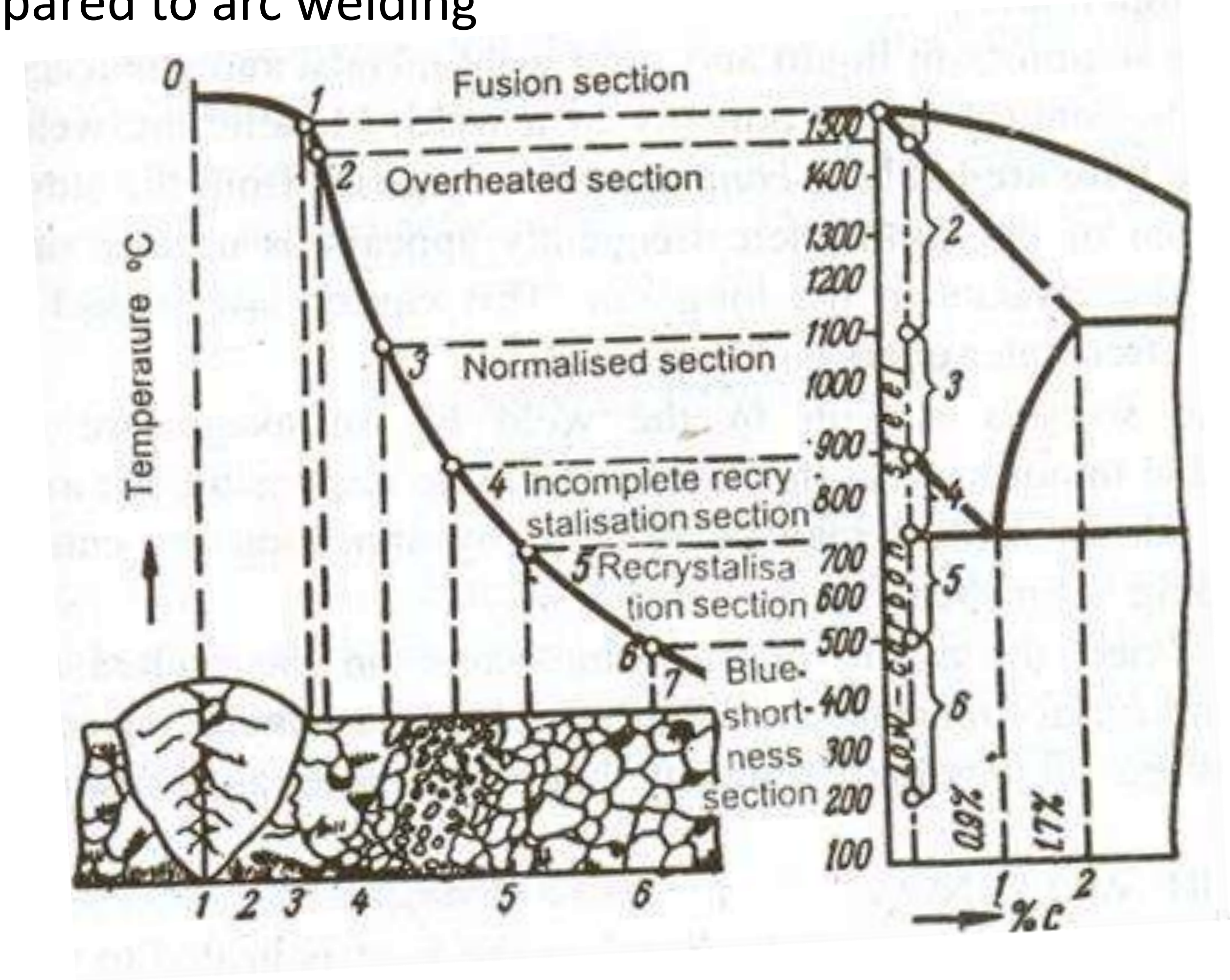
- Surface of the weld being contact with air cools fast and small chilled crystals are formed.

- The parent metal in the HAZ experiences grain growth.

METALLURGY OF WELD
Structure Of Weld Section



- HAZ distinguished in to 3 region
  - Grain growth region (coarse grain)
  - Grain refined region   (fine grain)
  - Transition zone
  - Gas welding have large HAZ compared to arc welding



METALLURGY OF WELD

- The heat affected zone is wide with gas welding than arc welding because heat is concentrated for longer time in gas welding.
- The weld metal, at the molten state has a good capacity of dissolving gases which comes in contact with it such as oxygen, nitrogen.
- As the molten metal cools, this capacity decreases and makes impossible for the gases to escape freely. This causes gas pockets and pores in the weld.

Solidification of the Weld Metal

- After the application of heat and the introduction of the filler metal (if any) into the weld zone, the weld joint is allowed to cool to ambient temperature.
- The *solidification* process is similar to that in casting and begins with the formation of columnar (dendritic) grains.
- These grains are relatively long and form parallel to the heat flow.
- Grain structure and grain size depend on the specific metal alloy, the particular welding process employed, and the type of filler metal. Because it began in a molten state, the weld metal basically has a cast structure, and since it has cooled slowly, it has coarse grains.
- Consequently, this structure generally has low strength, toughness, and ductility. However, the proper selection of filler-metal composition or of heat treatments following welding can improve the mechanical properties of the joint.

- The microstructure depends on the particular alloy, its composition, and the thermal cycling to which the joint is subjected.
- Cooling rates may be controlled and reduced by ***preheating*** the general weld area prior to welding.
- Preheating is important, particularly for metals having high thermal conductivity, such as aluminum and copper.
- Without preheating, the heat produced during welding dissipates rapidly through the rest of the parts being joined.

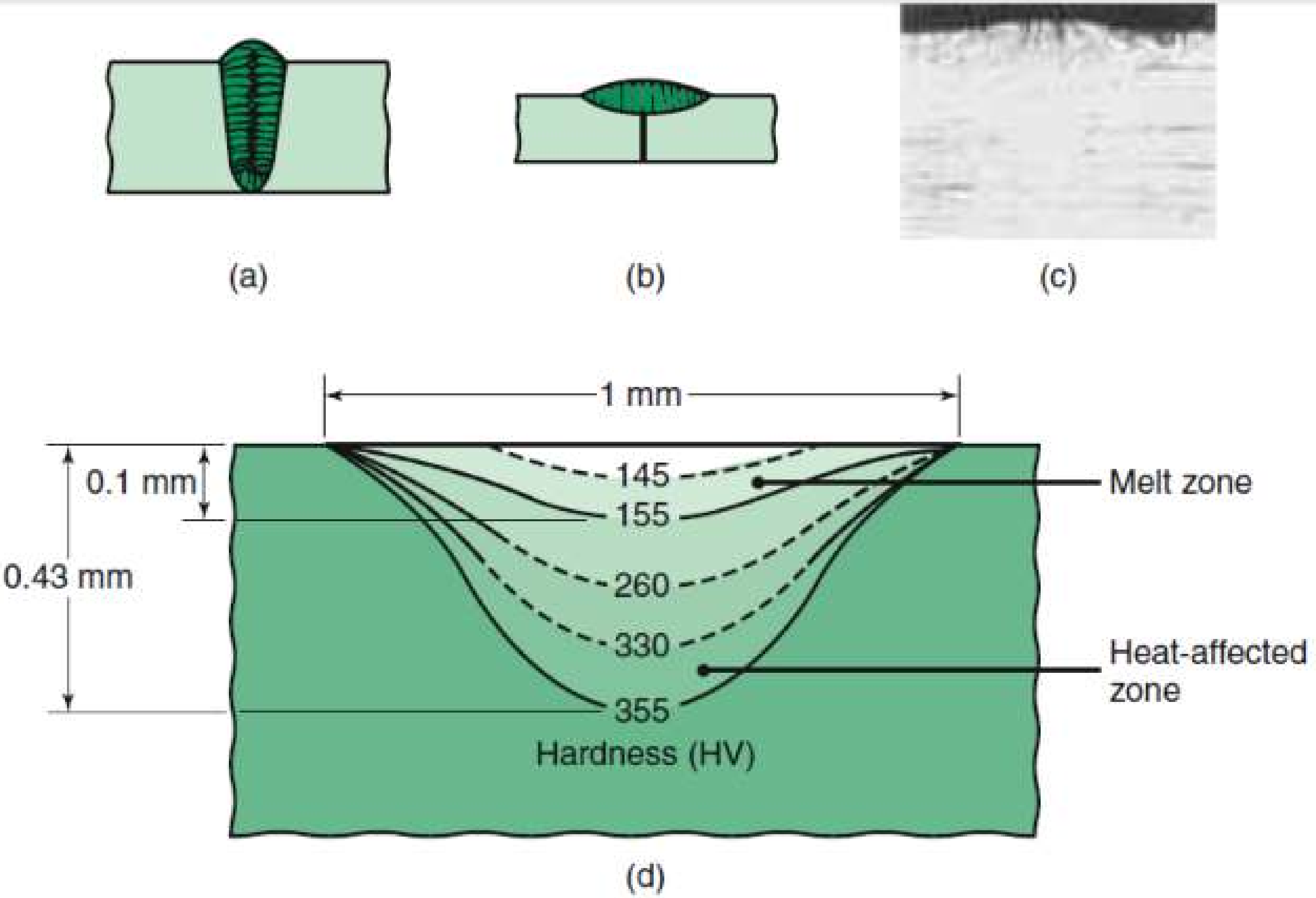


FIGURE 30.18 Grain structure in (a) a deep weld and (b) a shallow weld. Note that the grains in the solidified weld metal are perpendicular to their interface with the base metal. (c) Weld bead on a cold-rolled nickel strip produced by a laser beam. (d) Microhardness (HV) profile across a weld bead.

Gas welding

- **Fusion welding** process
- Gas welding is done by burning a **combustible gas** with air or oxygen in a concentrated flame of high temperature. The purpose of the flame is to heat and melt the parent metal and filler rod of a joint.
- During the welding heat from the flame is concentrated on the joint edges until the metal melts and starts to flow. When the molten metal from both sides melts it starts to fuse, when the metal cools down the two parts become Permanently joined.

Oxy-acetylene gas welding

- Oxy-acetylene gas welding is accomplished by melting the edges or surface to be joined by acetylene gas flame and allowing the molten metal to flow together, thus forming a solid continuous joint upon cooling.

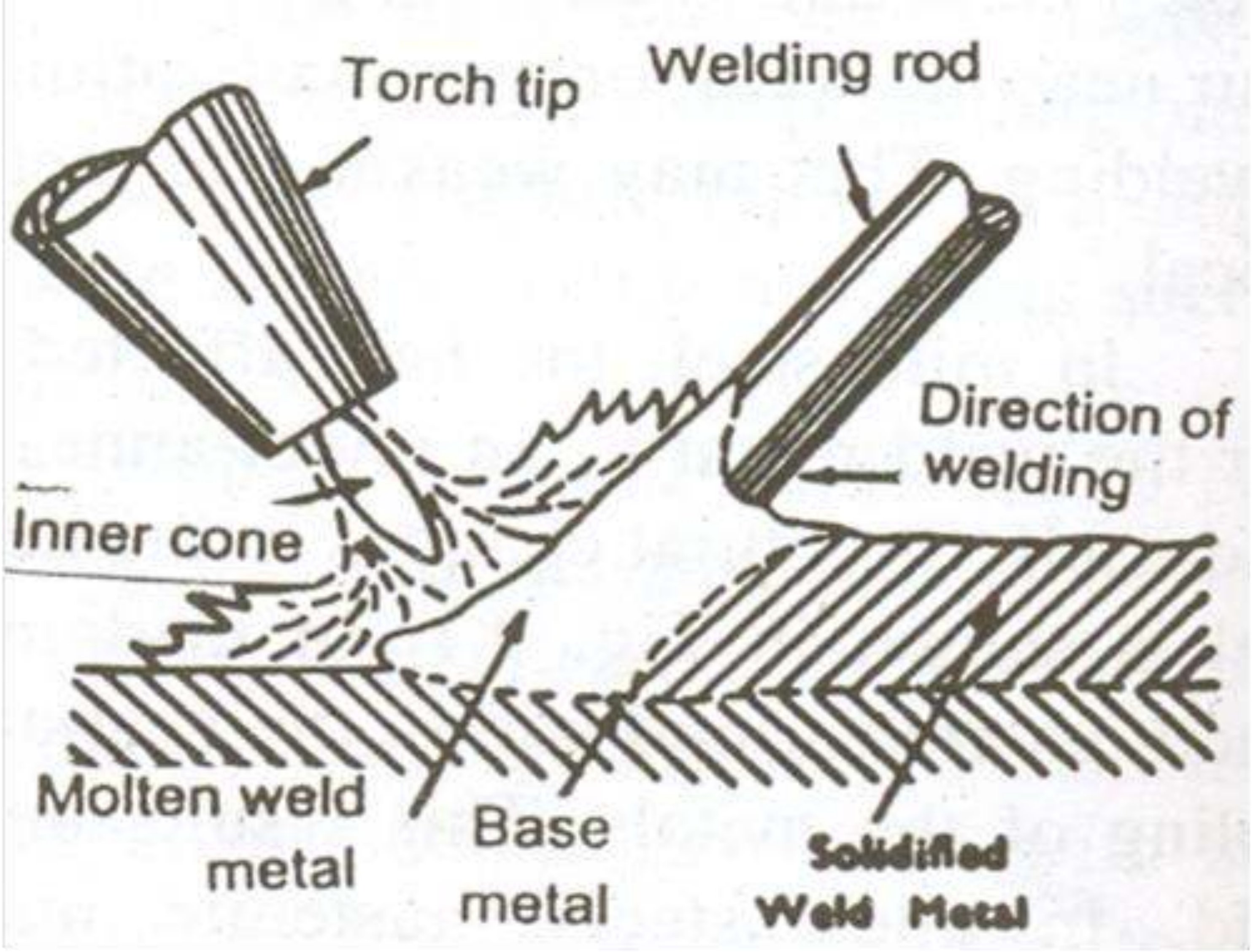
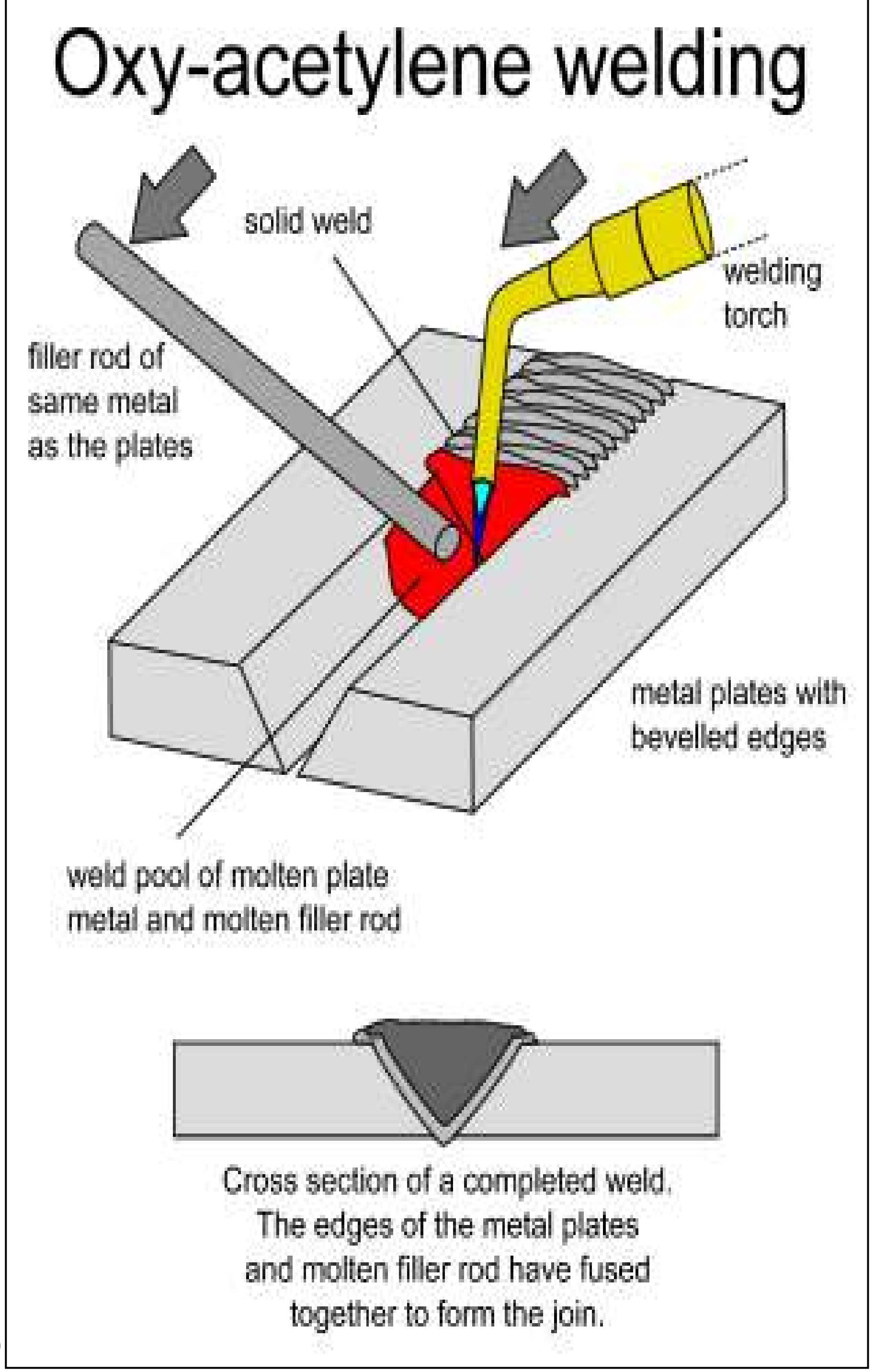
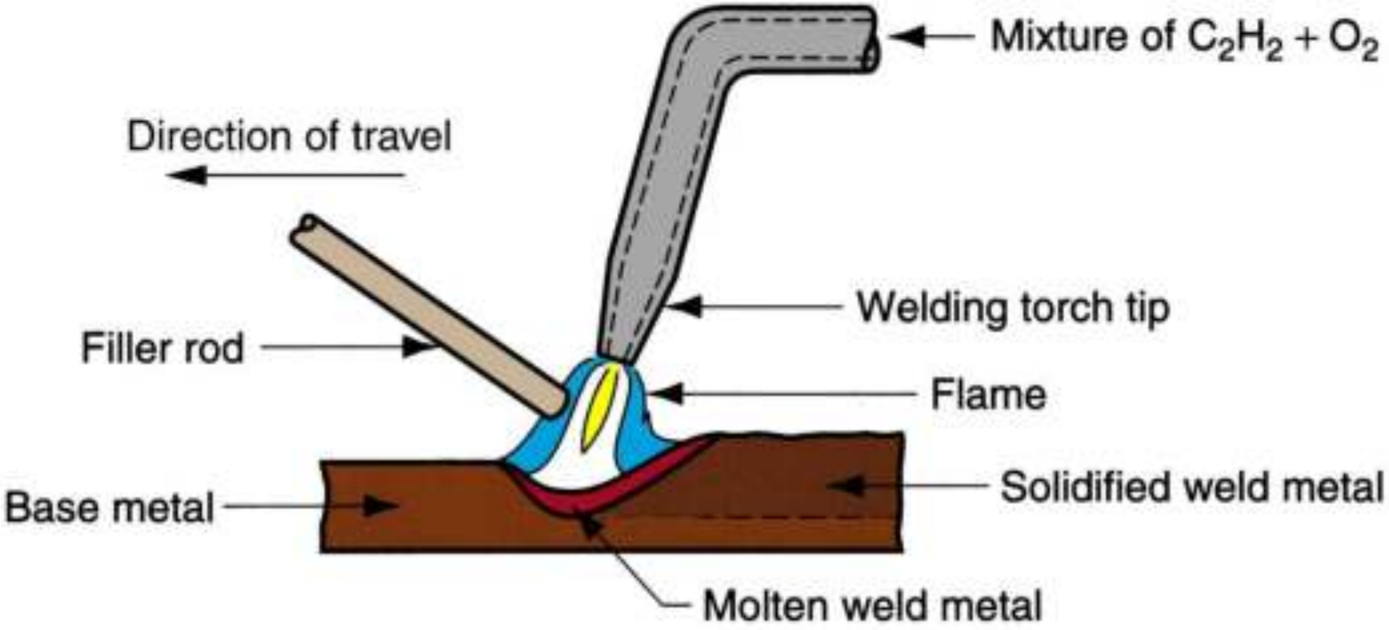


Fig: Oxy Acetylene gas welding



Oxy-acetylene welding
solid weld
welding torch
filler rod of same metal as the plates
metal plates with bevelled edges
weld pool of molten plate metal and molten filler rod
Cross section of a completed weld. The edges of the metal plates and molten filler rod have fused together to form the join.



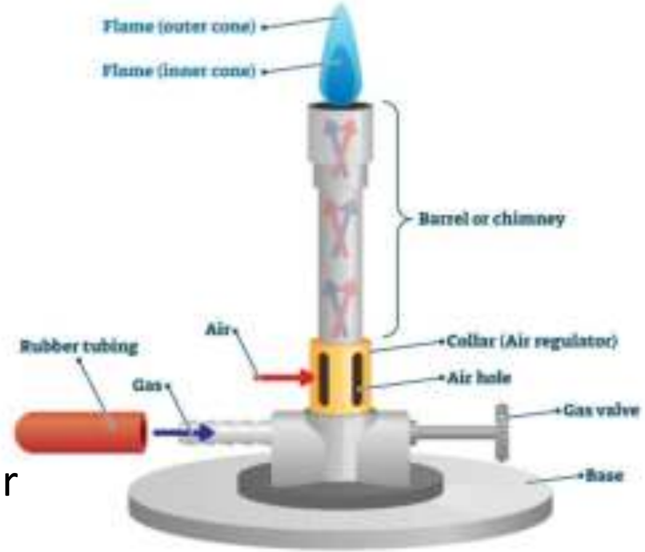
Mixture of $C_2H_2 + O_2$
Direction of travel
Welding torch tip
Filler rod
Flame
Base metal
Solidified weld metal
Molten weld metal

Oxy-hydrogen welding

- The oxygen-hydrogen process was once used extensively to weld low temperature metals such as aluminium, lead, and magnesium
- The process is similar to oxygen -acetylene system, with the only difference being a *special regulator* used in metering the hydrogen gas.

Air –acetylene welding

- This process uses a torch similar to a Bunsen burner and operates on the Bunsen burner principle. The air is drawn into the torch as required and mixes with the fuel flame. The gas is then ejected and ignited, producing an air-fuel flame



Bunsen burner

Weld Metal Protection

- During fusion welding, the molten metal in the weld “puddle” is susceptible to oxidation
- Must protect weld puddle (arc pool) from the atmosphere
- Methods
  1. Weld Fluxes
     - The function of limestone (calcium carbonate) is to remove impurities from the molten iron. The limestone reacts chemically with impurities, acting like a flux (meaning to flow as a fluid) that causes the impurities to melt at a low temperature. The limestone combines with the impurities and forms a slag (which is light), floats over the molten metal, and, subsequently, is removed. Dolomite (an ore of calcium magnesium carbonate) also is used as a flux.
  2. Inert Gases
  3. Vacuum

Filler rod

- Filler rods are used when additional filler metal is required in the weld area.
- Made with metal compactable to base metal and may be coated with flux.

Flux

- During welding if the metal is heated/melted in air, oxygen from air combines with the metal to form oxides which results in poor quality, low strength etc..
- Fluxes protect the weld pool from contamination by oxygen and nitrogen, they are normally in paste form placed on a heated filler rod before welding begins.
- A substance that prevents formation of oxides and other contaminants in welding, or dissolves them and facilitates removal.
- The purpose of the flux is to retard oxidation of the surfaces of the parts being welded by generating a *gaseous shield* around the weld zone.
- Provides protective atmosphere for welding
- Slag (compounds of oxides, fluxes, and electrode-coating materials) is formed when flux chemically reacts with oxides. Slag floats over the molten metal which later removed.
- Slag cover the top of the molten pool of metal and thus help to keep out atmospheric oxygen and other gases.

Gas welding equipment

- Gas cylinders
- Hose and hose fittings
- Pressure regulator
- Welding tip
- Welding torch.
- Goggles, gloves and spark lighter

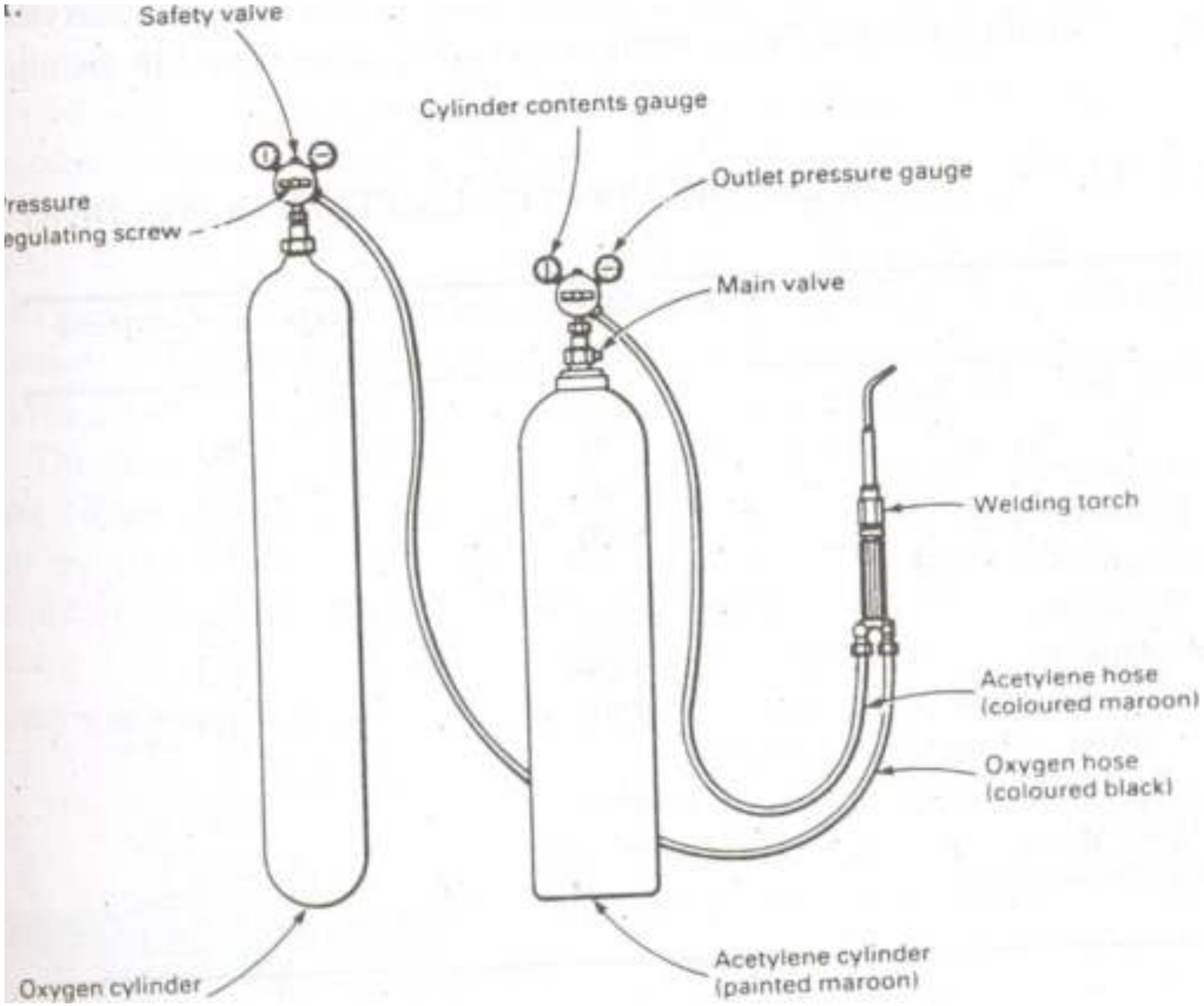


FIGURE : Oxy-acetylene welding set

1. Gas Cylinders

Pressure

Oxygen – 120 ksc

vol -6.91 m3

Acetylene – max 15 ksc

2. Regulators

Reduce cylinder pressure to Working pressure of oxygen 1 kg/cm2 and produce study flow

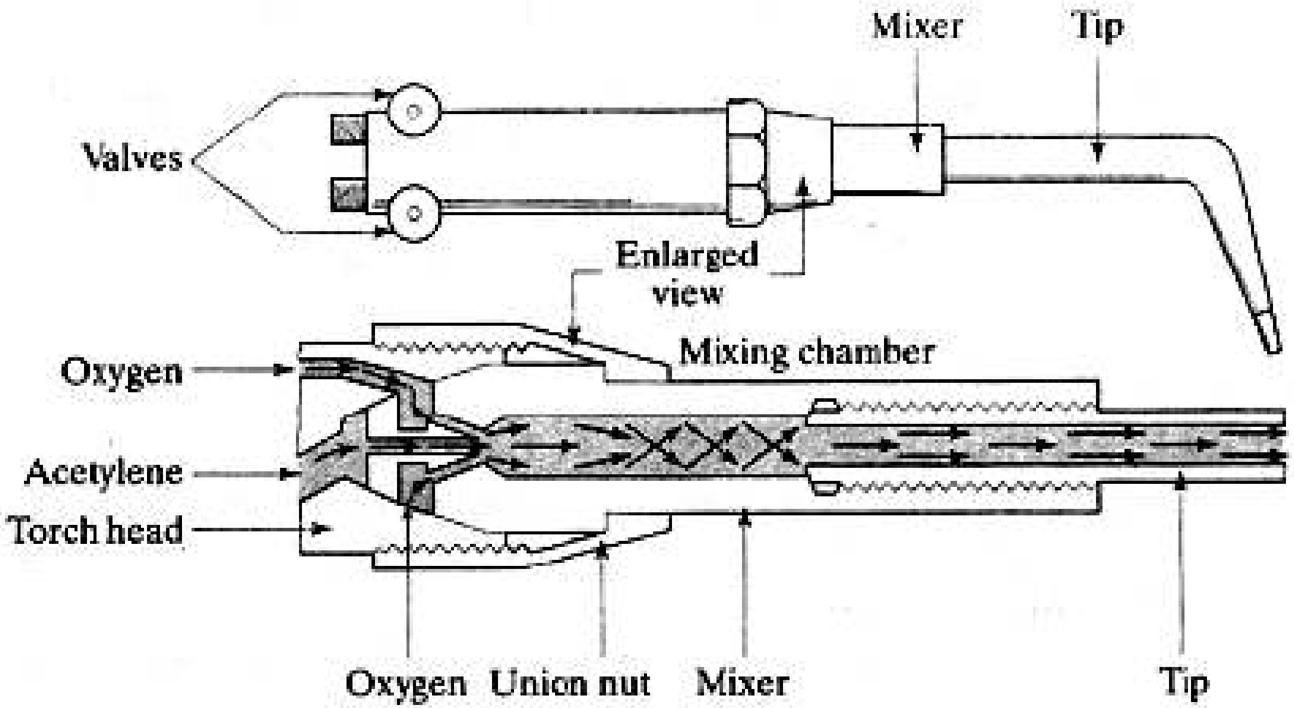
Working pressure of acetylene 0.15 kg/cm2

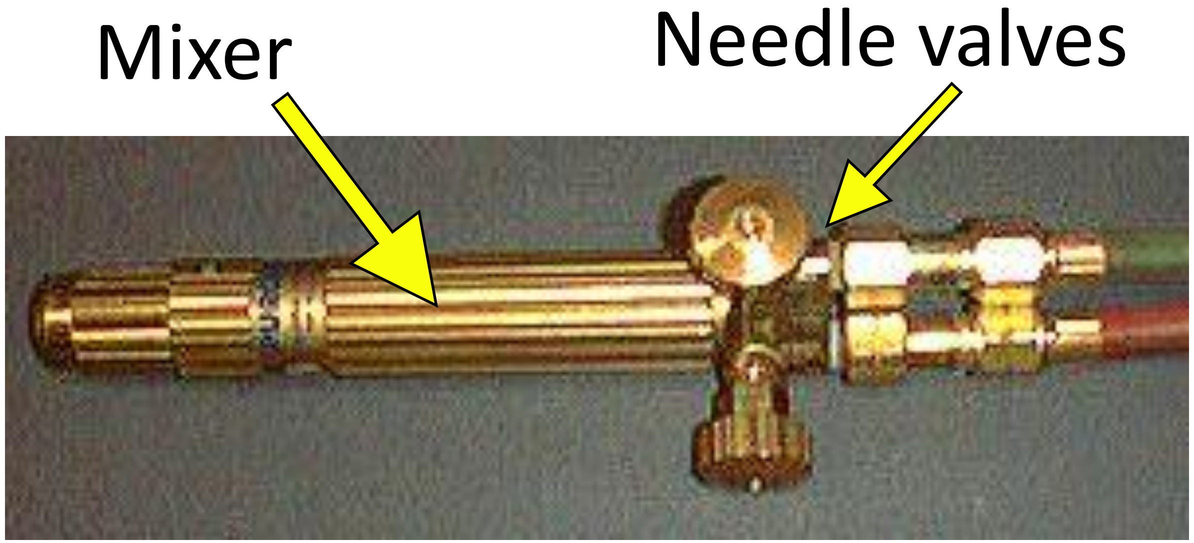
3. Pressure Gauges

4. Hoses

5. Welding torch

6.Flashback Arrestors


Mixer
Tip
Valves
Enlarged
view
Mixing chamber
Oxygen
Acetylene
Torch head
Oxygen
Union nut
Mixer
Tip


Mixer
Needle valves

Type of flames

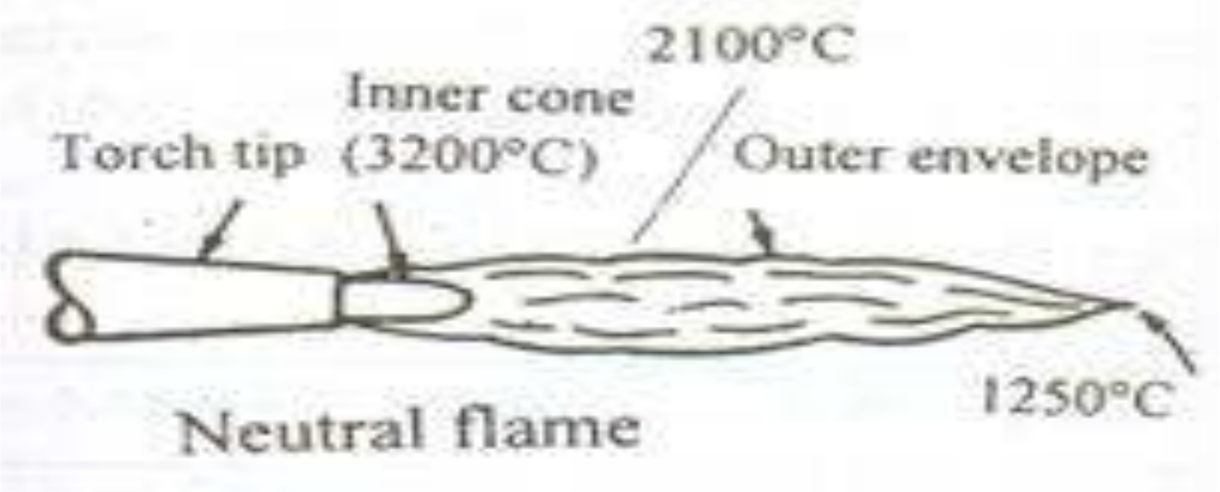
<u>Neutral Flame</u>

When oxygen and acetylene are supplied to torch in equal volumes

- A *neutral flame* has two definite zones
  - a sharp inner cone extending a short distance from tip of the torch
  - an outer cone or envelope only faintly luminous and of a bluish color
  - Fusion of metal is achieved by passing the inner cone of the flame over the metal
- Primary reaction in inner core
- ***$2C_2H_2 + 20_2 = 4CO + 2H_2$ + heat***

One third of total heat

- secondary reaction in outer
- ***$4CO + 2H_2 + 30_2 = 4C0_2 + 2H_20$+heat***
- *Temperature developed is 3300 degree C*
- Note that the reaction also produces water vapor.
- Used to weld all ferrous and non furors metal, except Brass

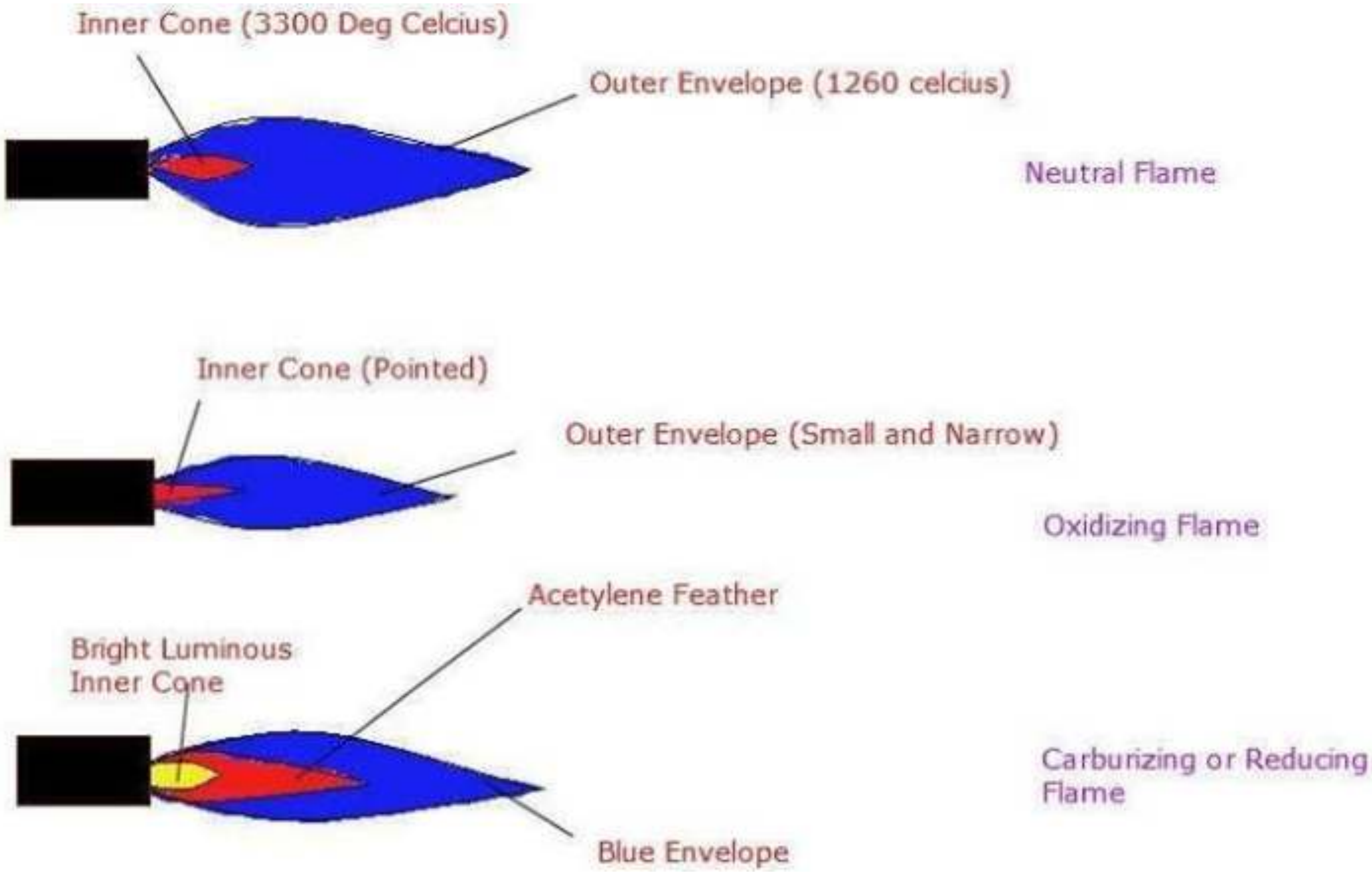


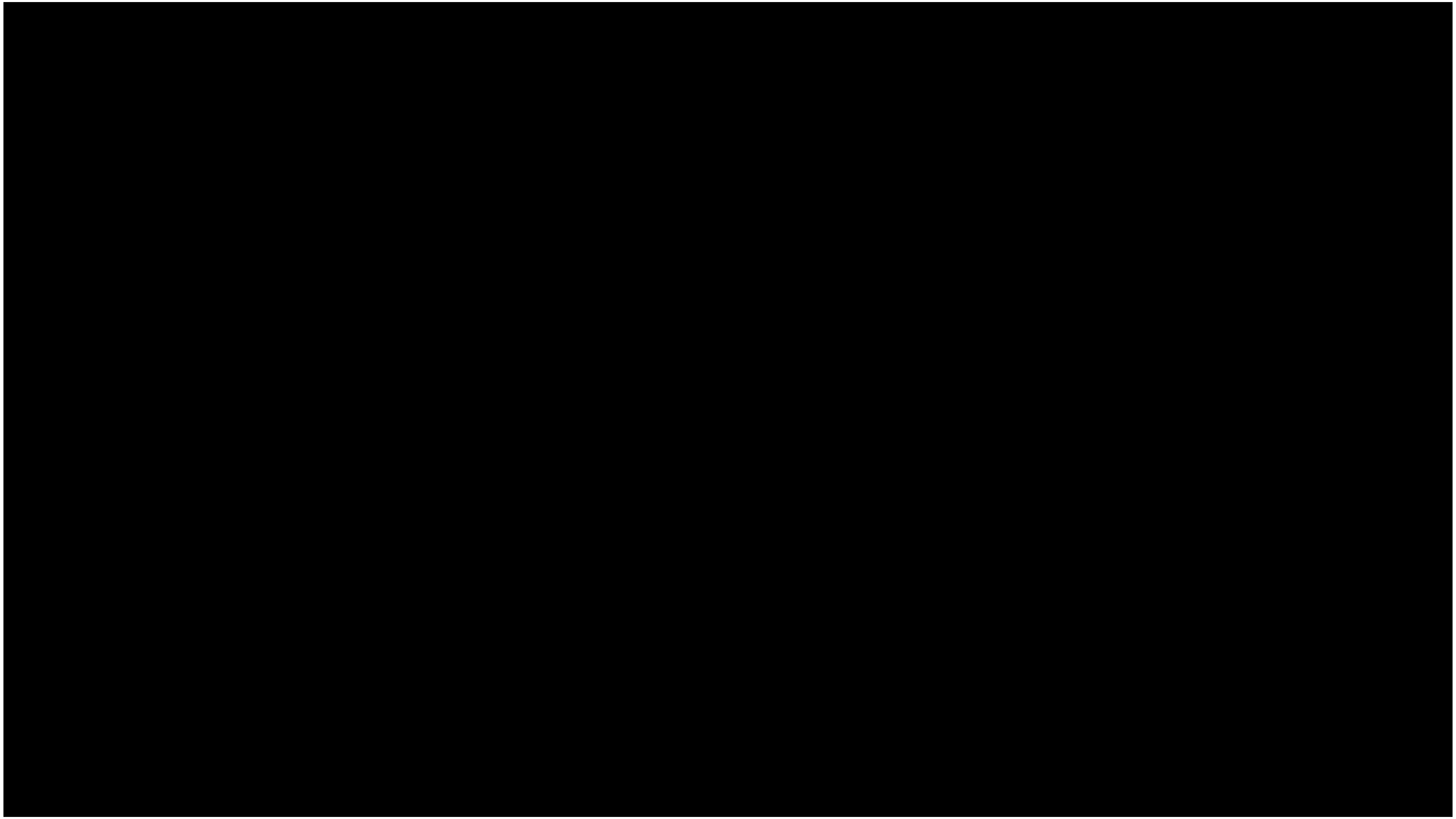
Oxidizing flame

- An *oxidizing flame* is one in which there is an excess of oxygen. This flame has two zones :
  - $O_2 : C_2H_2$ is ratio about 1.5
  - The small pointed inner cone which has much blue in color and
  - Much shorter outer cone or envelope
  - Temperature is 3482 degree C
  - Not suitable for steel, Al, and Mn. It oxidize the metal
  - Used for joining high melting point materials
  - Used for weld Brass?????

Carburizing Flame

- A carburizing flame is one in which there is an excess of acetylene. This flame has three zones
  - $O_2 : C_2H_2$ is ratio about 0.95
  - Temperature 3037 degree c
  - The sharply defined inner cone, and long
  - An intermediate feather of whitish color, and
  - The bluish outer cone.
  - Temperature is lower so it can used for brazing and soldering
  - Not suitable for joining high melting point materials
  - Not used to join ferrous metals. Since carbon absorption leads to brittleness and reduce toughness.
  - But it can used for high carbon steel

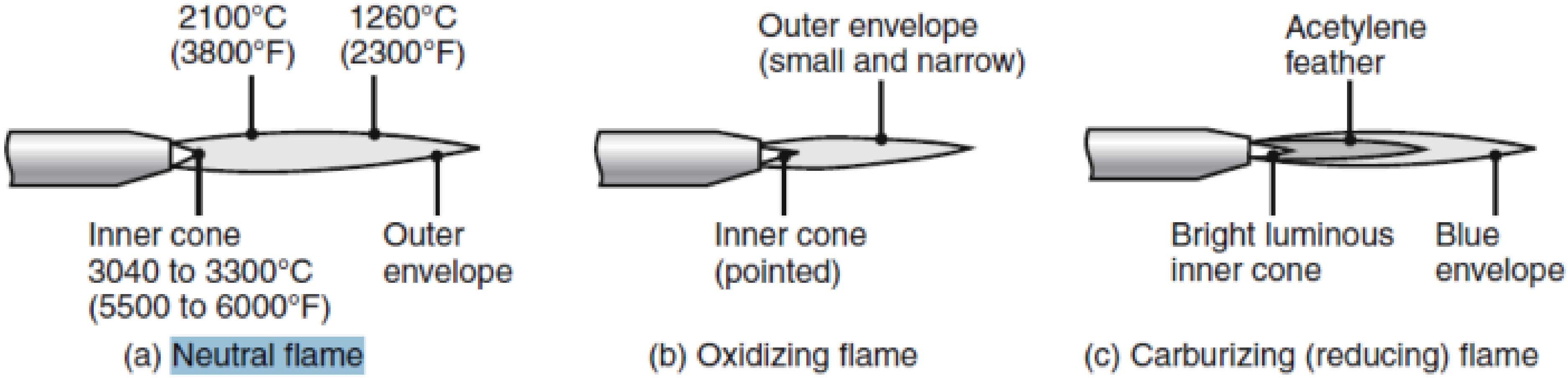

Inner Cone (3300 Deg Celcius)
Outer Envelope (1260 celcius)
Neutral Flame
Inner Cone (Pointed)
Outer Envelope (Small and Narrow)
Oxidizing Flame
Acetylene Feather
Bright Luminous
Inner Cone
Carburizing or Reducing
Flame
Blue Envelope



Neutral

Oxidising

Carburising

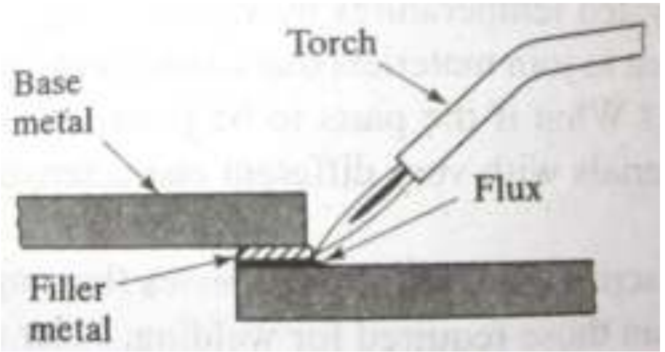


Applications

- For joining of thin material
- In sheet metal fabrication plants
- For joining ferrous and non ferrous metals
- For joining materials in whose case extremely high temperature would cause certain elements in the metal to escape into atmosphere
- For joining materials in whose case extremely high temperature or rapid heating and cooling of the job would produce unwanted or harmful changes in the metal

Brazing

- Brazing is a joining process in which a filler metal is placed at or between the surface to be joined
- And the temperature is raised enough to melt the filler metal but not the work piece
- The molten metal fills the closely fitting space by capillary action
- Upon cooling and solidification of the filler metal, a strong joint is obtained
- There are two types of brazing,
    - Ordinary brazing
    - Braze welding



- Filler metals used for brazing generally melt above 450°C
- Temperature employed in brazing are below the melting point (solidus temperature) of the metal to be joined
- Fluxes are also used to prevent oxidation, clean surface need for brazing


NOCOLOK® Zn Flux

BRAZING

Brazing methods

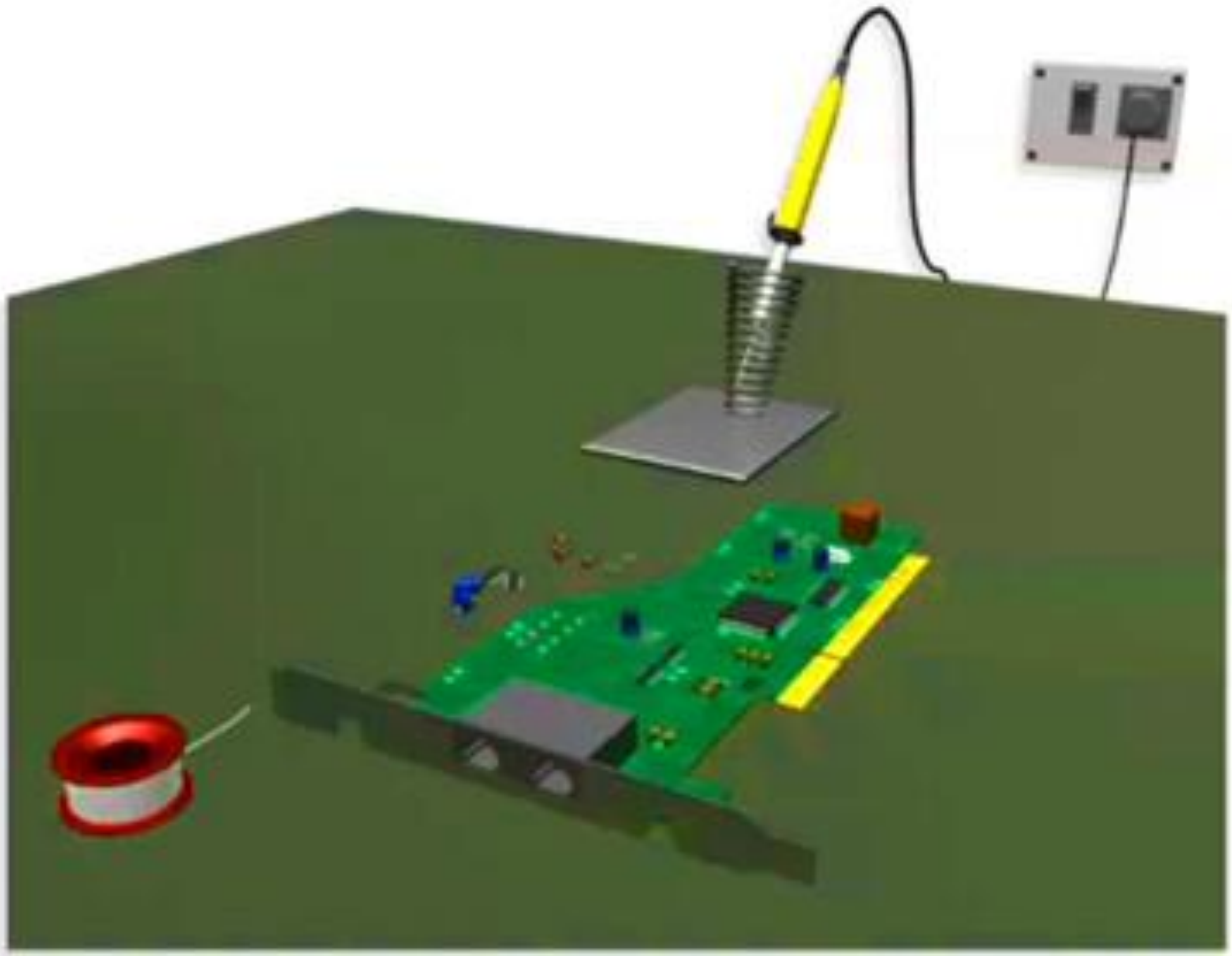
1. Torch brazing
   - Heat source is oxyfuel gas with a carburizing flame. Brazing is performed by first heating the joint with the torch, then depositing the brazing rod or wire in the joint
2. Furnace brazing
   - Here the braze metal is placed in between the work piece along with flux. Keep it in furnace, adjust the temperature , the braze metal melts, then allow it to solidify
3. Induction Brazing
   - The source of heat is the induction heating by high frequency AC current
4. Resistance Brazing
   - The source of heat is the electrical resistance of the components to be brazed

5. Dip brazing
   - Dipping the assemblies to be brazed into either a molten filler metal bath or a molten salt bath at a temperature just above the melting point of the filler metal
6. Infrared brazing
   - The source of heat is a high intensity quartz lamp
7. Diffusion brazing
   - Carried out in a furnace where, with proper control of temperature and time, the filler metal diffuses in to the surfaces of the components to be joined

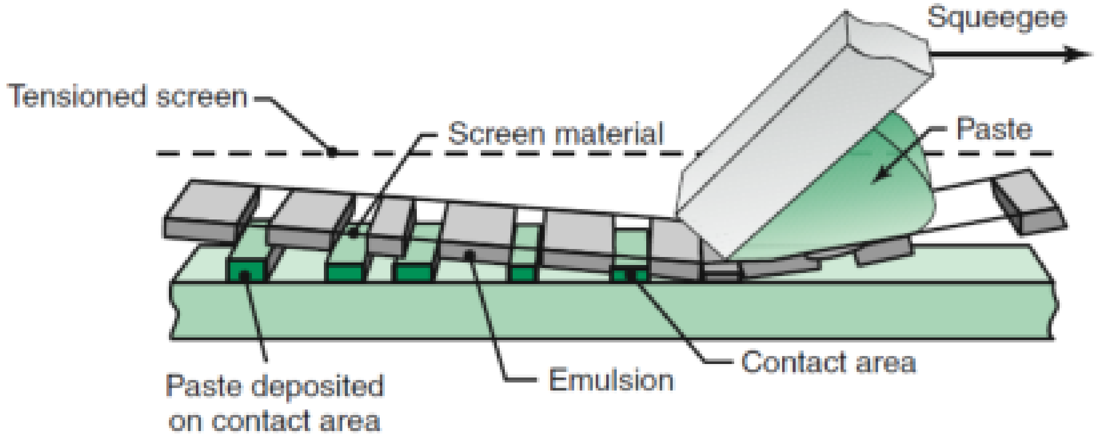
Soldering

- A joining process by which two substrates are bonded together using a filler metal (solder) with a liquidus temperature that generally does not exceed 450^oC
- The base materials remain solid during the bonding process.
- The solder is usually distributed between the properly fitted surfaces of the joint by capillary action
- Heat source for soldering are usually soldering irons, torches or ovens.
- Soldering techniques are,
  - Torch soldering
  - Furnace soldering
  - Iron soldering (with use of soldering iron)
  - Induction soldering

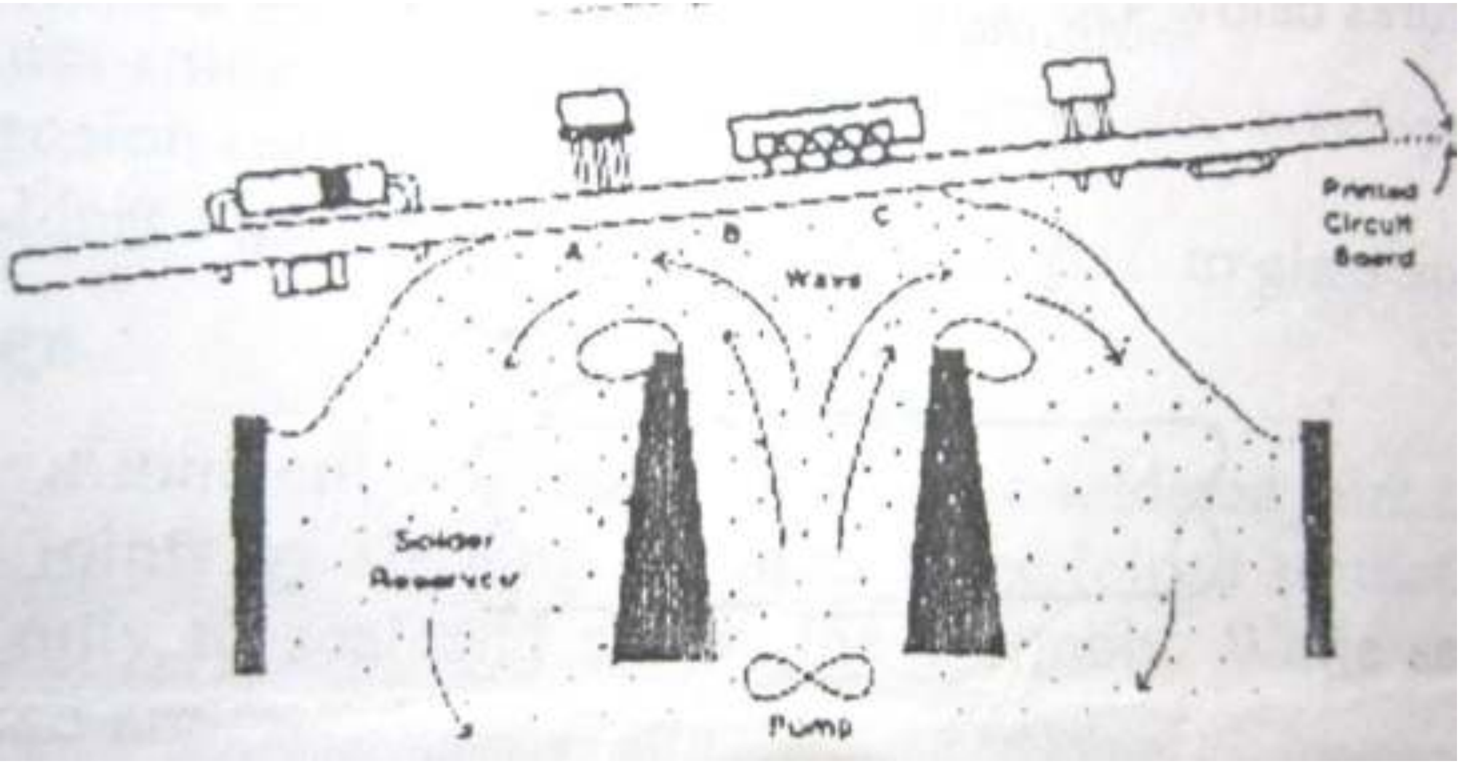
SOLDERING



- Resistance soldering
- Dip soldering
- Infrared soldering
- Ultrasonic soldering
- Reflow (paste) soldering
  - Solder pastes are solder-metal particles held together by flux and by binding and wetting agents. The paste is placed directly onto the joint, or on flat object for finer details.
  - Once the paste has been placed and joint assembled , the paste is heated in a furnace and reflow soldering takes place.



- Wave soldering
  - One of the primary techniques for mass assembly of printed wiring boards involving through holes, surface mount devices, or a combination of these two technologies
  -




AGROWTEK
Technology to Help You Grow

- **Difference between brazing and welding?**

- **Difference between brazing and soldering?**

Adhesive bonding

- Many components and products can be joined and assembled by the use of an adhesive rather than by one of the joining methods described thus far
- Common application of adhesive bonding are,
  - Labeling, packaging, book binding, footwear
- Plywood is a typical example of the adhesive bonding of several layers of wood with glue
- Adhesive are available in several forms
  - Liquid, paste, solution, emulsion, powder, tape and film
- When applied adhesive generally are about 0.1 mm thick
- An adhesive need following properties for better joint
  - Strength: shear and peel
  - Toughness
  - Resistance to various fluids and chemicals
  - Resistance to environmental degradation, including heat and moisture
  - Capability to wet the surfaces to be bonded.

- The three basic types of adhesives are the following
  - Natural adhesives (starch, dextrin, soya flour)
  - Inorganic adhesives(sodium silicate and magnesium oxychloride)
  - Synthetic organic adhesive (thermoplastics or thermosetting polymers)
- Adhesion is generally due to molecular attraction between adhesive and work piece
- The adhesive is applied between the faying surfaces after cleaning them thoroughly by chemical or mechanical means
- Electrically conducting adhesives replace lead based solder alloys in electronic industry
- Adhesives can be used for bonding a wide variety of similar and dissimilar metallic and non metallic materials and components with different shapes, sizes and thickness

Adhesive Systems. These may be classified on the basis of their specific chemistries:

- Epoxy-based systems: These systems have high strength and high-temperature properties to as high as 200°C (400°F). Typical applications include automotive brake linings and bonding agents for sand molds for casting.
- Acrylics: These adhesives are suitable for applications with substrates that are not clean.
- Anaerobic systems: The curing of these adhesives is done under oxygen deprivation, and the bond is usually hard and brittle. Curing times can be reduced by external heat or by ultraviolet (UV) radiation.
- Cyanoacrylate: The bond lines are thin and the bond sets within 5 to 40s.
- Urethanes: These adhesives have high toughness and flexibility at room temperature, and they are used widely as sealants.
- Silicones: Highly resistant to moisture and solvents, these adhesives have high impact and peel strength; however, curing times are typically in the range from 1 to 5 days.

TABLE 12.6 Typical properties and characteristics of chemically reactive structural adhesives.

	Epoxy	Polyurethane	Modified acrylic	Cyanocrylate	Anaerobic
Impact resistance	Poor	Excellent	Good	Poor	Fair
Tension-shear strength, MPa	15–22	12–20	20–30	18.9	17.5
Peel strength[a], N/m	<523	14,000	5250	<525	1750
Substrates bonded	Most	Most smooth, nonporous	Most smooth, nonporous	Most non-porous metals or plastics	Metals, glass, thermosets
Service temperature range, °C	55 to 120	40 to 90	70 to 120	55 to 80	55 to 150
Heat cure or mixing required	Yes	Yes	No	No	No
Solvent resistance	Excellent	Good	Good	Good	Excellent
Moisture resistance	Good-Excellent	Fair	Good	Poor	Good
Gap limitation, mm	None	None	0.5	0.25	0.60
Odor	Mild	Mild	Strong	Moderate	Mild
Toxicity	Moderate	Moderate	Moderate	Low	Low
Flammability	Low	Low	High	Low	Low

Note: (a) Peel strength varies widely depending on surface preparation and quality.

Major advantages of adhesive bonding

- The interfacial bond has sufficient strength for structural applications, but is also used for nonstructural purposes, such as sealing, insulation, the prevention of electrochemical corrosion between dissimilar metals, and the reduction of vibration and of noise (by means of internal damping at the joints).
- Adhesive bonding distributes the load at an interface and thereby eliminates localized stresses that usually result from joining the components with mechanical fasteners, such as bolts and screws. Moreover, structural integrity of the sections is maintained (because no holes are required).
- The external appearance of the bonded components is unaffacted.
- Very thin and fragile components can be bonded without significant increase in their weight.
- Porous materials and materials of very different properties and sizes can be joined.
- Because adhesive bonding usually is carried out at a temperature between room temperature and about 200°C (400°F), there is no significant distortion of the components or change in their original properties. Avoiding distortion is important, particularly for materials that are heat sensitive.

Major disadvantages of adhesive bonding

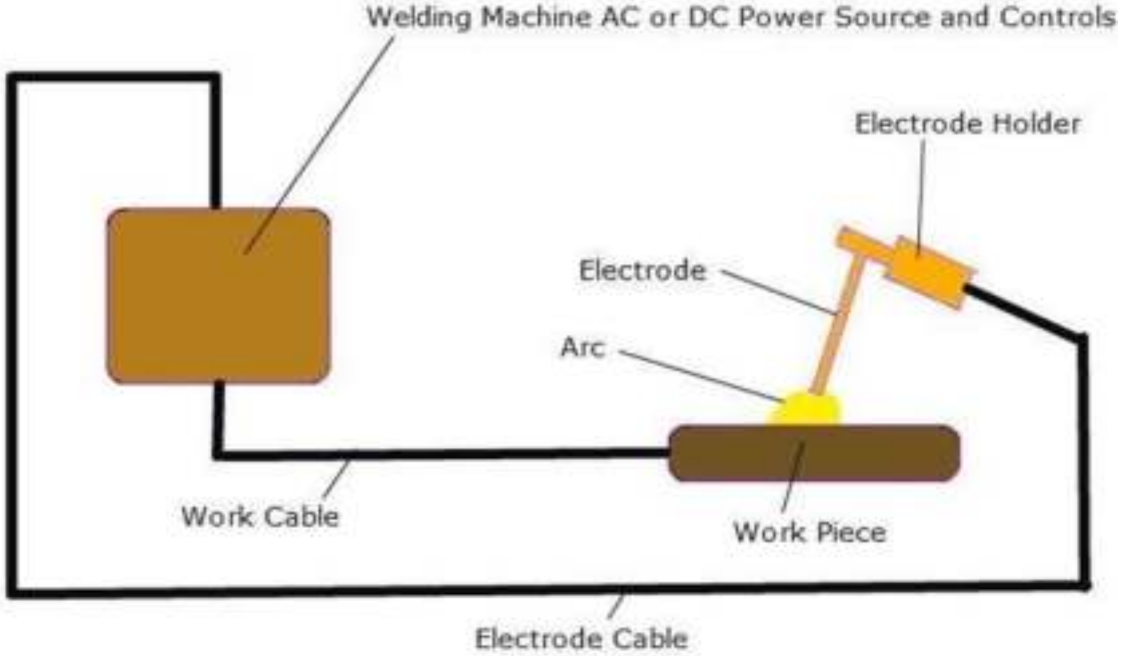
- There is a limited range of service temperatures.
- Bonding time can be long.
- There is a need for great care in surface preparation.
- Bonded joints are difficult to test nondestructively, particularly for large structures.
- The limited reliability of adhesively bonded structures during their service life and under hostile environmental conditions (such as degradation by temperature, oxidation, stress corrosion, radiation, or dissolution) may be a significant concern.

Applications

- Major industries that use adhesive bonding extensively are the aerospace, automotive, appliances, and building products industries.
- Applications include
  - automotive brake-lining assemblies,
  - laminated windshield glass,
  - appliances, helicopter blades,
  - honeycomb structures, and aircraft bodies and control surfaces.
- An important consideration in the use of adhesives in production is *curing time*, which can range from a few seconds (at high temperatures) to several hours (at room temperature), particularly for thermosetting adhesives.
- Thus, production rates can be low compared with those of other joining processes. Furthermore, adhesive bonds for structural applications rarely are suitable for service above 250°C (500°F).
- Nondestructive inspection of the quality and strength of adhesively bonded
- components can be difficult.

ARC WELDING

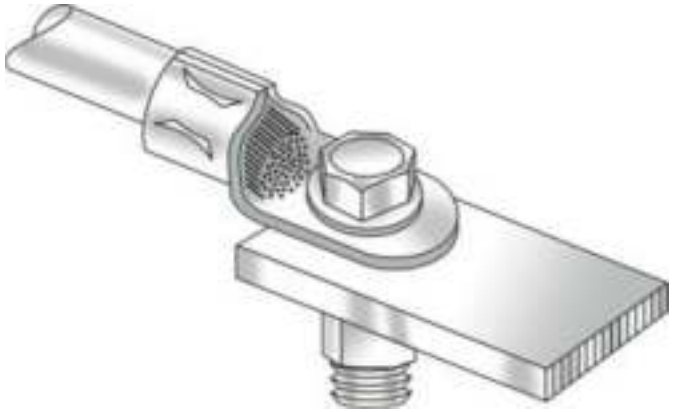
- Here source of heat is electric arc.
- The arc column is generated between an anode, which is positive pole of DC power supply, and the cathode the negative pole.
- When these two conductors of an electric circuit are brought tougher and separated by a small distance (2 to 4 mm) such that the current continuous to flow through a path of ionized particle called plasma, and an arc is formed.
- The heat of the arc raises the temperature of the parent metal which is melted forming a pool of molten metal.



- Two third of heat developed near the positive terminal (anode) remaining one third is developed near the negative terminal(cathode).
- The electrode metal is also melted and is transformed into molten metal
- Deposited metal serves to fill and bond the joint.
- The arc generates temperatures of about 30,000°C

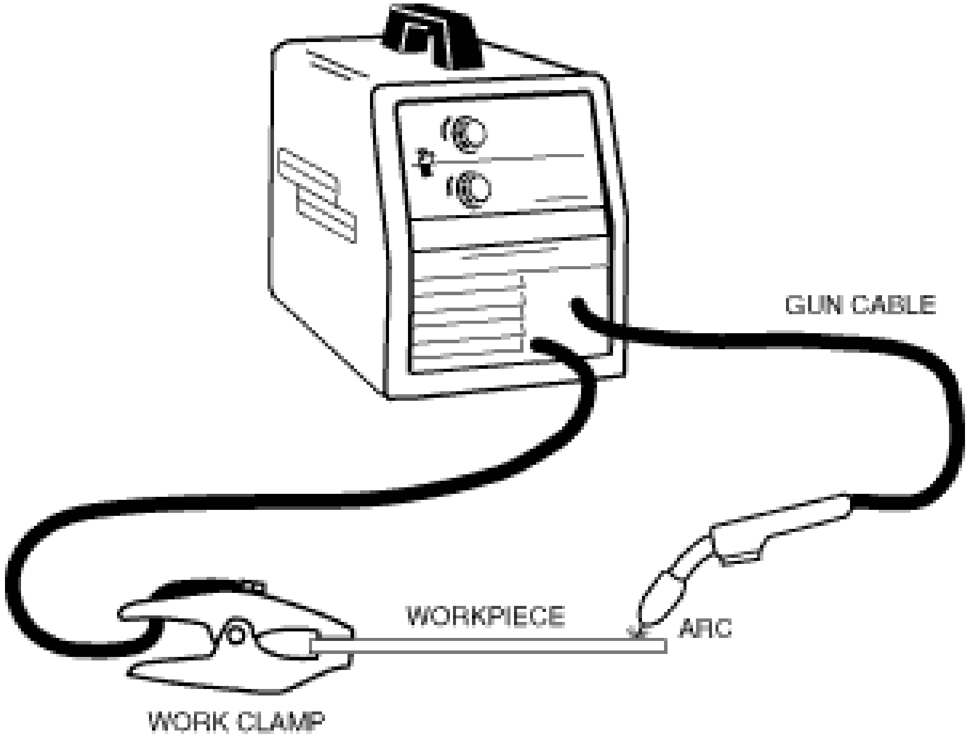
Equipment

- AC or DC machine
- Electrode
- Electrode holder
- Cable, cable connectors
- Cable lug
- Chipping hammer
- Wire brush
- Helmet
- Safety goggles
- Hand gloves



Welding cable

- Two types of cable,
  - Electrode lead
  - Ground lead
- The cables are insulated with rubber, above this insulation there is an outer jacket of durable layer of rubber of neoprene



DC Power Source

Electrodde polarity in arc welding

- Two third of heat developed near the positive terminal (anode)

1. Straight polarity (DCSP)
   - Electrode connected to negative terminal and work piece to the positive terminal
   - For thick material welding
   - Used where non-consumable electrode are used.to minimize heat losses
2. Reverse polarity(DCRP)
   - Electrode to positive terminal and work piece to negative terminal
   - For welding thin material
   - For consumable electrode is used, the metal transfer from the wire electrode to the work piece is more uniform, frequent and better directed if the electrode is made positive.

Arc AC welding power sources

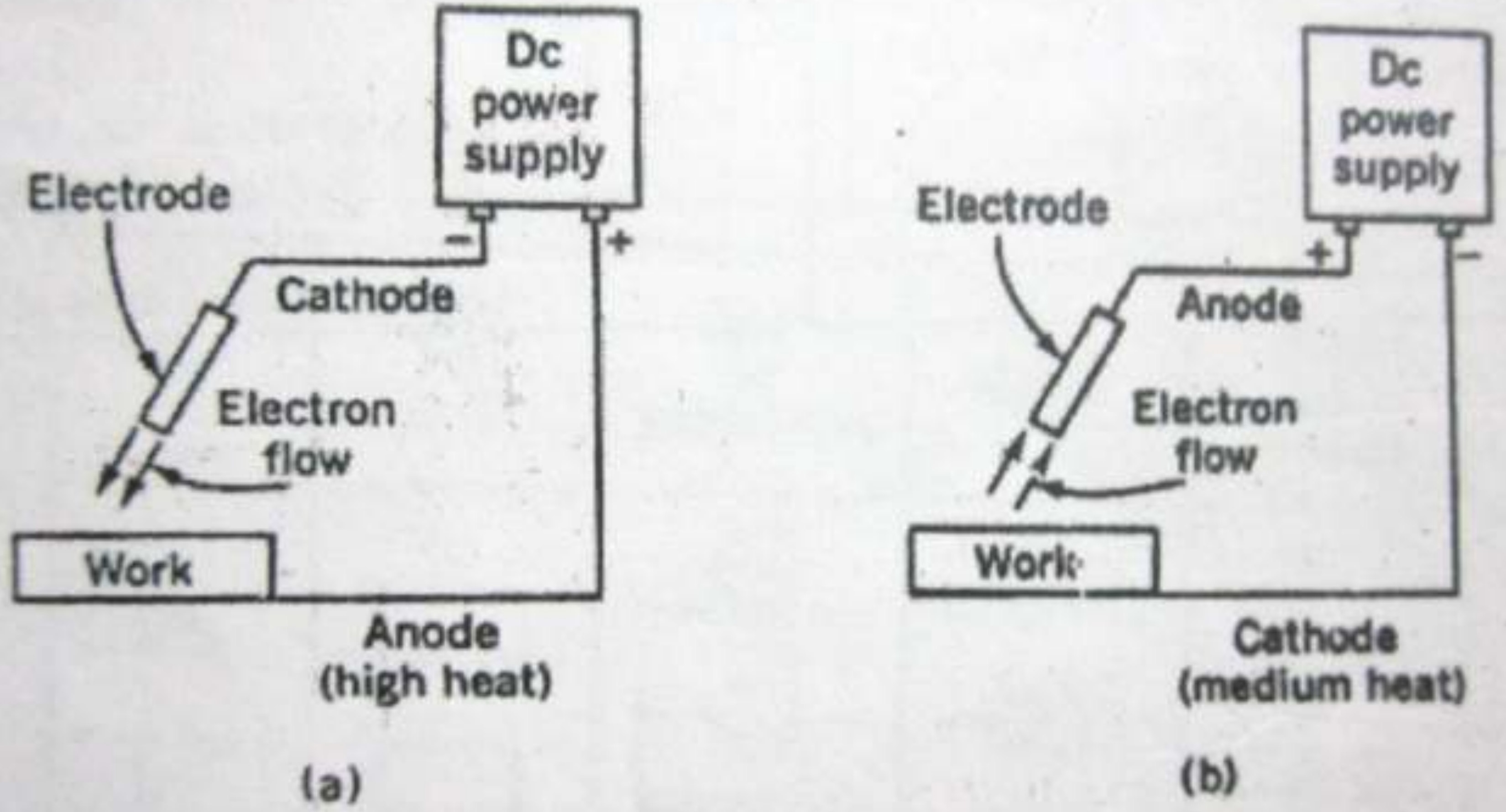
- Designed to change high voltage low amperage current into safe voltage b/w (50-100V) and heavy current supply(200-600A) suitable for arc welding.

Arc welding power source can divided into 3 categories

1. Those that supply DC
    1. Motor generator set
    2. Diesel engine driven generator
    3. Transformer rectifier sets
2. Those that supply AC
    1. Transformer and AC generator
3. AC or DC arc welding combination supplying either AC or DC

ACHF(Alternating current high frequency)

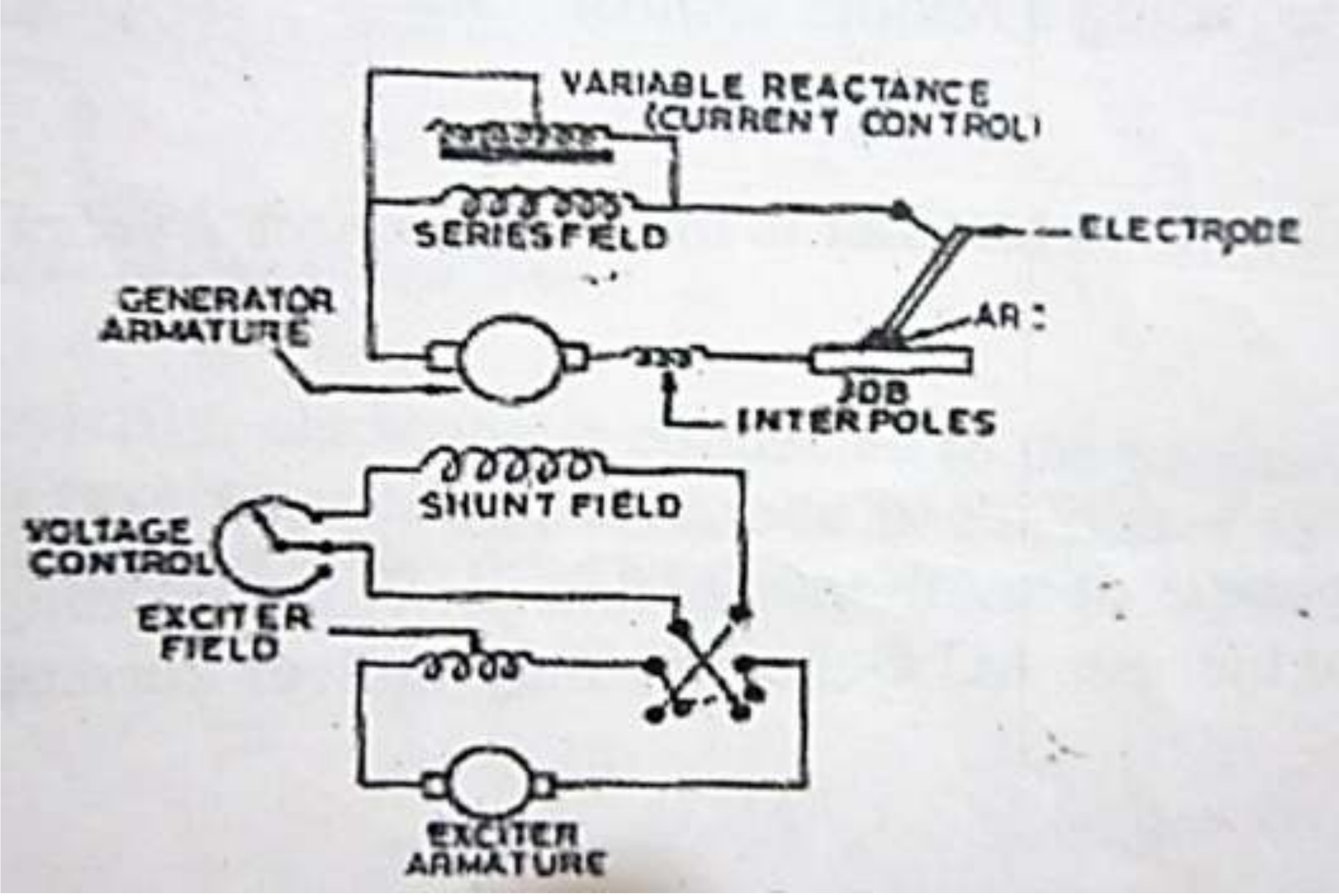
- Heat generated in 1:1 ratio.



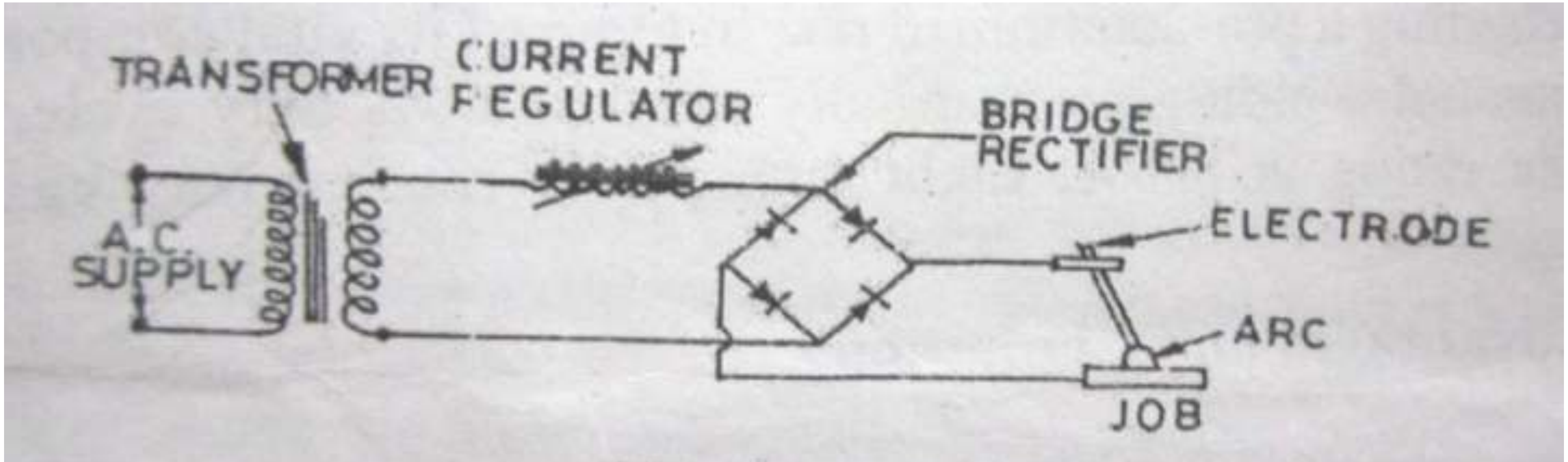
Dc polarity. (a) Straight polarity. (b) Reverse polarity.

- **DC generator Sets**
  - Current produced by rotating armature in electric field
  - Armature rotated by electric motor or engine
  - Polarity switch for straight or reverse polarity

Reference



- AC-DC Rectifiers
  - It can supply any type of current (AC or DC) needed although some transformer rectifiers are designed to supply only DC
  - By turning a switch the output terminal can be changed to AC or to DC and give AC or DC straight or reverse polarity current

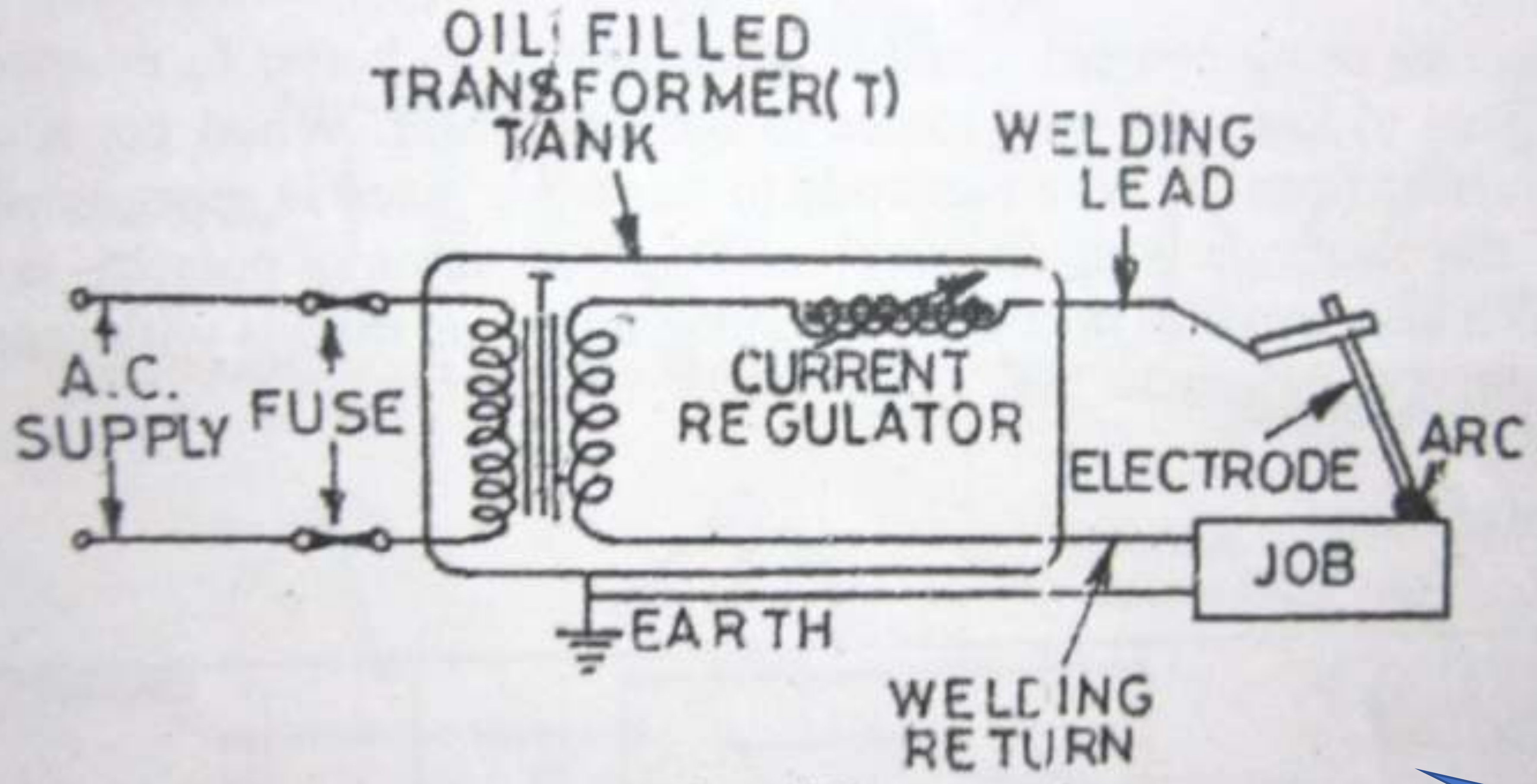


A transformer-rectifier set.

Reference

- AC generator
  - It consist of an alternator that provides welding current.
  - It driven by motor or diesel engine
- AC transformer
  - Welding transformer changes high voltage low amperage power to low voltage high amperage welding power(step down)
  - Least expensive, smallest welding machine
  - Two periods in every cycle when welding current is zero
  - Arc would extinguish during this period and continuous welding become difficult, this difficulty removed by ,
    - Building in automatic arc stabilization in the welder winding
    - Development of electrode coatings that produce the more complete ionization in the arc stream and keep the arc igniting as the current pass through zero.

Reference



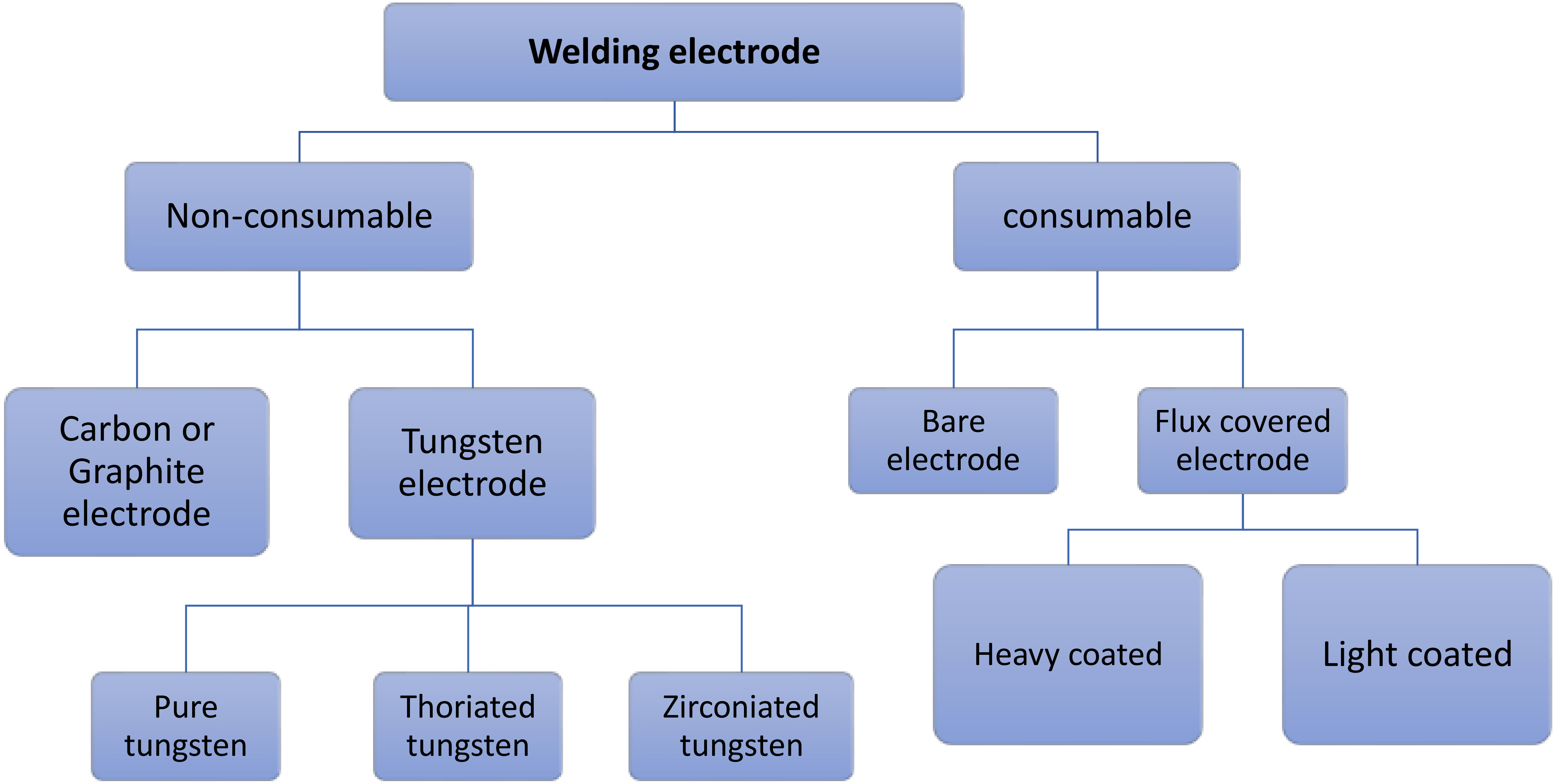
A welding transformer.

Reference

Governing factor in fusion welding

- The characteristics of the heat source
- The nature of deposition of the filler material in the fusion zone
- Heat flow characteristics in the joint
- The gas metal or slag metal reaction in the fusion zone
- The cooling of the fusion zone with the associated contraction, residual stress, and metallurgical changes

Electrodes and types




The Edison Tech Center 2010

- Selection of electrode depends,
  - Availability of current
  - Composition of base metal
  - Thickness of base metal
  - Welding position
  - Amount of penetration required in welding

- Consumable electrode
- Non-Consumable electrode
- Bare electrode
- Coated electrode

- *Electrodes* for consumable arc-welding processes are classified according to the following properties:

    - Strength of the deposited weld metal
    - Current (AC or DC)
    - Type of coating

- Electrodes are identified by numbers and letters or by color code if the numbers and letters are too small to imprint.
- Specifications for electrodes and filler metals (including dimensional tolerances, quality control procedures, and processes) are published by the American Welding Society (AWS) and the American National Standards Institute (ANSI). Some specifications appear in the Aerospace Materials Specifications (AMS) by the Society of Automotive Engineers (SAE).

Electrode Coatings.

- Electrodes are *coated* with claylike materials that include silicate binders and powdered materials, such as oxides, carbonates, fluorides, metal alloys, cotton cellulose, and wood flour. The coating, which is brittle and takes part in complex interactions during welding, has the following basic functions:
  - Stabilize the arc
  - Generate gases to act as a shield against the surrounding atmosphere; the gases produced are carbon dioxide, water vapor, and small amounts of carbon monoxide and hydrogen.
  - Control the rate at which the electrode melts
  - Act as a flux to protect the weld against the formation of oxides, nitrides, and other inclusions and, with the resulting slag, to protect the molten-weld pool
  - Add alloying elements to the weld zone to enhance the properties of the joint—among these elements are deoxidizers to prevent the weld from becoming brittle.
- Bare electrodes and wires made of stainless steels and aluminum alloys also are available. They are used as filler metals in various welding operations.

Types of arc welding

- Shielded Metal-arc Welding
- Submerged Arc Welding (SAW)
- Gas Metal-arc Welding
- Flux cored arc
- Electro slag
- Plasma arc
- Atomic hydrogen

1.Shielded Metal-arc Welding

- *Shielded metal-arc welding* (SMAW) is one of the oldest, simplest, and most versatile joining processes. About 50% of all industrial and maintenance welding currently is performed by this process.
- The electric arc is generated by touching the tip of a ***coated electrode*** against the workpiece and withdrawing it quickly to a distance sufficient to maintain the arc

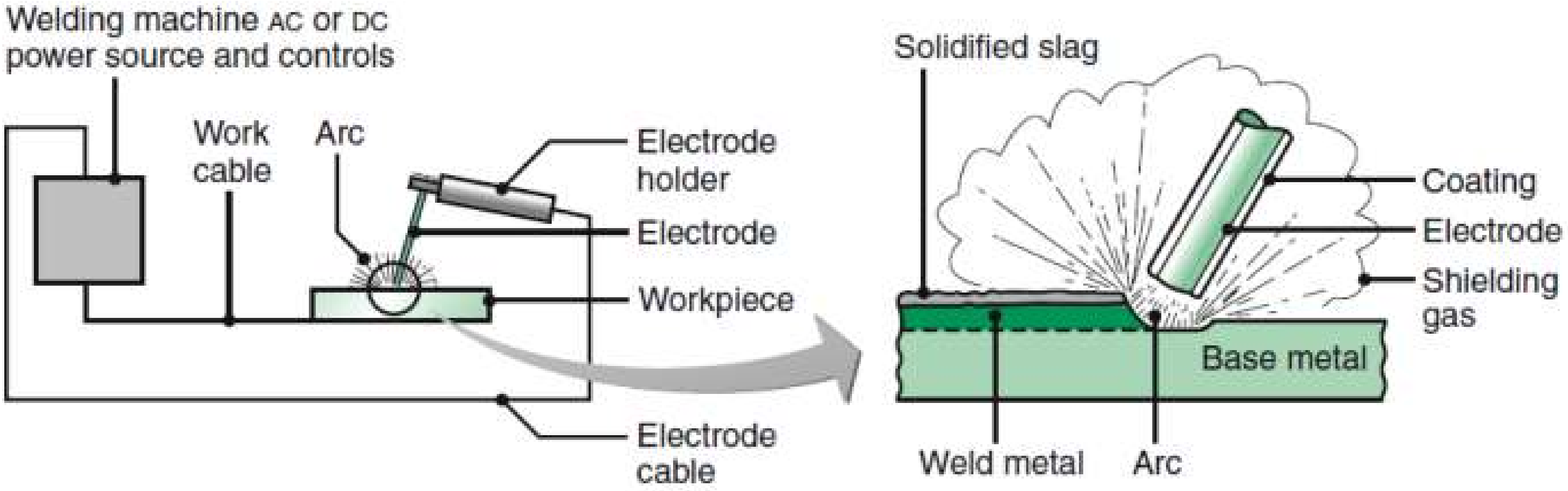


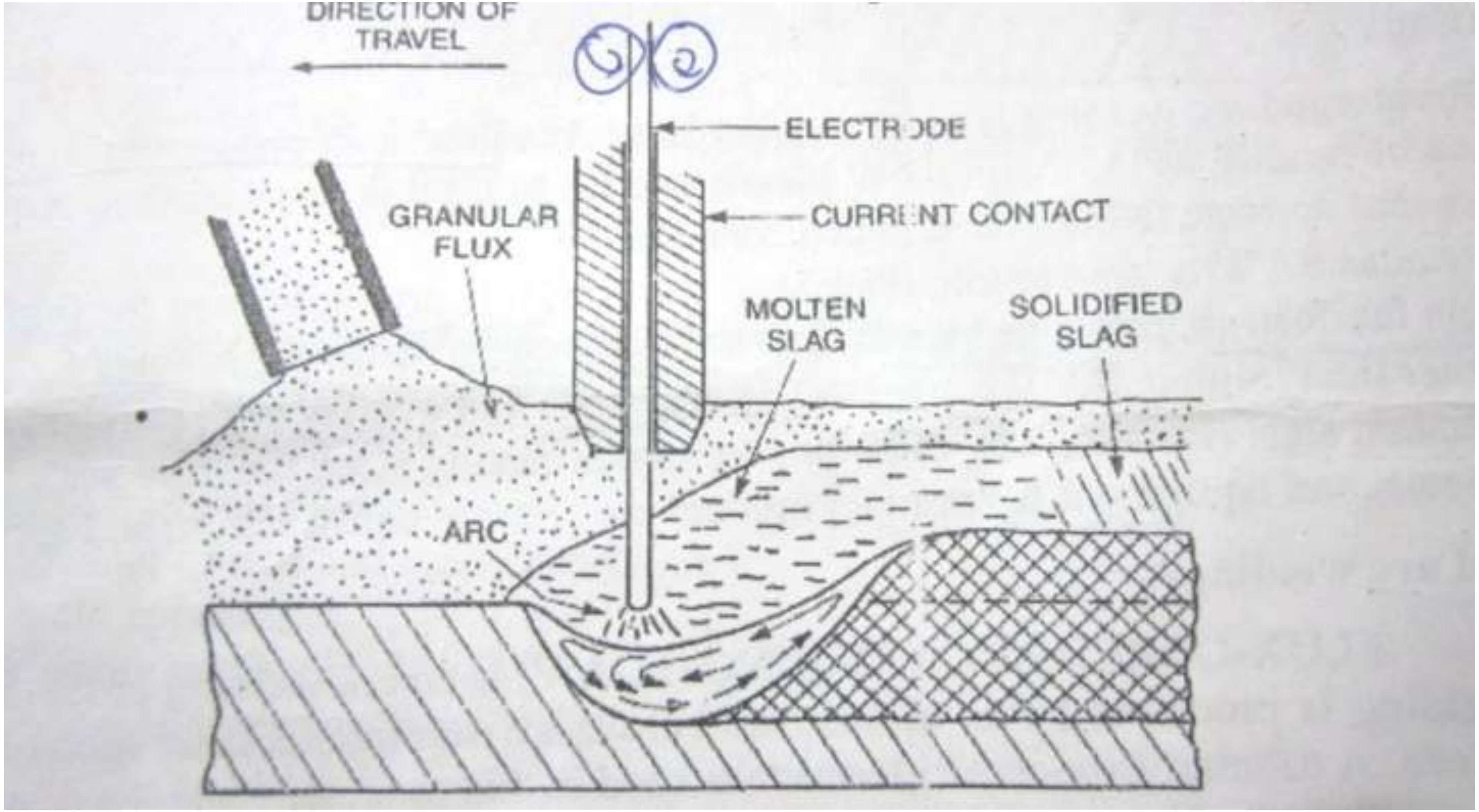
FIGURE 30.7 Schematic illustration of the shielded metal-arc welding process. About 50% of all large-scale industrial-welding operations use this process.

Shielded Metal-arc Welding

- The SMAW process has the advantages of being relatively simple, versatile, and requiring a smaller variety of electrodes. The equipment consists of a power supply, cables, and an electrode holder.
- A bare section at the end of the electrode is clamped to one terminal of the power source, while the other terminal is connected to the workpiece being welded. The current, which may be DC or AC, usually ranges from 50 to 300 A.
- The heat generated melts a portion of the electrode tip, its coating, and the base metal in the immediate arc area. The molten metal consists of a mixture of the base metal (the workpiece), the electrode metal, and substances from the coating on the electrode; this mixture forms the weld when it solidifies.
- The electrode coating deoxidizes the weld area and provides a shielding gas to protect it from oxygen in the environment.

2.Submerged Arc Welding (SAW)

- Here arc is created between a bare, consumable wire or strip electrode and the work piece
- Arc is concealed by a blanket of granular and fusible flux.
- *Granular flux* consisting of lime, silica, manganese oxide, calcium fluoride, and other compounds.
- Arc is submerged under a layer of flux and so arc is invisible
- The arc is maintained in a cavity of molten flux or slag, which refines the weld metal and protects it from atmospheric contamination.
- It also prevents spatter and sparks and suppresses the intense ultraviolet radiation and fumes characteristic of the SMAW process.
- Acts as a thermal insulator.


DIRECTION OF TRAVEL
ELECTRODE
CURRENT CONTACT
GRANULAR FLUX
MOLTEN SLAG
SOLIDIFIED SLAG
ARC

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- A continuous electrode is being fed into the joint by mechanically powered drive rolls
- Current supplied to electrode through the contact tube
- After welding is completed and the weld metal has solidified, the unfused flux and slag are removed
- <u>Advantages</u>
  - Arc under the blanket of flux so it eliminate arc flash, spatter, and fume
  - High deposition rate, operating cost low, no safety equipment required
- <u>Disadvantage</u>
  - Initial cost high, only in flat position, can’t see the weld progress.
- <u>Applications</u>
  - For join plain carbon steel, to join thick section, Primarily used for shipbuilding, pipe fabrication, penstocks, pressure vessel
  - Circular welds can be made on pipes and cylinders—provided that they are rotated during welding.

- The quality of the weld is very high— with good toughness, ductility, and uniformity of properties.
- The SAW process provides very high welding productivity, depositing 4 to 10 times the amount of weld metal per hour as the SMAW process.
- Typical applications include thick-plate welding for shipbuilding and for pressure vessels.
- It is especially useful for work in remote areas where a portable fuel-powered generator can be used as the power supply. SMAW is best suited for workpiece thicknesses of 3 to 19 mm (0.12 to 0.75 in.)
- But it can used for thick weld with multiple pass

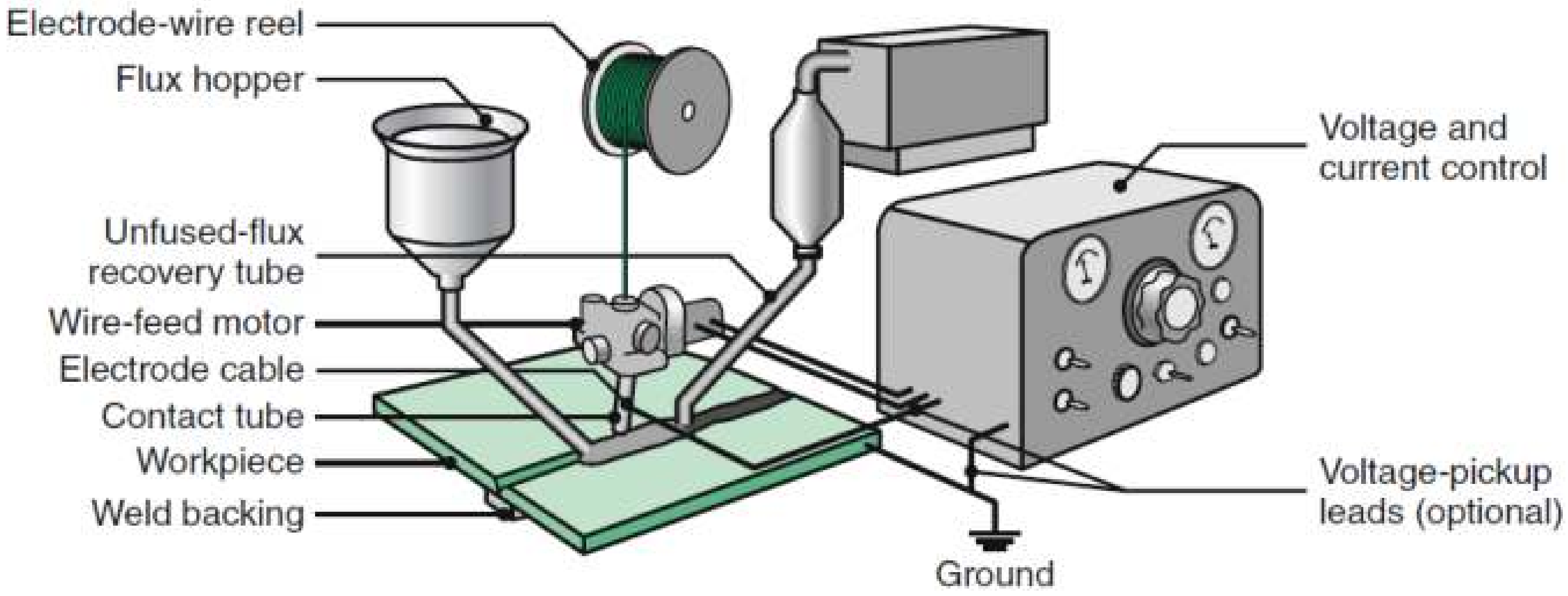
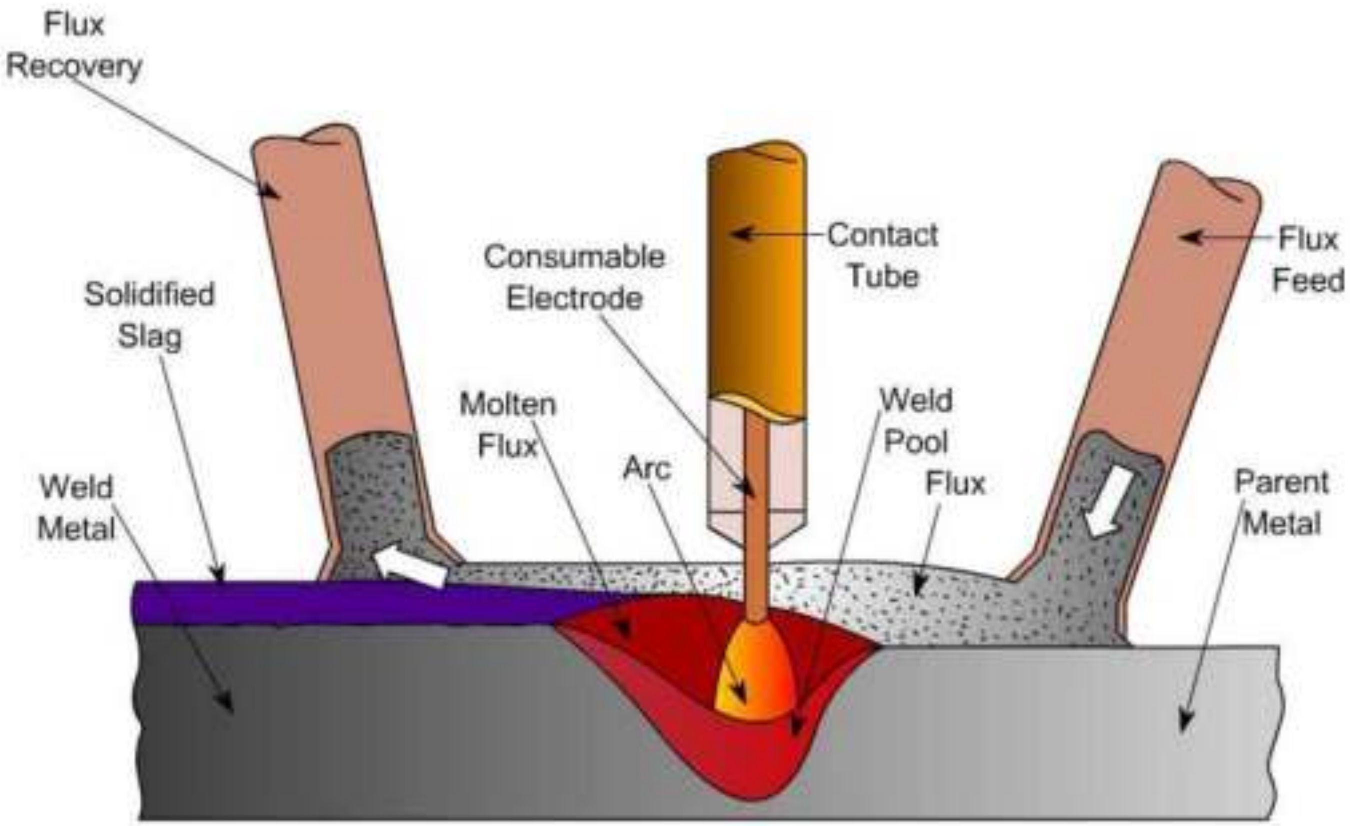
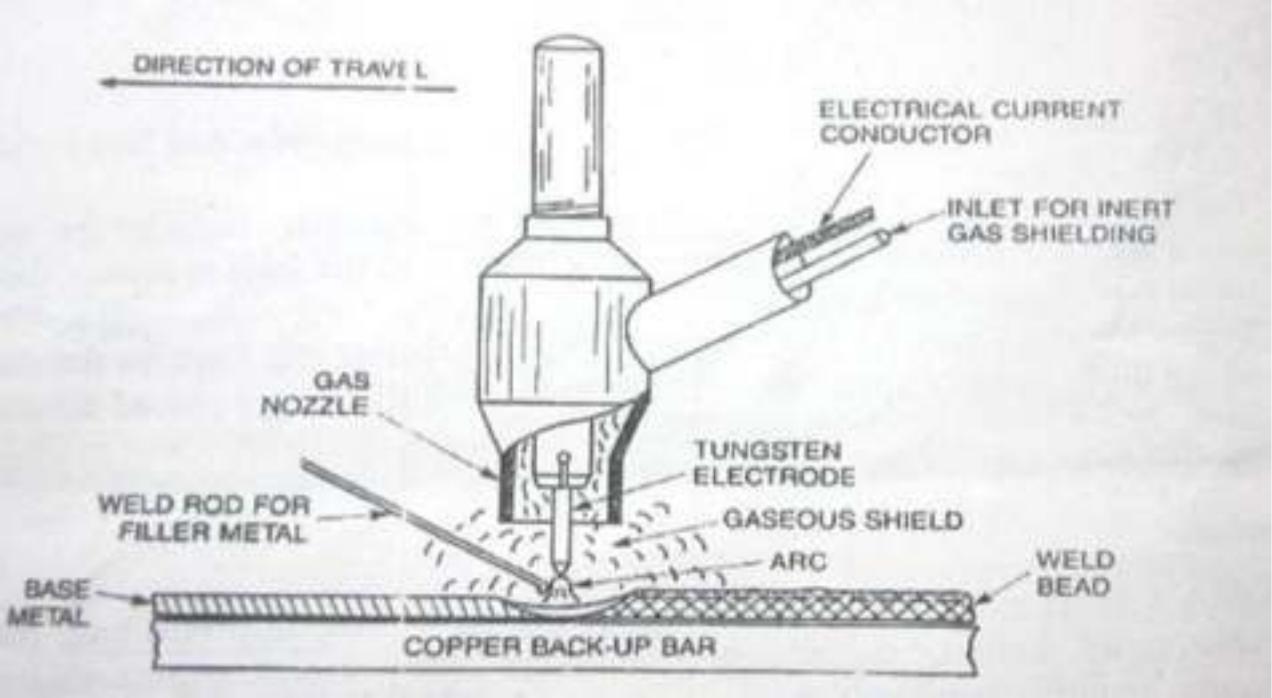


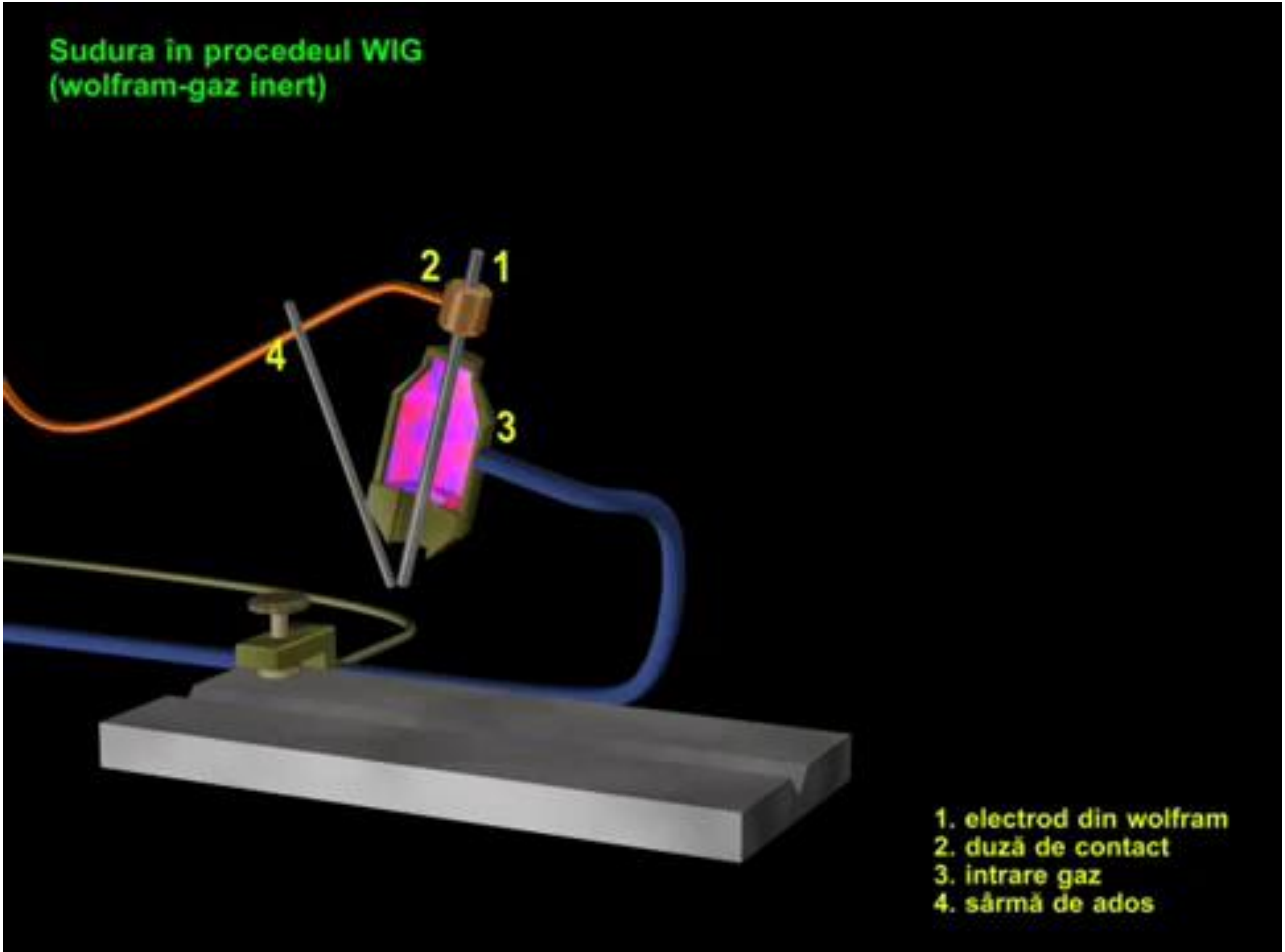
FIGURE 30.9 Schematic illustration of the submerged-arc welding process and equipment. The unfused flux is recovered and reused.


Flux
Recovery
Contact
Tube
Flux
Feed
Consumable
Electrode
Solidified
Slag
Molten
Flux
Weld
Pool
Flux
Arc
Weld
Metal
Parent
Metal

Tungsten inert gas welding (TIG or GTAW)

- Weld is produced by heating the job with an electric arc struck between a tungsten electrode (Non Consumable) and the work piece to be welded.
- Tungsten electrode used only to generate arc.
- A shielding gas (argon, helium or their mixture) is used to avoid atmospheric contamination of molten weld pool.

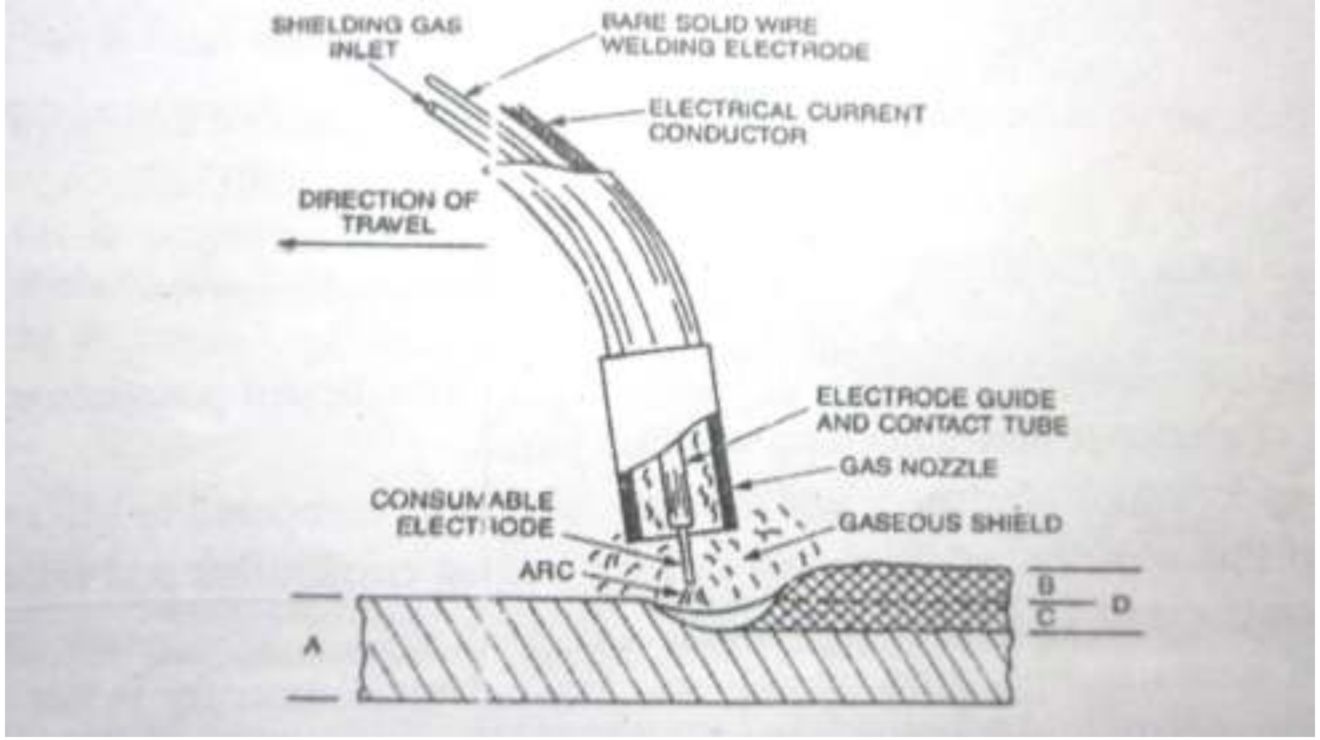


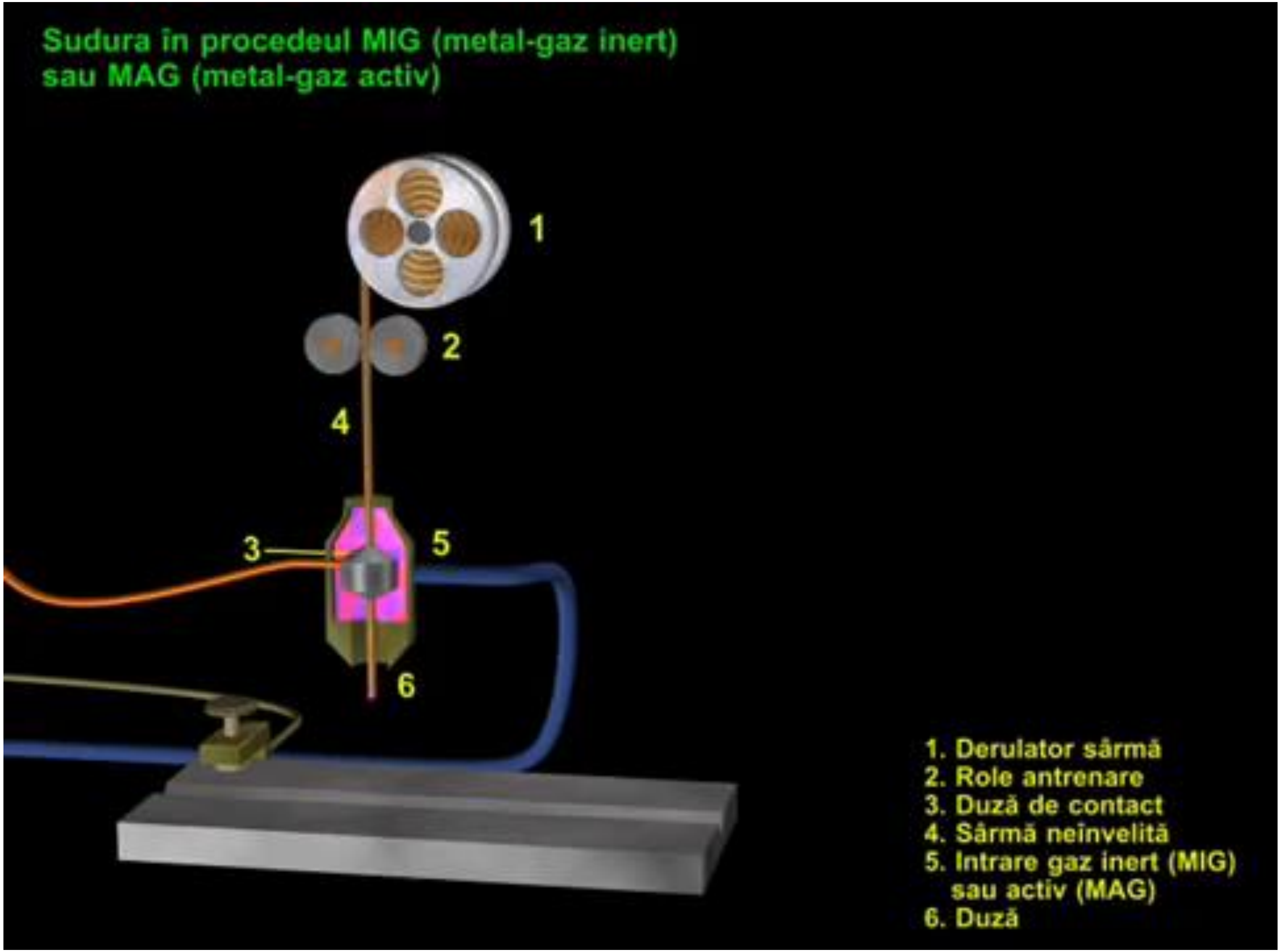

Sudura în procedeul WIG
(wolfram-gaz inert)
2
1
4
3
1. electrod din wolfram
2. duză de contact
3. intrare gaz
4. sârmă de ados

- A filler metal may be added, if required.
- Electrode material may be tungsten or tungsten alloy.
- Coolant provided around the electrode to avoid the melting of the electrode.
- Advantages
  - High quality , low distortion weld.
  - Can weld almost all metals, including dissimilar ones.
  - Highly reactive metals like Al, Mg can be welded very easily .
  - HAZ is very low.
- Disadvantage
  - Lower deposition rates, and costly welding.
  - For joining above 5 mm thickness plate additional filler rod must be used.
  - Tungsten atoms if diffused to molten weld pool can contaminate the same and increase the brittleness of the joint.
- Applications
  - For non ferrous metal welding.
  - Rocket motor chamber for launch vehicle.

3. Gas Metal Arc welding (GMA or MIG)

- Welding metals by heating them with an electric arc that is established between a consumable electrode and work piece
- The electrode is continuously fed through a gun.
- Welding wire is often bare electrode.
- An externally supplied gas or gas mixture act to shield the arc and molten weld pool.





Sudura in procedeul MIG (metal-gaz inert)
sau MAG (metal-gaz activ)
1
2
4
3
5
6
1. Derulator sârmă
2. Role antrenare
3. Duză de contact
4. Sârmă neînvelită
5. Intrare gaz inert (MIG)
sau activ (MAG)
6. Duză

- Helium and argon or CO_2 or their mixture are the commonly employed shielding gases. Selection of gas depends on the base metal used.
- The arc is established between a continuously fed electrode of filler metal and the work piece
- Arc length should maintained to set value.
- Advantages
  - Easily mechanized.
  - Highly reactive metal can join.
- Disadvantage
  - More complex, costly.
  - High spatter loss
  - Max 10% of the w/p thickness can weld in single pass. Up to 30 mm thickness
- Applications
  - Ship building, pressure vessel, refrigerator parts, railway coaches

CO_2 Welding (MAG -metal active gas) –(MIG -CO_2 Welding)

- CO_2 process is a variant of GMAW process in which CO_2 is used as a shielding gas.
- CO_2 is an active gas, so the process is known as Metal Active Gas (MAG) welding
- Used for carbon and low alloy steel
- During welding under high temperature arc CO_2 changes to carbon monoxide and oxygen
  - $2\ CO_2 \longrightarrow 2CO + O_2 \longrightarrow O_2 + 2O$
- The nascent oxygen could be damaging, if wrong type electrode is used
  - So the electrode wire for CO_2 welding must contain deoxidizer such as manganese and silicon that readily combine with oxygen and prevent it from combining with the weld metal
  - The oxides formed SiO_2 and MnO pass in to slag.

Flux cored arc welding (FCAW)

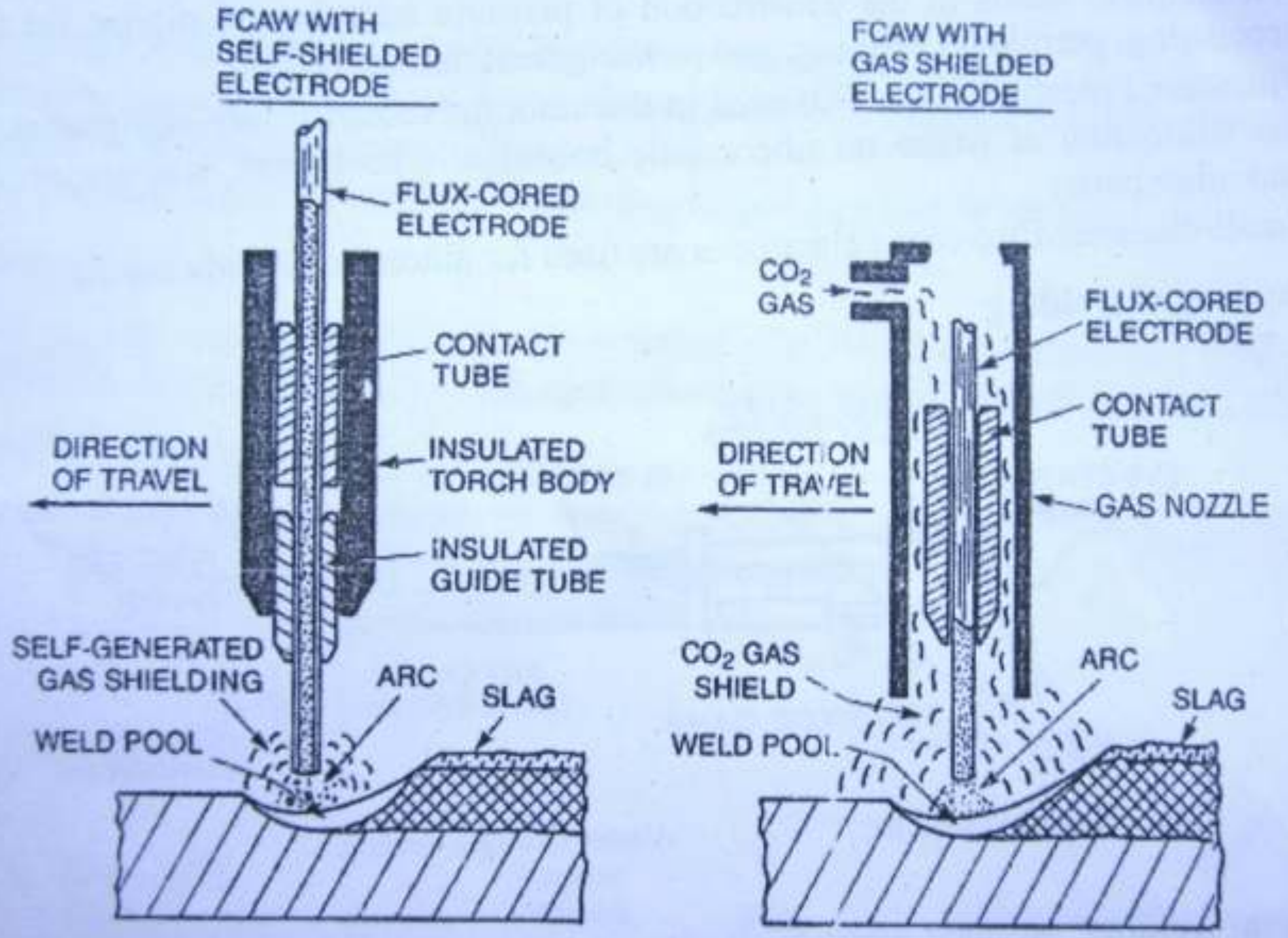
- Similar to GMA welding with exception that the electrode is tubular in shape and is filled with flux.
- FCAW has two major variations,

1. Gas shielded FCAW process uses an externally supplied gas to assist in shielding the arc from N_2 and O_2 in the atmosphere.

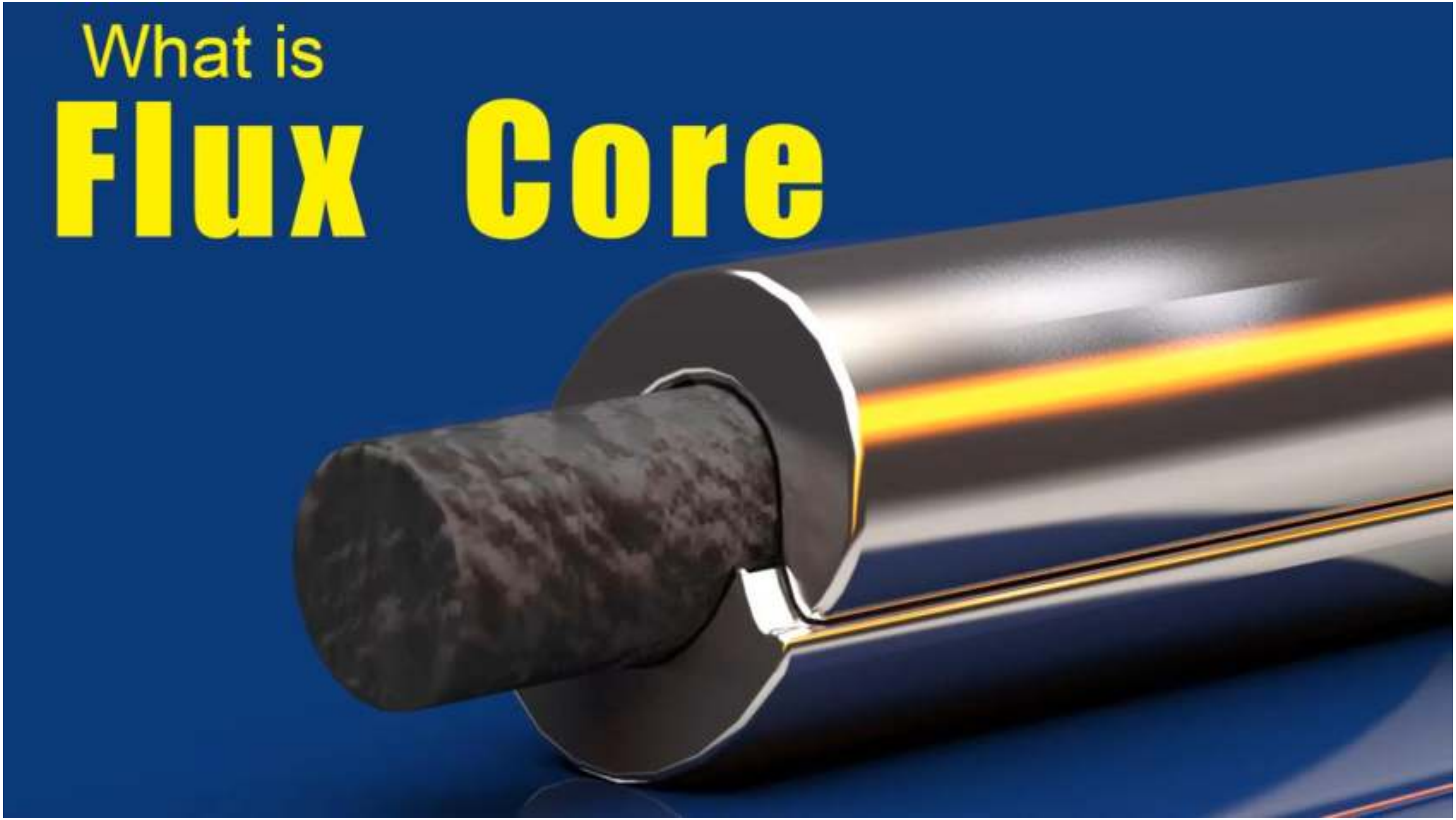
- Core ingredients in gas shielding electrodes are,
  - Slag formers
  - Deoxidizers
  - Arc stabilizers and
  - Alloy elements

2. In the self shielding FCAW process the core ingredients protect the weld metal from the atmosphere without external shielding.

- Some self shielding electrodes provides their own shielding gas through the decomposition of core ingredients.
- Others protect molten weld pool from atmosphere by a slag covering.



Diagrammatic sketches of the flux cored arc welding process (FCAW)


What is
Flux Core

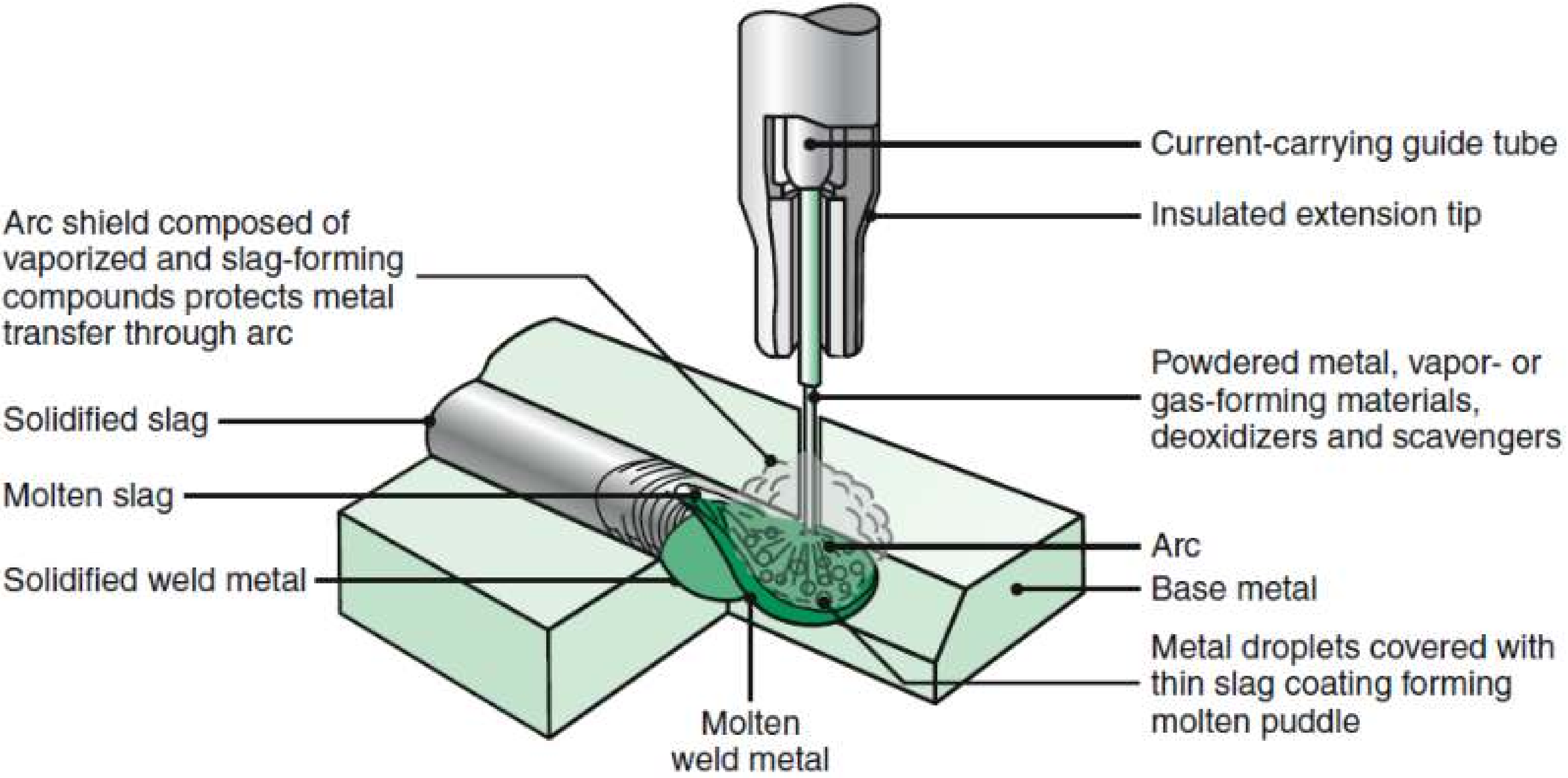


FIGURE 30.11 Schematic illustration of the flux-cored arc-welding process. This operation is similar to gas metal-arc welding, shown in Fig. 30.10.

- Advantages
  - Can easily mechanized
  - Cored electrode produce more stable arc, and improve the weld contour and the mechanical properties of the joint.
  - Alloy elements can add along with flux core.
  - Less operator skill required than for GMAW.
  - Simpler and more adaptable than SAW.
- Disadvantages
  - More smoke and fumes are produced in FCAW than GMAW & SAW
  - Electrode wire is more expensive
  - Slag must be removed from the weld
- Application
  - For fabrication of structures from carbon and low alloy steel
  - Small diameter flux cored electrodes are used for automotive body repair

12.3.1 Heat Transfer in Arc Welding

The heat input in arc welding can be calculated from the equation

$$\frac{H}{l} = e\frac{VI}{v}, \tag{12.3}$$

where H is the heat input in Joules, l is the weld length, V is the voltage applied, I is the current in amperes, and v is the welding speed. The term e is the efficiency of the process, and varies from around 75% for shielded metal arc welding to 90% for gas metal arc and submerged arc welding. The efficiency is an indication that not all of the available energy is used to melt material, and some of the available heat is conducted through the

TABLE 12.3 Approximate specific energies required to melt a unit volume of commonly-welded metals.

Material	Specific Energy, u J/mm^3	BTU/in^3
Aluminum alloys	2.9	41
Cast irons	7.8	112
Copper	6.1	87
Bronze	4.2	59
Magnesium	2.9	42
Nickel	9.8	142
Steels	9.7	137
Stainless steels	9.4	135
Titanium	14.3	204

workpiece and some is lost by radiation and convection to the surrounding environment.

The heat input, given by Eq. (12.3), melts some material, usually the electrode or the filler metal, and can also be expressed as

$$H = u(\text{Volume}) = uAl, \tag{12.4}$$

where u is the specific energy required for melting and A is the cross section of the weld. Typical values of u are given in Table 12.3. Equations (12.3) and (12.4) allow an expression of the welding speed as

$$v = e\frac{VI}{uA}. \tag{12.5}$$

Although these equations have been developed for arc welding, similar expressions can be obtained for other fusion-welding operations, taking into account differences in weld zone geometry and process efficiency.

EXAMPLE 12.1 Estimation of Welding Speed for Different Materials

Given: A welding operation is being performed with $V = 20$ volts, $I = 200$ A, and the cross-sectional area of the weld bead is 30 mm^2.

Find: Estimate the welding speed if the workpiece and electrode are made of (a) aluminum; (b) carbon steel; and (c) titanium. Use an efficiency of 75%.

Solution: For aluminum, note from Table 12.3 that the specific energy required is $u = 2.9$ J/mm^3. From Eq. (12.5) then,

$$v = e\frac{VI}{uA} = (0.75)\frac{(20)(200)}{(2.9)(30)} = 34.5 \text{ mm/s}.$$

Similarly, for carbon steel, u is taken from Table 12.3 as 9.7 J/mm^3, leading to $v = 10.3$ mm/s. For titanium, $u = 14.3$ J/mm^3, so that $v = 7.0$ mm/s.

EXAMPLE 12.2 Heat and Speed of Shielded Metal Arc Welding

Given: A shielded metal arc welding operation takes place on a steel workpiece (with a steel electrode) with a 20 volt power supply.

Find: If a weld with a triangular cross section with a 10 mm leg length is to be produced, estimate the current needed for a welding speed of 10 mm/s. Use an efficiency of 75%.

Solution: The cross-sectional area of the weld is calculated from the given geometry as:

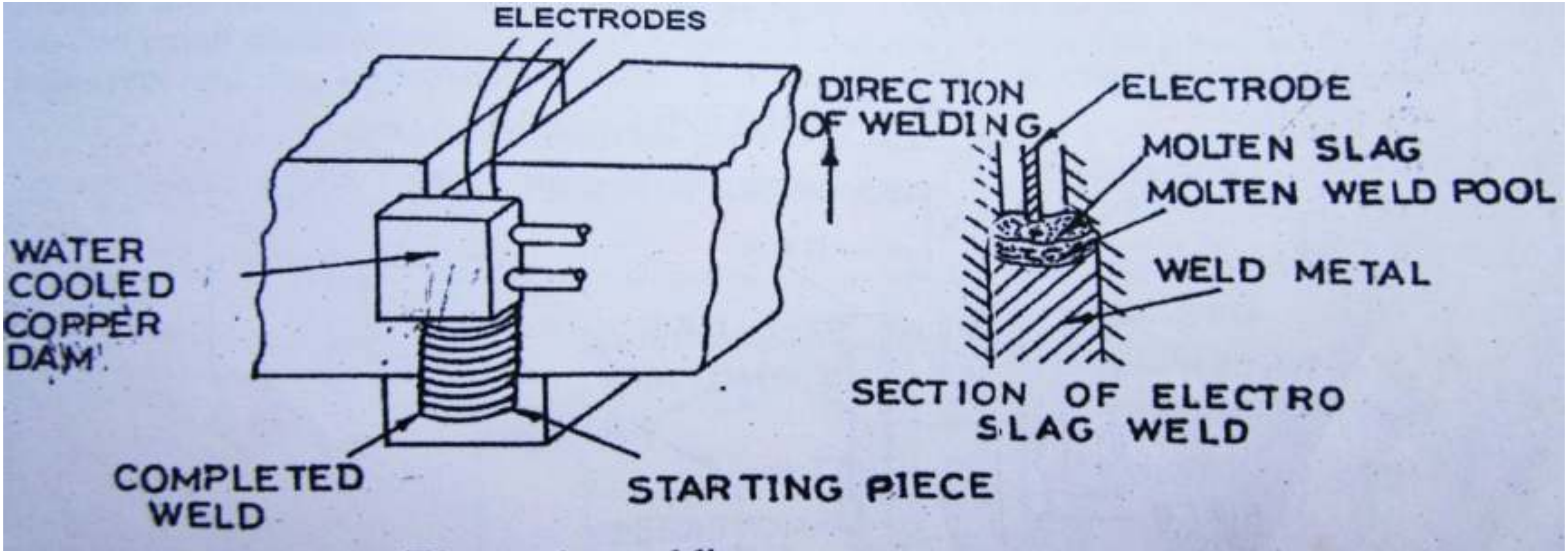
$$A = \frac{1}{2}bh = \frac{1}{2}(10)(10) = 50 \text{ mm}^2.$$

The specific energy needed to melt the steel electrode is taken from Table 12.3 as 10.3 J/mm^2. Therefore, Eq. (12.5) yields:

$$v = e\frac{VI}{uA}; \qquad I = \frac{vuA}{eV} = \frac{(10)(10.3)(50)}{(0.75)(20)} = 343 \text{ A}.$$

Electroslag welding (ESW)

- Joint is produced by molten slag which melts the filler metal and the work to be welded.
- Welding initiated by starting arc between electrode and the work piece.
- This arc heats the flux and melts it to form the slag.
- The arc is then extinguished and the conductive slag is maintained in molten condition by its resistance to the flow of electric current between the electrode and work.
- The temperature of the slag is enough to melt the edges of the w/p and electrode.
- The molten metal pool remains shielded by the molten slag.
- Which moves along the full cross section of the joint as the welding progress.
- Electrode should dip in the molten slag.



Electroslag welding.

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ELECTROSLAG WELDING PROCEDURE

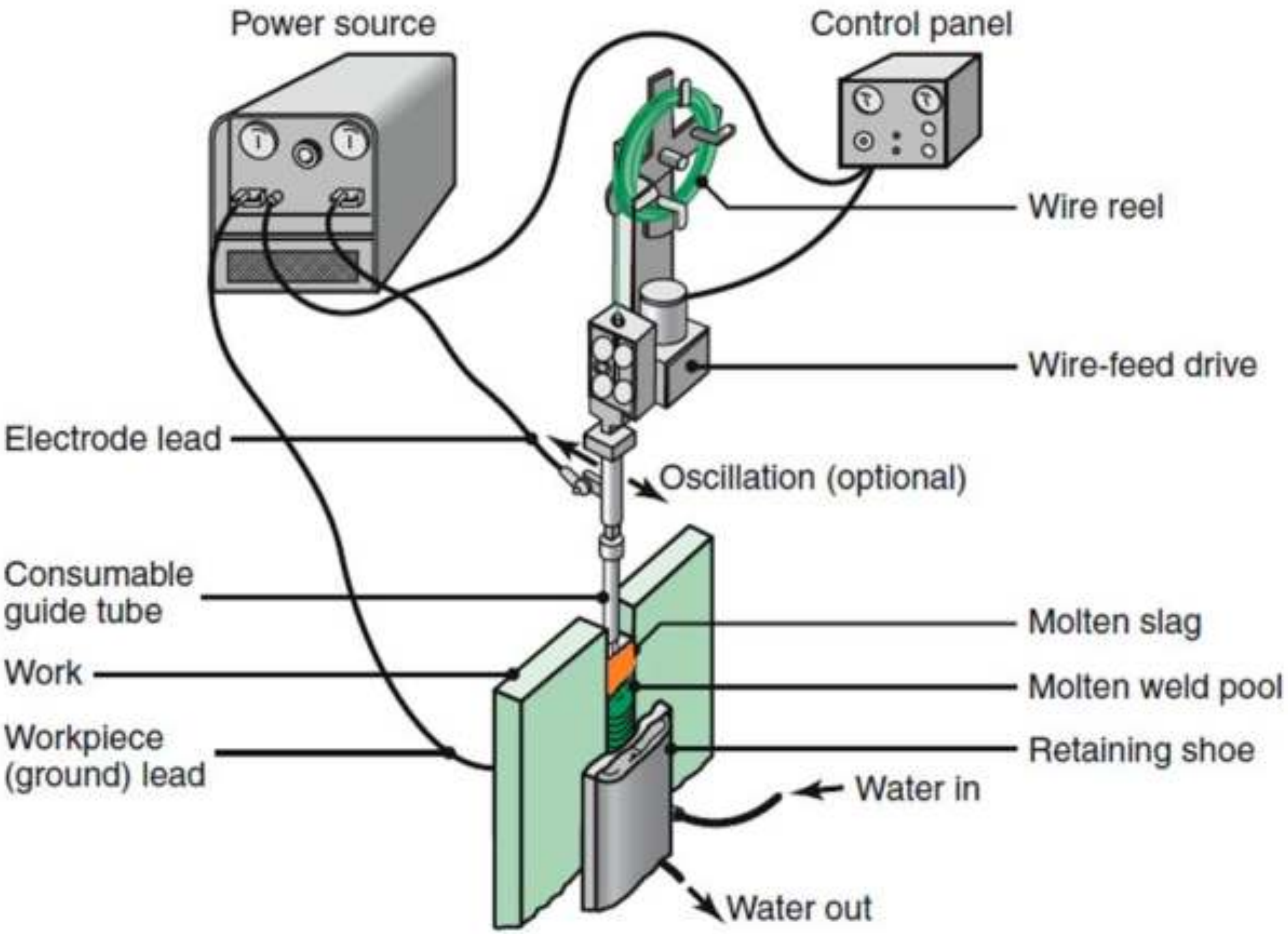
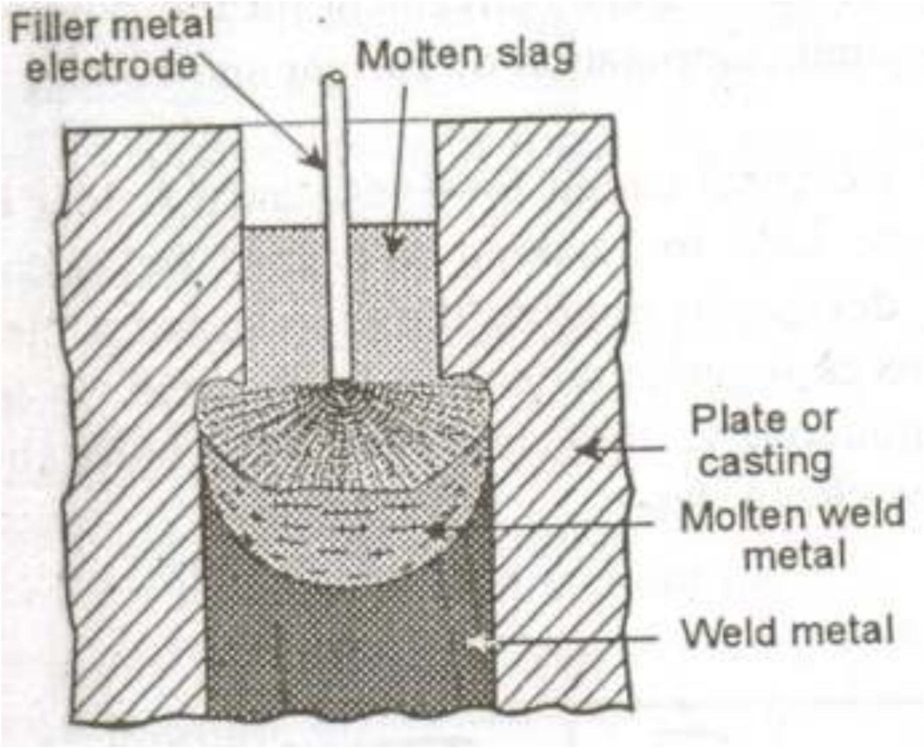


FIGURE 30.13 Equipment used for electroslag-welding operations.



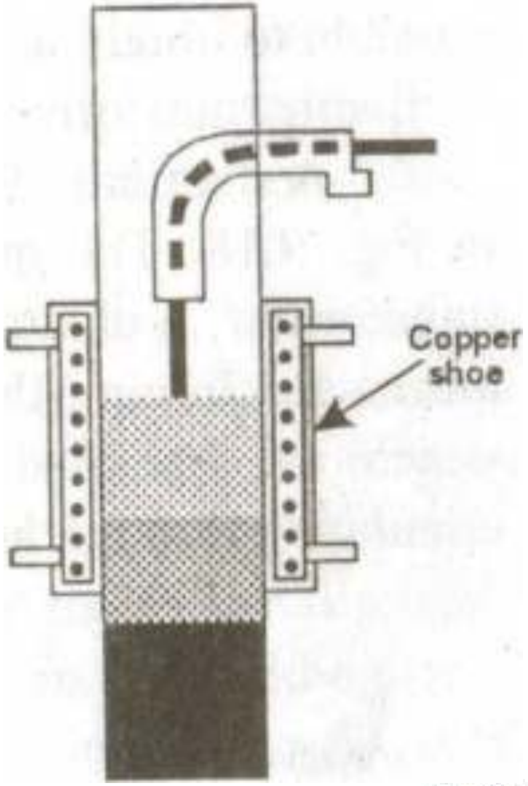
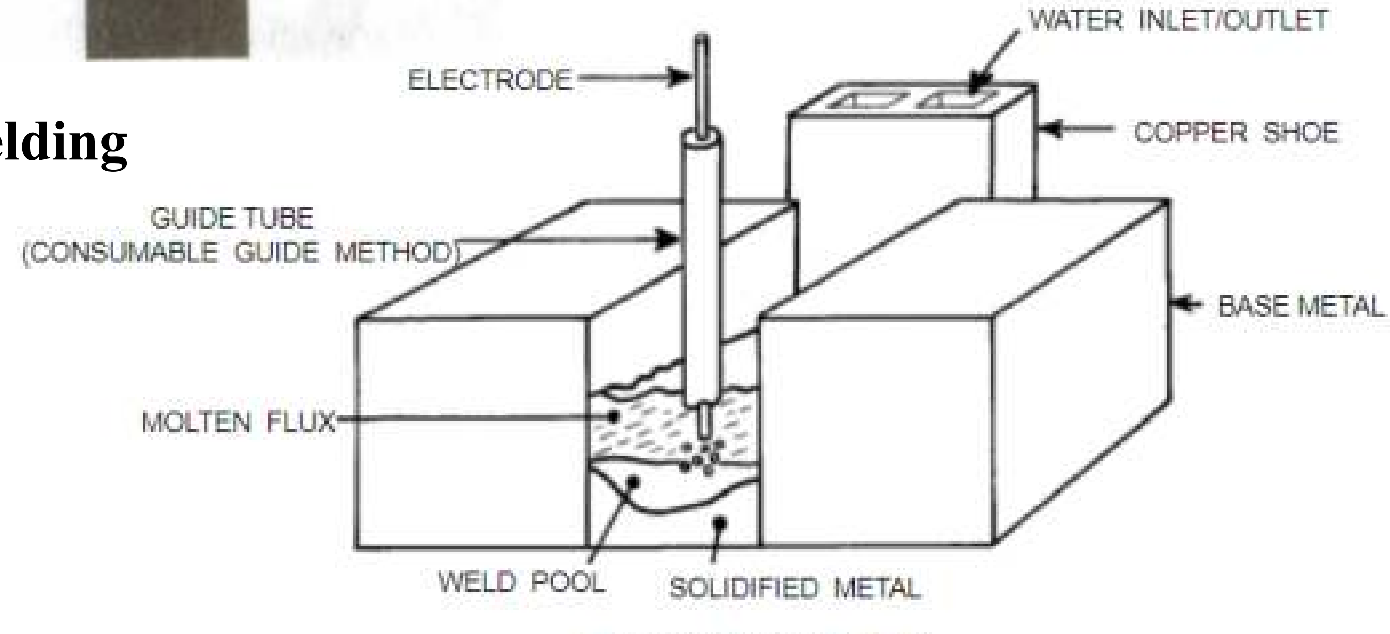


Figure : Electro slag welding



- Advantage
  - Joint preparation is simple than other welding.
  - Thicker steel can weld in single pass.
  - High deposition rate.
- Disadvantage
  - **SAW more economical**
- Application
  - Heavy plate welding.
  - Low carbon, medium carbon steel .
  - For plates with uniform thickness or uniform taper.

Electrogas welding (EGW)

- *Electrogas welding* (EGW) is used primarily for welding the edges of sections vertically and in one pass with the pieces placed edge to edge (butt joint).
- The weld metal is deposited into a weld cavity between the two pieces to be joined.
- The space is enclosed by two water-cooled copper *dams* (*shoes*) to prevent the molten slag from running off; mechanical drives move the shoes upward.
- Circumferential welds (such as those on pipes) also are possible, with the workpiece rotating.

- Single or multiple electrodes are fed through a conduit, and a continuous arc is maintained by flux-cored electrodes at up to 750 A or solid electrodes at 400 A.
- Power requirements are about 20 kW.
- Shielding is done by means of an inert gas, such as carbon dioxide, argon, or helium—depending on the type of material being welded.
- The gas may be provided either from an external source, from a flux-cored electrode, or from both.
- Weld thickness ranges from 12 to 75 mm (0.5 to 3 in.) on steels, titanium, and aluminum alloys. Typical applications are in the construction of bridges, pressure vessels, thick-walled and large-diameter pipes, storage tanks, and ships.

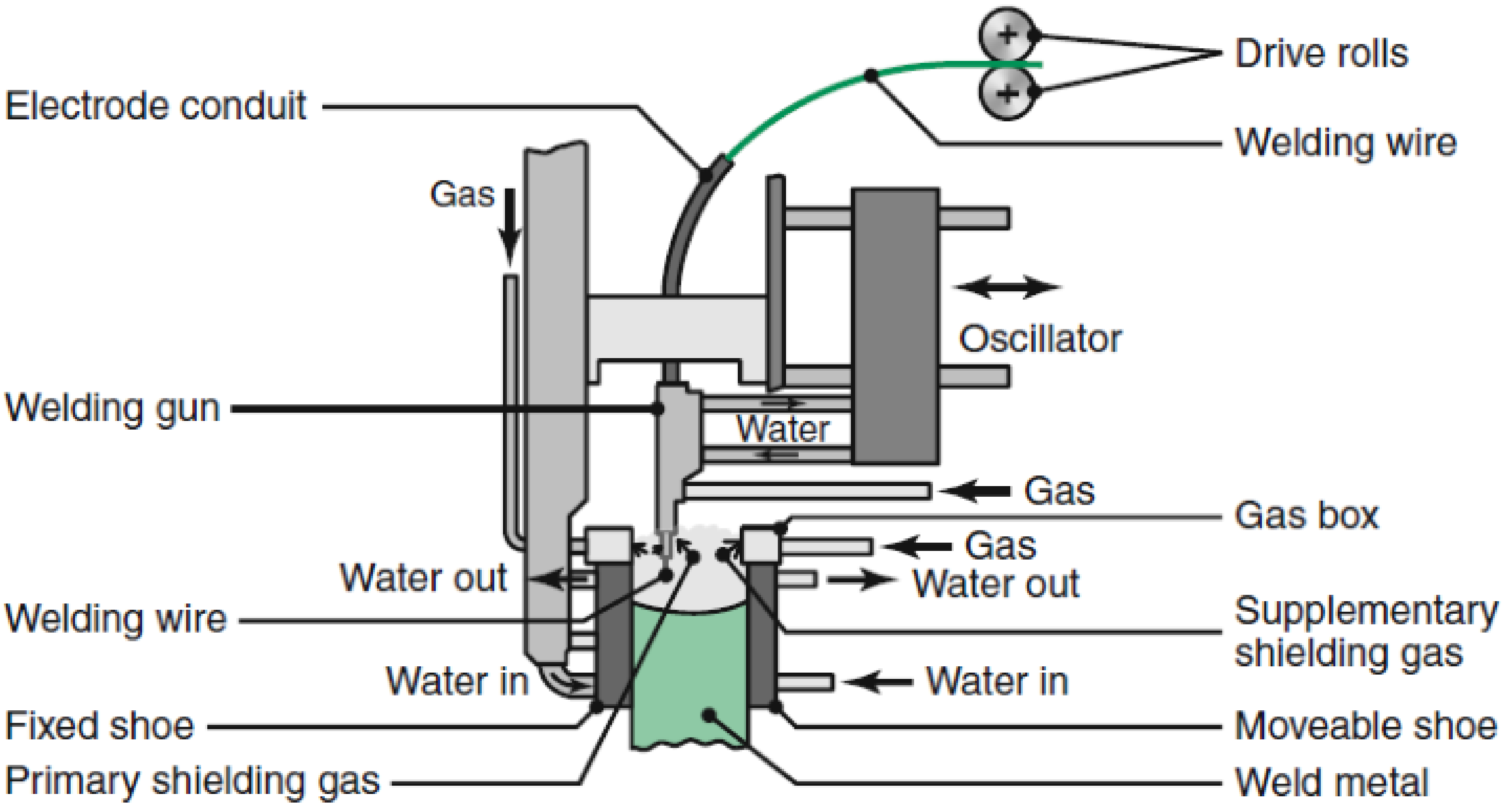
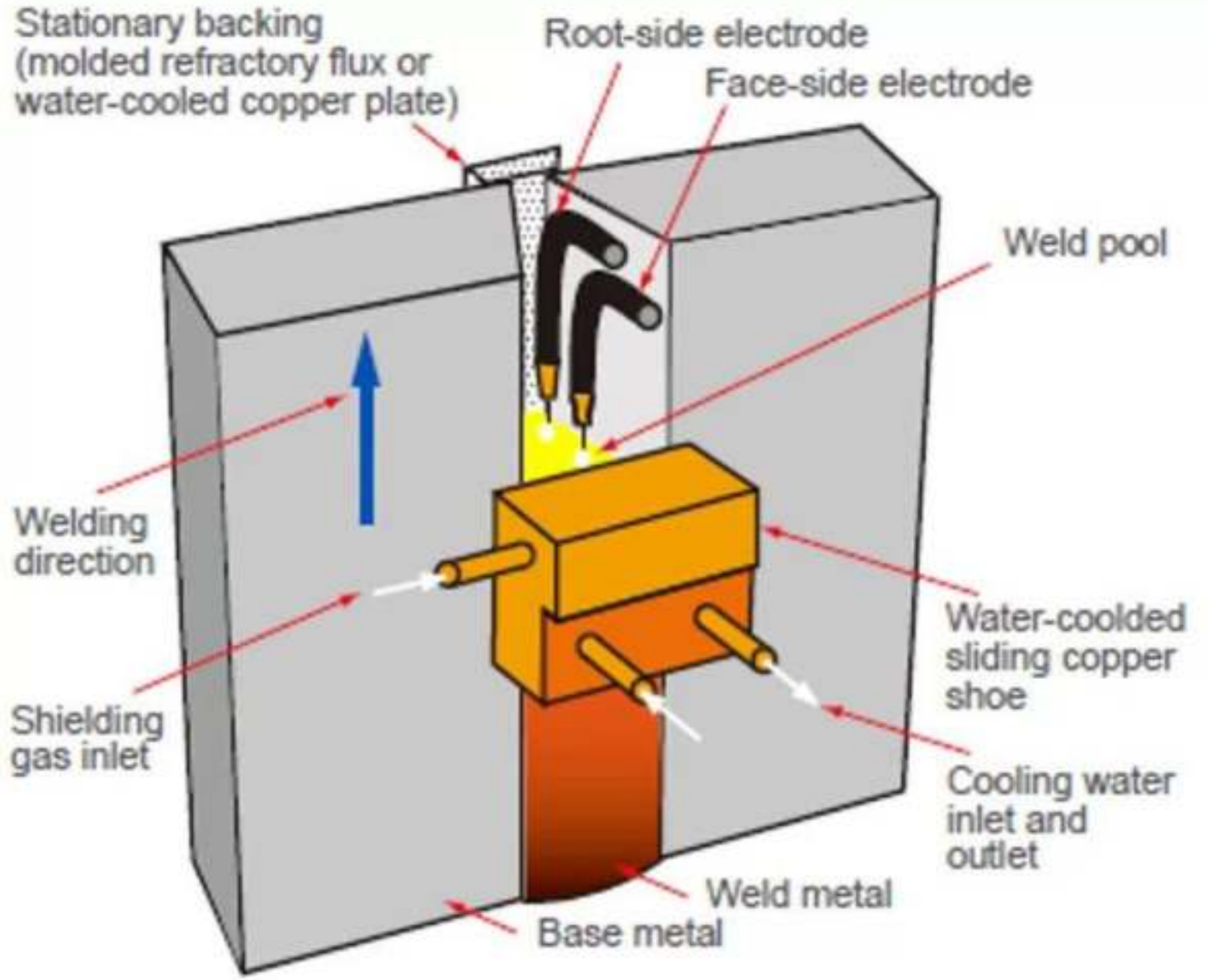
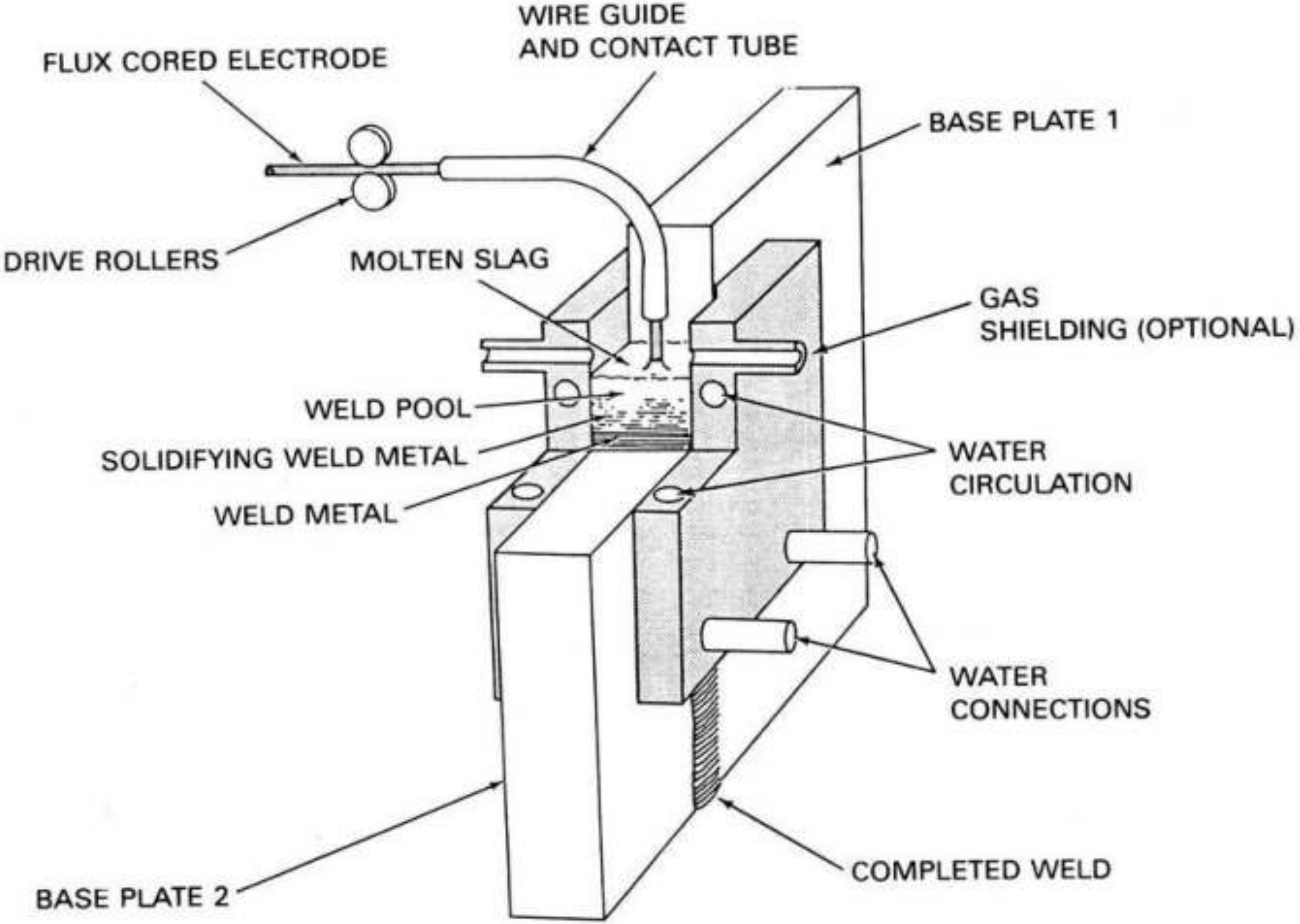


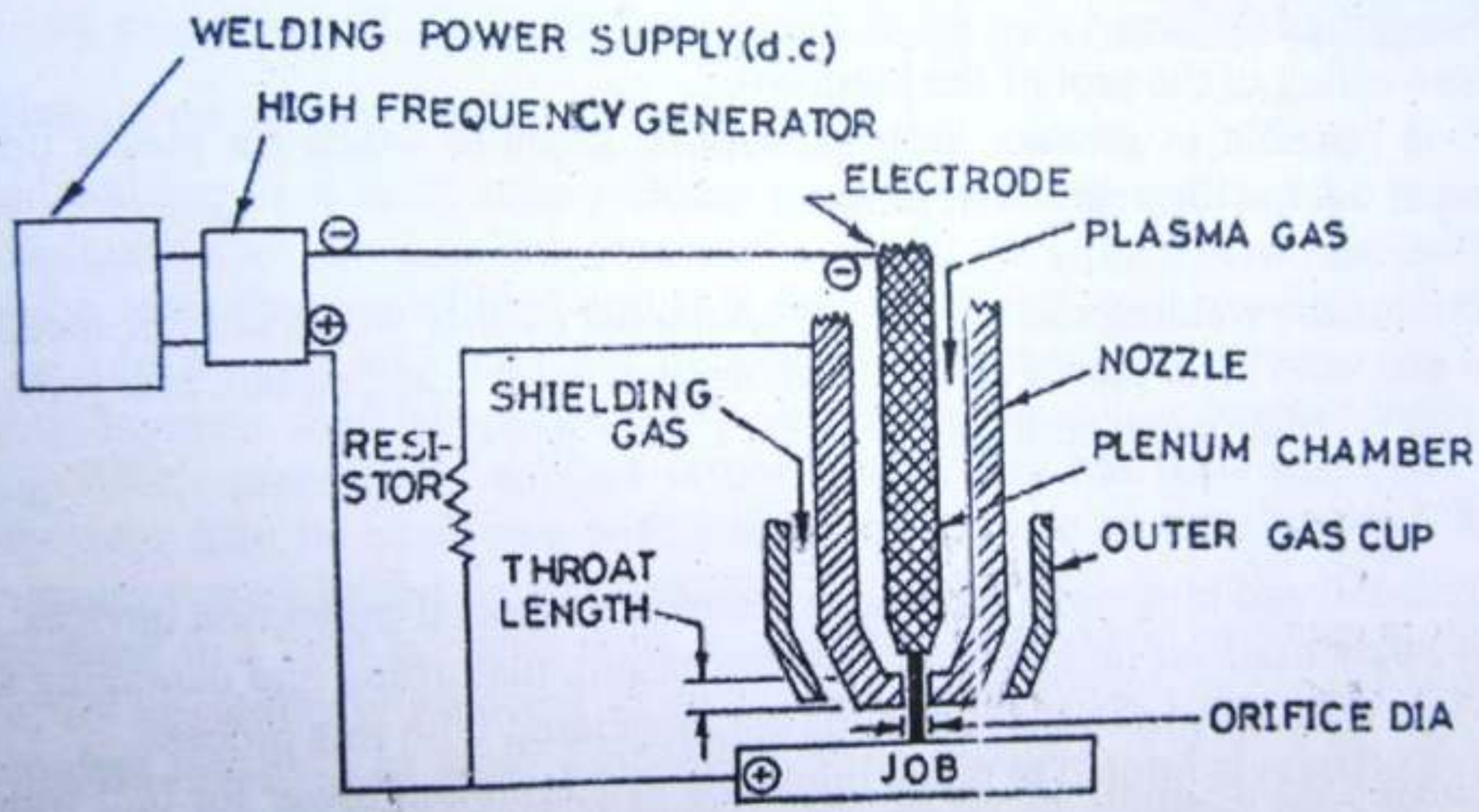
FIGURE 30.12 Schematic illustration of the electrogas-welding process.


Stationary backing
(molded refractory flux or
water-cooled copper plate)
Root-side electrode
Face-side electrode
Weld pool
Welding
direction
Shielding
gas inlet
Water-coolded
sliding copper
shoe
Cooling water
inlet and
outlet
Weld metal
Base metal


WIRE GUIDE
AND CONTACT TUBE
FLUX CORED ELECTRODE
BASE PLATE 1
DRIVE ROLLERS
MOLTEN SLAG
GAS
SHIELDING (OPTIONAL)
WELD POOL
SOLIDIFYING WELD METAL
WATER
CIRCULATION
WELD METAL
WATER
CONNECTIONS
COMPLETED WELD
BASE PLATE 2

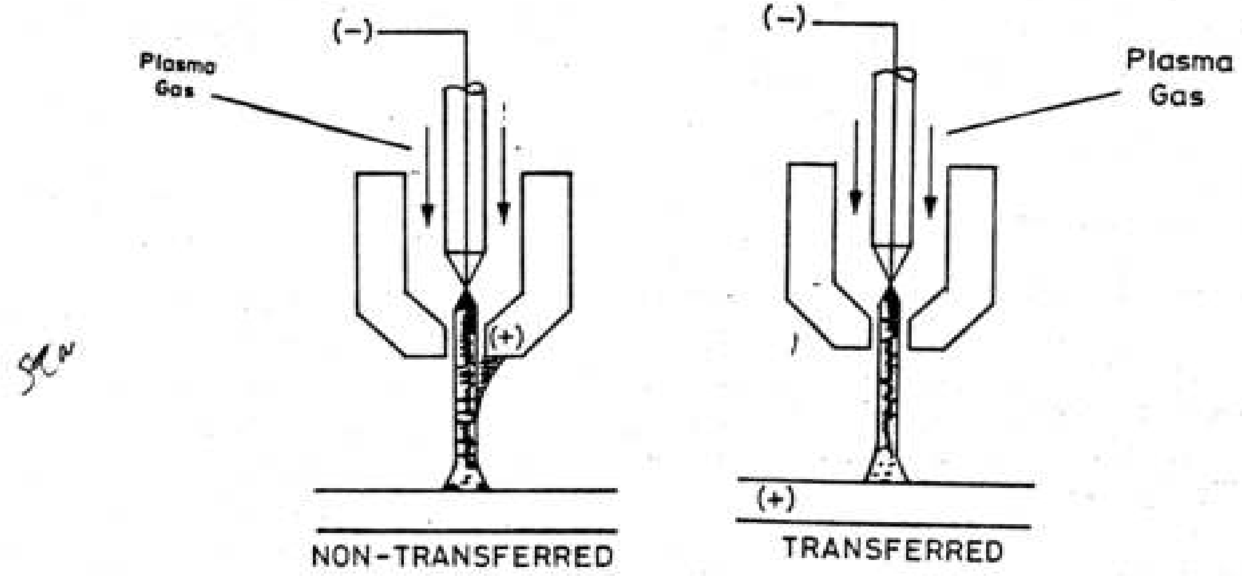
Plasma Arc Welding (PAW)

- Plasma is a high temperature ionized gas.
- When the gas is passed across an electric arc and then through a constrained opening, the gas get ionized and become plasma.
- Concentrated plasma is produced and directed towards the weld area.
- A non-consumable tungsten electrode, water cooled copper nozzle and gas shield(argon) is employed for welding.
- The plasma is initiated between the tungsten electrode and the orifice by a low-current pilot arc.
- Operating currents usually are below 100 A.
- Arc and weld-zone shielding is supplied by means of an outer-shielding ring and the use of gases such as argon, helium, or mixtures.
- The temperature of a constrained plasma arc may be the order of 8000-25000 ^{o}C



Plasma arc welding system.

- PAW system operates either on non-transferred arc mode or transferred system
- In Non-transferred arc system, the power is transferred between the electrode and nozzle. It ionizes a high velocity gas that is streaming towards the workpiece.
- Workpiece can be electrically conductive or non-conductive.
- In Transferred arc system, arc is maintained between the electrode and electrically conductive workpiece.



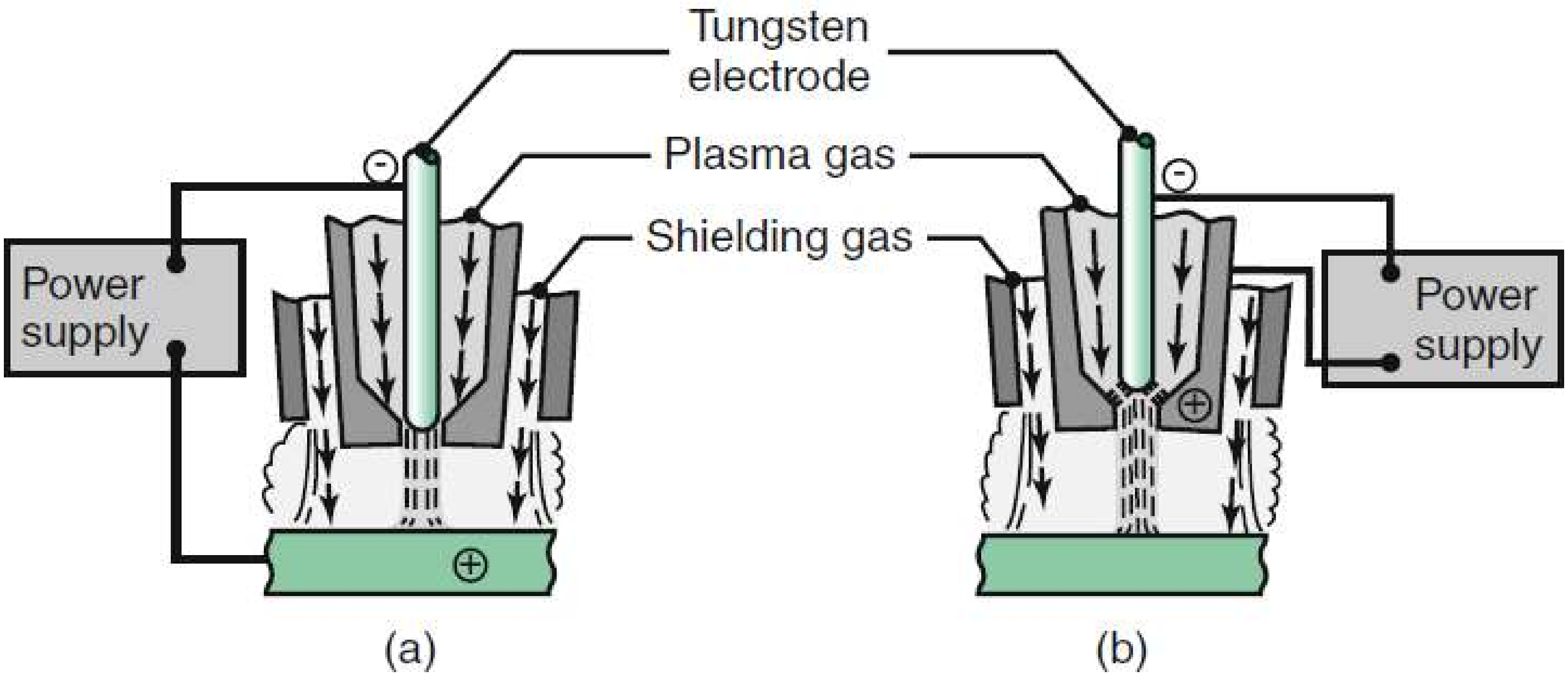
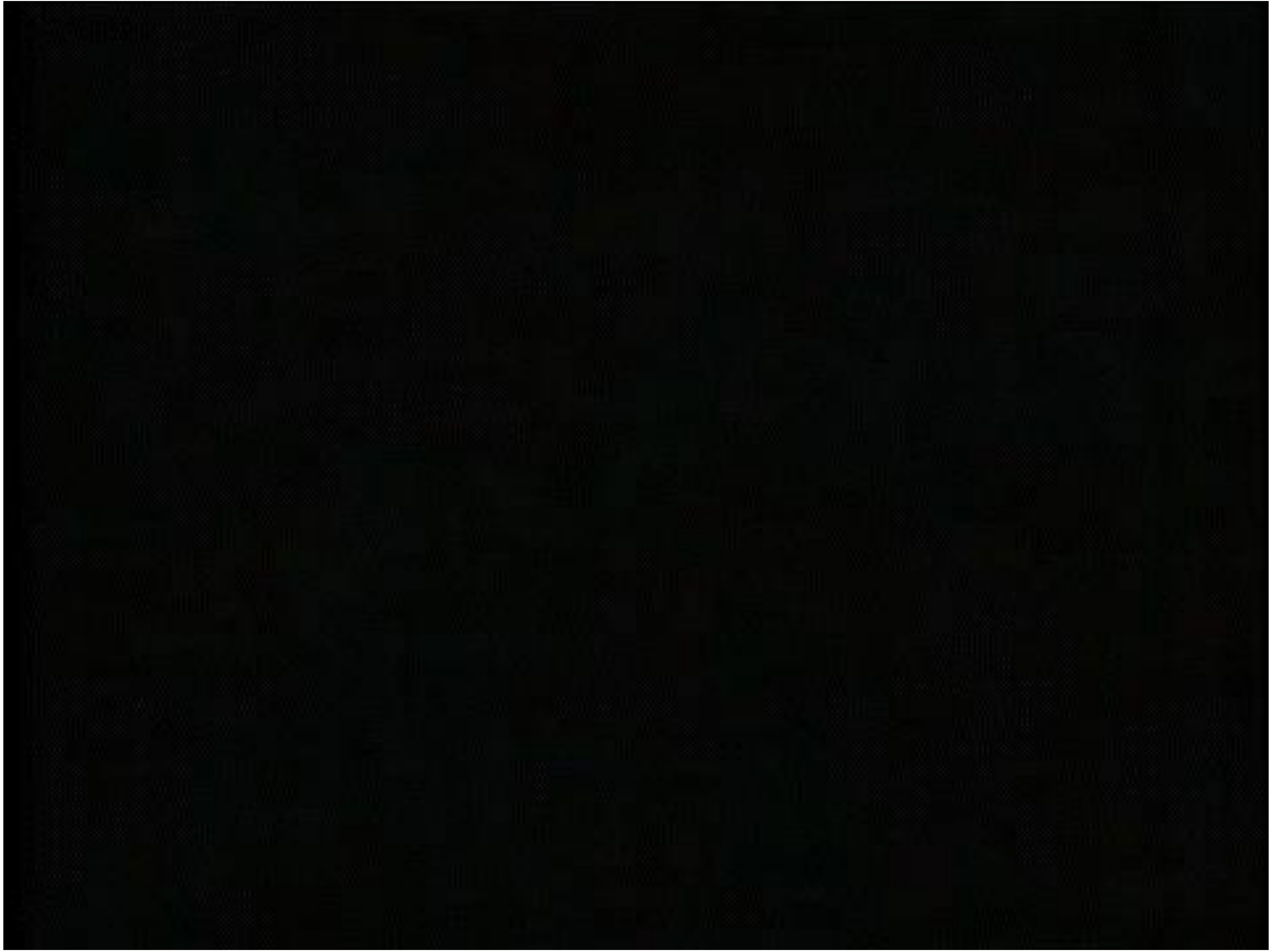


FIGURE 30.6 Two types of plasma-arc welding processes: (a) transferred and (b) nontransferred. Deep and narrow welds can be made by these processes at high welding speeds.



Advantages

- Plasma-arc welding has better arc stability
- Less thermal distortion
- Higher energy concentration
- Permitting deeper and narrower welds.
- Higher welding speeds
- Variety of metals can be welded
- Uniform penetration
- Excellent weld quality

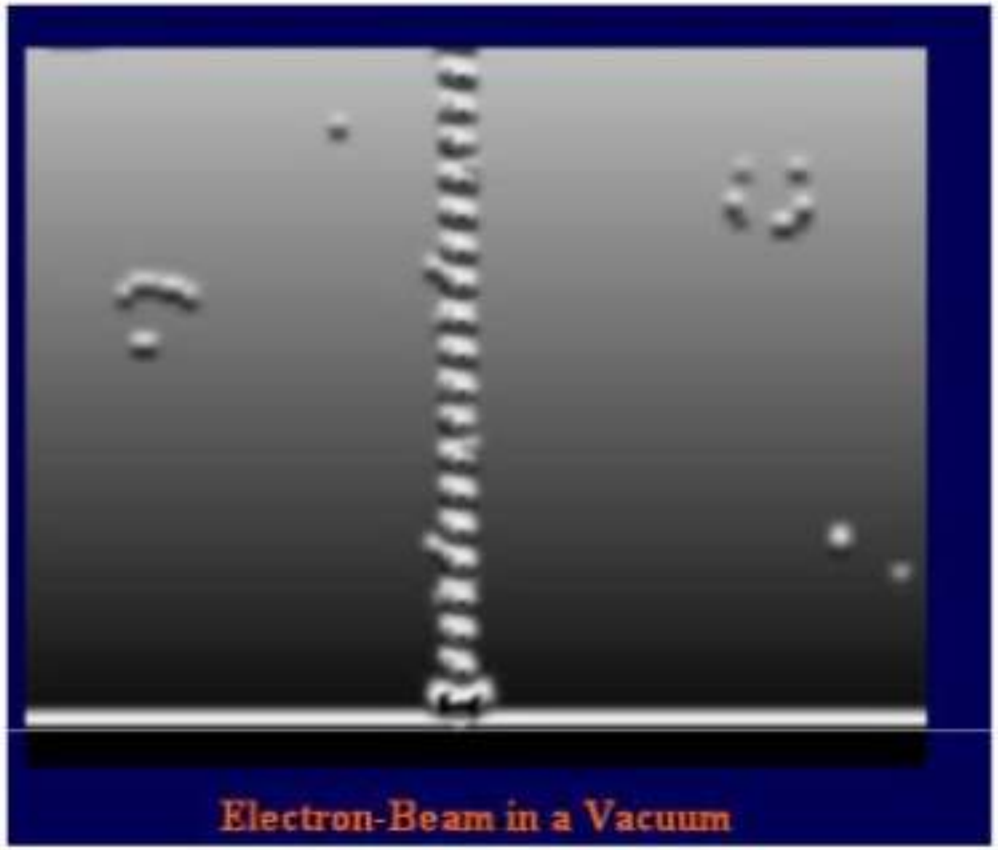
Disadvantage

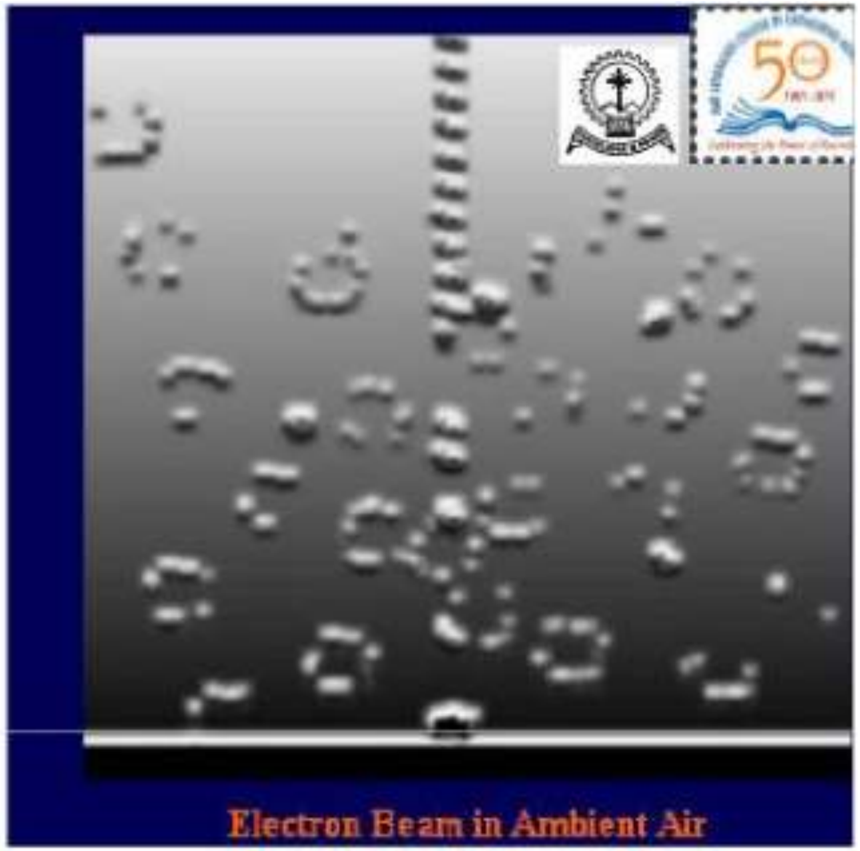
- IR and UV radiations protection.
- Process limited to metal thickness of 25 mm.
- Proper training and skill are essential for operators who use this equipment.

Electron beam welding (EBW)

- It is a fusion welding process with high energy beam.
- Heat obtained from a concentrated beam of high velocity electrons.
- As the high velocity electrons strike the surface to be joined, their kinetic energy changes to thermal energy thereby causing the work piece metal to melt and fuse.
- EBW equipment includes the following subsystems,
  - An electron beam gun with a high voltage power supply and controls
  - A **vacuum pumping system**
  - Mechanical tooling – fixtures, drives and motor controls
  - A beam alignment system including
    - Optics,
    - Scanner,
    - Tape control, &
    - Tracker

- The higher the vacuum, the more the beam penetrates, and the greater is the depth-to-width ratio.
- Almost any metal can be butt or lap welded by EBW, and workpiece thicknesses can range from foil to plate at thicknesses upto 150 mm.
- Generally, no shielding gas, flux, or filler metal is required.
- Electron-beam welding equipment generates X-rays; hence, proper monitoring and periodic maintenance are essential.

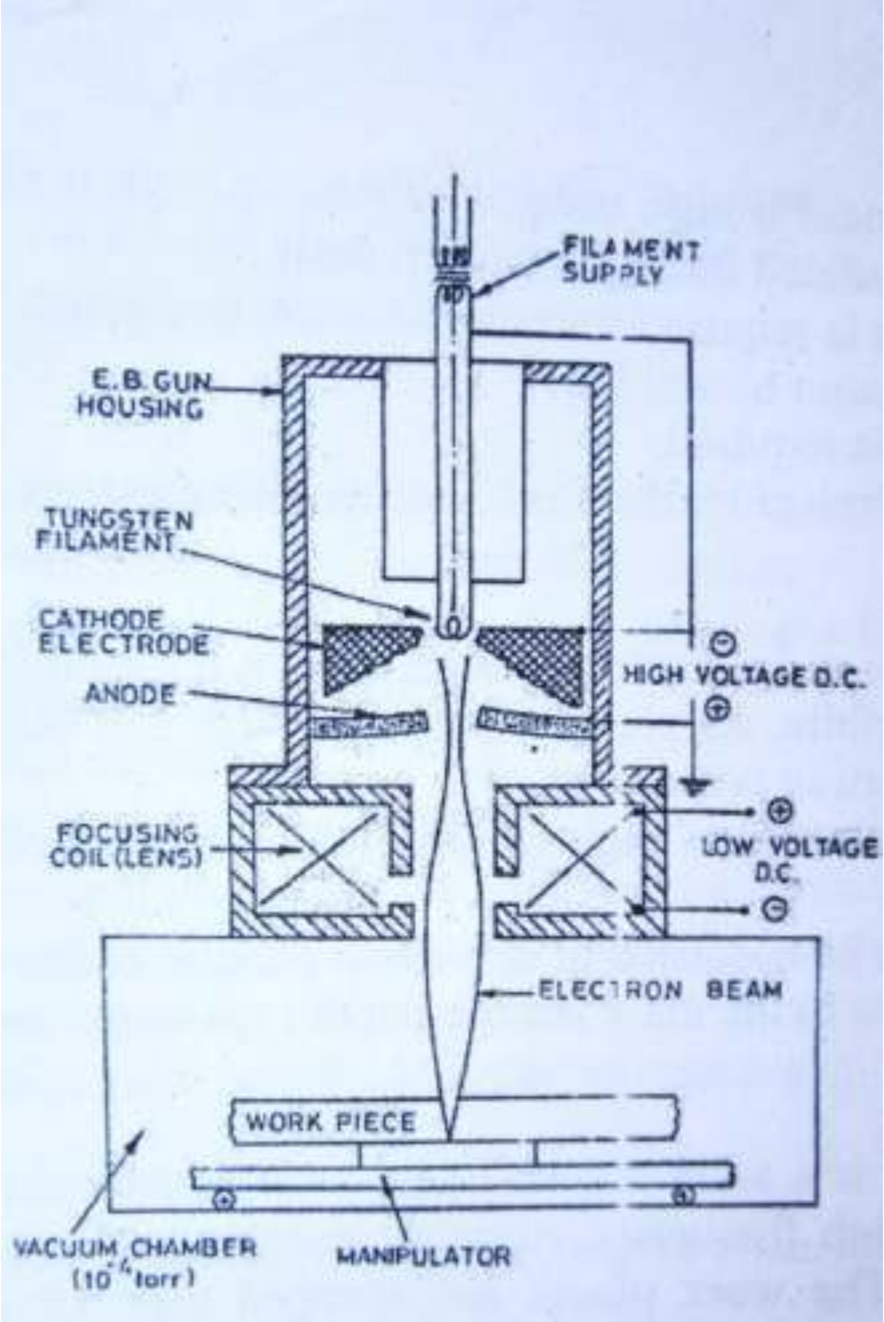




The entire process occurs in a vacuum chamber because a collision between an electron and an air molecule causes the electrons to veer off course. LBM doesn't need vacuum because the size and mass of a photon is numerous times smaller than the size of an electron.


Control Vision Inc
LaserStrobe- Electron Beam Welding

- The tungsten filament in the electron beam gun is electrically heated in vacuum to 2000^{o}C and it emits electrons.
- e^- emitted from carry negative charge and repelled by the cathode and are made to pass through the central hole of the anode.
- e^- accelerated by the tremendous difference of potential voltage between the cathode and anode.
- e^- beam then focused by means of an electromagnetic focusing coil(lens).
- It focus e- beam to weld area.
- K.E of the e^- is converted to heat energy when striking the work piece.



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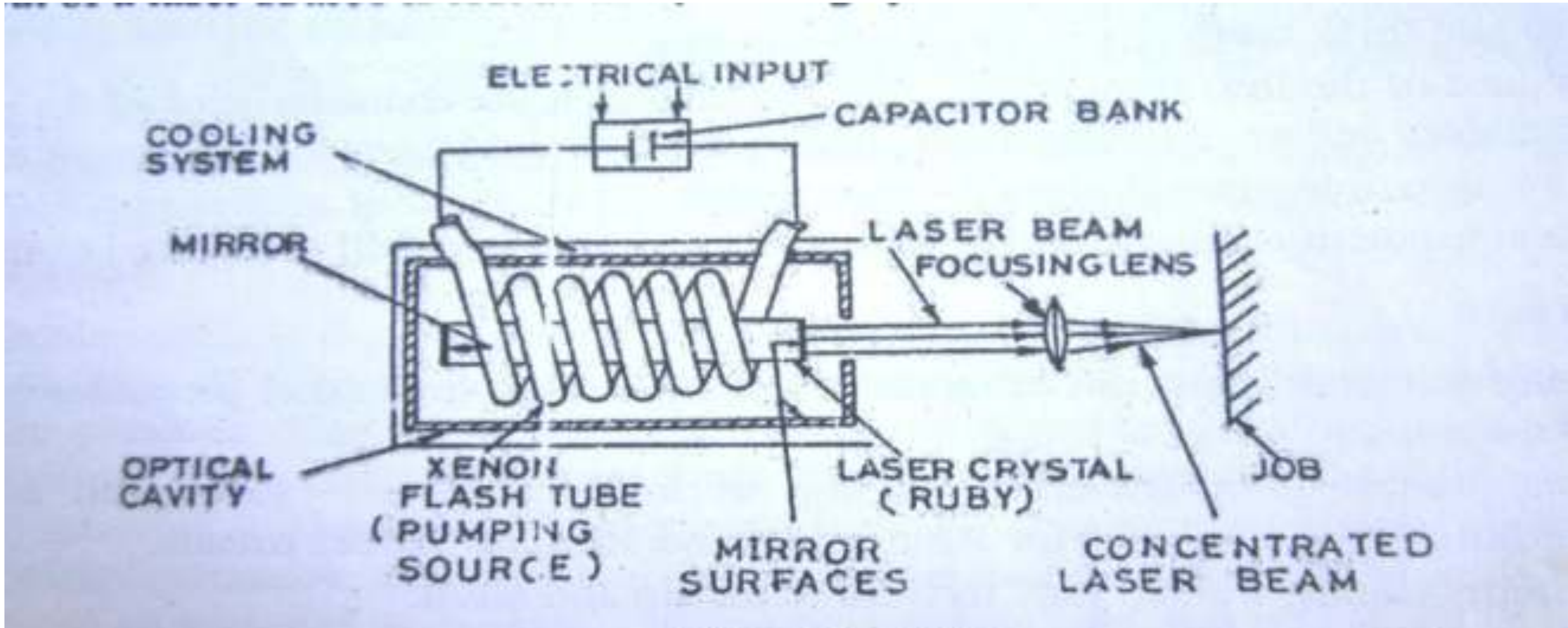
- Advantage
  - High quality weld at high speed
  - Very narrow HAZ
  - High reactive metal can weld
  - Precise control is possible
  - Distortion and shrinkage in the weld area are minimal
- Disadvantages
  - Work piece size is limited
  - Initial cost is high
  - Portable equipment is rare
- Applications
  - Welding of high reactive metal in atomic energy and rocket field
  - High quality automatic welding
  - Aerospace, air plane, equipment's where especially low distortion is required

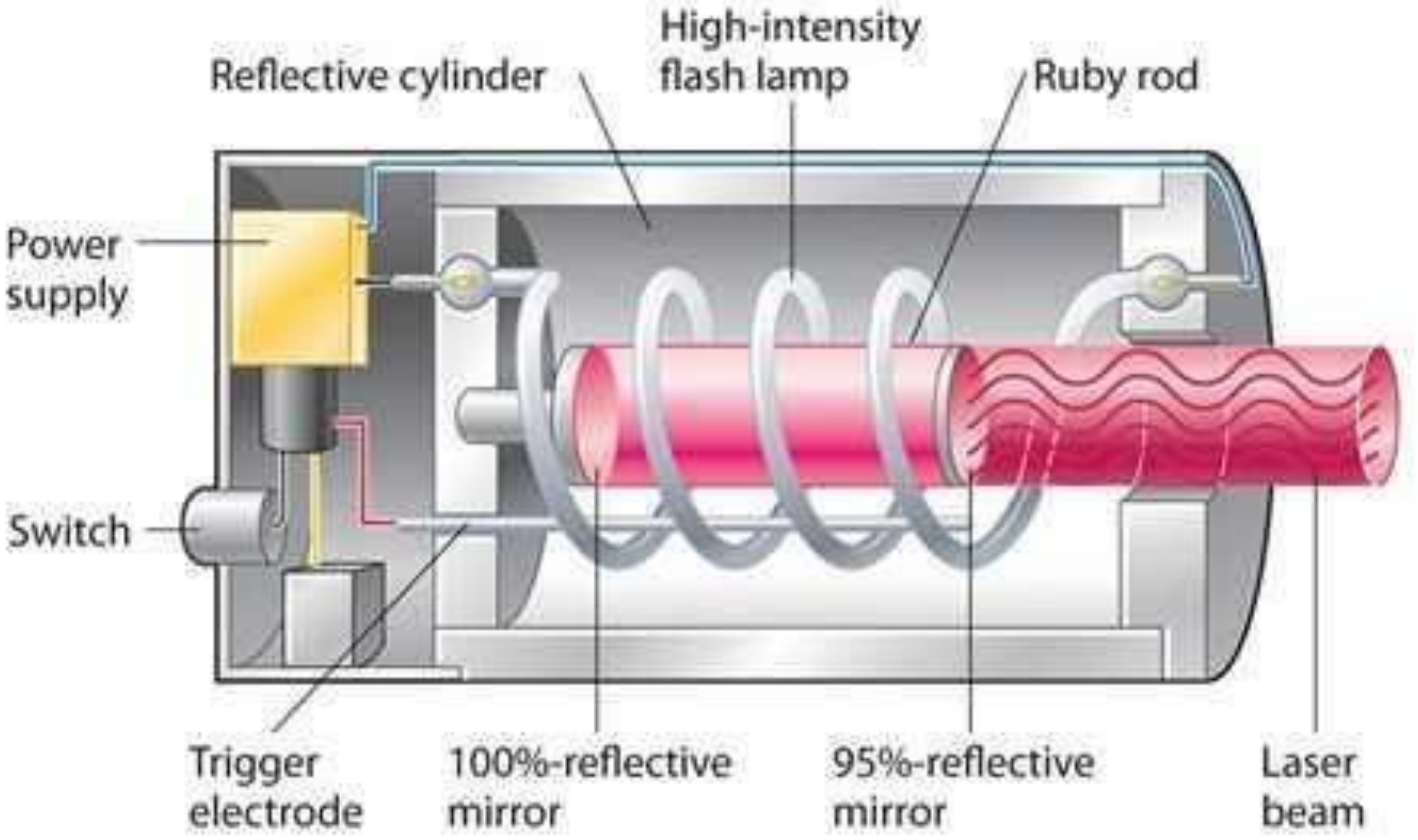
LASER BEAM WELDING

- High-power laser beam as the source of heat to produce a fusion weld
- LASER – Light Amplification by Stimulated Emission of Radiation
- Laser beam is highly directional, strong monochromatic and coherent.
- Joint is produced by heat obtained from a laser beam impinging upon the surfaces to be joined
- Beam can focused to a very small spot giving a very high energy density of 10^9 W/mm^2
- There are three basic types of lasers
  - Solid state, Gas laser, Semi conductor laser
- Welding system consist of,
  - Ruby road, flash tube, capacitor tank, mirror, optical focusing system and cooling system
- Flash tube produce white light flashes of about 1/1000 sec duration
- As ruby rod is exposed to intense flash light, a Laser beam is emitted from partially reflective mirror.

- This narrow Laser beam focused by an optical focusing lens to produce a small intense spot of laser on the job.
- Optical energy as it impacts the work piece is converted into heat energy and the temperature generated is sufficient to melt the work pieces to be welded.



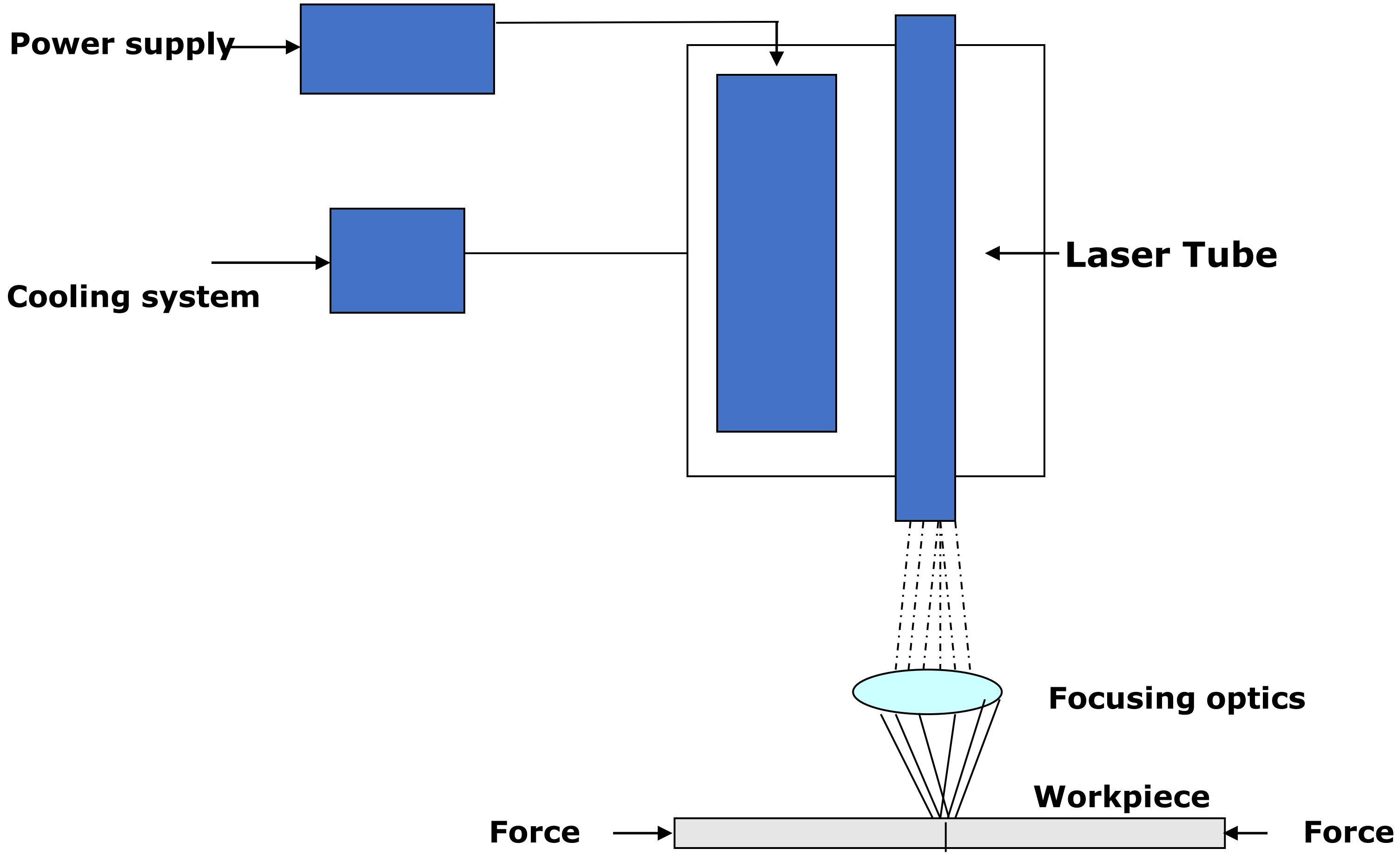
Laser beam welding.

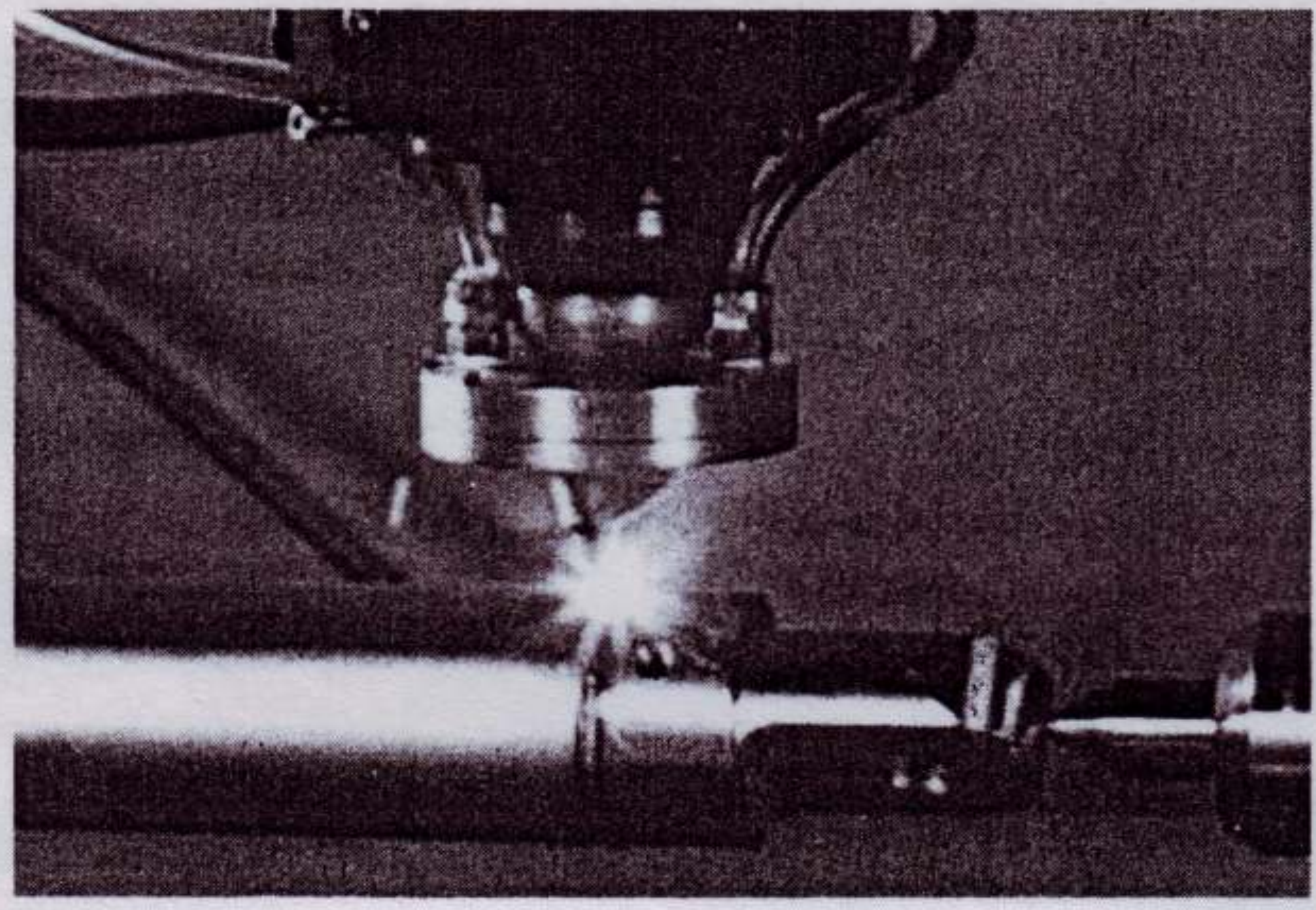


RUBY ROD LASER

- Laser beam may be pulsed for application such as spot welding of thin materials, Continuous multi-KW laser systems are used for deep welds on thick sections.
- In laser welding, a minute puddle is melted and frozen in a matter of microseconds. Since this time is very short, no chemical reaction between the molten metal and atmosphere take place and hence in laser welding no protection is needed against atmospheric contamination.
- Deep-narrow joints can produce.
- Advantages
  - Area not readily accessible can also be welded.
  - Unlike EBW no vacuum required.
  - Narrow HAZ.
  - Process can be easily automated.
  - Good quality weld with minimum shrinkage and distortion and other defects.
  - Do not generate X ray
- Disadvantages
  - Laser welding limited to depth of 1.5mm , Slow welding speed.

Laser Beam Welding





laser welded. Courtesy of Laser Machining, Inc.

Comparison with other welding processes

Properties	Resistance Welding	Electron Beam welding	Laser Beam Welding
Heat Generation	Moderate to High	Moderate	Low
Weld Quality	Good	Excellent	Excellent
Welding Speed	Moderate	High	Moderate
Cost	Cheap	Very Expensive	Moderate
Controllability	Low	Very Good	Very Good
Joining Dissimilar Matls.	Narrow	Very Wide Range	Very Wide Range

Applications

- For joining leads on small electronic equipments and in integrated circuitry in the electronic industry.
- In space and aircraft industry for welding light gauge materials.
- LBW is used for micro welding purposes. It is suitable for the welding of miniaturized and micro miniaturized components.
- Forming of butt-welded sheet metal in automobile body.

Thermit Welding

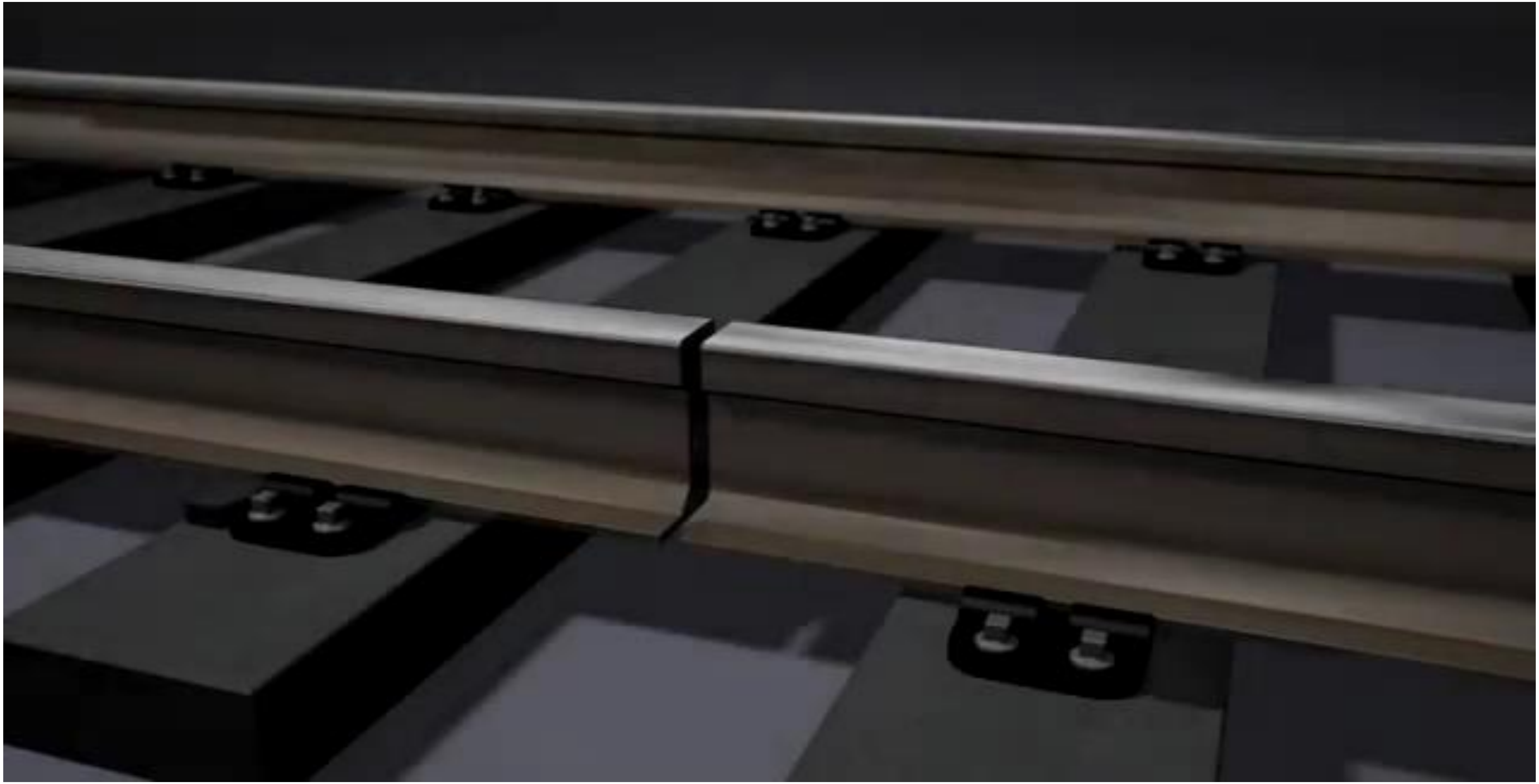
- Utilizes heat from a chemical reaction for welding.
- Mixture of aluminium powder and a metal oxide called thermit is ignited to produce the required quantity of molten metal by an exothermic reaction.
- The superheated metal so produced is poured at the desired place which on solidification results in a weld joint.
- Metal oxide + (Al powder) ⟶ Metal+ Al oxide + Heat
- Commonly used metal oxide is iron oxide.
- Mixture is ignited with ignition powder or an ignition rod.

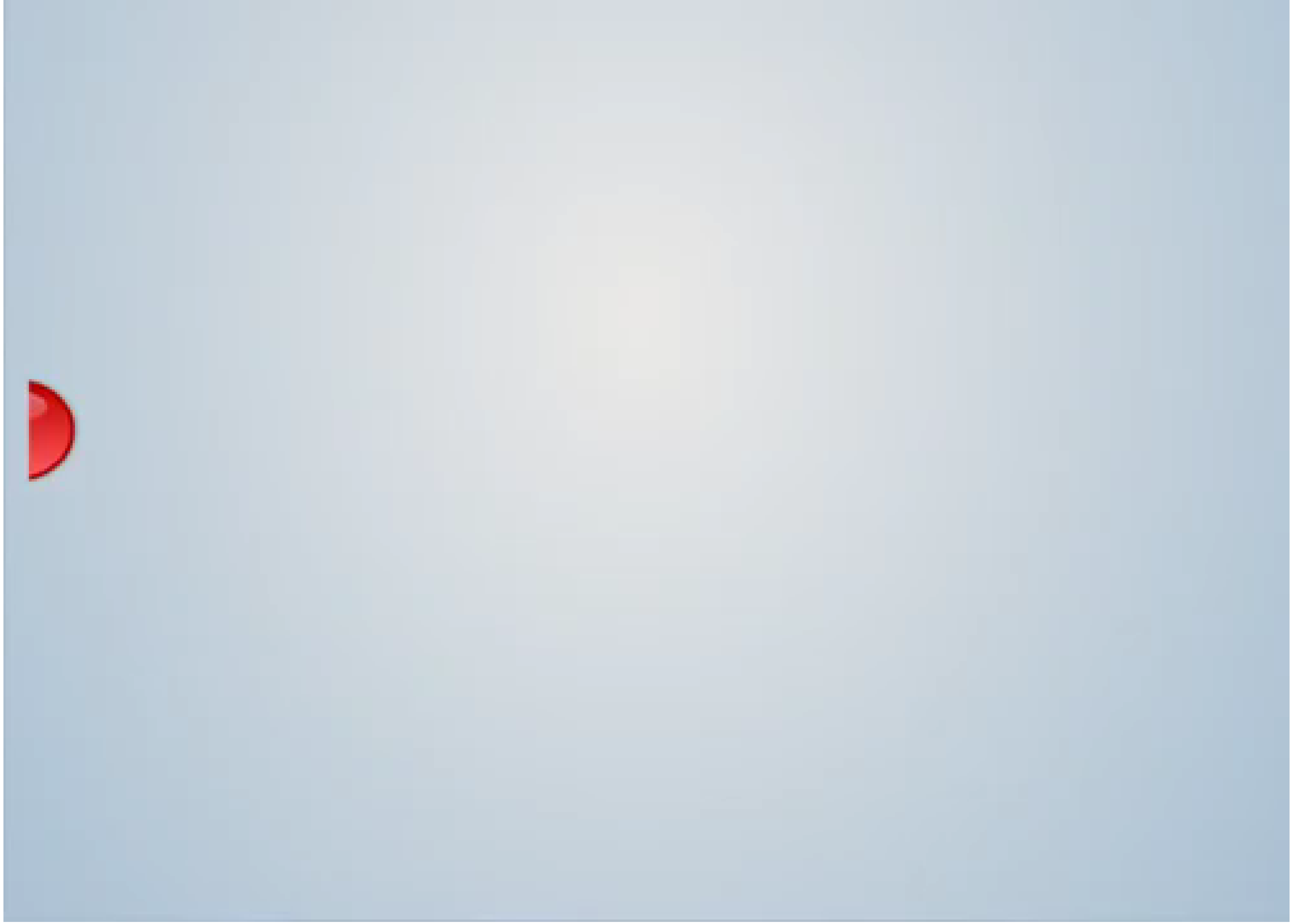
With iron

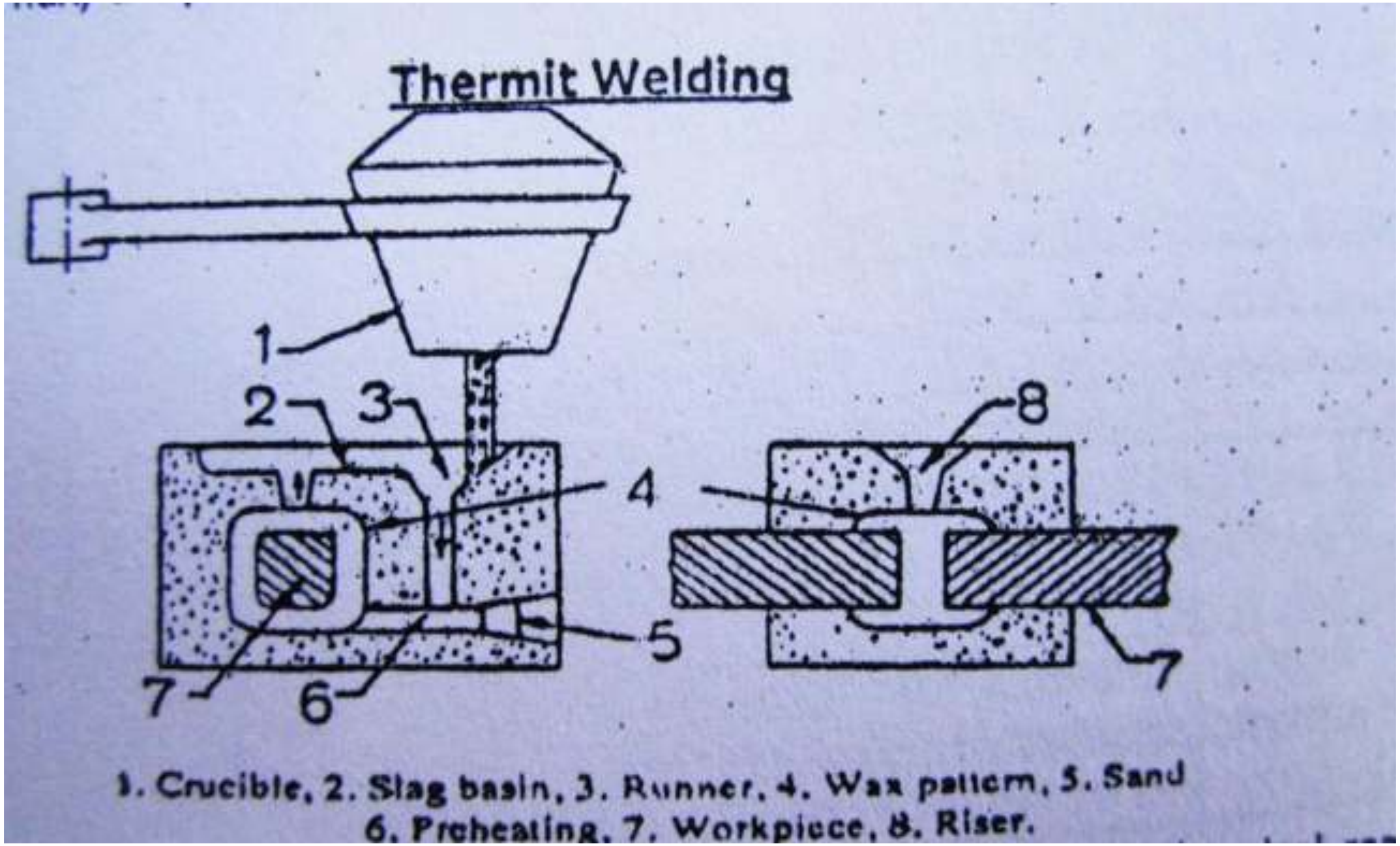
$3Fe_3O_4 + 8Al \rightarrow 9Fe + 4Al_2O_3 + 3010\ KJ/mol$ (3090 °C)

$Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3 + 759\ KJ/mol$ (2960 °C)

$3FeO + 2Al \rightarrow 3Fe + Al_2O_3 + 783\ KJ/mol$ (2500 °C)







- The major use of thermit welding is for joining of rails at site and repair welding of heavy components

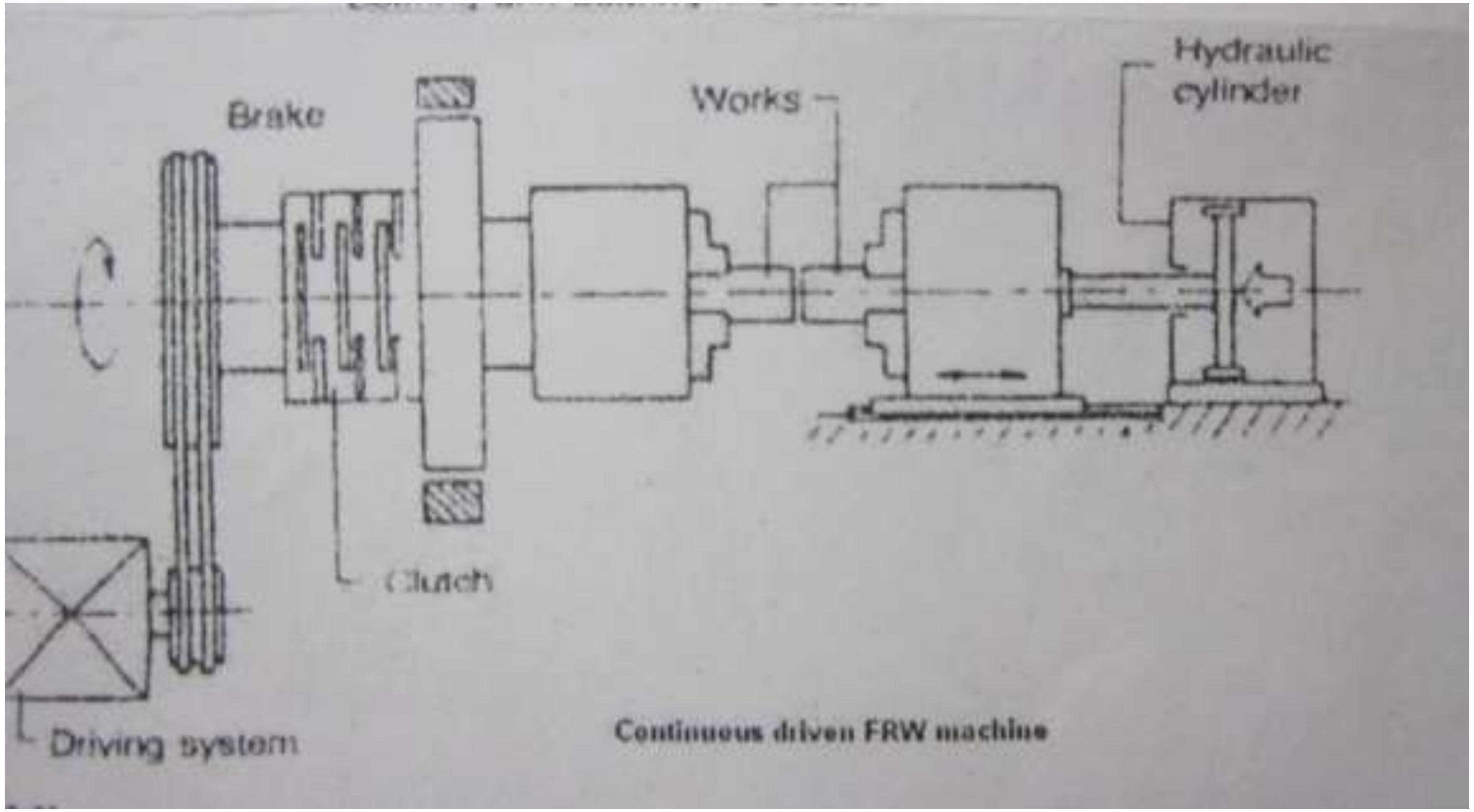
- Due to considerable difference between the specific gravities of the molten metal and slag, the two get separated with the slag floating on the top giving protection to the molten metal from atmosphere.
- Advantages
  - No power supply is required
  - So can use in remote locations
- Disadvantages
  - Can use only for ferrous metal parts of heavy sections
- Applications
  - Repair of fractured rails
  - Butt welding pipes end to end
  - Welding broken frames of machine
  - End welding of reinforcing bars to be used in concrete construction

Solid state welding

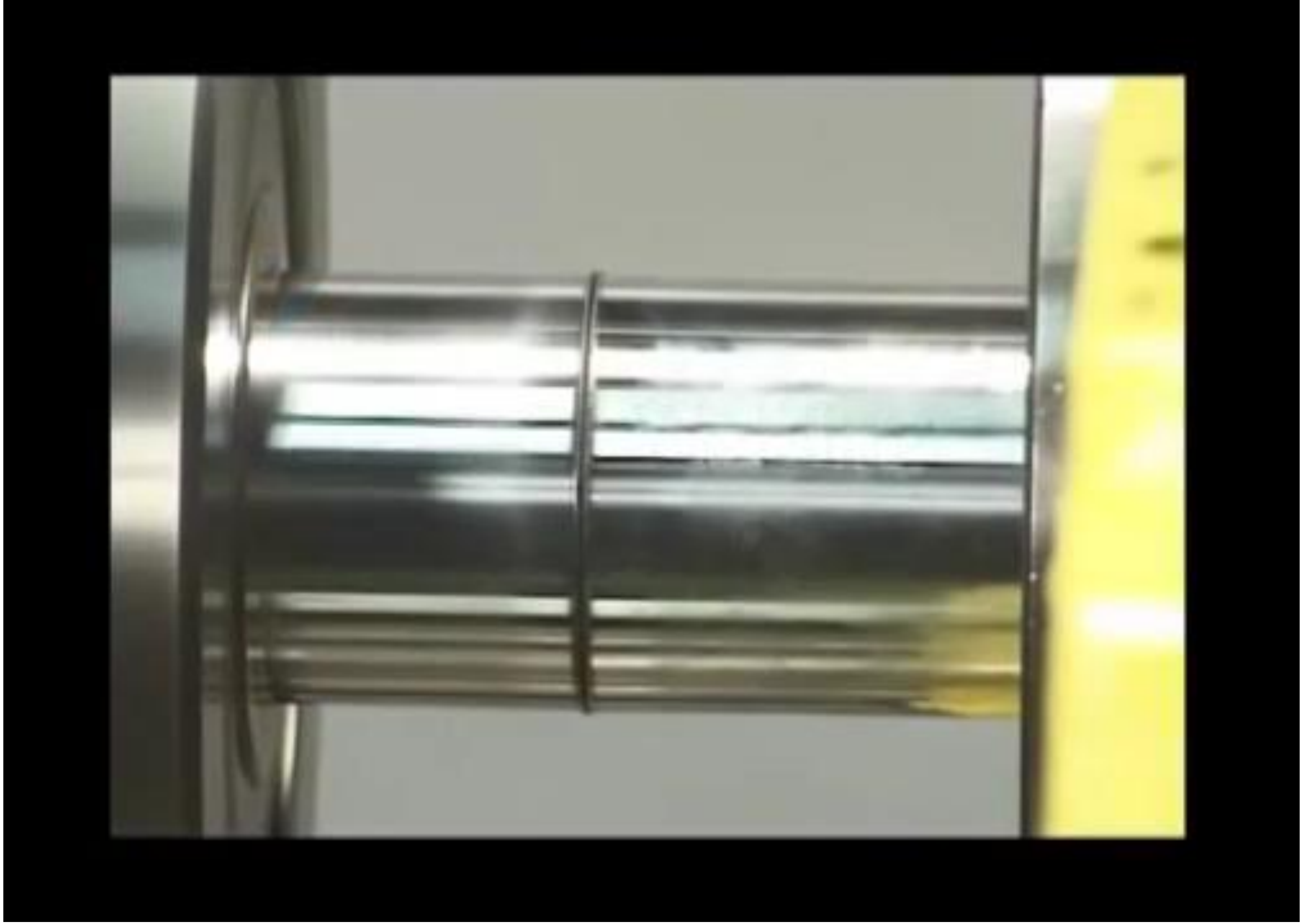
- Joining take place without fusion (melting) of the work piece.
- Joints produced at temperature essentially below the melting point of the base metals being joined, pressure is applied.
- Solid state welding includes,
    - Friction welding
    - Ultrasonic welding
    - Diffusion welding
    - Explosive welding

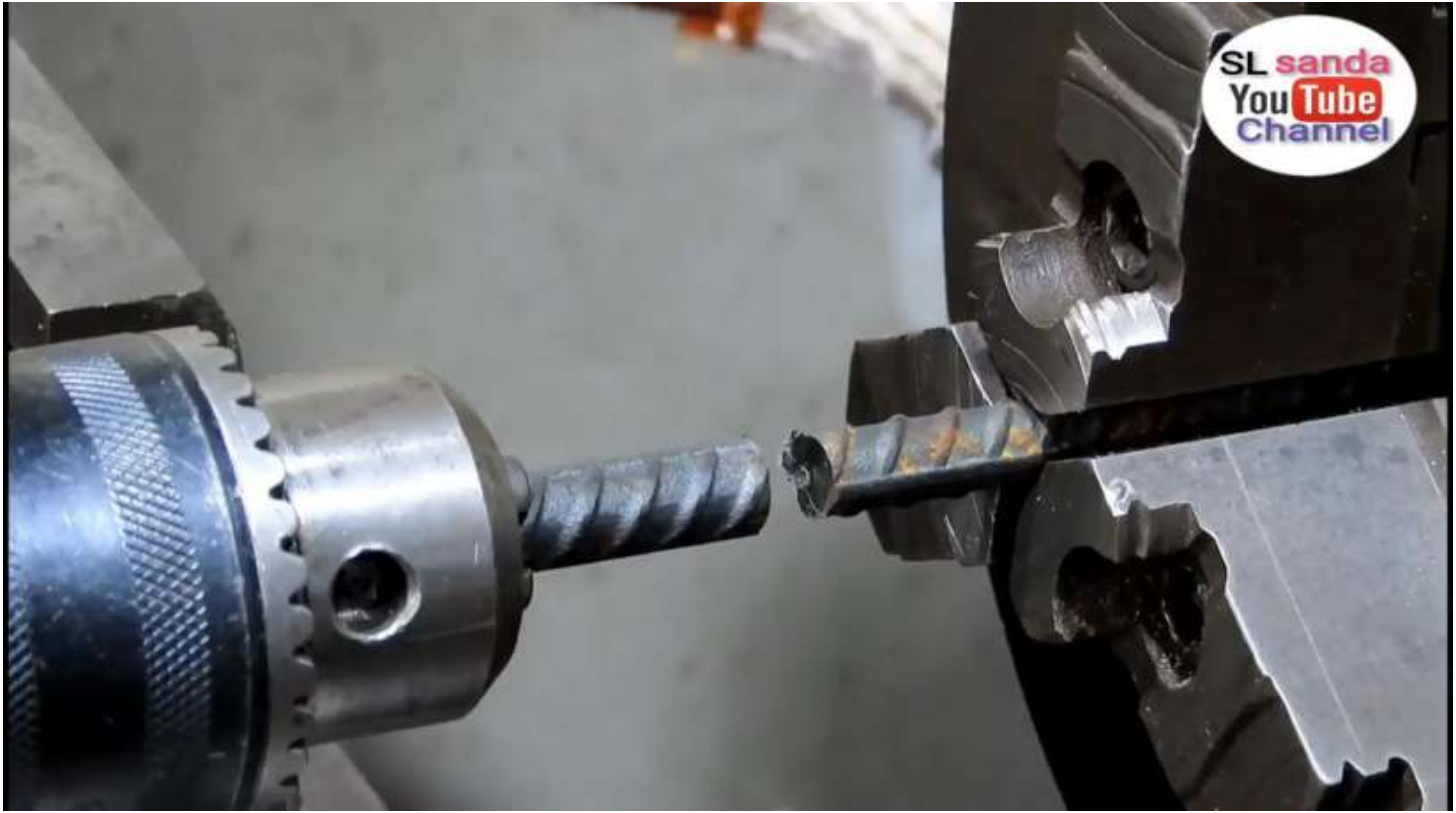
Friction welding

- Friction welding is a process in which the energy required to achieve the weld is provided by the frictional heat generated at the rubbing surface under heavy pressure.



- One of the workpiece components remains stationary while the other is placed in a chuck or collet and rotated at a high constant speed. The two members to be joined are then brought into contact under an axial force.
- The surface speed of the rotating parts may be as high as 900 m/min.
- After sufficient contact is established, the rotating member is brought to a quick stop (so that the weld is not destroyed by shearing) while the axial force is increased.

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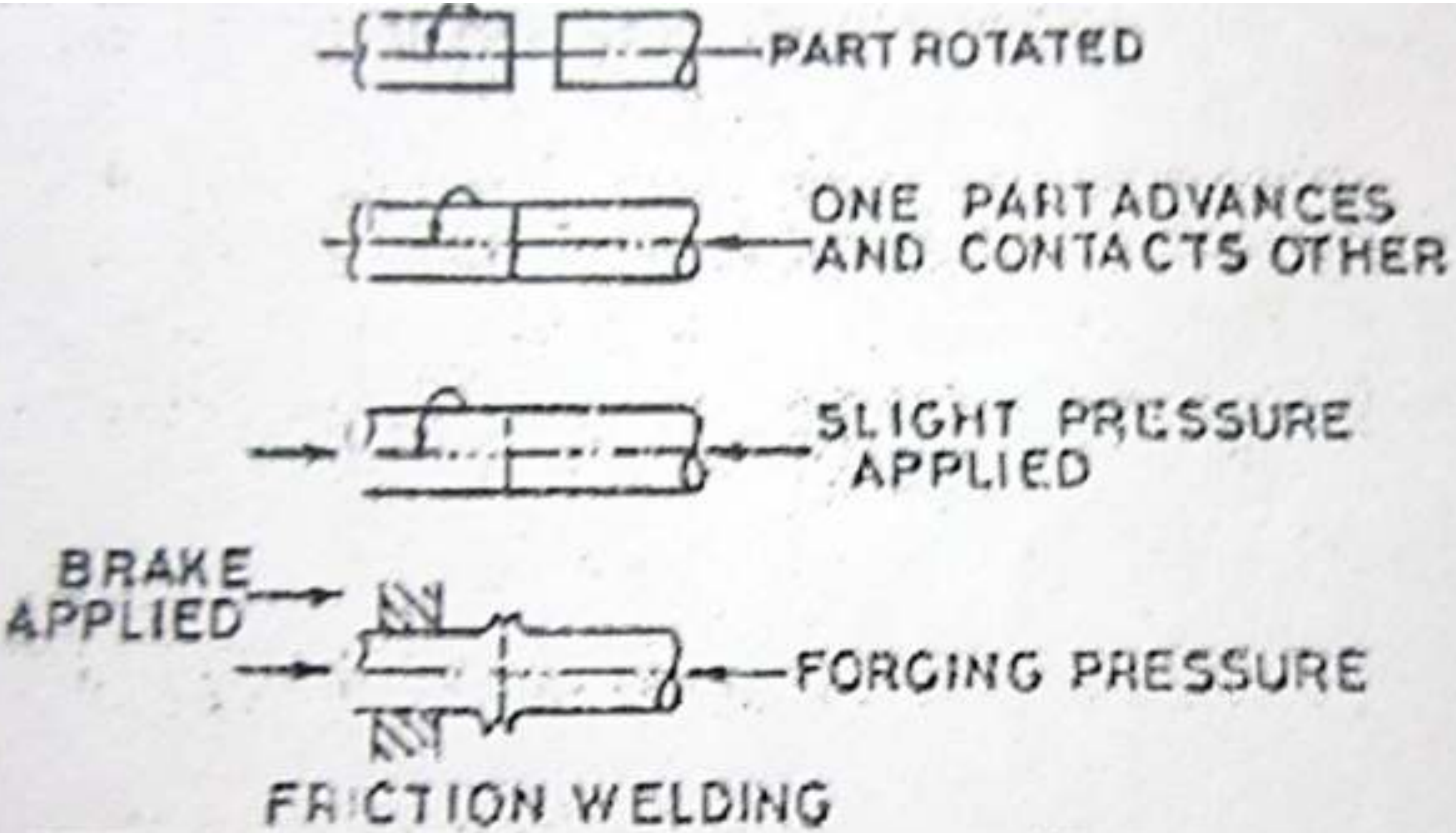


Operational steps in friction welding.

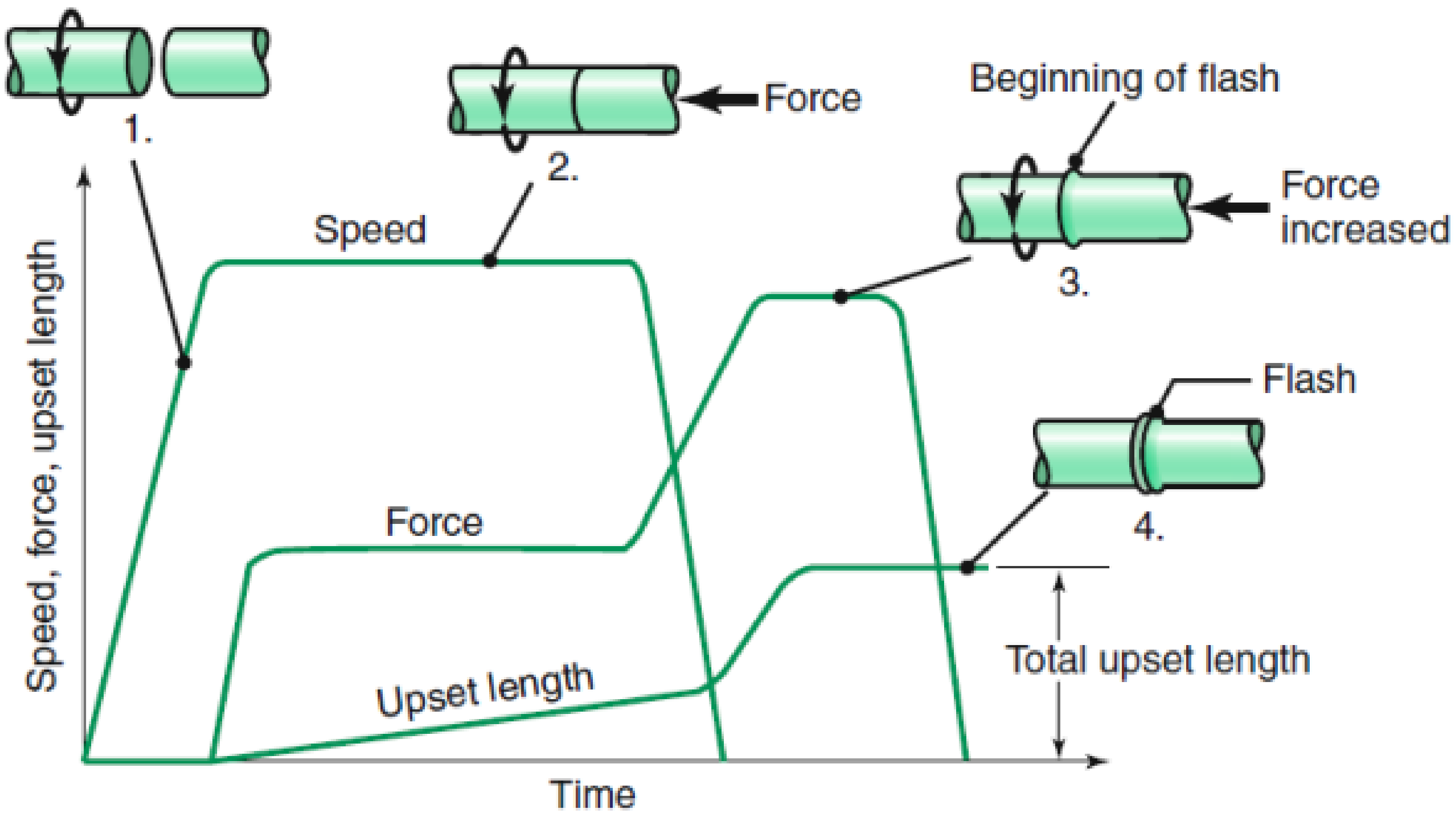


FIGURE 31.3 Sequence of operations in the friction-welding process: (1) The part on the left is rotated at high speed; (2) The part on the right is brought into contact with the part on the left under an axial force; (3) The axial force is increased, and the part on the left stops rotating; flash begins to form; (4) After a specified upset length or distance is achieved, the weld is completed. The *upset length* is the distance the two pieces move inward during welding after their initial contact; thus, the total length after welding is less than the sum of the lengths of the two pieces. The flash subsequently can be removed by machining or grinding.

- The shape of the welded joint depends on the rotational speed and on the axial pressure applied.
- Oxides and other contaminants at the interface are removed by the radially outward movement of the hot metal at the interface.

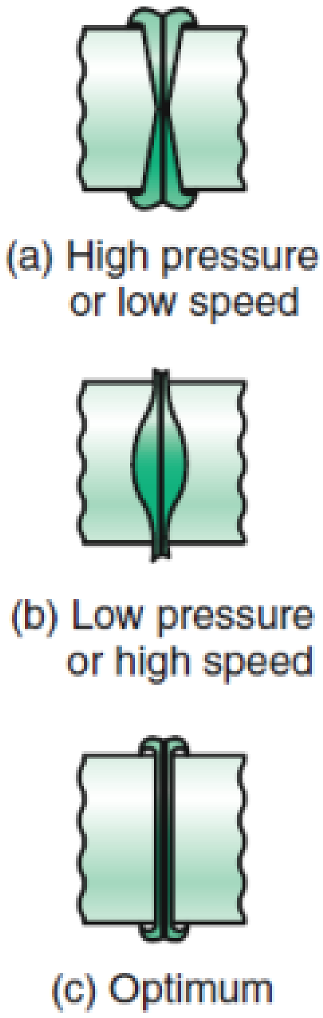
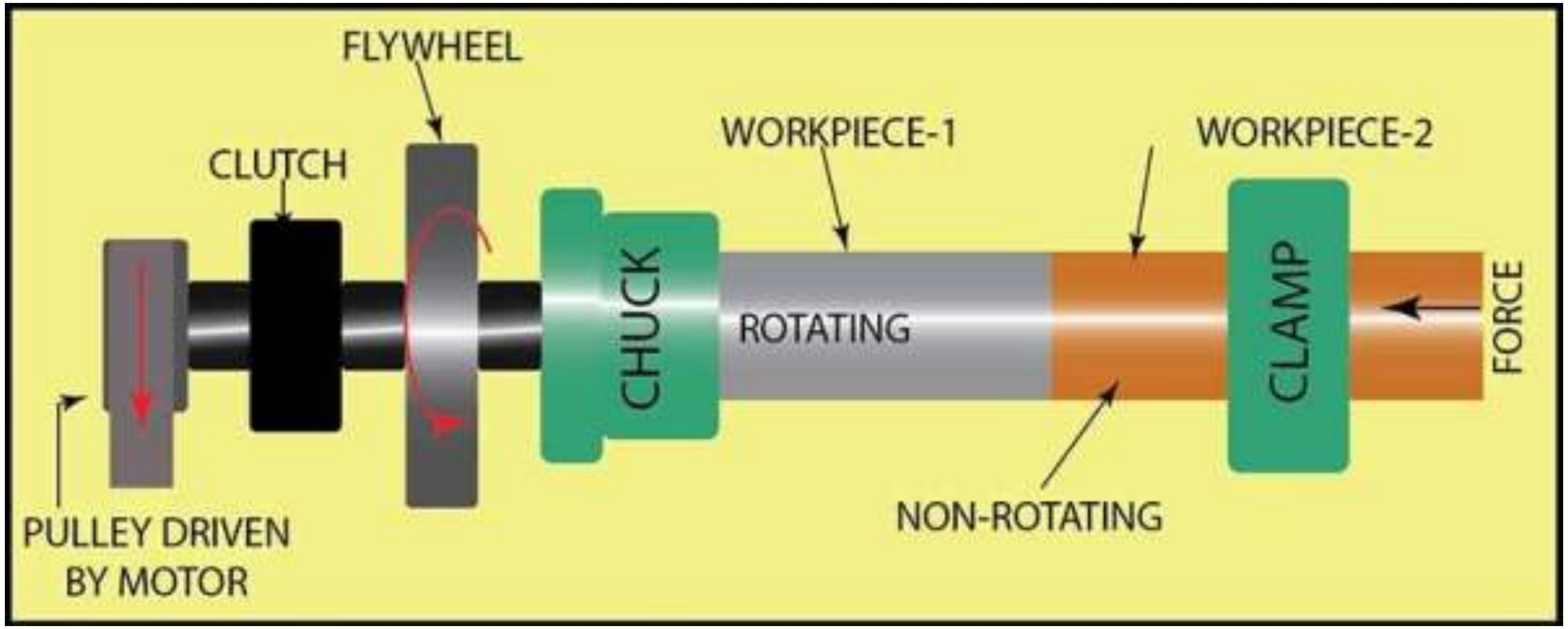
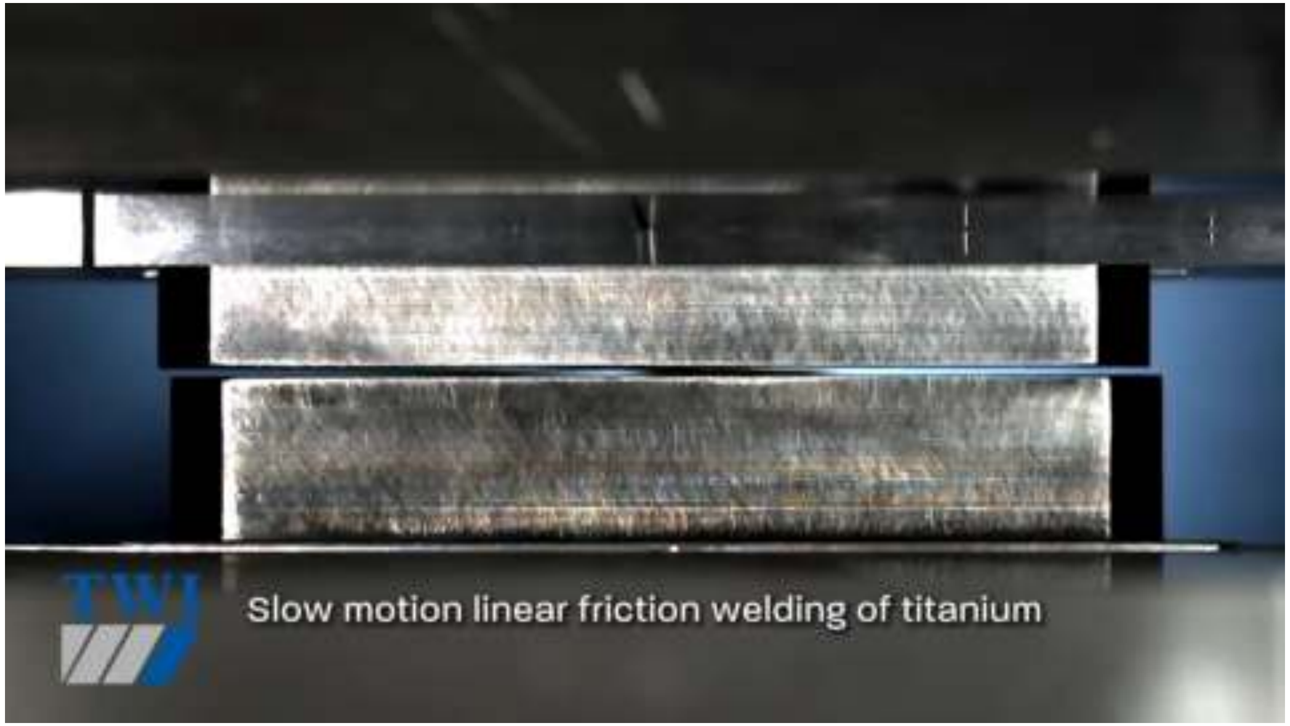


FIGURE 31.4 Shape of the fusion zones in friction welding as a function of the axial force applied and the rotational speed.

- There are several variations on the friction welding process,
  - Inertia Friction Welding
    - The energy required for frictional heating in inertia friction welding is supplied by the kinetic energy of a flywheel. The flywheel is accelerated to the proper speed, the two members are brought into contact, and an axial force is applied. As friction at the interface slows the flywheel, the axial force is increased. The weld is completed when the flywheel has come to a stop. The timing of this sequence is important for good weld quality.



- Linear Friction Welding.
    - In a further development of friction welding, the interface of the two components to be joined is subjected to a linear reciprocating motion, as opposed to a rotary motion. In linear friction welding, the components do not have to be circular or tubular in their cross section. The process is capable of welding square or rectangular components (as well as round parts) made of metals or plastics. In this process, one part is moved across the face of the other part by a balanced reciprocating mechanism.



- Friction Stir Welding
  - In the friction stir-welding (FSW) process, third body is rubbed against the two surfaces to be joined. A rotating non-consumable probe, typically 5 to 6 mm in diameter and 5 mm high, is plunged into the joint.
  - The probe at the tip of the rotating tool forces mixing (or stirring) of the material in the joint.

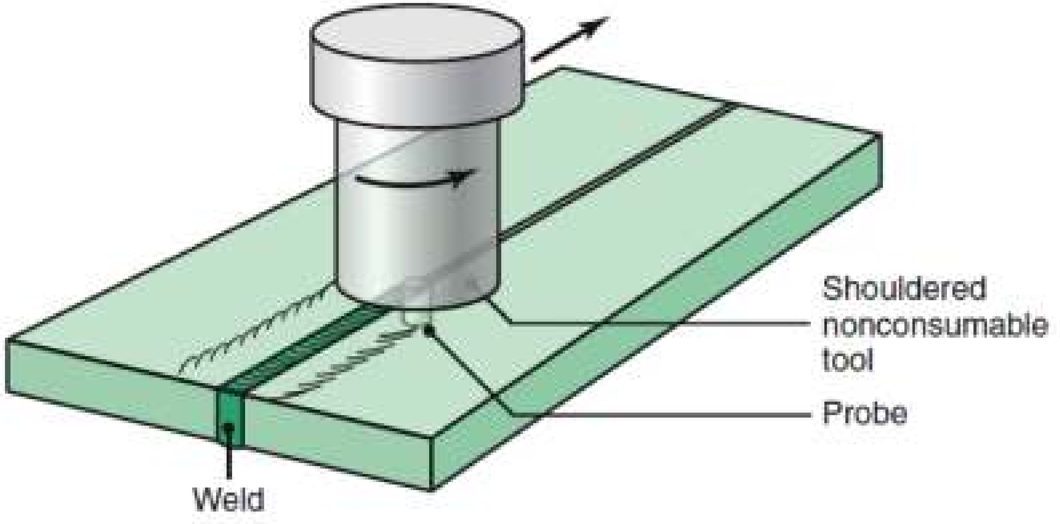
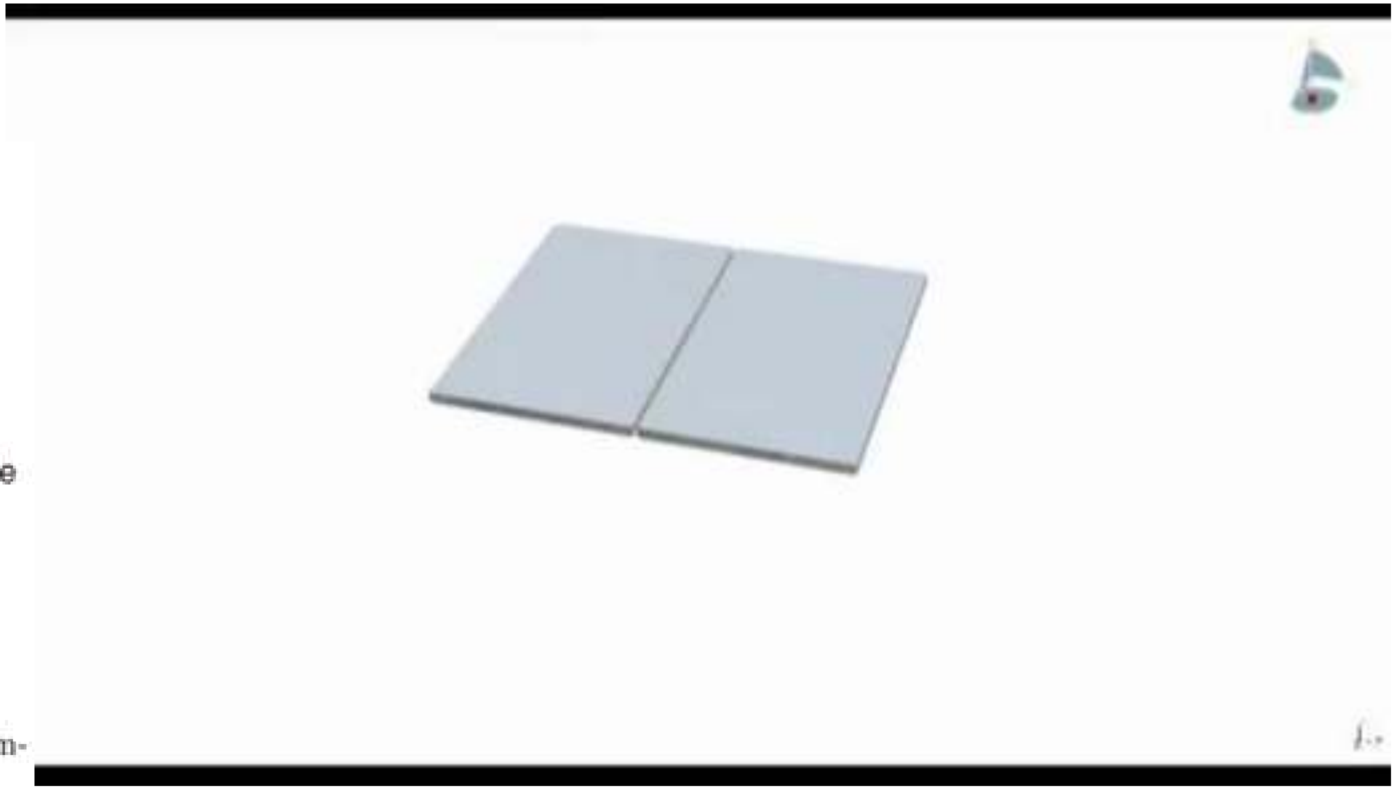


FIGURE 31.5 The principle of the friction-stir-welding process. Aluminum-alloy plates up to 75 mm (3 in.) thick have been welded by this process.

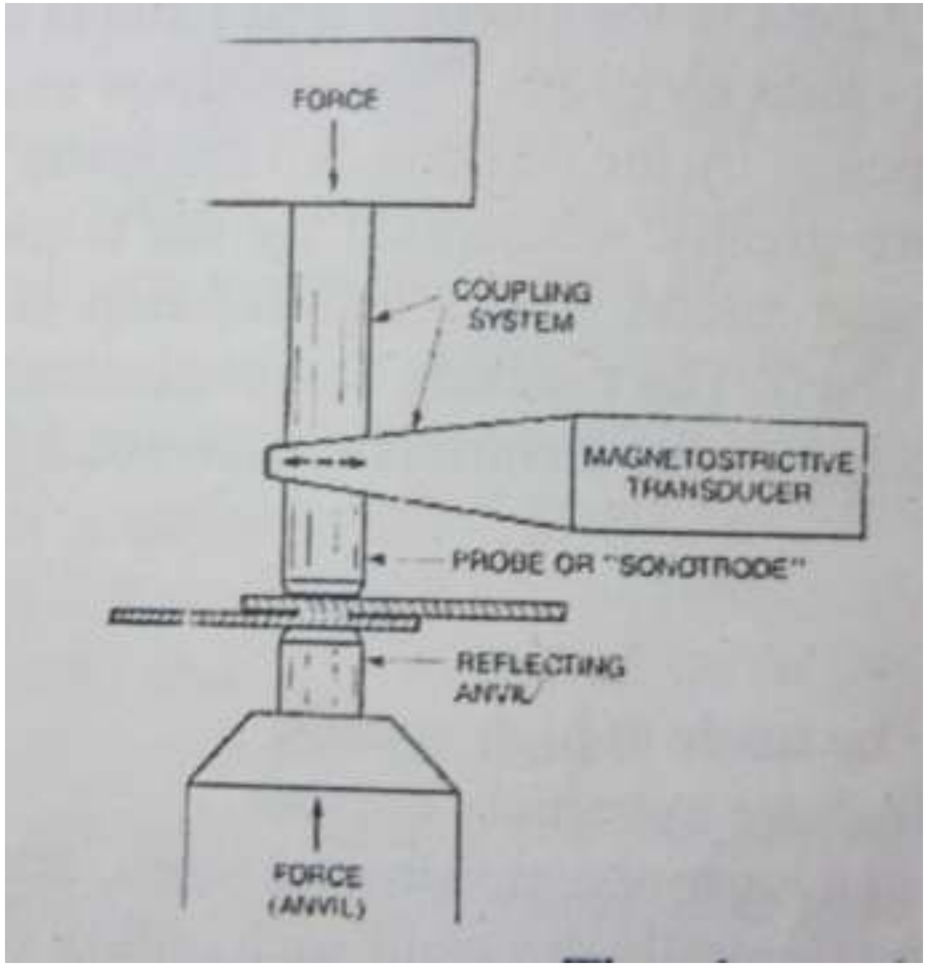


- Applications
  - Friction welding can be used to join a wide variety of materials, provided that one of the components has some rotational symmetry. Solid or tubular parts can be joined by this method with good joint strength. Solid steel bars up to 100 mm. in diameter and pipes up to 250 mm in outside diameter have been friction welded successfully.
- Advantages
  - Friction-welding machines are fully automated
  - The operator skill required is minimal

Ultrasonic welding

Reference

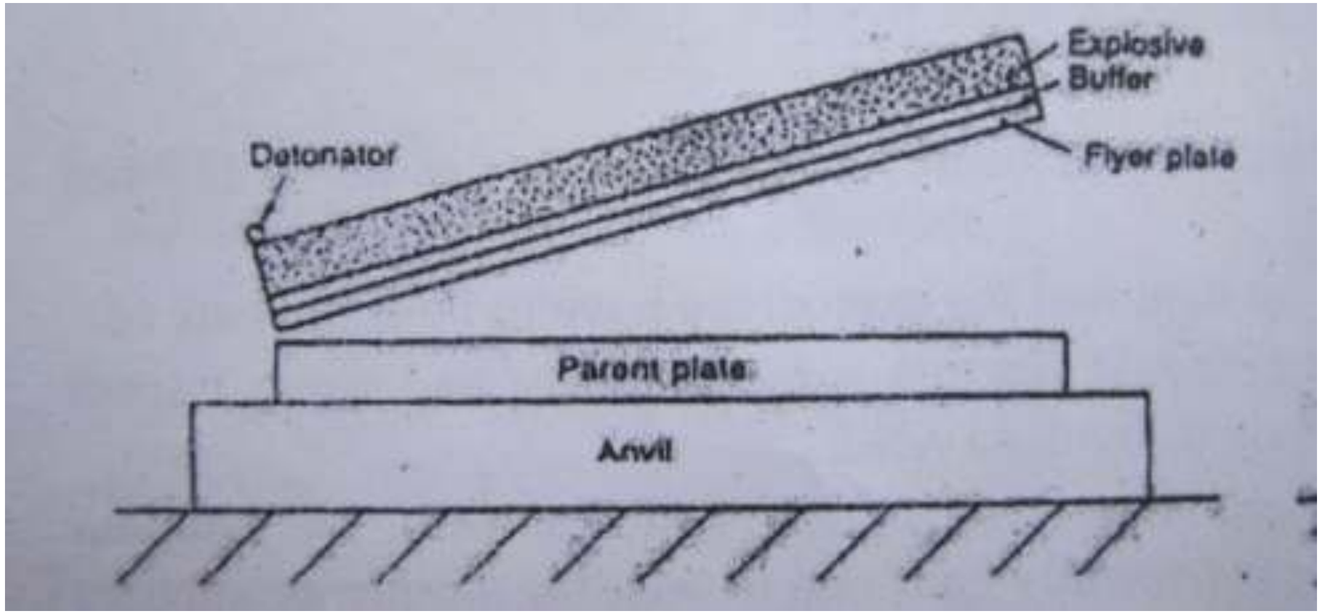
- Joint is produced by the local application of high frequency vibratory energy to the work piece as they are held together under pressure



Explosive welding

Reference

- Joint is produced by high velocity movement produced by a controlled detonation
- The process involves a high velocity impact between a plate propelled by an explosive charge and a stationary plate
- The flyer plate is to be joined with the parent plate



Resistance welding

- In resistance welding the metal parts to be joined are heated to a plastic state over a limited area by their resistance to flow of an electric current and mechanical pressure is used to complete the weld.
- Heat generated $H = I^2 \times R \times t$

where

H = Heat generated in joules (watt-seconds)
I = Current (in amperes)
R = Resistance (in ohms)
t = Time of current flow (in seconds).

- Similar or dissimilar metal can be joined by resistance welding
- These processes have major advantages, such as not requiring consumable electrodes, shielding gases, or flux.
- The major two factors responsible for resistance welding are,
  - Heat- : generation of heat takes place where two pieces are to be joined
  - Pressure : pressure is applied at the place where the joint is formed
- Current for resistance welding may be as high as 100,000A , although the voltage is typically only 0.5V -10 V

Resistance Welding

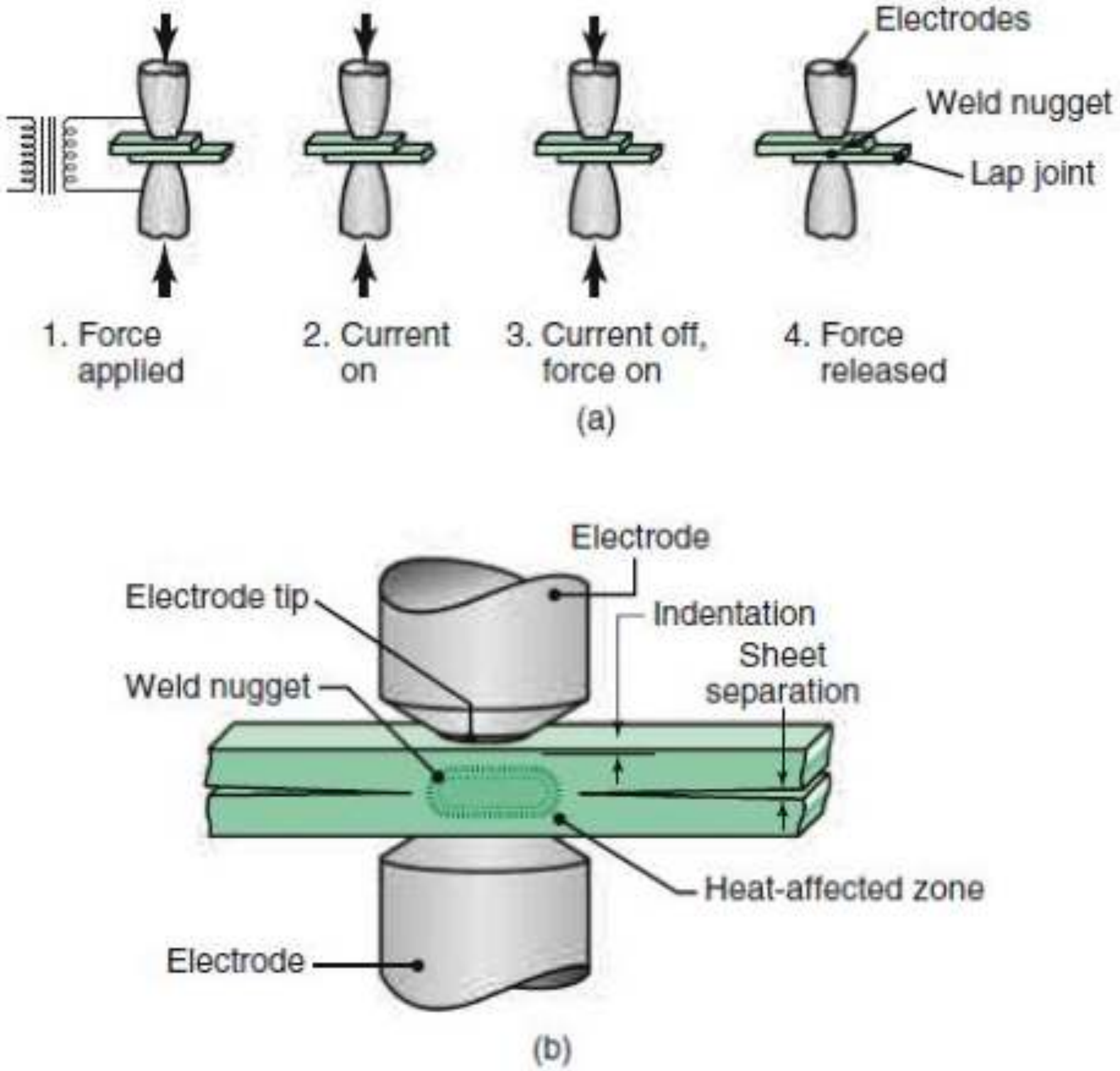


FIGURE 31.6 (a) Sequence of events in resistance spot welding. (b) Cross section of a spot weld, showing the weld nugget and the indentation of the electrode on the sheet surfaces. This is one of the most commonly used processes in sheet-metal fabrication and in automotive-body assembly.

The *total resistance* is the sum of the following properties (see Fig. 31.6):

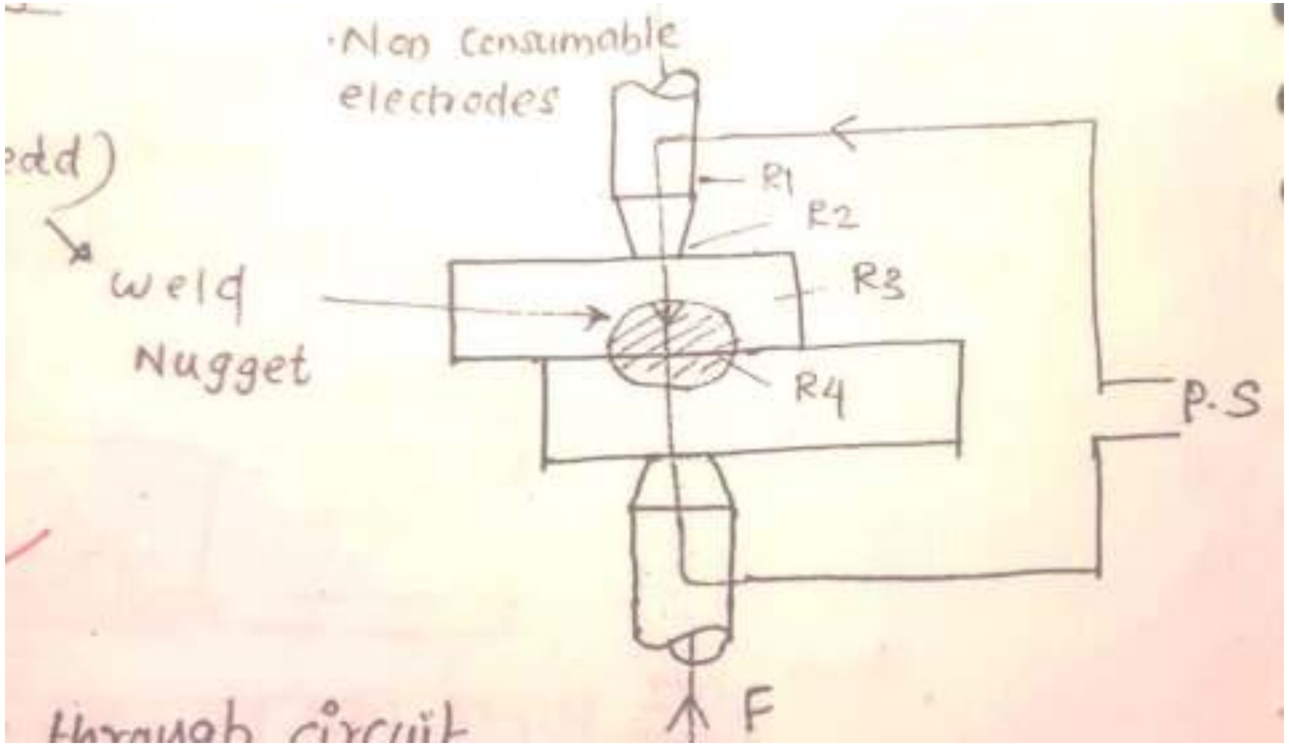
a. Resistances of the electrodes;
b. Electrode–workpiece contact resistance;
c. Resistances of the individual parts to be welded;
d. Contact resistance between the two workpieces to be joined (*faying surfaces*).

- Various resistance welding process are,
  - Spot welding
  - Seam welding
  - Projection welding
  - Resistance(upset) butt welding
  - Flash butt welding
  - Percussion welding
  - Resistance welding of tubes

Process Parameters

1. Resistance

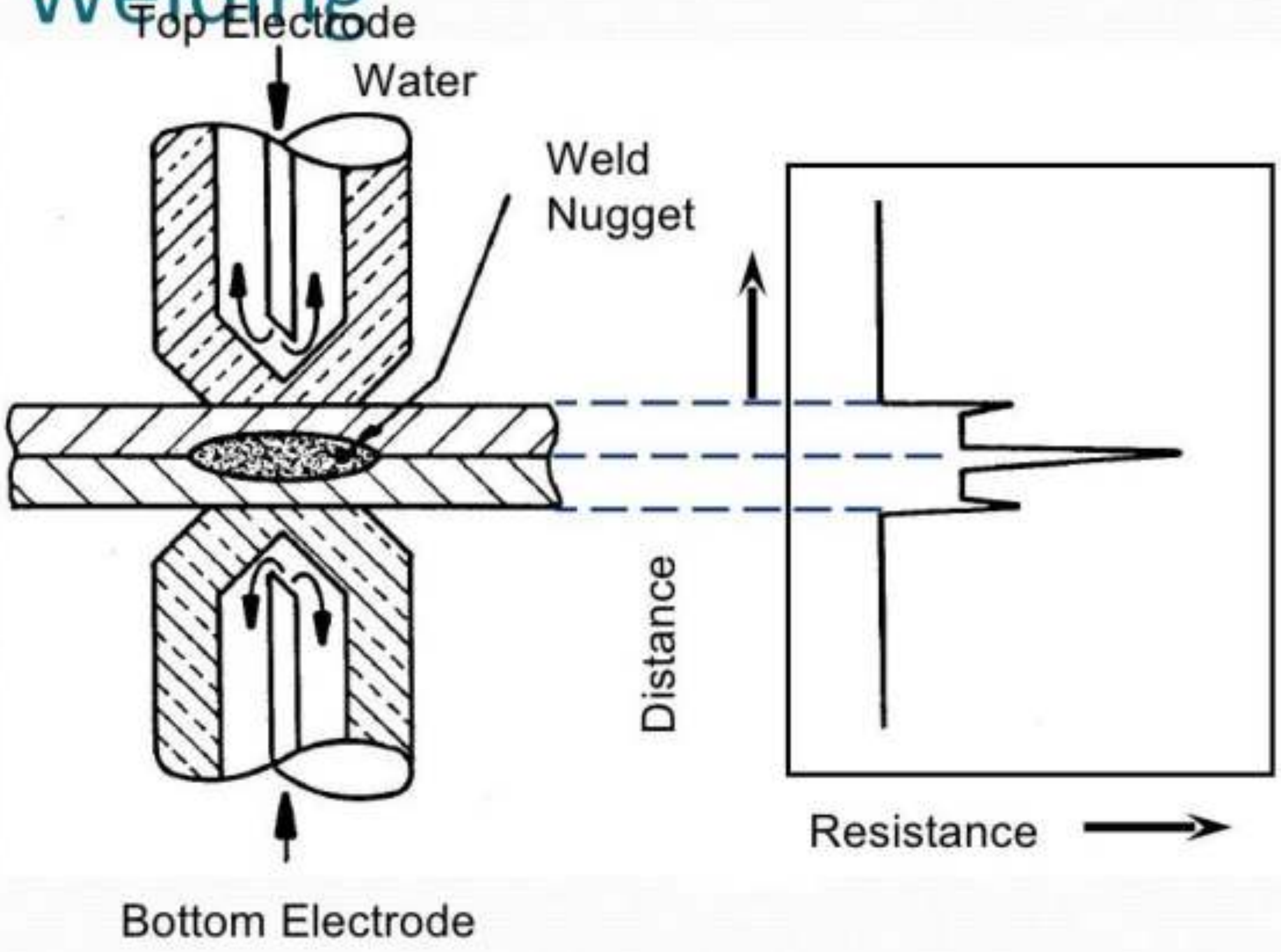
- R_1 – Resistance of electrode
- R_2 – Contact Resistance
- R_3 – Resistance of plate to be joined
- R_4 – Resistance of joint



- $R = 2(R_1 + R_2 + R_3) + R_4$

- R_1 should be minimum as possible
- So the material of electrode should have high good electrical conductivity, high melting point and high strength.
- eg. Tungsten, Cu.
- R_2 should be minimum as possible

Introduction to Resistance Spot Welding

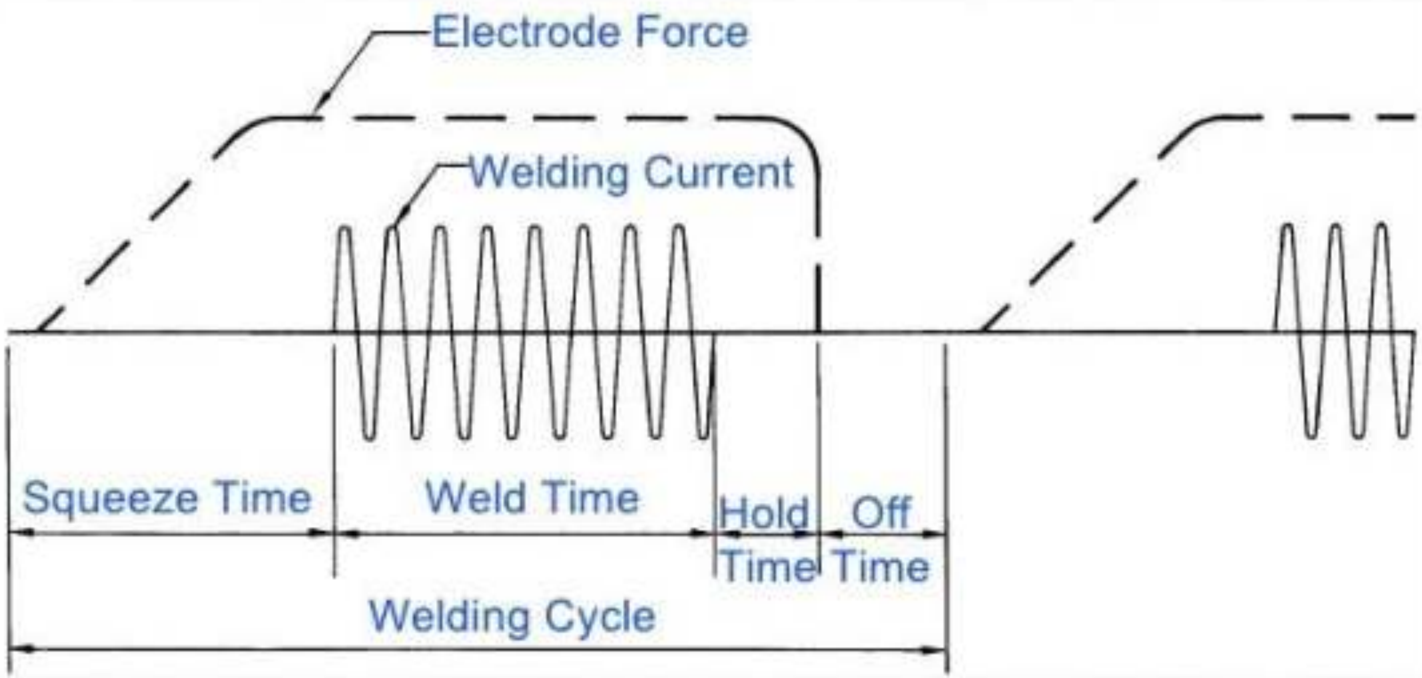


- R_3 should be minimum as possible
- R_4 should be maximum as possible, because this is the area where we are expecting total heat generation and joint formation to be take place.
- For that contact surface should be rough and clean.

2. Time

- In resistance welding current supply has to be controlled for a very short duration because the max temperature induced in resistance welding operation is 9000-12000^{0}C.
- At this temperature heat transfer by conduction to surrounding material is higher.
- So the complete plate may get melted and also at this temperature most of the metal will start evaporating. To avoid this time duration must be shorter.
- Very short duration of time for which the passage of current can be controlled by using AC power supply with relay.

Basic Single Impulse Welding Cycle



[Reference: Welding Handbook, Volume 2, AWS, p.538]

- Squeeze time.
  - Time during which air present at joint can be squeezed out.
- Weld time
  - Time during which current is passing through resistance welding current.
  - H = $H=I^2 x R x t$ Where, t is the weld time
- Hold time
  - Time during which force applied on plate will be continued to hold until liquid metal produced will get solidified., otherwise because of increased volume of molten metal the plate will get separated.
- OFF Time
  - Time during which total welding equipment is switched off. This is to account for,
    1. The time needed for shifting of electrodes from present position to next position.
    2. To account for the rest time in duty cycle of welding equipment.

EXAMPLE 12.3 Heat Generated in Resistance Spot Welding

Given: Two 1-mm-thick steel sheets are being spot welded at a current of 5000 A and current-flow time of $t = 0.1$ s. The electrodes are 5 mm in diameter.

Find: Estimate the amount of heat generated and its distribution in the weld zone. Use an effective resistance of 200 $\mu\Omega$.

Solution: According to Eq. (12.9),

$$\text{Heat} = (5000)^2\,(0.0002)(0.1) = 500\ \text{J}.$$

If it is assumed that the material below the electrode is heated enough to melt and fuse, the weld nugget volume can be calculated as

$$V = \left(\frac{\pi}{4}d^2\right)(t) = \frac{\pi}{4}(5)^2(2) = 39.3\ \text{mm}^3.$$

From Table 12.3, u for steel is 9.7 J/mm^3. Therefore, the heat required to melt the weld nugget is, from Eq. (12.4),

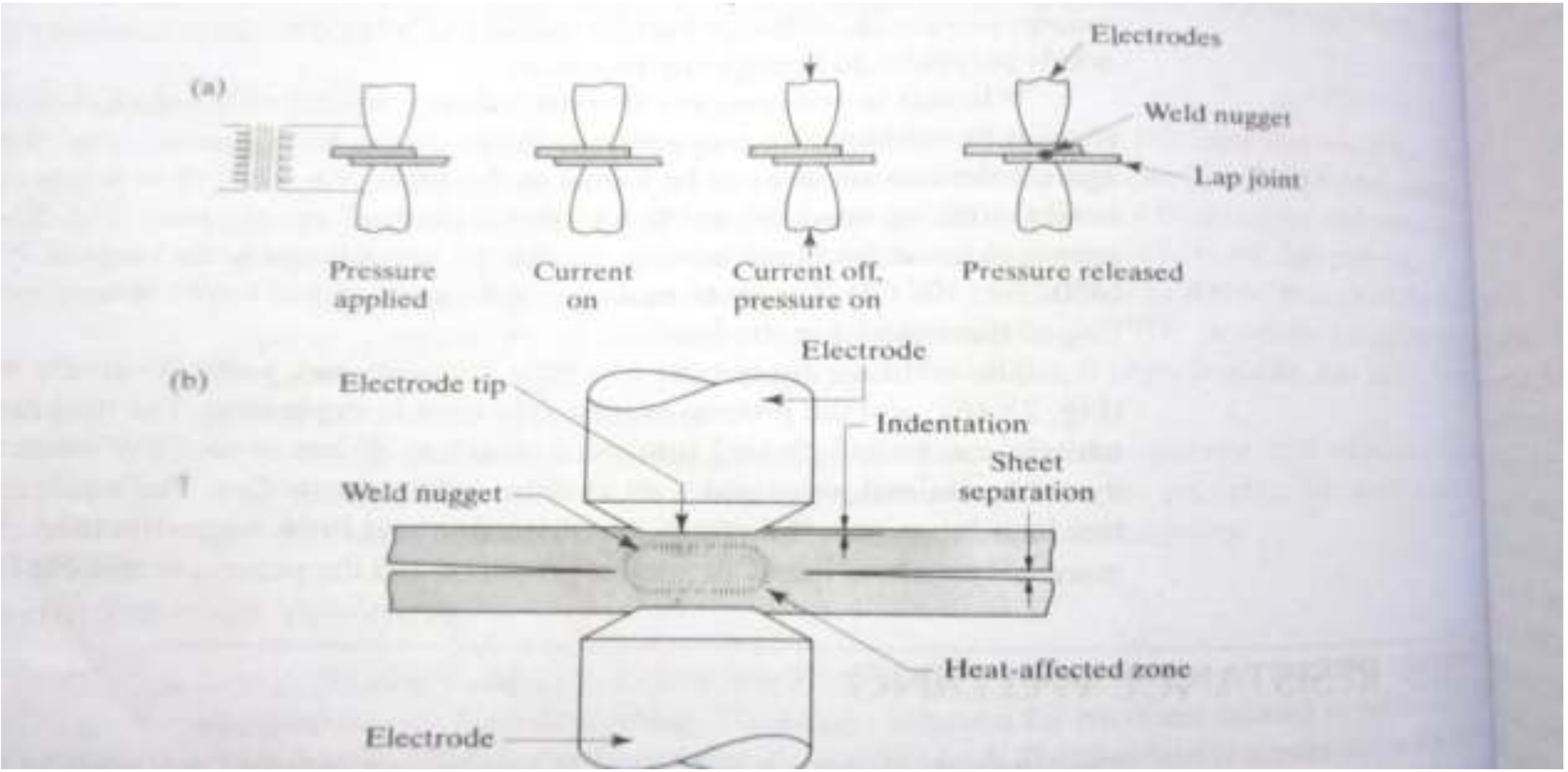
$$H = u(\text{Volume}) = (9.7)(39.3) = 381\ \text{J}.$$

Consequently, the remaining heat (119 J), or 24%, is dissipated into the metal surrounding the nugget.

Various resistance welding process

Resistance Spot welding(RSW)

- The tip of two opposing solid cylindrical electrode touch a lap joint of two sheet metal, and resistance heating produces a spot weld.
- In order to obtain a strong bond in the weld nugget, pressure is applied until the current is turned off.



- In resistance spot welding, "the welding of overlapping pieces of metal at small points by application of pressure and electric current" creates a pool of molten metal that quickly cools and solidifies into a round joint known as a "**nugget**."

SPOT WELDING

- Application
  - Assembly of sheet metal products such as automotive body assembly

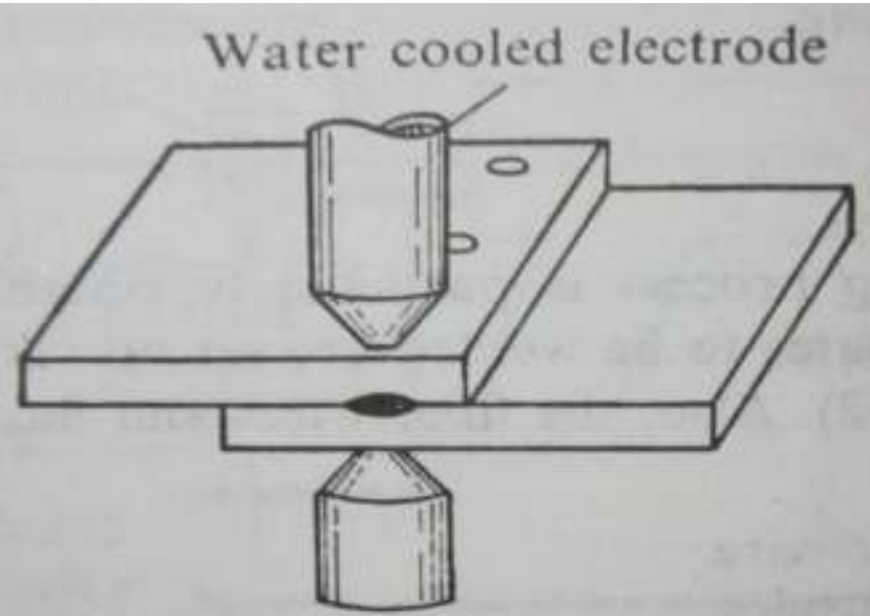
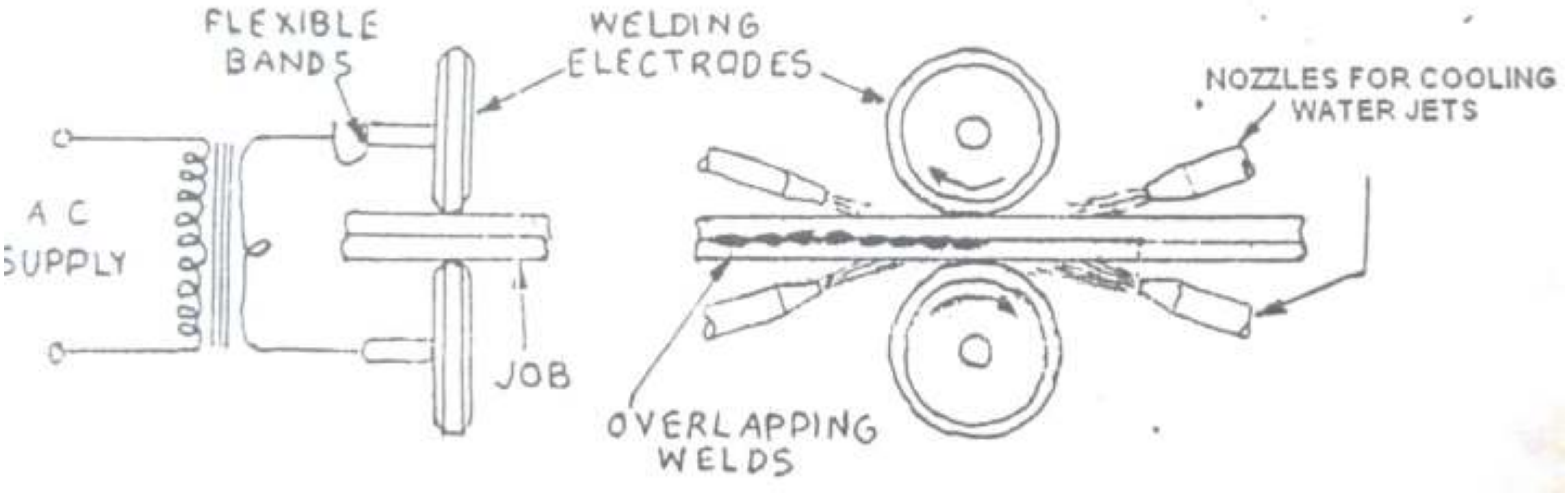


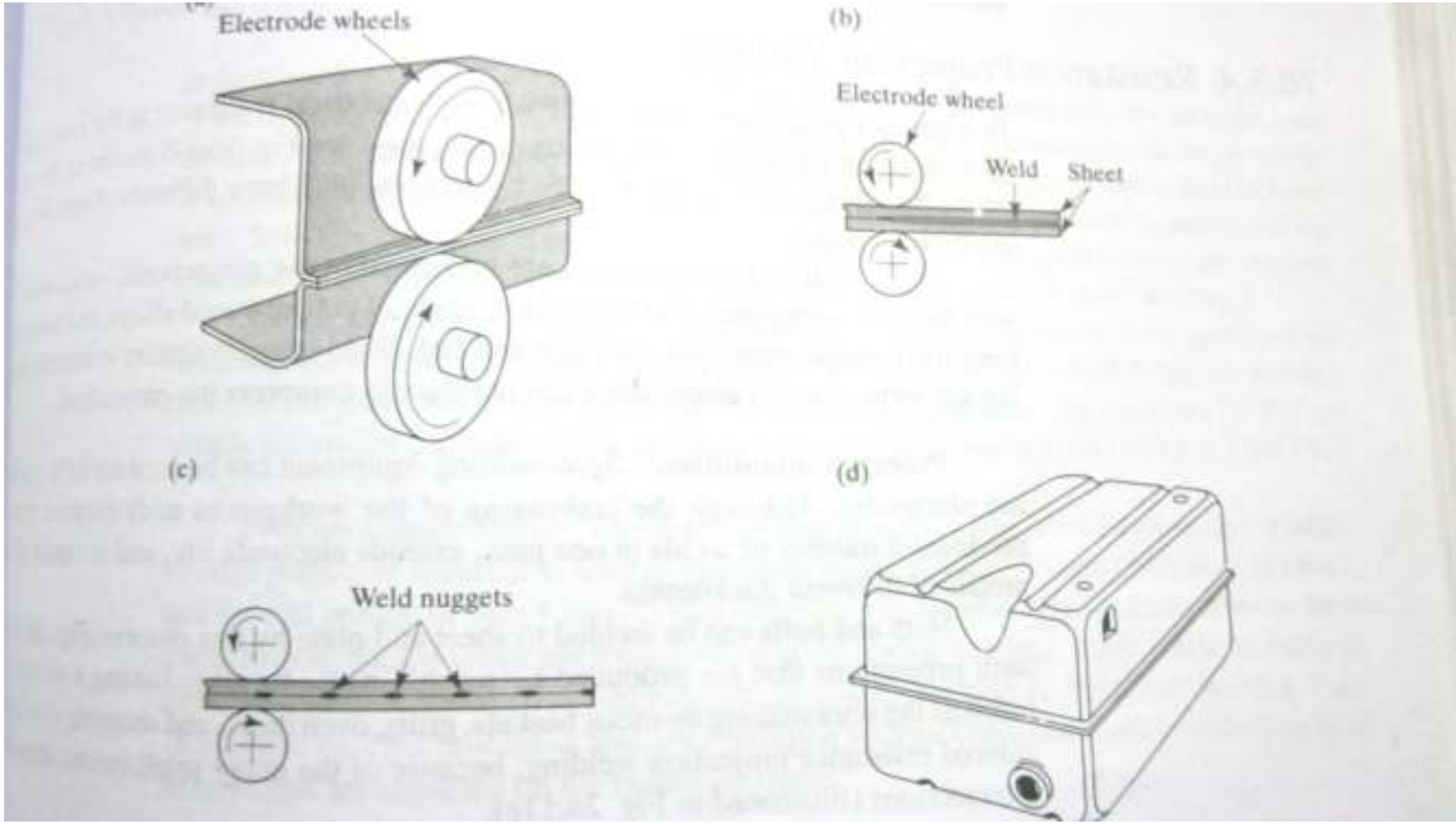
Fig. 5.33 Resistance spot welding.

Resistance seam welding (RSEW)

- Seam welding is a continuous spot welding process where overlapped parts to be welded are fed through a pair of copper alloy electrodes to form a continuous seam
- Here we use rotating wheel or roller electrode
- Produce a liquid tight and gas tight joint



Principle of seam welding


Electrode wheels
(b)
Electrode wheel
Weld
Sheet
(c)
(d)
Weld nuggets

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RESISTANCE SEAM WELDING

Resistance Projection welding (RPW)

- Current flow is concentrated at the point of contact with a local geometric extension of one (or both) of the parts being welded
- These projections are used to concentrate heat generation at the point of contact
- High localized temperature are generated at the projections, which are in contact with the flat mating parts

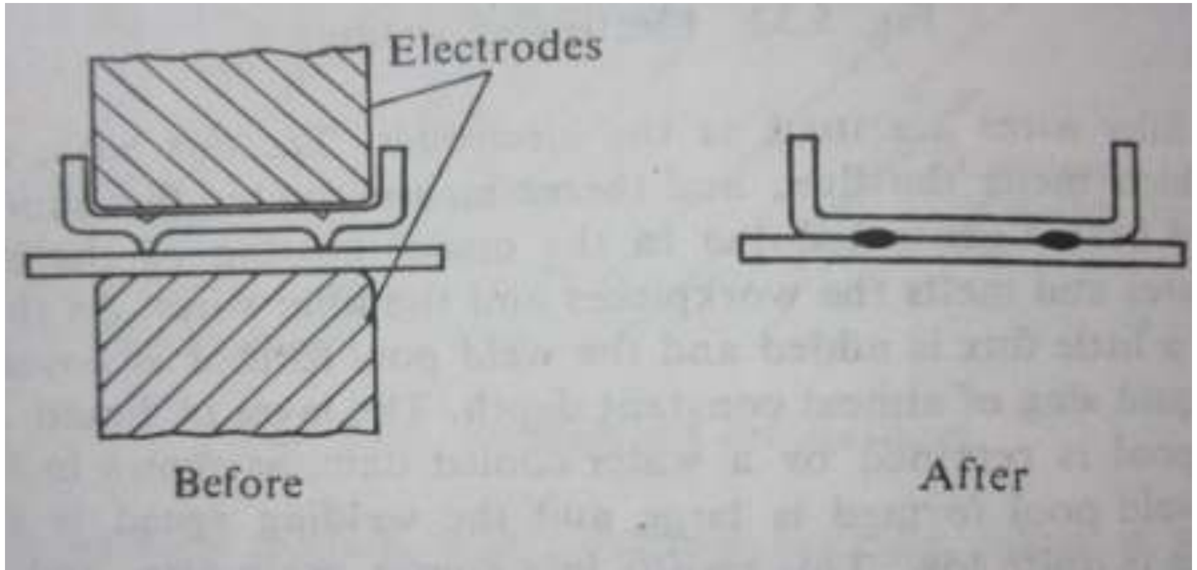
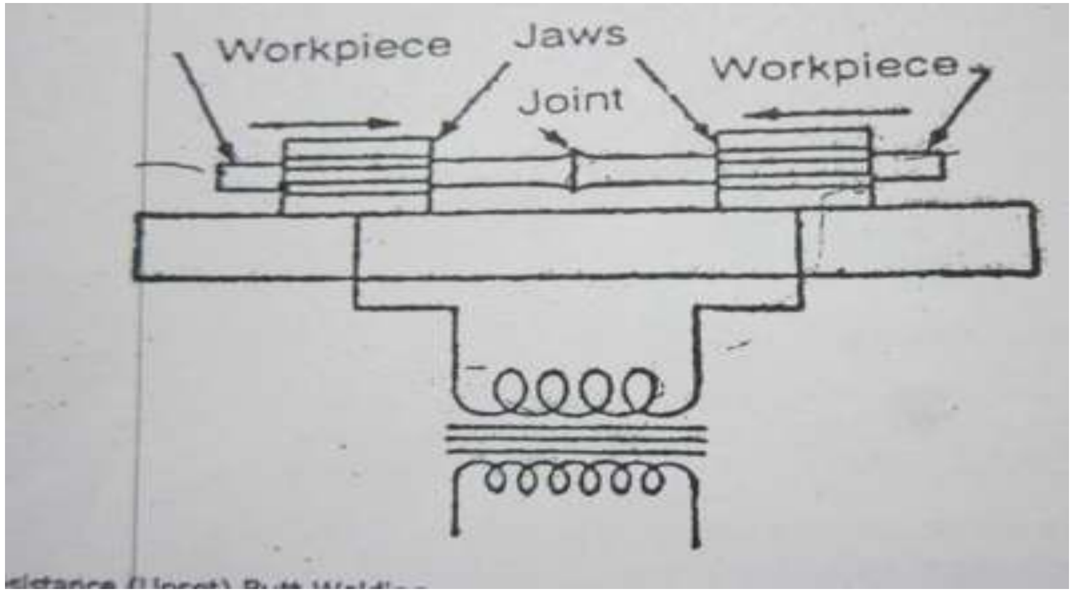


Fig. 5.34 Projection welding.

PROJECTION WELDING

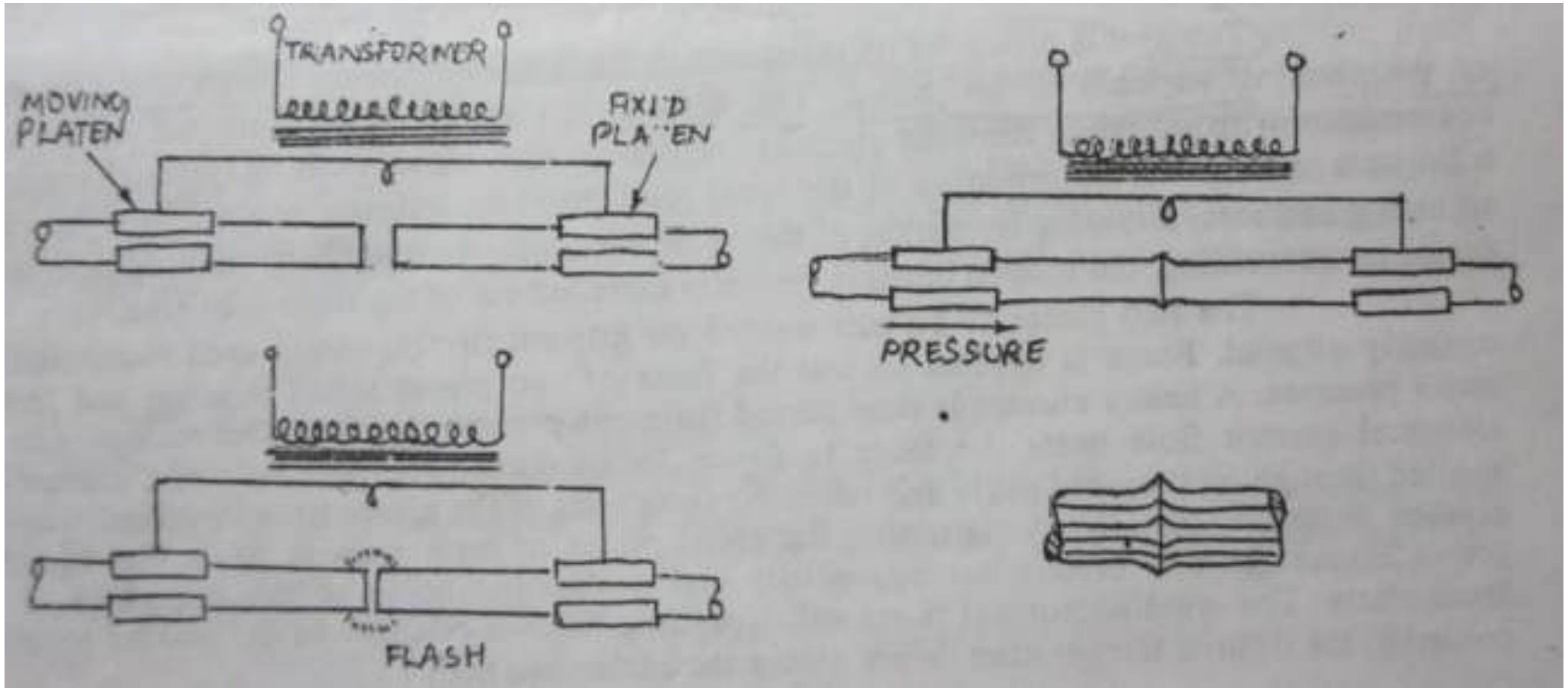
Resistance(upset)butt welding

- The heat is produced by resistance to the flow of electrical current at the interface of the a butting surface to be joined
- Two jobs to be welded are aligned. Moderate force is applied
- A heavy current is then passed from one piece to another
- Both pressure and current are applied throughout the weld cycle and when the ends of the pieces become plastic they are pressed together more firmly
-



Resistance flash welding

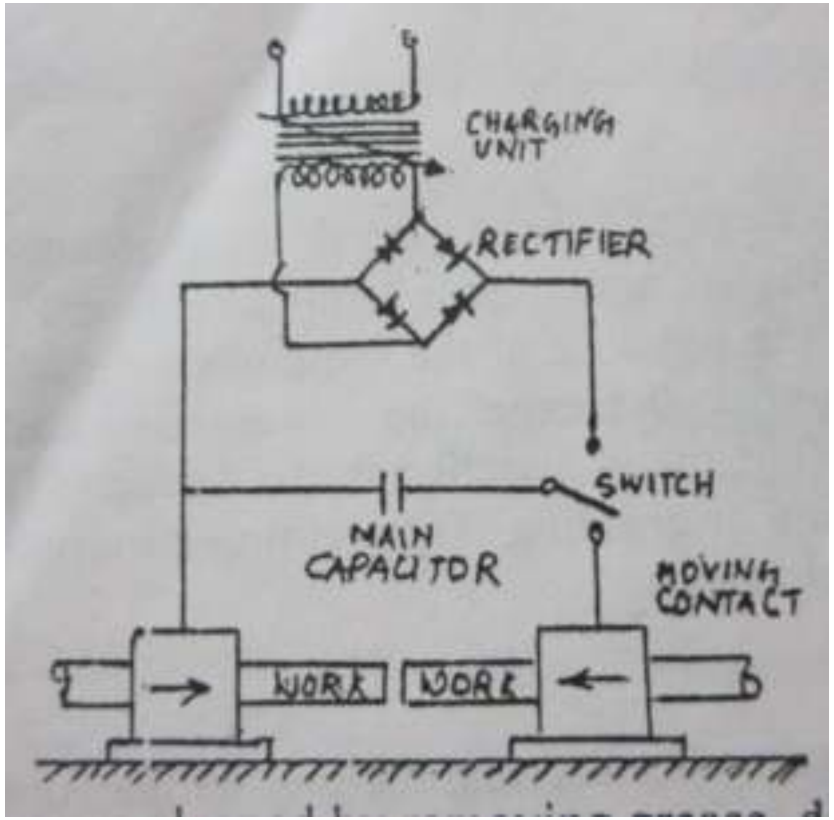
- Heat is generated from the arc as the ends of the two members begin to make contact and develop an electrical resistance at the joint
- After proper temperature is reached and the interface begins to soften, an axial force is applied at a controlled rate, and a weld is formed by plastic deformation of the joint




Seam welding
Flash butt welding
Upset butt welding
Resistance welding
Projection welding
Spot welding

Percussion welding(PEW)

- The resistance welding process already described usually employ an electrical transformers to meet power requirements
- In PEW electrical energy for welding may be stored in a capacitor
- The power is discharged within 1 to 10 milliseconds to develop localized high heat at the joint



Welding defects(weld or joint quality)

- As a result of a history of thermal cycling and its attendant microstructural changes, a welded joint may develop various **discontinuities.**
- The major discontinuities that affect weld quality are,

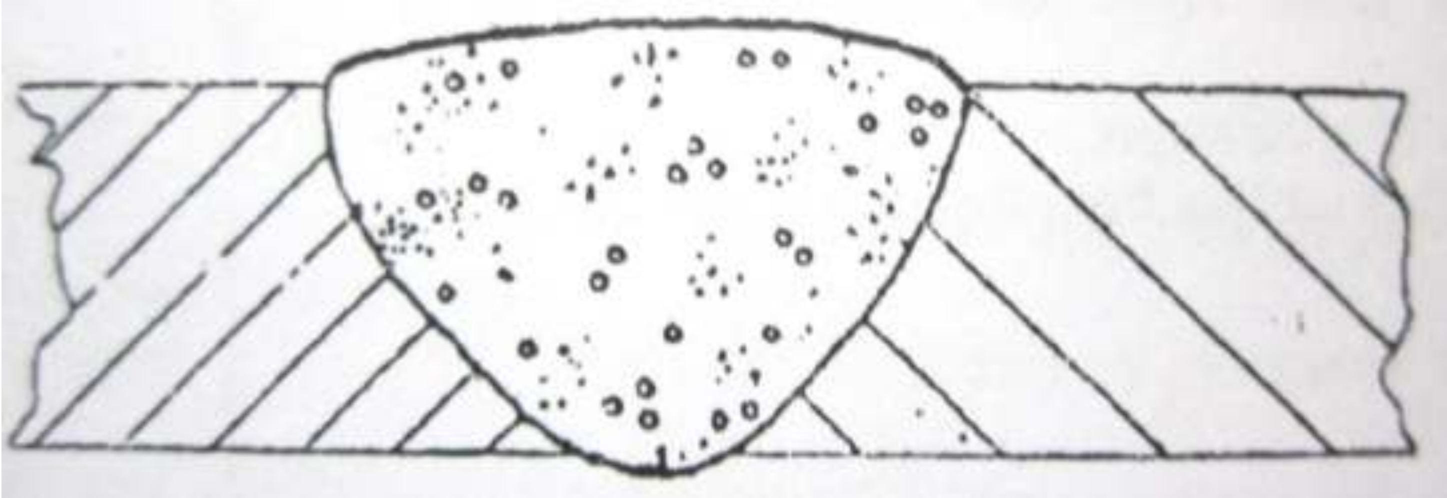
1. Porosity
2. Slag Inclusions
3. Incomplete Fusion and Penetration
4. Weld Profile
5. Cracks
6. Lamellar Tears
7. Surface Damage
8. Residual Stresses

Reference: Manufacturing processes for engineering materials by Serope Kalpakjian

1. Porosity and blow holes

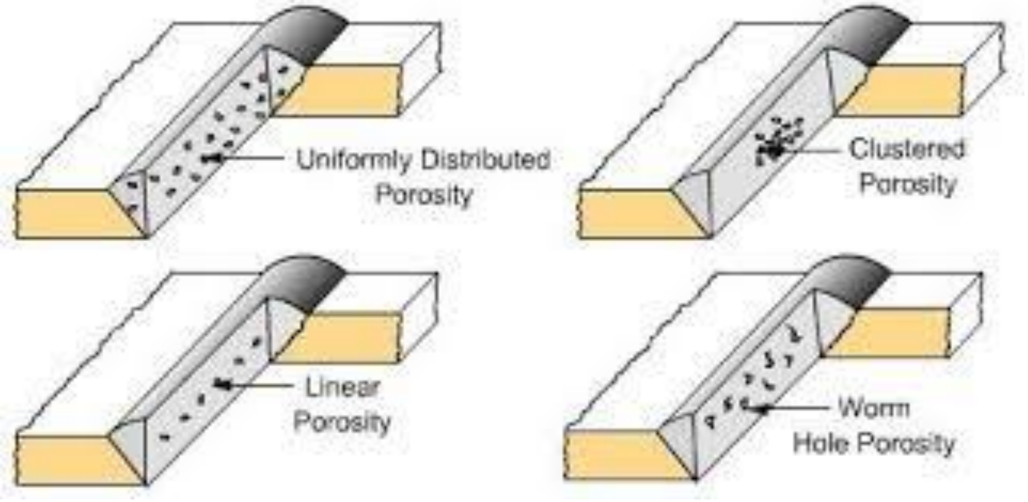
- Blow holes and porosity are voids, holes or cavities formed by gas trapped by the solidifying weld metal.
- Porosity is a group of small voids.
- Blow holes or gas pockets are comparatively bigger isolated holes or cavities.

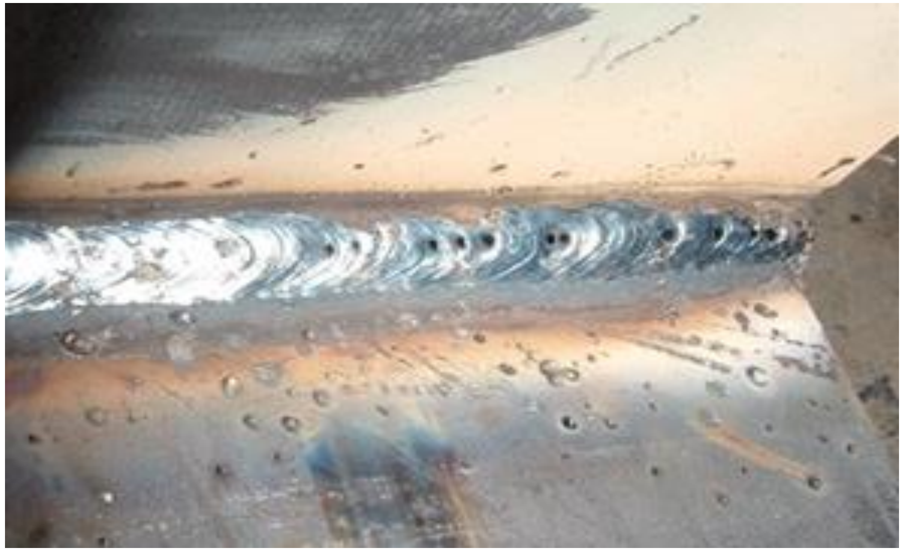
- *Porosity* in welds may be caused by,
  - Gases released during melting of the weld area, but trapped during solidification.
  - Chemical reactions during welding.
  - Contaminants.

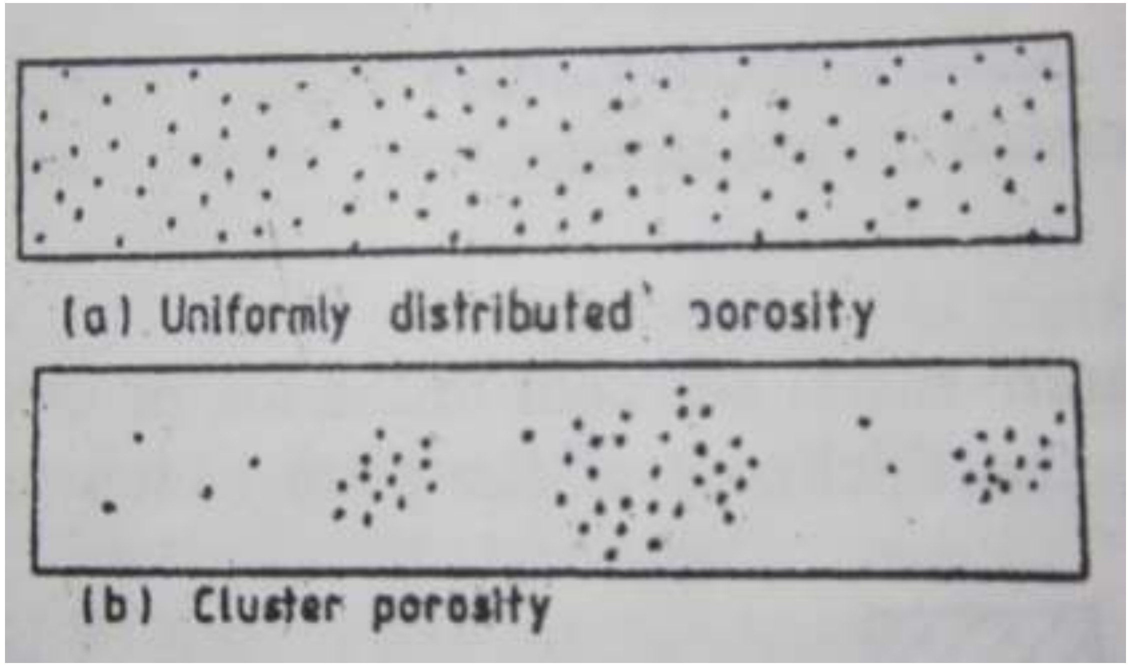


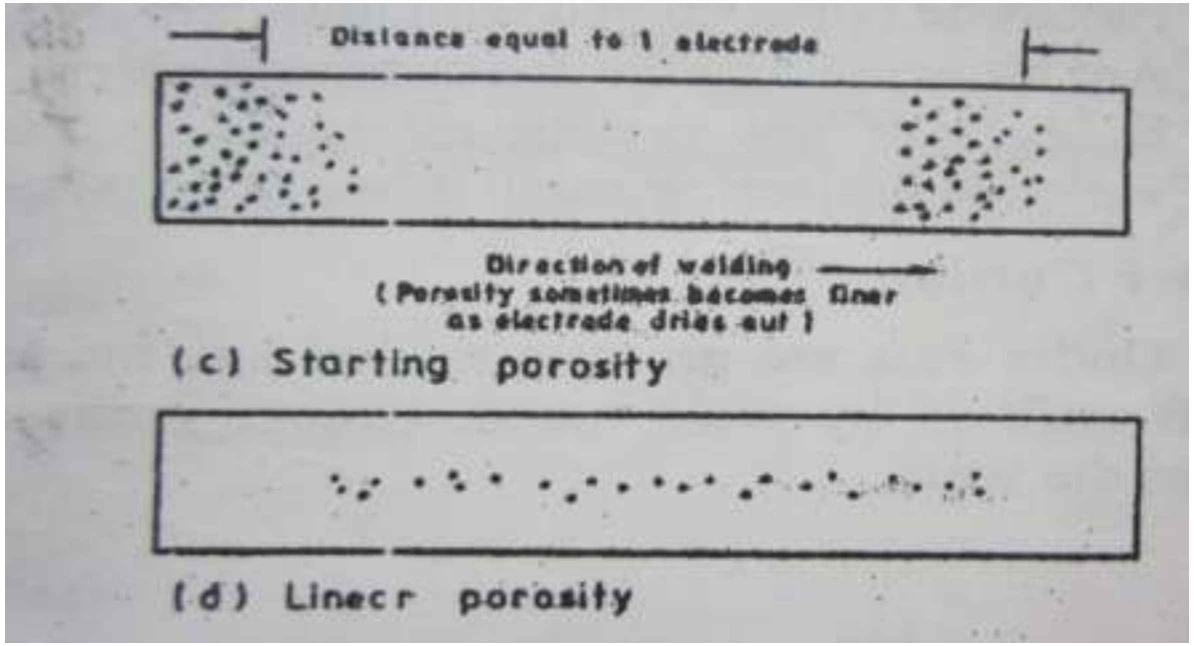
- Sources of trapped gases,
  - Impurities and moisture in the shielding gas.
  - Excessive welding speed.

- Porosity in welds can be reduced by the following practices:
  - Proper selection of electrodes and filler metals.
  - Improved welding techniques, such as preheating the weld area or increasing the rate of heat input.
  - Proper cleaning and the prevention of contaminants from entering the weld zone.
  - Reduced welding speeds to allow time for gas to escape.



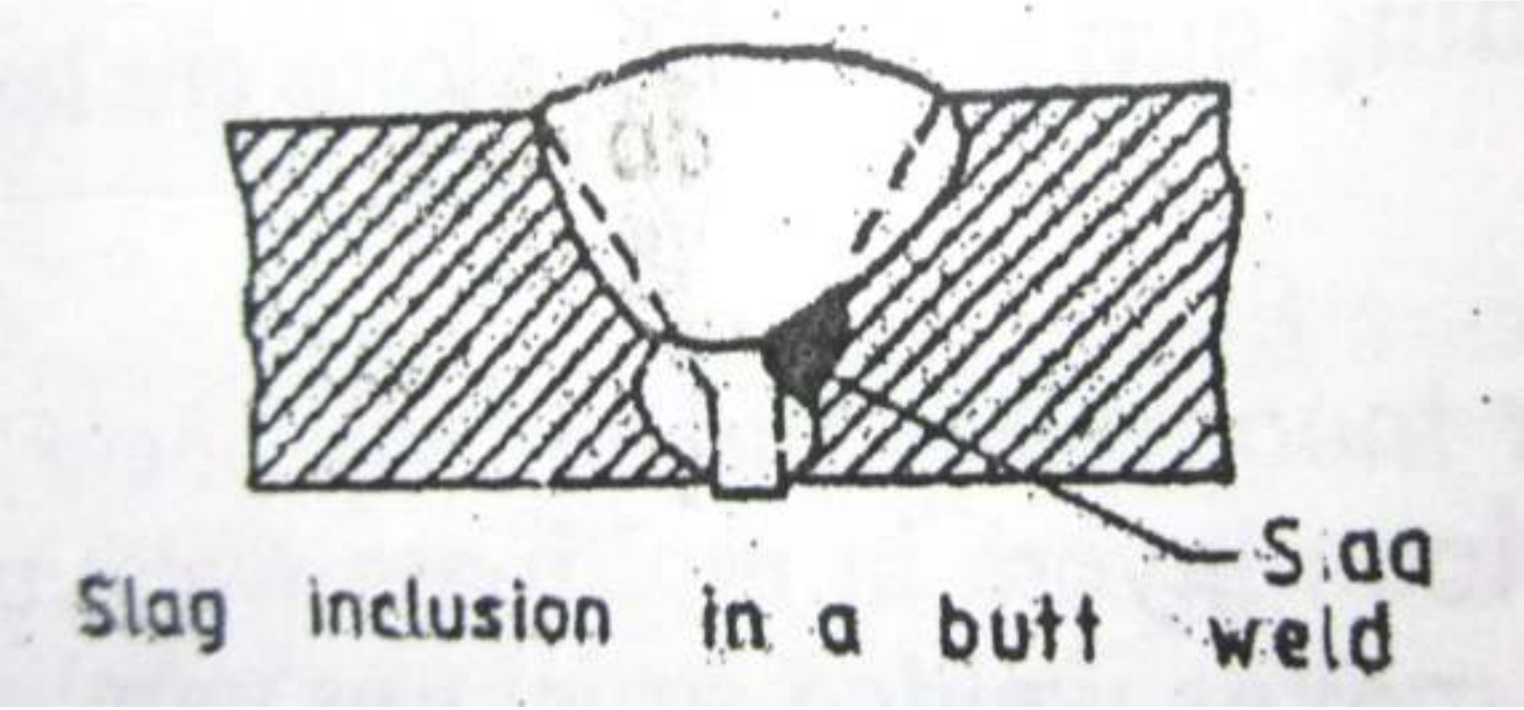



(a) Uniformly distributed porosity
(b) Cluster porosity


Distance equal to 1 electrode
Direction of welding
(Porosity sometimes becomes finer as electrode dries out)
(c) Starting porosity
(d) Linecr porosity

2. Inclusion

- Entrapment of slag or other impurities in the weld
- Slag inclusion occur as a result of,
  - Incomplete deslagging of a previous pass.
  - Use of too large electrodes.

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- Slag inclusions are compounds such as oxides, fluxes, and electrode coating materials that are trapped in the weld zone. If shielding gases are not effective during welding, contamination from the environment also may contribute to such inclusions.

- Welding conditions are important as well: With control of welding process parameters, the molten slag will float to the surface of the molten weld metal and thus will not become entrapped.

- Slag inclusions can be prevented by the following practices:
  - Cleaning the weld-bead surface by means of a wire brush (hand or power) or a chipper before the next layer is deposited.
  - Providing sufficient shielding gas.
  - Redesigning the joint to permit sufficient space for proper manipulation of the puddle of molten weld metal.


Slag
Weld

3.Incomplete Fusion and Penetration

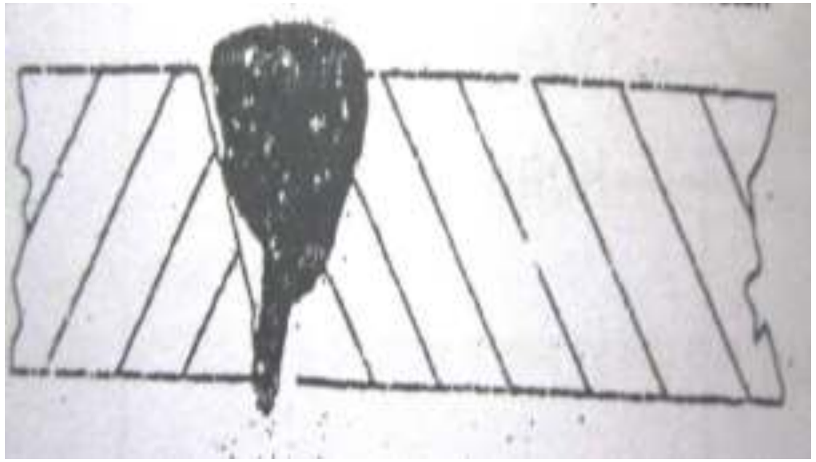
Failure of filler metal to fuse with the parent metal.

Causes

Insufficient heat.

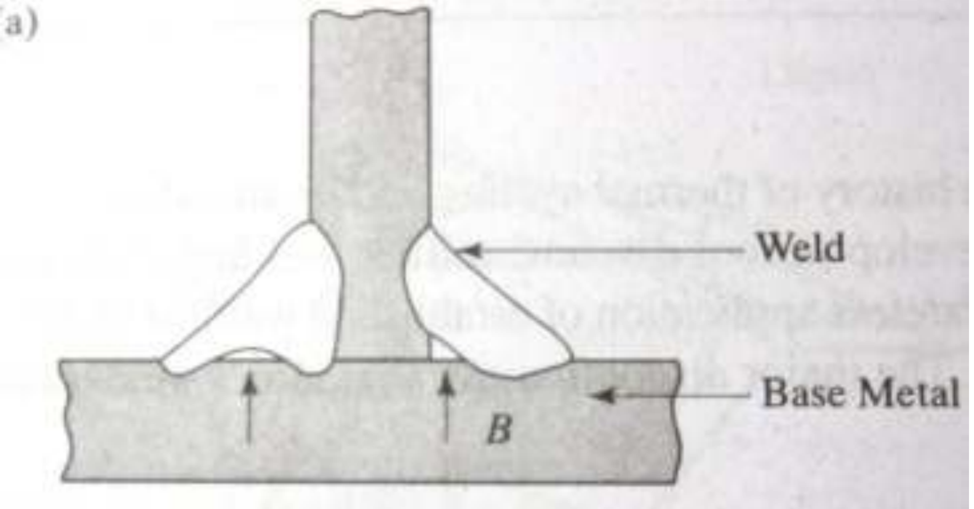
Low arc current.

Incorrect welding technique.



A better weld can be obtained by the use of the following practices:

- Raising the temperature of the base metal.
- Modifying the joint design and changing the type of electrode used.
- Cleaning the weld area before welding.
- Providing sufficient shielding gas.



Incomplete fusion in fillet welds. *B* is often termed 'bridging'

INCOMPLETE FUSION

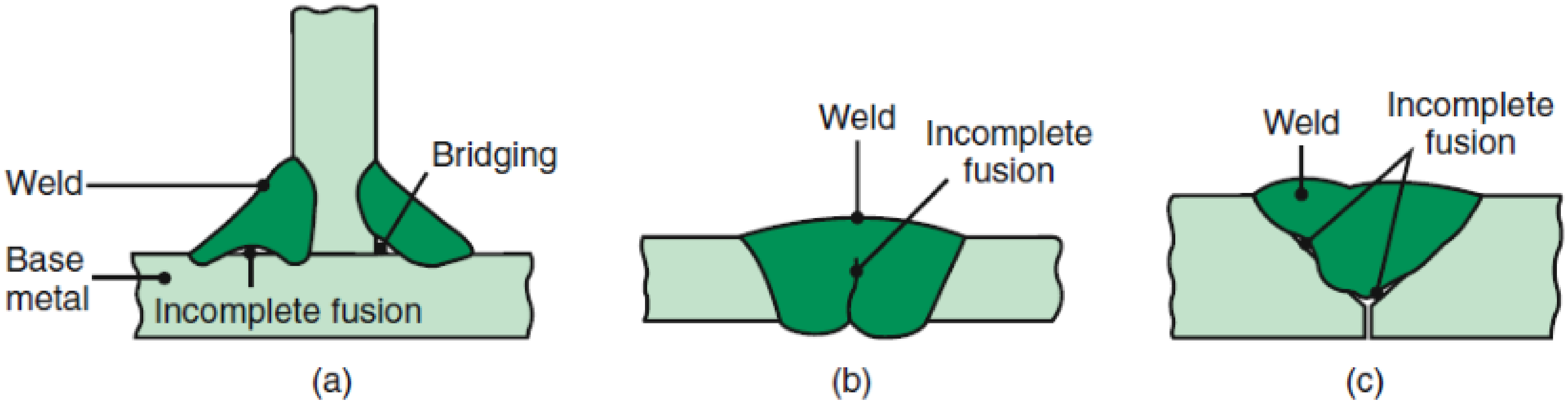
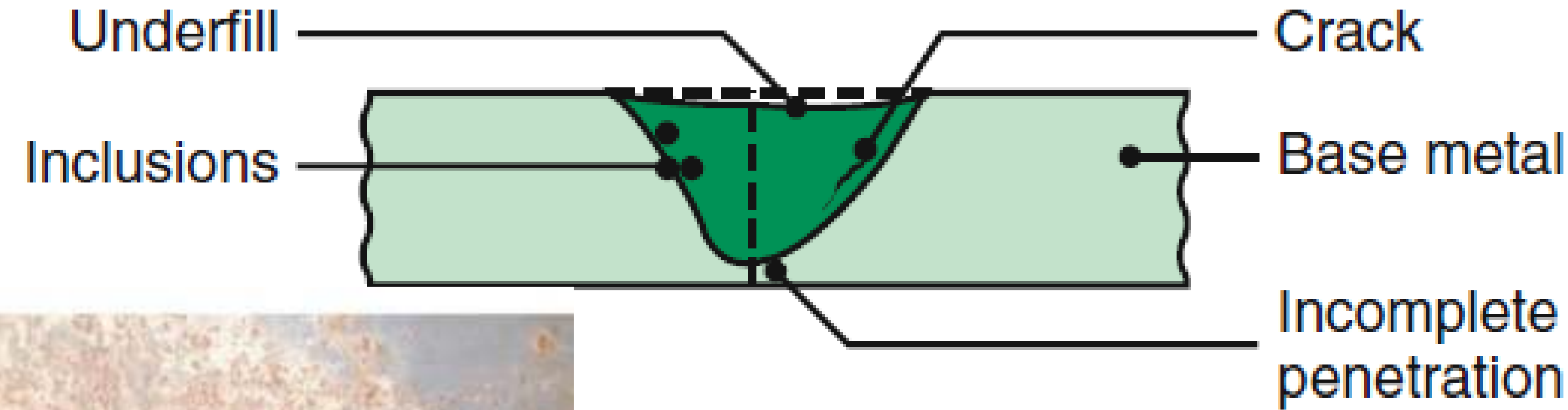


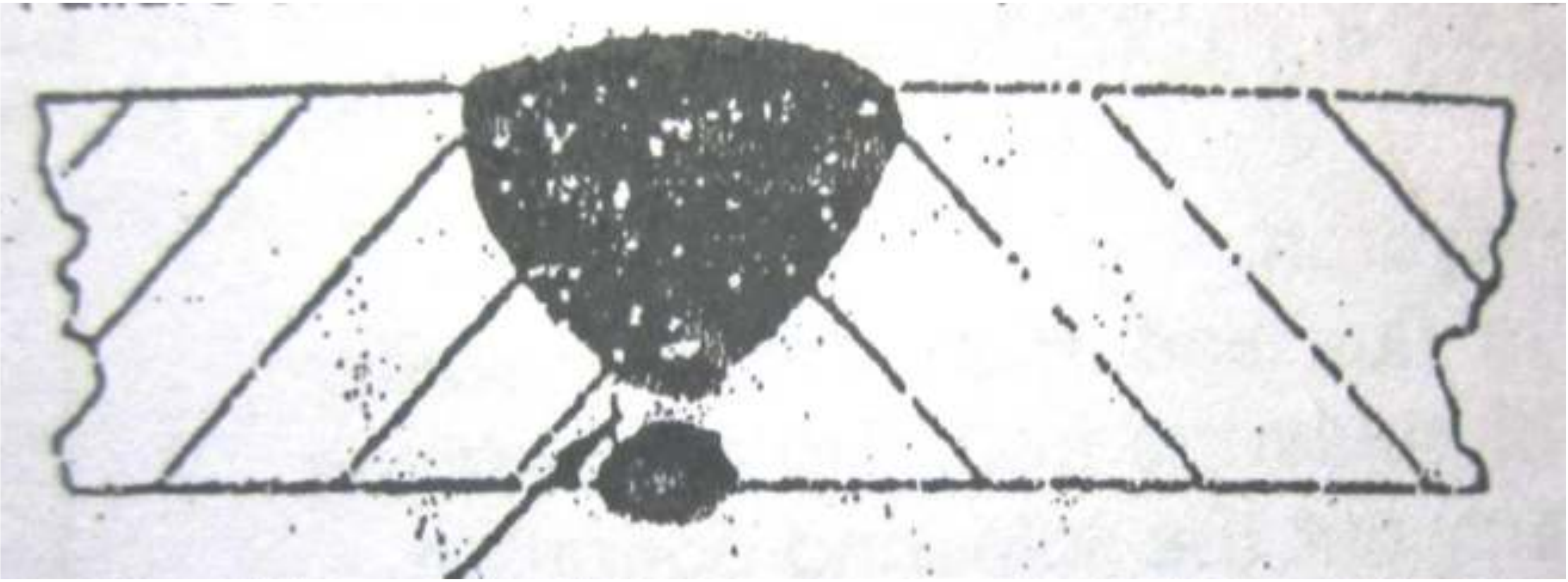
FIGURE 30.19 Examples of various discontinuities in fusion welds.

- *Incomplete penetration* occurs when the depth of the welded joint is insufficient. Penetration can be improved by the following practices:
  - Increasing the heat input.
  - Reducing the travel speed during the welding.
  - Modifying the joint design.
  - Ensuring that the surfaces to be joined fit each other properly.



Lack of penetration

- Failure of the filler metal to penetrate into the joint

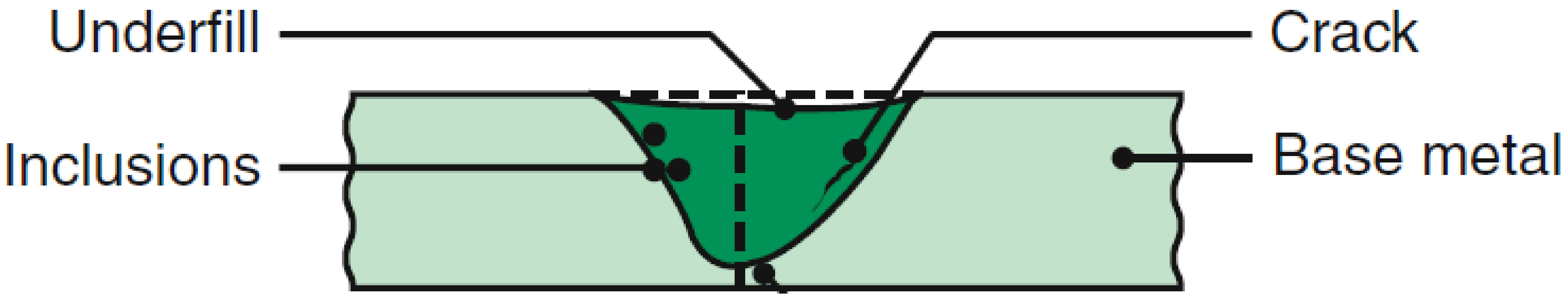


- <u>Causes</u>
  - Incorrect edge preparation
  - Incorrect welding technique

4. Weld Profile related defects

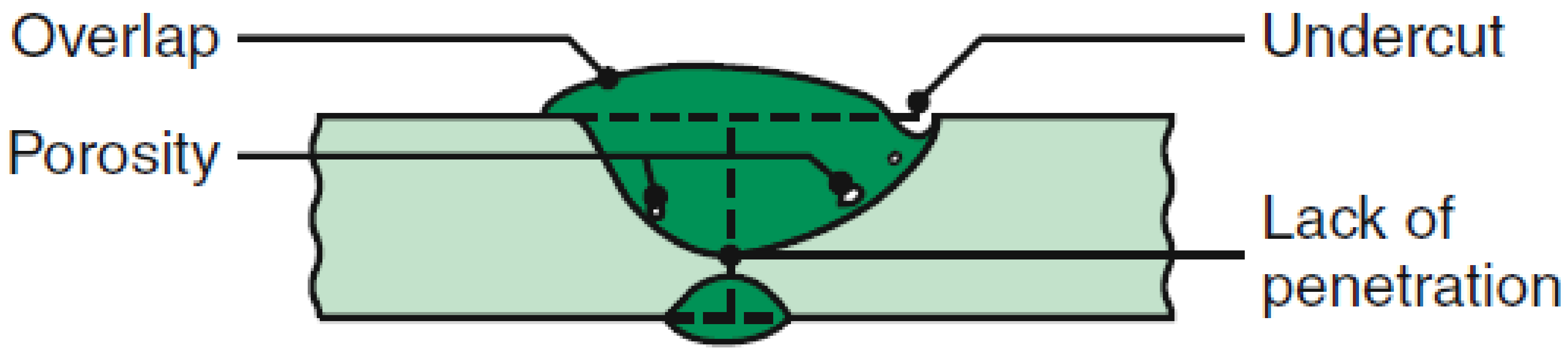
- Weld profile is important not only because of its effects on the strength and appearance of the weld, but also because it can indicate incomplete fusion or the presence of slag inclusions in multiple-layer welds.

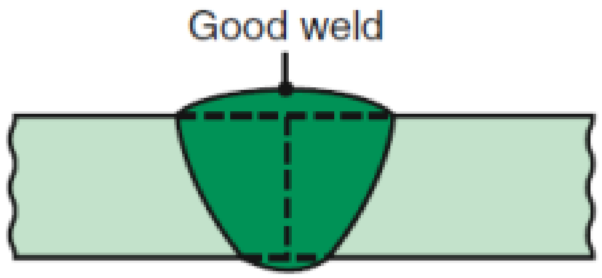
a) **Underfilling** results when the joint is not filled with the proper amount of weld metal.



UNDERFILL

b) **Overlap** is a surface discontinuity usually caused by poor welding practice or by the selection of improper materials.





(c)

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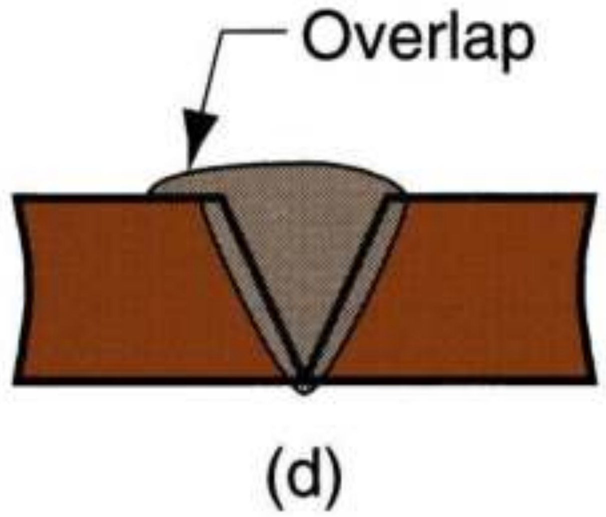
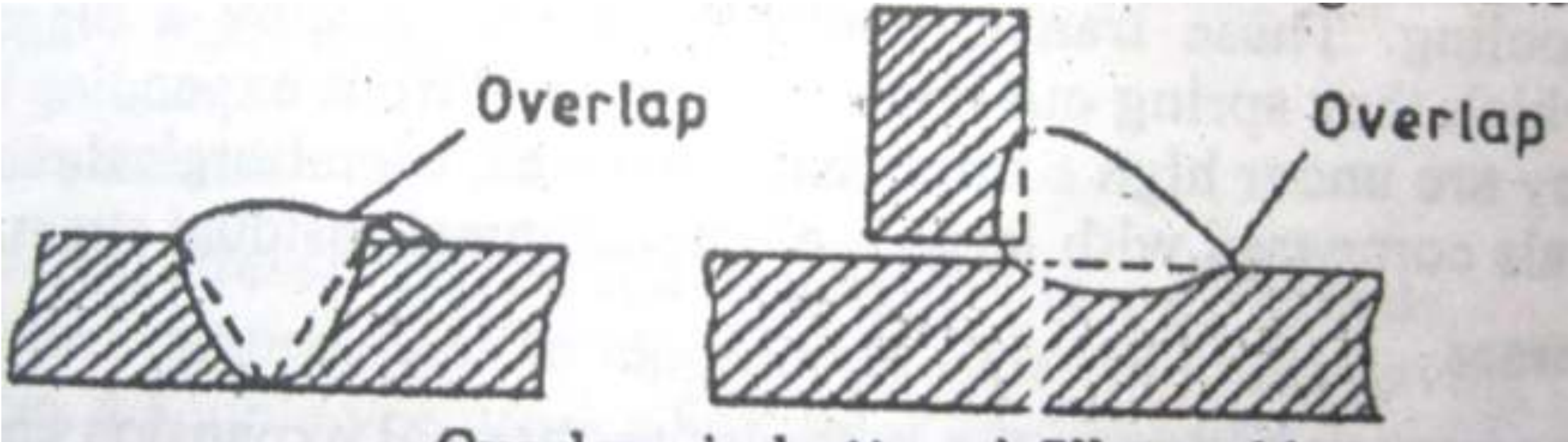
- **Overlap** is a surface discontinuity usually caused by poor welding practice or by the selection of improper materials.
- An overlap occurs when the molten metal from the electrode flows over the parent metal surface and remains there without getting properly fused and united with the same.

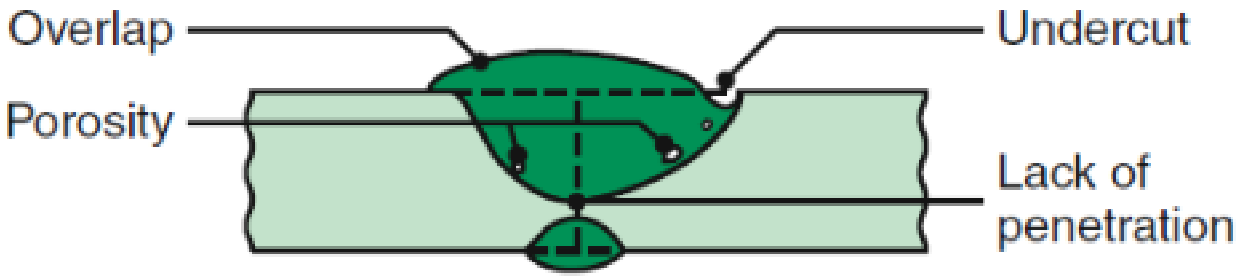


(d)



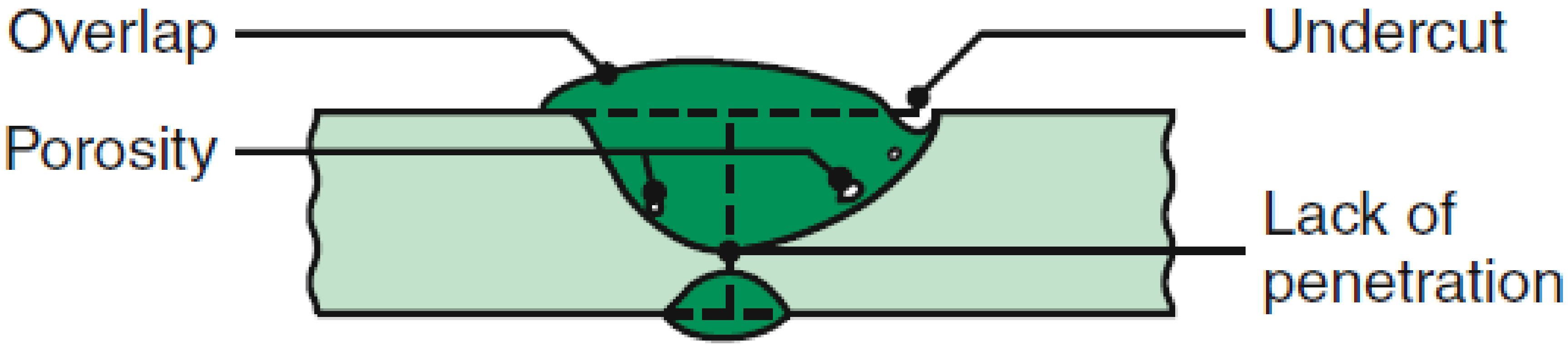
Overlaps in butt and fillet welds.

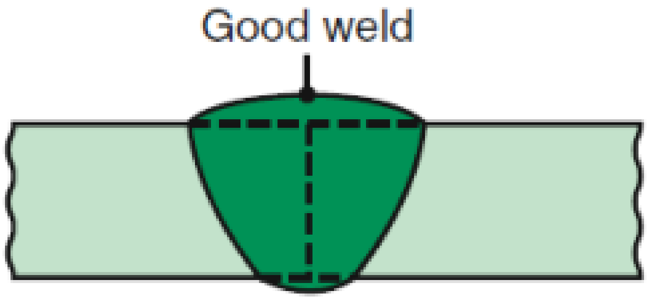
- Occur due to,
  - Excessive welding current
  - Longer arc
  - Incorrect electrode diameter




OVERLAP

c) **Undercutting** results from the melting away of the base metal and the consequent generation of a groove in the shape of a sharp recess or notch. If it is deep or sharp, an undercut can act as a stress raiser and can reduce the fatigue strength of the joint; in such cases, it may lead to premature failure.

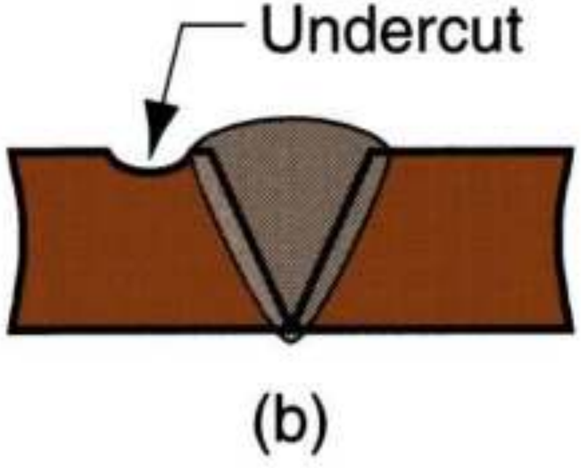


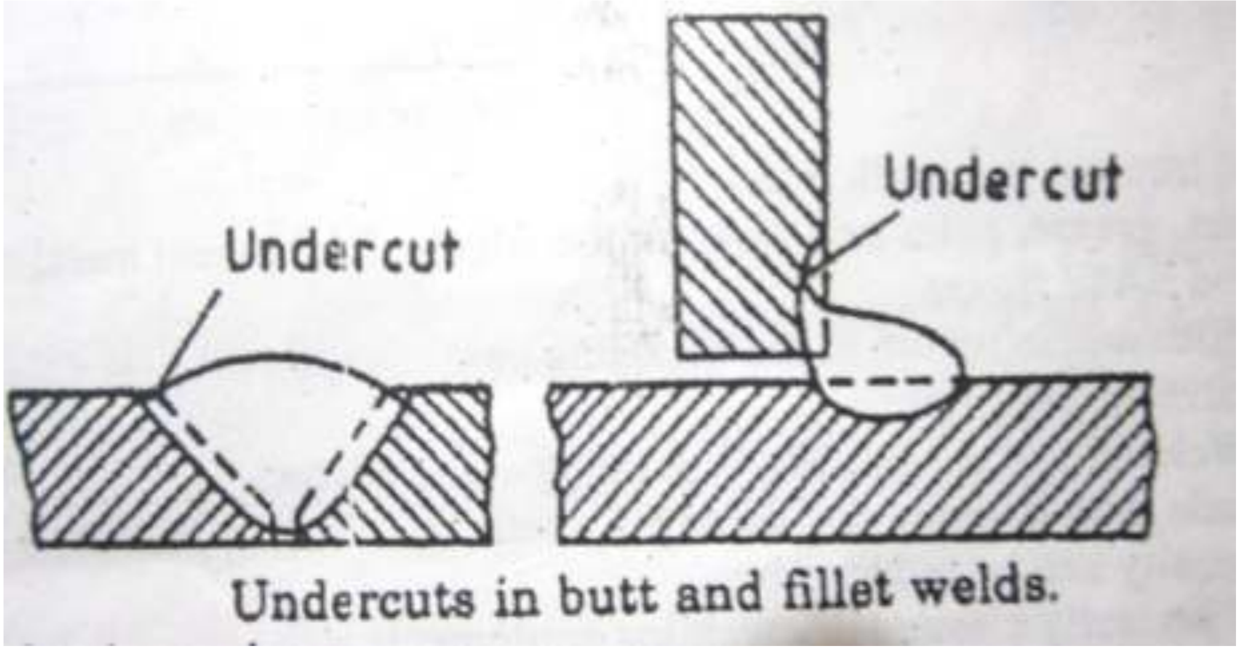


(c)

UNDERCUT

- Grooves or slots along the edges of weld
- Grooves reduces the thickness of the plate which in turn weakens the weld

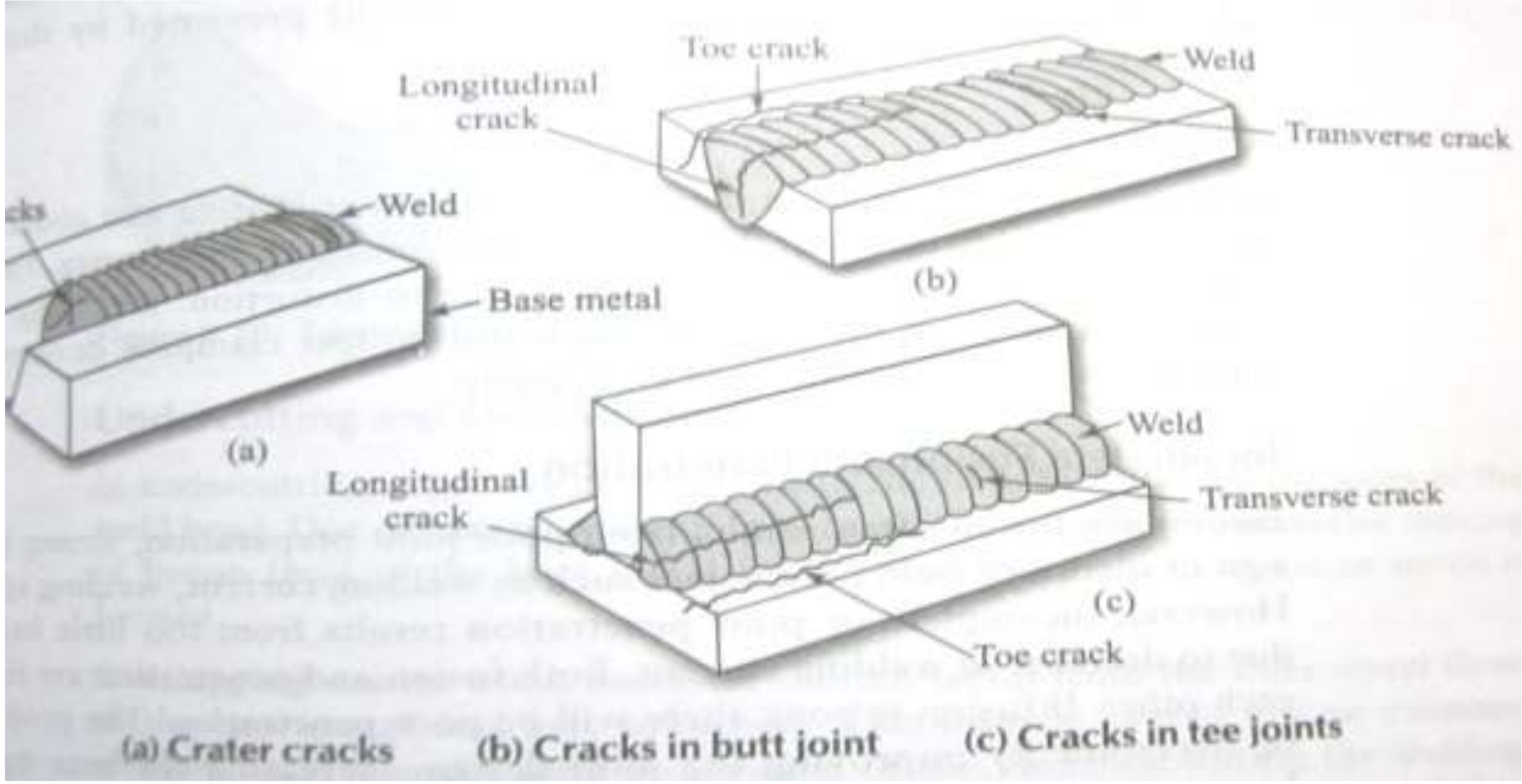


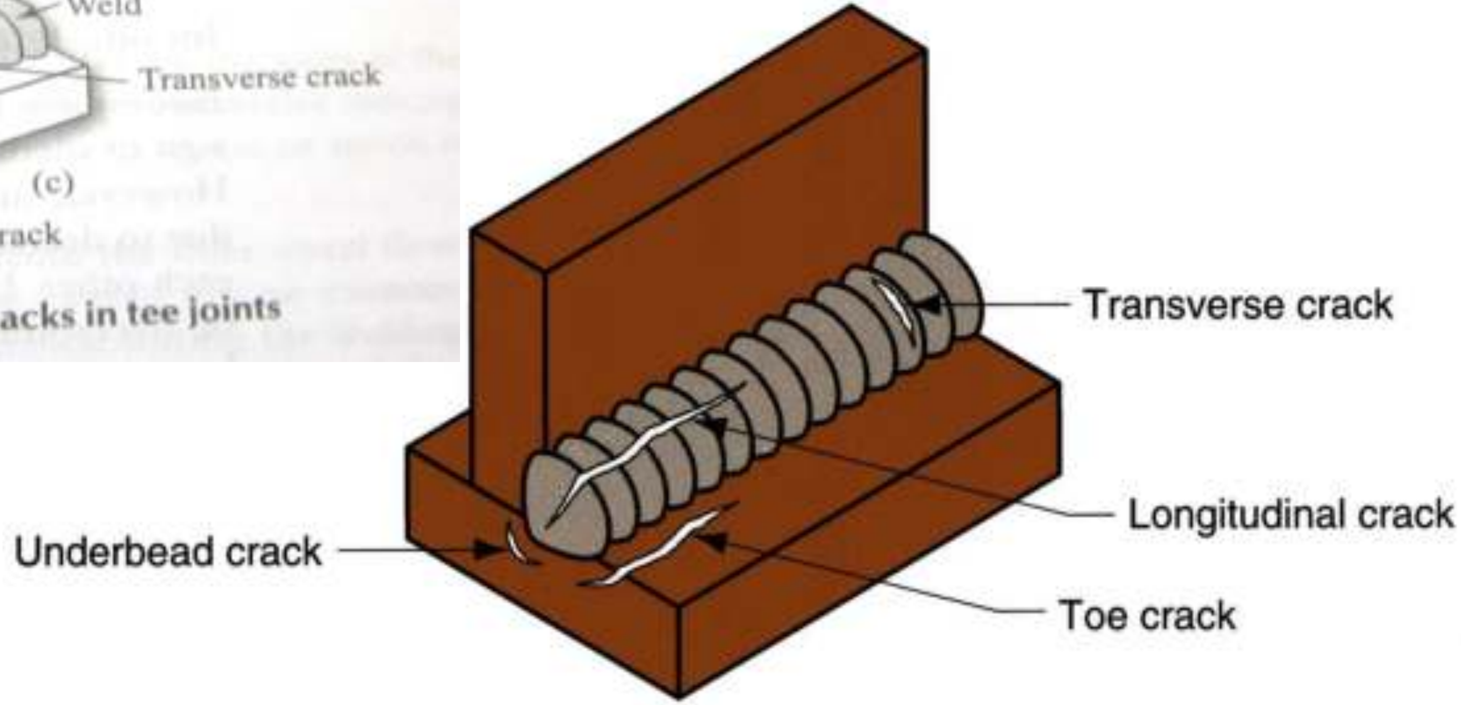


- <u>Causes</u>
  - Excessive welding current
  - Large electrode diameter

5. Crack

- Crack is a form of stress relief in the weld metal or HAZ
- Typical types of cracks are longitudinal, transverse, crater, underbead, and toe cracks





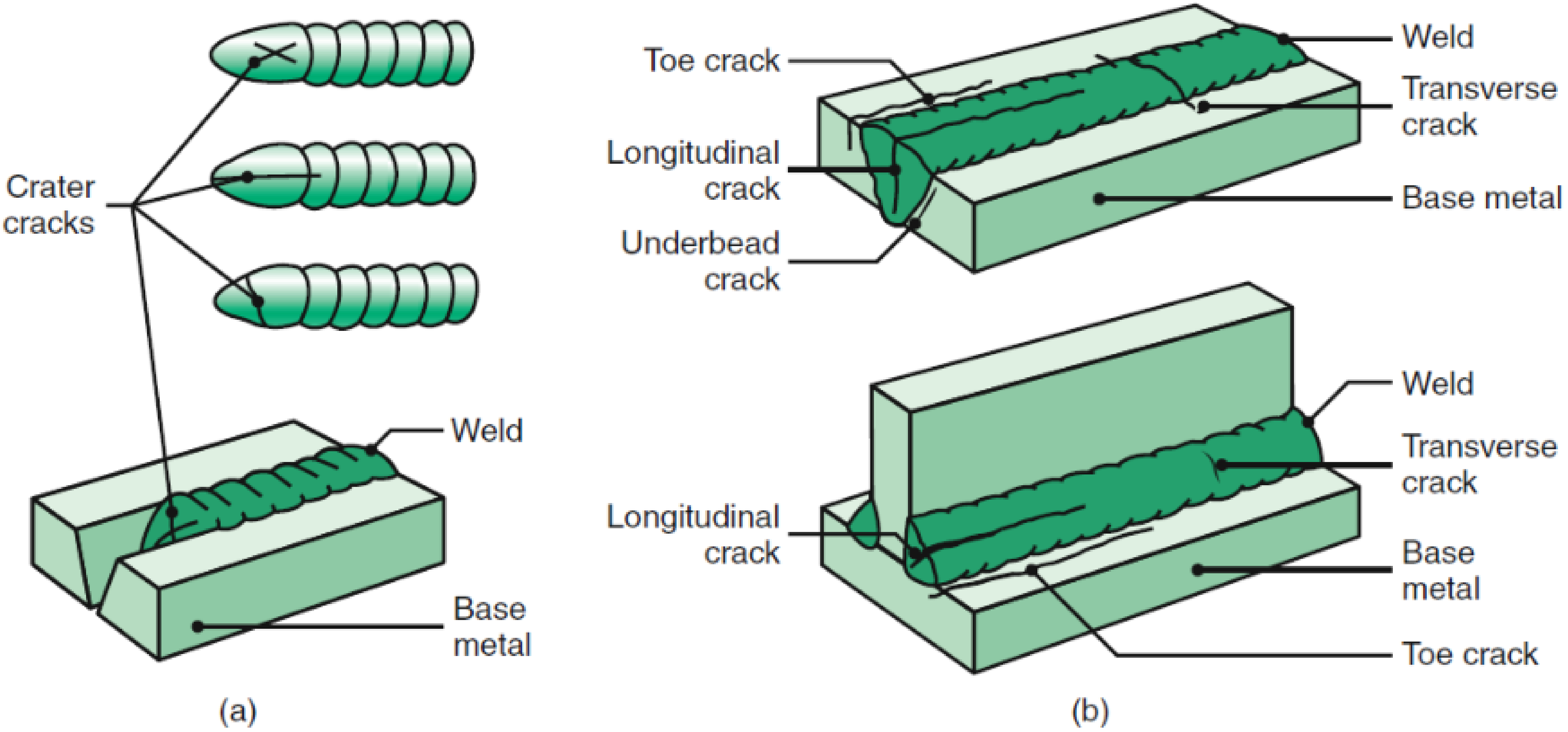


FIGURE 30.21 Types of cracks developed in welded joints. The cracks are caused by thermal stresses, similar to the development of hot tears in castings, as shown in Fig. 10.12.

- Cracks generally result from a combination of the following factors:
  - Temperature gradients that cause thermal stresses in the weld zone.
  - Variations in the composition of the weld zone that cause different rates of contraction during cooling.
  - Embrittlement of grain boundaries caused by the segregation of such elements as sulfur to the grain boundaries and occurring when the solid–liquid boundary moves when the weld metal begins to solidify.
  - Hydrogen embrittlement.
  - Inability of the weld metal to contract during cooling and is related to excessive restraint of the workpiece during the welding operation.
- The basic crack-prevention measures in welding are the following:
  - Modify the joint design to minimize stresses developed from shrinkage during cooling.
  - Change the parameters, procedures, and sequence of the welding operation.
  - Preheat the components to be welded.
  - **Avoid rapid cooling of the welded components.**

Surface profile induced cracking

- The final mechanism that generates centerline cracks is **surface profile conditions**

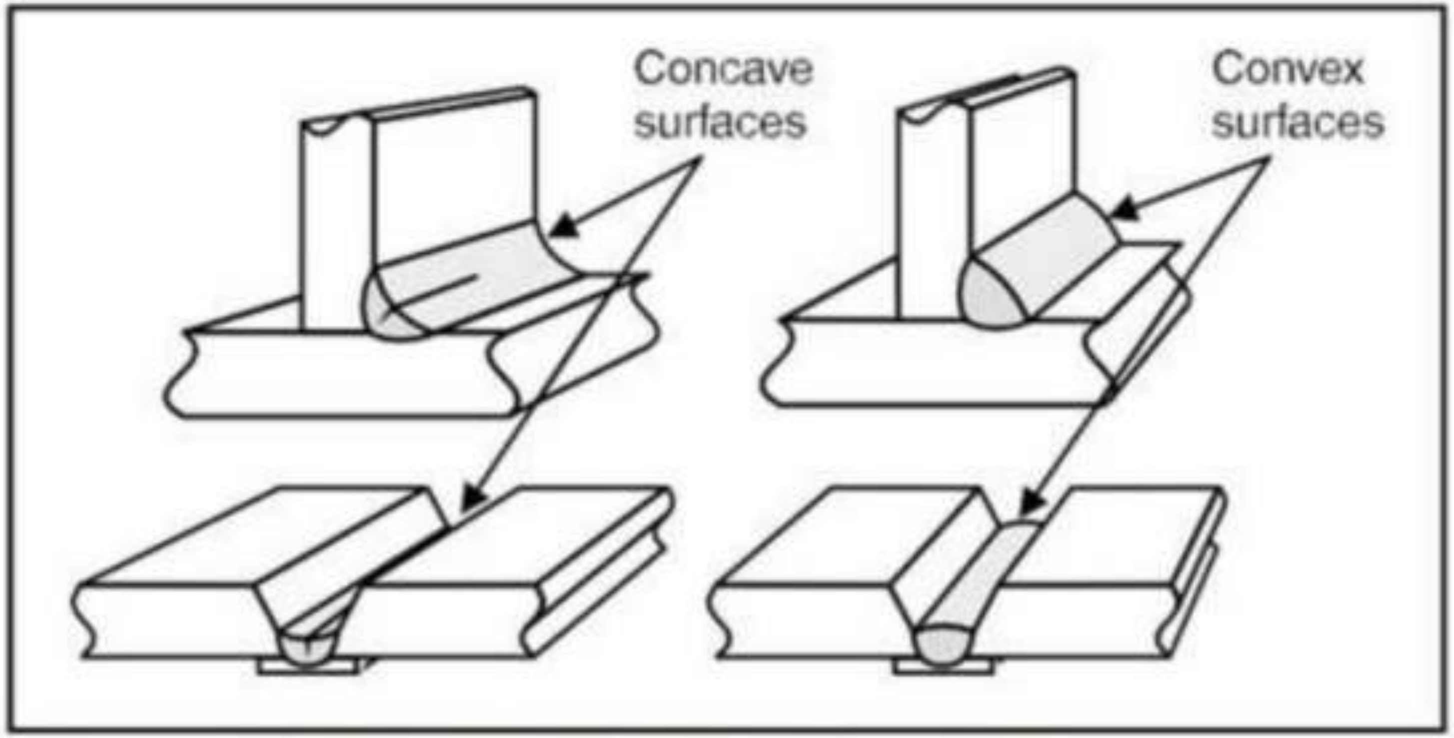


Figure 4 Surface profile induced cracking

- When concave weld surfaces are created, internal shrinkage stresses will place the weld metal on the surface into tension.
- Conversely, when convex weld surfaces are created, the internal shrinkage forces will pull the surface into compression.
- Concave weld surfaces frequently are the result of high arc voltages.
- A slight decrease in arc voltage will cause the weld bead to return to a slightly convex profile and eliminate the cracking tendency.

6. Surface Damage

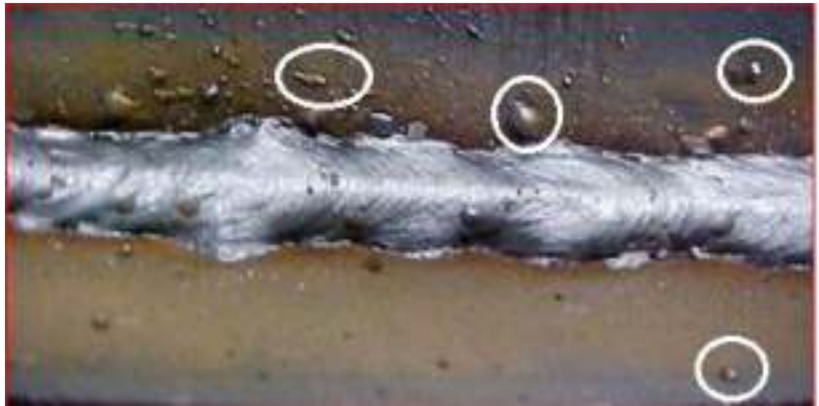
- Some of the metal may spatter during welding and be deposited as small droplets on adjacent surfaces.
- In arc-welding processes, the electrode inadvertently may touch the parts being welded at places other than the weld zone. (Such encounters are called arc strikes.)
- The surface discontinuities thereby produced may be objectionable for reasons of appearance or of subsequent use of the welded part.
- If severe, these discontinuities adversely may affect the properties of the welded structure, particularly for notch-sensitive metals. Using proper welding techniques and procedures is important in avoiding surface damage.

Spatter are small metal particles which are thrown out of the arc during welding and get deposited on the base metal around the weld bead along its length

Causes

Excessive arc current

Longer arc



7. Residual Stresses

- Because of localized heating and cooling during welding, the expansion and contraction of the weld area causes residual stresses in the workpiece.

- When two plates are being welded, a long, narrow zone is subjected to elevated temperatures, while the plates are essentially at ambient temperature. After the weld is completed and as time elapses, the heat from the weld zone dissipates laterally into the plates, while the weld area cools. Thus, the plates begin to expand longitudinally, while the welded length begins to contract. Leads to residual stress.

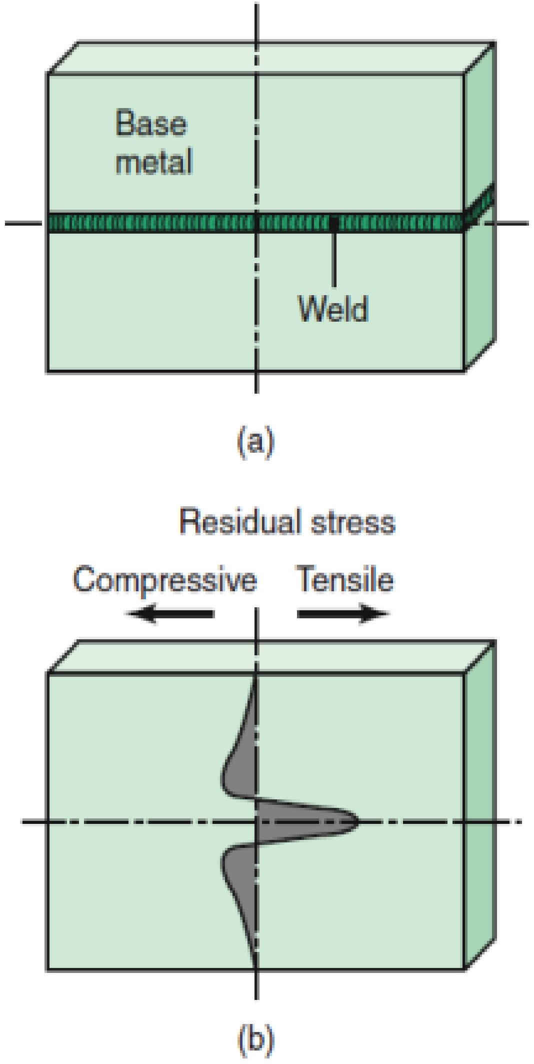


FIGURE 30.24 Residual stresses developed in (a) a straight-butt joint. Note that the residual stresses shown in (b) must be balanced internally. (See

- Residual stresses can lead to the following defects:
  - Distortion, warping, and buckling of the welded parts.
  - Stress-corrosion cracking.
  - Further distortion if a portion of the welded structure is subsequently removed, such as by machining or sawing.
  - Reduced fatigue life of the welded structure.

- Before welding, the structure is stress free, The shape may be rigid, and fixturing also may be present to support the structure. When the weld bead is placed, the molten metal fills the gap between the surfaces to be joined and flows outward to form the weld bead. At this point, the weld is not under any stress. Afterward, the weld bead solidifies, and both the **weld bead and the surrounding material** cool to room temperature. As these materials cool, they tend to contract, but are constrained by the bulk of the weldment. The result is that the weldment distorts, and residual stresses develop.

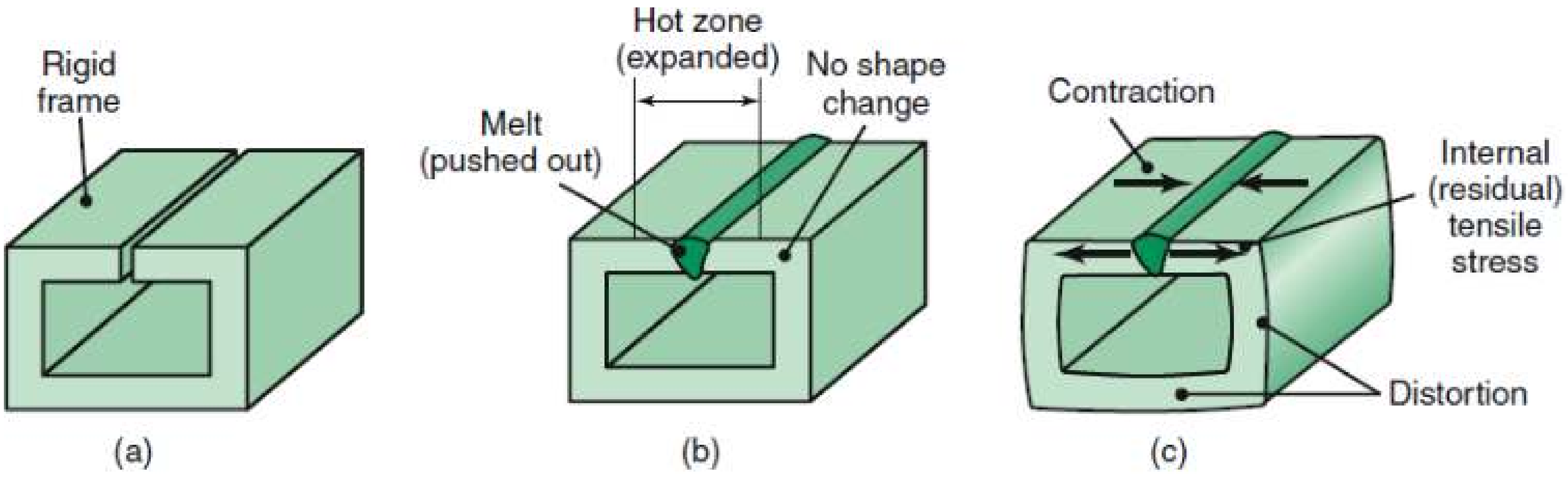


FIGURE 30.25 Distortion of a welded structure. *Source:* After J.A. Schey.

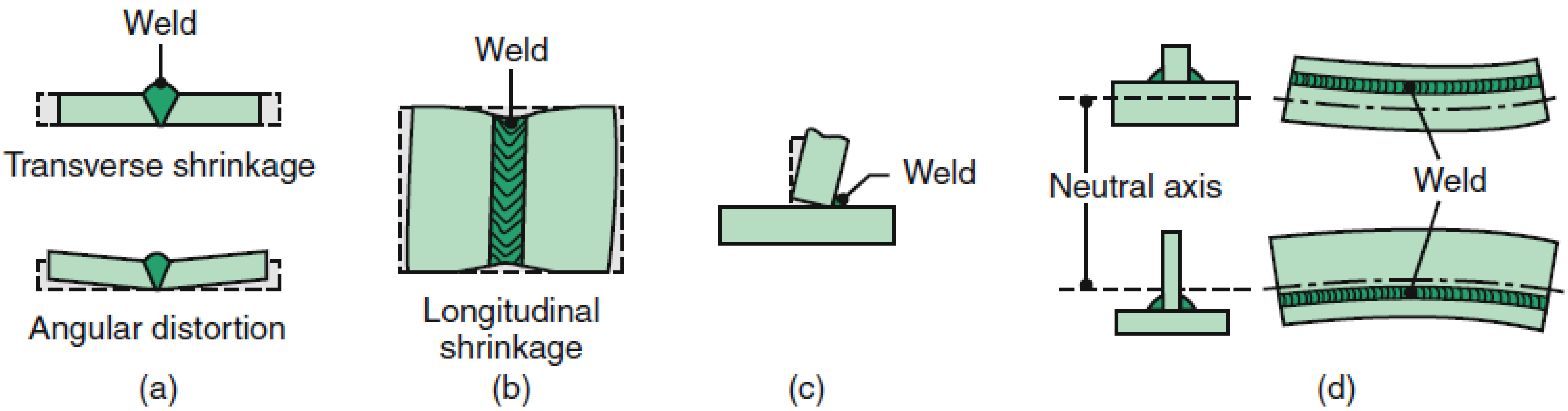


FIGURE 30.23 Distortion of parts after welding. Distortion is caused by differential thermal expansion and contraction of different regions of the welded assembly.

Stress Relieving of Welds

- The problems caused by residual stresses (such as distortion, buckling, and cracking) can be reduced by preheating the base metal or the parts to be welded.
- Preheating reduces distortion by reducing the cooling rate and the level of thermal stresses developed (by lowering the elastic modulus). This technique also reduces shrinkage and possible cracking of the joint.
- The temperature and time required for stress relieving depend on the type of material and on the magnitude of the residual stresses developed.
- Other methods of stress relieving include peening, hammering, or surface rolling of the weld-bead area. These techniques induce compressive residual stresses, which, in turn, lower or eliminate tensile residual stresses in the weld.
- Residual stresses can also be relieved or reduced by plastically deforming the structure by a small amount.

Heat treatment of welded joints

- In addition to being preheated for stress relieving, welds may be heat treated by various other techniques in order to modify other properties. These techniques include the annealing, normalizing, quenching, and tempering of steels and the solution treatment and aging of various alloys.
- **Heating a material to a temperature, holding it at that temperature for a period followed by cooling at a specified rate is called heat treatment.**

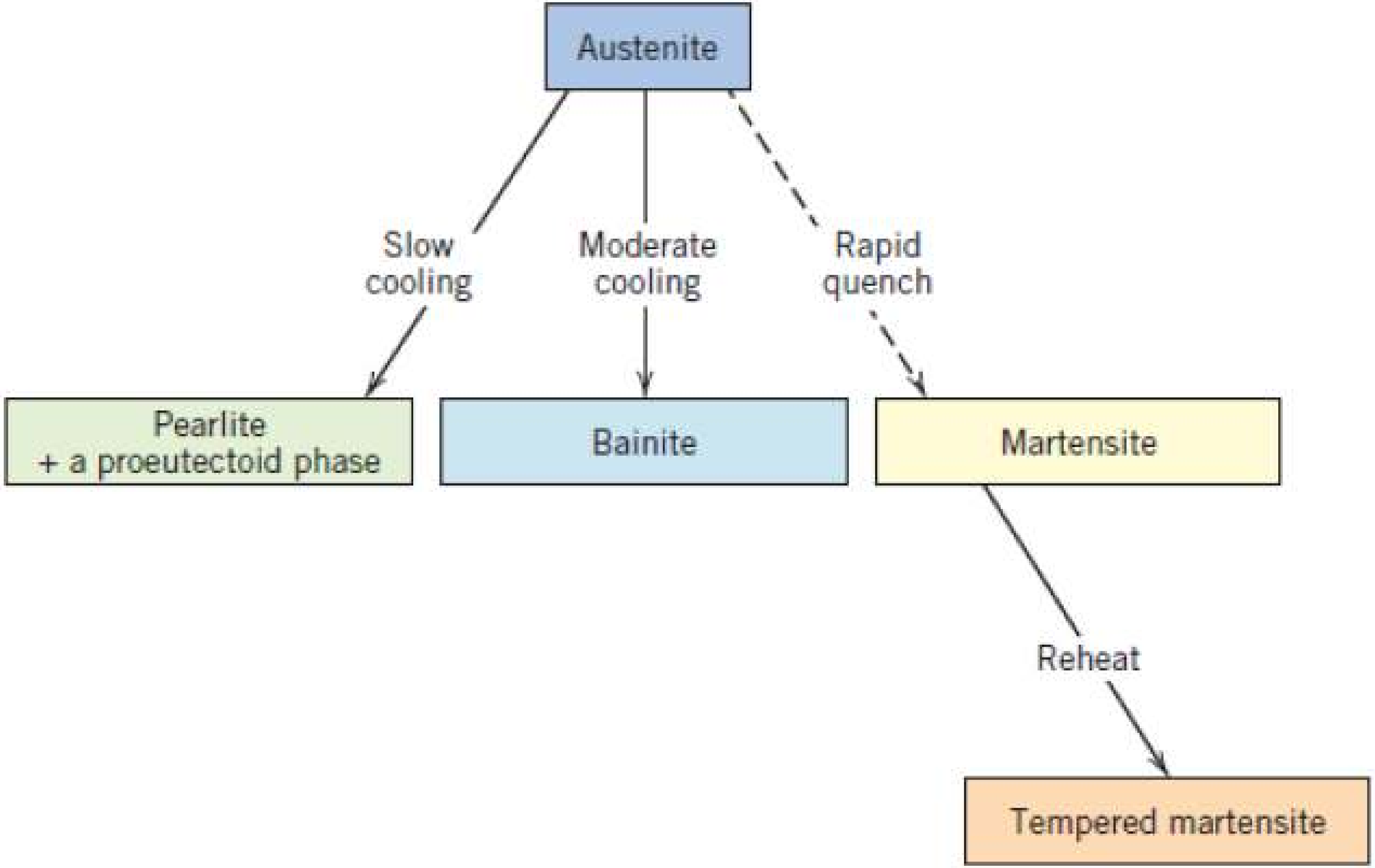
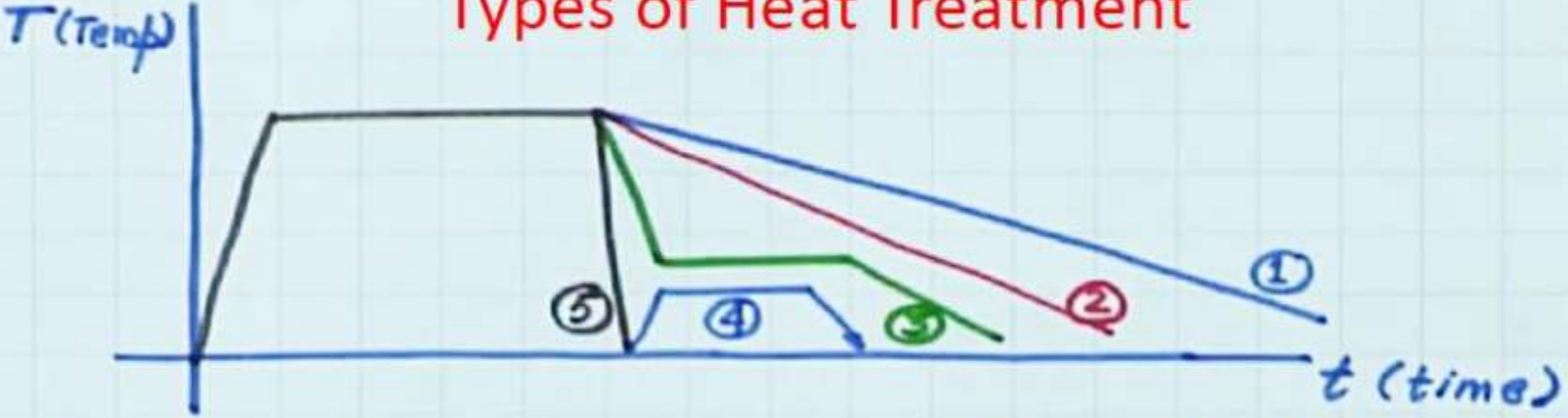


Figure 10.36 Possible transformations involving the decomposition of austenite. Solid arrows, transformations nvolving diffusion; dashed arrow, diffusionless transformation.

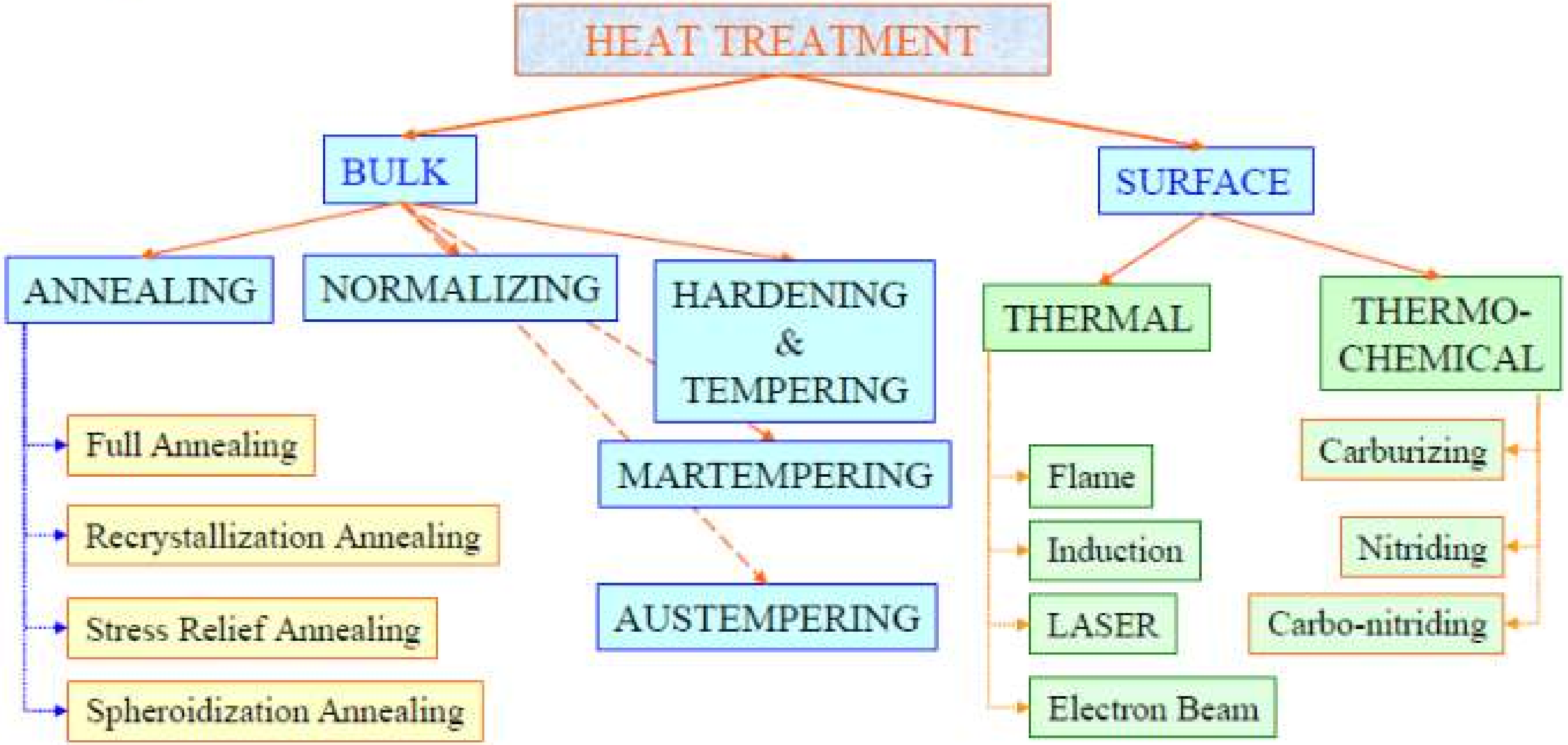
Types of Heat Treatment



1	Annealing	Slow cooling (Furnace ")	Coarse Pearlite
2.	Normalizing	Faster cooling (Air cooling)	Fine Pearlite
3.	Austempering	Interrupted Quench	Bainite.
4.	Tempering	Heating after Quench	Tempered Martensite.
5.	Quenching	V. Fast Cooling (Water)	Martensite.

Types of Heat Treatment

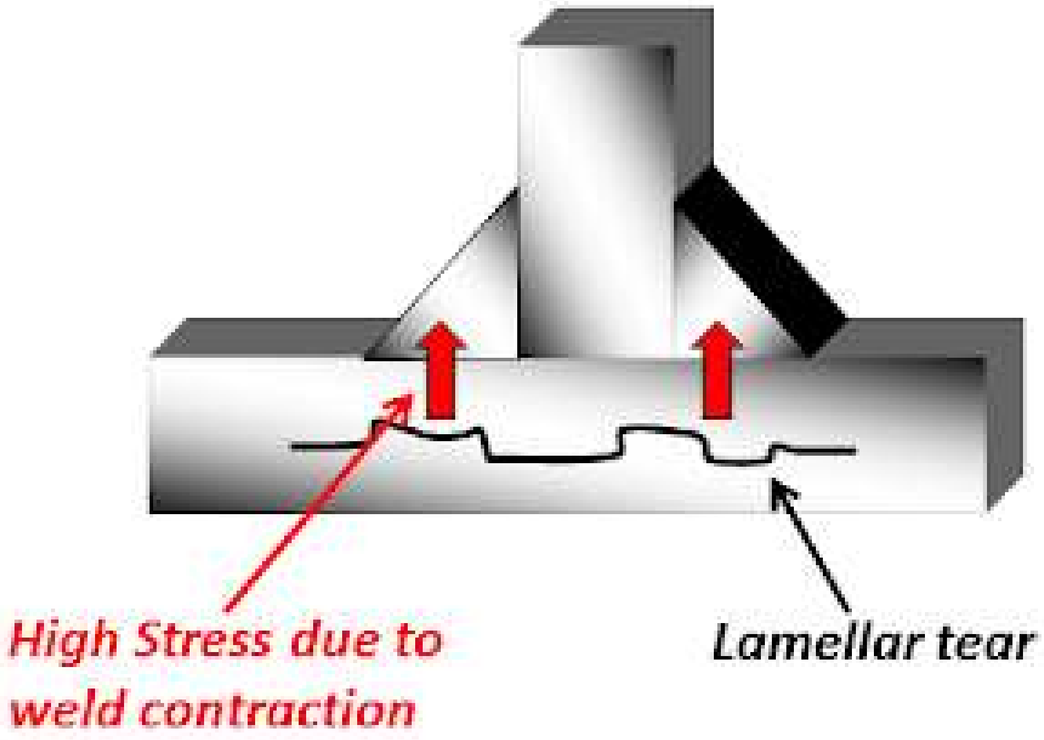
- A broad classification of heat treatments possible are given below. Many more specialized treatments or combinations of these are possible.

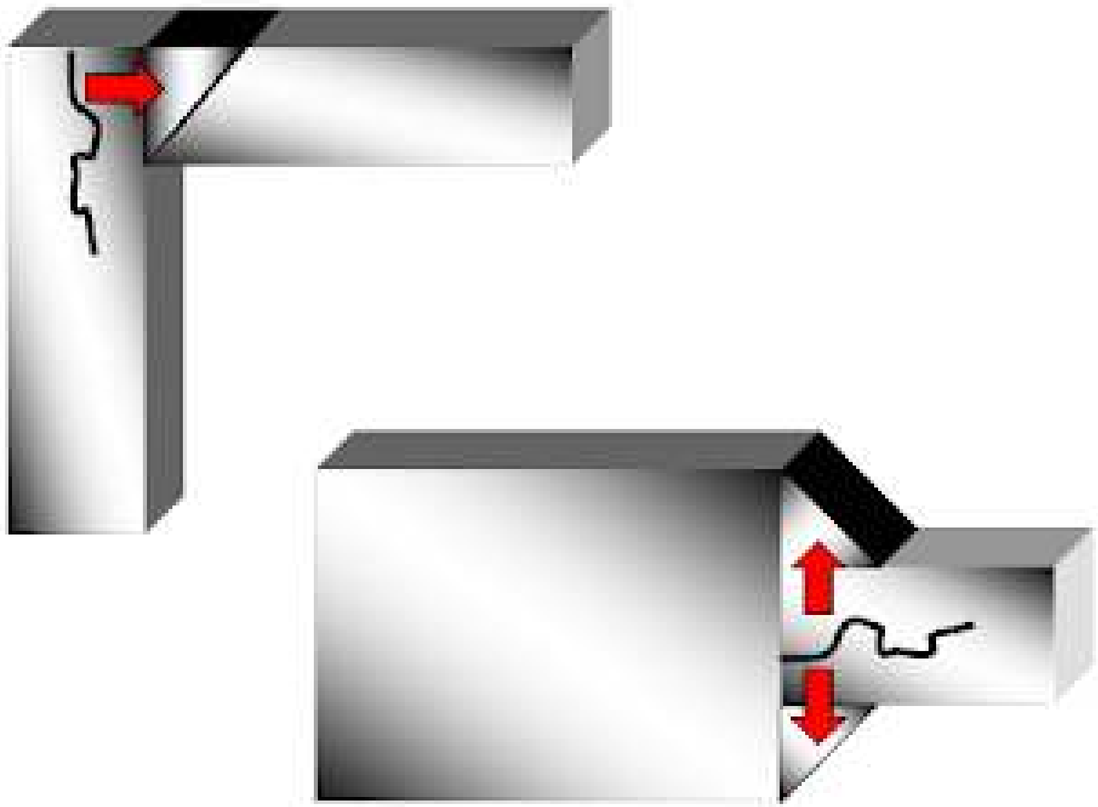


8. Lamellar Tears

- In describing the anisotropy of plastically deformed metals , it was stated that the workpiece is weaker when tested in its thickness direction because of the alignment of nonmetallic impurities and inclusions (stringers).
- This condition is particularly evident in rolled plates and in structural shapes.
- In welding such components, lamellar tears may develop because of shrinkage of the restrained components of the structure during cooling. Such tears can be avoided by providing for shrinkage of the members or by modifying the joint design to make the weld bead penetrate the weaker component more deeply.
- Lamellar Tear is a crack that is a step in the base metal under the welding line. The cracks lie parallel to the work surface, especially with the Rolled Steel Plate.
- Lamellar Tear is caused by Tensile Stress in Through-Thickness direction. This comes from the shrinkage of the weld and the base metal itself has impurities or inclusions that are parallel to the work surface. Thus causing a tear or crack Lamellar Tearing up.

- ***Step-like crack*** in the base metal with a basic orientation ***parallel to the plate surface and weld fusion boundary***
- ***Caused by Tensile stresses*** in the through-thickness direction of the base metal and low quality base materials, high levels of ***Impurities and Inclusions parallel to the metal surface***





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Weldability

- The *weldability* of a metal is usually defined as its capacity to be welded into a specific structure that has certain properties and characteristics and will satisfactorily meet service requirements.
- Material characteristics (such as alloying elements, impurities, inclusions, grain structure, and processing history) of both the base metal and the filler metal are important parameters affect weldability.
- Mechanical and physical properties affects weldability are strength, toughness, ductility, notch sensitivity, elastic modulus, specific heat, melting point, thermal expansion, surface-tension characteristics of the molten metal, and corrosion resistance.
- Other factors that affect weldability are shielding gases, fluxes, moisture content of the coatings on electrodes, welding speed, welding position, cooling rate, and level of preheating, as well as such post welding techniques as stress relieving and heat treating.

- The preparation of surfaces for welding is important, as are the nature and properties of surface-oxide films and of adsorbed gases.

Weldability of Ferrous Materials:

- *Plain-carbon steels:* Weldability is excellent for low-carbon steels, fair to good for medium-carbon steels, poor for high-carbon steels.
- *Low-alloy steels:* Weldability is similar to that of medium-carbon steels.
- *High-alloy steels:* Weldability generally is good under well-controlled conditions.
- *Stainless steels:* These generally are weldable by various processes.
- *Cast irons:* These generally are weldable, although their weldability varies greatly.

Weldability of Nonferrous Materials:

- *Aluminum alloys:* These are weldable at a high rate of heat input. An inert shielding gas and lack of moisture are important. Aluminum alloys containing zinc or copper generally are considered unweldable.
- *Copper alloys:* Depending on composition, these generally are weldable at a high rate of heat input. An inert shielding gas and lack of moisture are important.
- *Magnesium alloys:* These are weldable with the use of a protective shielding gas and fluxes.
- *Nickel alloys:* Weldability is similar to that of stainless steels. The lack of sulfur is undesirable.
- *Titanium alloys:* These are weldable with the proper use of shielding gases.
- *Tantalum:* Weldability is similar to that of titanium.
- *Tungsten:* Weldable under well-controlled conditions.
- *Molybdenum:* Weldability is similar to that of tungsten.
- *Niobium (columbium):* Possesses good weldability.

Weld inspection (Assignment 1)

- The principal objective of weld inspection is to assure the high quality of weld structure through the careful examination of the components at each stage of the fabrication process.
- Several standardized tests and test procedures have been established. They are available from many organizations, such as the American Society for Testing and Materials (ASTM), the American Welding Society (AWS), the American Society of Mechanical Engineers (ASME), the American Society of Civil Engineers (ASCE), and various federal agencies.
- Weld inspection methods are,
  - Destructive testing
  - Non-destructive testing
- <u>Destructive testing</u>

1. Tension test
2. Bend test
3. Impact test
4. Hardness test
5. Nick break test
6. Pillow test for seam weld

2. Non-destructive testing
    - Visual inspection
    - Liquid (dye) penetrant inspection
    - Ultrasonic inspection
    - Radiographic test
    - Magnetic particle inspection
    - Eddy current inspection
    - Leak test
    - Acoustic emission monitoring

Thank you...

Plastic Deformation of Metals & Rolling

Content

1. Plastic deformation of metals
2. Stress-strain relationships
3. State of stress
4. Yield criteria of Tresca, Von Mises
5. Comparisons and applications of Yield criteria
6. Flow rules
7. Power and Energy deformations
8. Heat generation and heat Transfer in metal forming process
9. Temperature in forging.

3.1	Rolling:- principles - types of rolls and rolling mills - mechanics of flat rolling, roll pressure distribution, neutral point, front and back tension, torque and power, roll forces in hot rolling, friction, deflection and flattening, spreading -– simple problems.	3	CO4 CO5
3.2	rolling defects-vibration and chatter - flat rolling -miscellaneous rolling process: shape, roll forging, ring, thread and gear, rotary tube piercing, tube rolling - applications – simple problems. (Kalpakjian).	2	CO4
3.3	Plastic deformation of metals - stress-strain relationships- State of stress - yield criteria of Tresca, von Mises, and comparisons - applications.	2	
3.4	Flow rules -power and energy deformations - Heat generation and heat transfer in metal forming process -temperature in forging. (ASM- Taylan Altan).	1	CO4

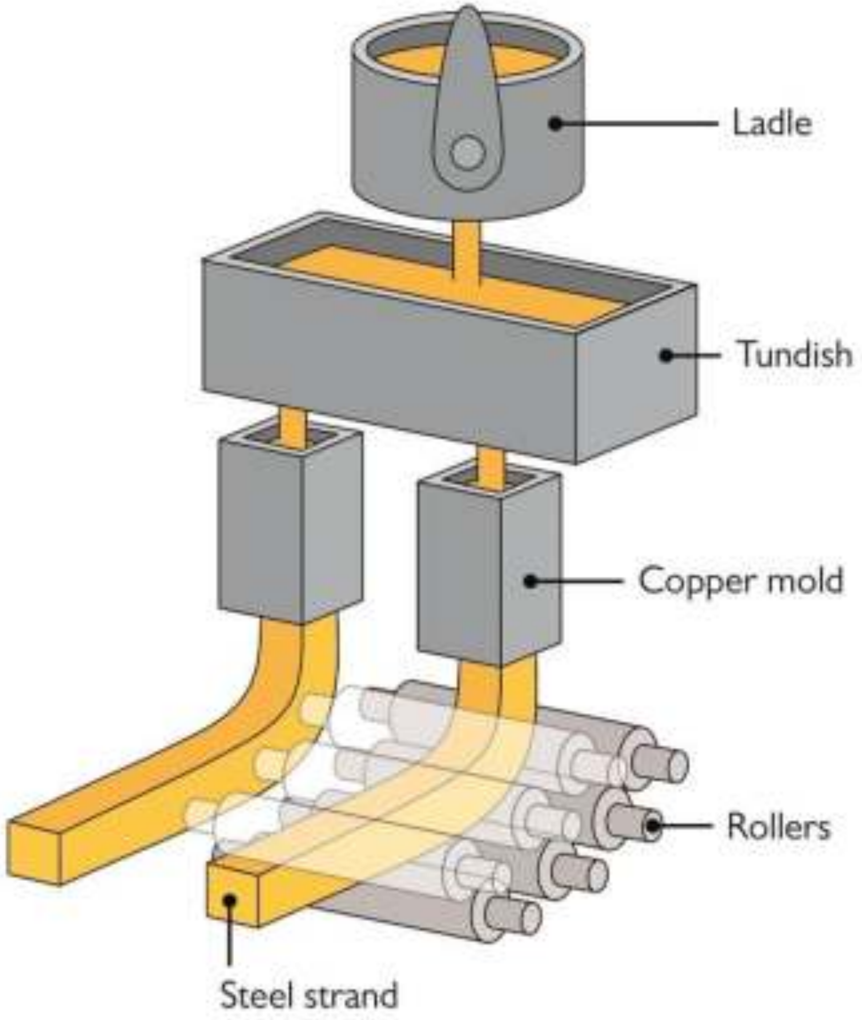
Course Outcomes - At the end of the course students will be able to

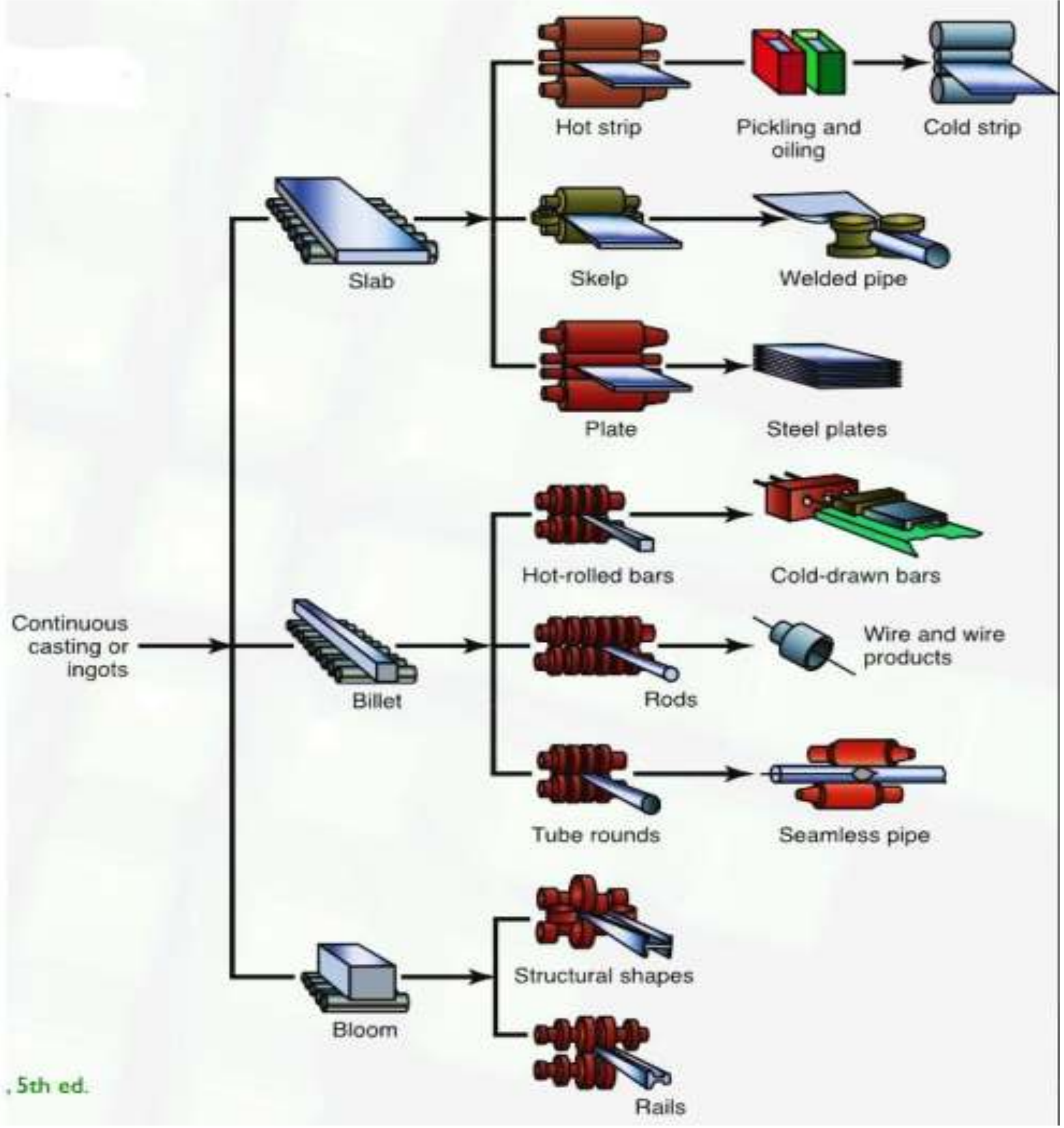
CO 4	Student will estimate the working loads for pressing, forging, wire drawing etc. processes
CO 5	Recommend appropriate part manufacturing processes when provided a set of functional requirements and product development constraints.

1.Introduction

- The manufacture of metal parts and assemblies can be classified, in a simplified manner, into five general areas:
- ***Primary shaping*** processes, such as casting, die casting, and pressing of metal powder. In all these processes, the material initially has no shape but obtains a well-defined geometry through the process.
- ***Metal forming processes*** such as rolling, extrusion, cold and hot forging, bending, and deep drawing, where metal is formed by plastic deformation.
- ***Metal cutting processes***, such as sawing, turning, milling and broaching where removing metal generates a new shape.
- ***Metal treatment processes***, such as heat treating, anodizing and surface hardening, where the part remains essentially unchanged in shape but undergoes change in properties or appearance.
- ***Joining processes***, including (a) metallurgical joining, such as welding and diffusion bonding, and (b) mechanical joining, such as riveting, shrink fitting, and mechanical assembly.

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

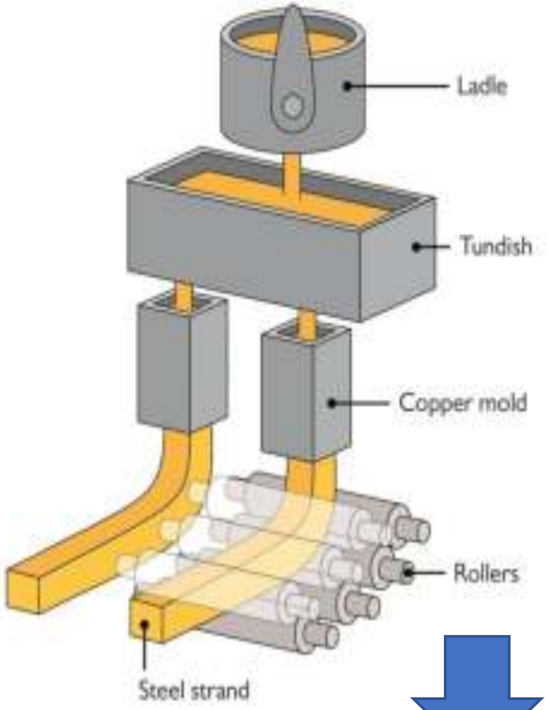




Reference: manufacturing processes for engineering materials by Serope Kalpakjian

how it's made

Crank Shaft



Eld

Metal Forming (Plastic deformation of metals)

- Metal forming is the backbone of modem manufacturing industry besides being a major industry in itself.
- 15 to 20% of **GDP of industrialized nations comes from forming industry.**
- In metal forming processes, the product shapes are produced by **plastic deformation.**
- Metal Forming includes a large group of manufacturing processes in which plastic deformation is used to change the shape of metal work-pieces.
- Deformation results from the use of a tool, usually a die in metal forming, which applies stresses that **exceed the yield strength** of the metal.

Reference: Manufacturing processes for engineering materials by Serope Kalpakjian

Metal Forming (Plastic deformation of metals)

- Among all manufacturing processes, **metal forming technology** has a special place because it helps to produce parts of superior mechanical properties with minimum waste of material.
- In metal forming, the starting material has a relatively simple geometry. The material is plastically deformed in one or more operations into a product of relatively complex configuration.
- Forming to near-net- or to net-shape dimensions drastically reduces metal removal requirements, resulting in significant material and energy savings.
- Metal forming usually requires relatively expensive tooling. Thus, the process is economically attractive only when a large number of parts must be produced and/or when the mechanical properties required in the finished product can be obtained only by a forming process.

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

Why Forming

Forming

- High production rate
- Improved mechanical properties
- Reduced internal defects
- Compressive residual stress
- Easy automation
- Close control over the properties
- High strength to weight ratio

- Anisotropic structure and properties
- Limited to simple shapes
- Needs machining to achieve required finish and tolerance
- Difficult control of process parameters
- Mechanical properties namely yield strength and ductility affects success of process

- Metal forming includes a large number of manufacturing processes producing industrial products as well as military components and consumer goods. These processes include
  (a) Massive forming operations such as forging, rolling, and drawing
  (b) Sheet forming processes, such as brake forming, deep drawing, and stretch forming.
- Forming processes are especially attractive in cases where:
  - The part geometry is of moderate complexity and the production volumes are large, so that tooling costs per unit product can be kept low (e.g., automotive applications).
  - The part properties and metallurgical integrity are extremely important (e.g., load carrying aircraft, jet engine, and turbine components).

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

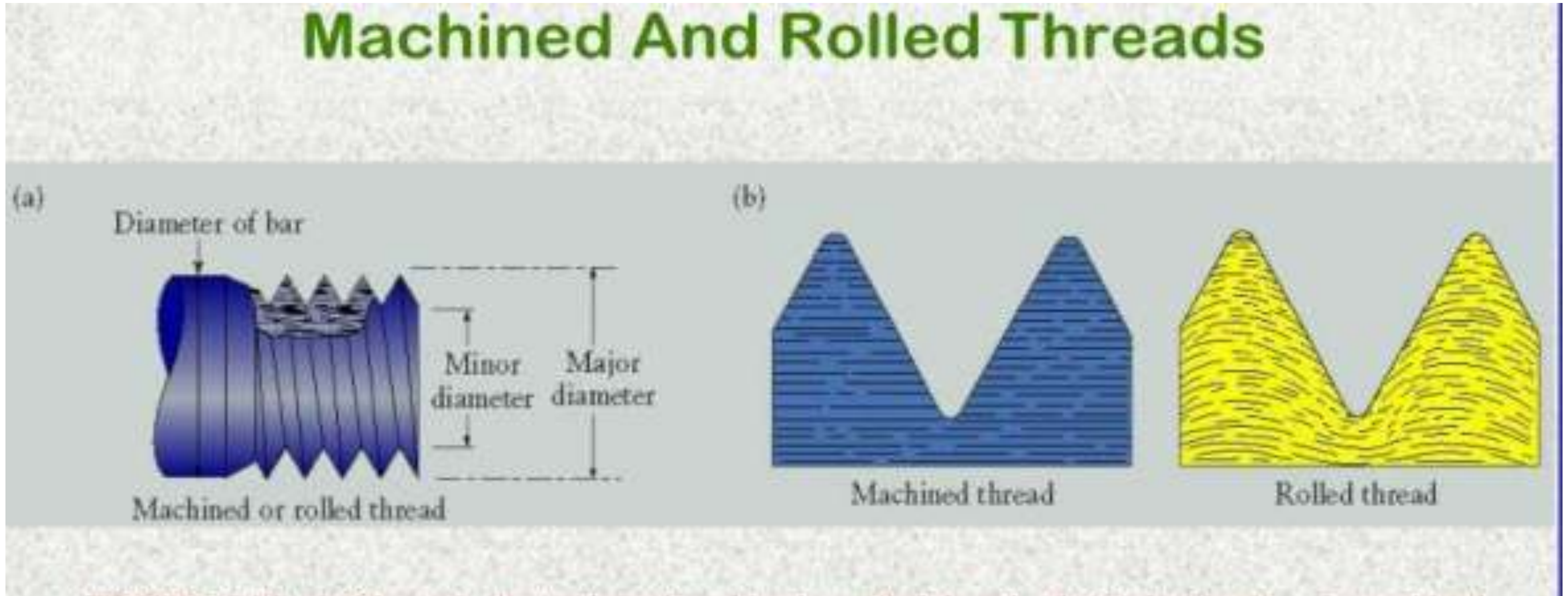
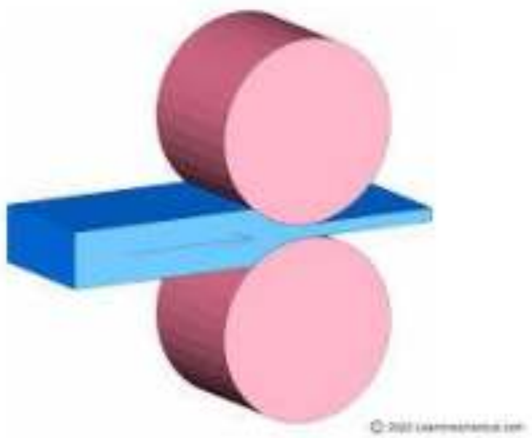


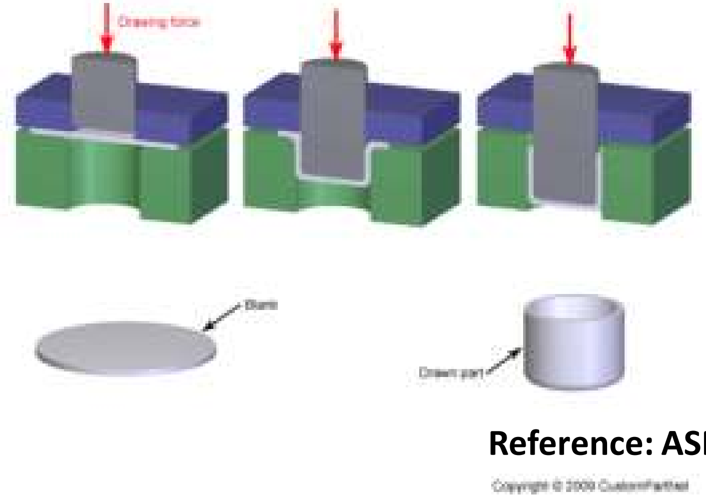
FIGURE 6.47 (a) Schematic illustration of machined or rolled threads. (b) Grain-flow lines in machined and rolled threads. Unlike machined threads, which are cut through the grains of the metal, rolled threads follow the grains and are stronger, because of the cold working involved.

Reference: manufacturing processes for engineering materials by Serope Kalpakjian

Classification of Metalworking Processes

- Metal-forming processes are usually classified according to two broad categories:
  - Bulk, or massive, forming operations
  - Sheet forming operations
- In bulk forming, the input material is in billet, rod, or slab form, and the **surface to volume ratio in the formed part increases** considerably under the action of largely compressive loading.
- In sheet forming, on the other hand, a piece of sheet metal is plastically deformed by **tensile loads into a three-dimensional shape, often without significant changes in sheet thickness or surface characteristic.**





Reference: ASM Metals Handbook, Vol 14

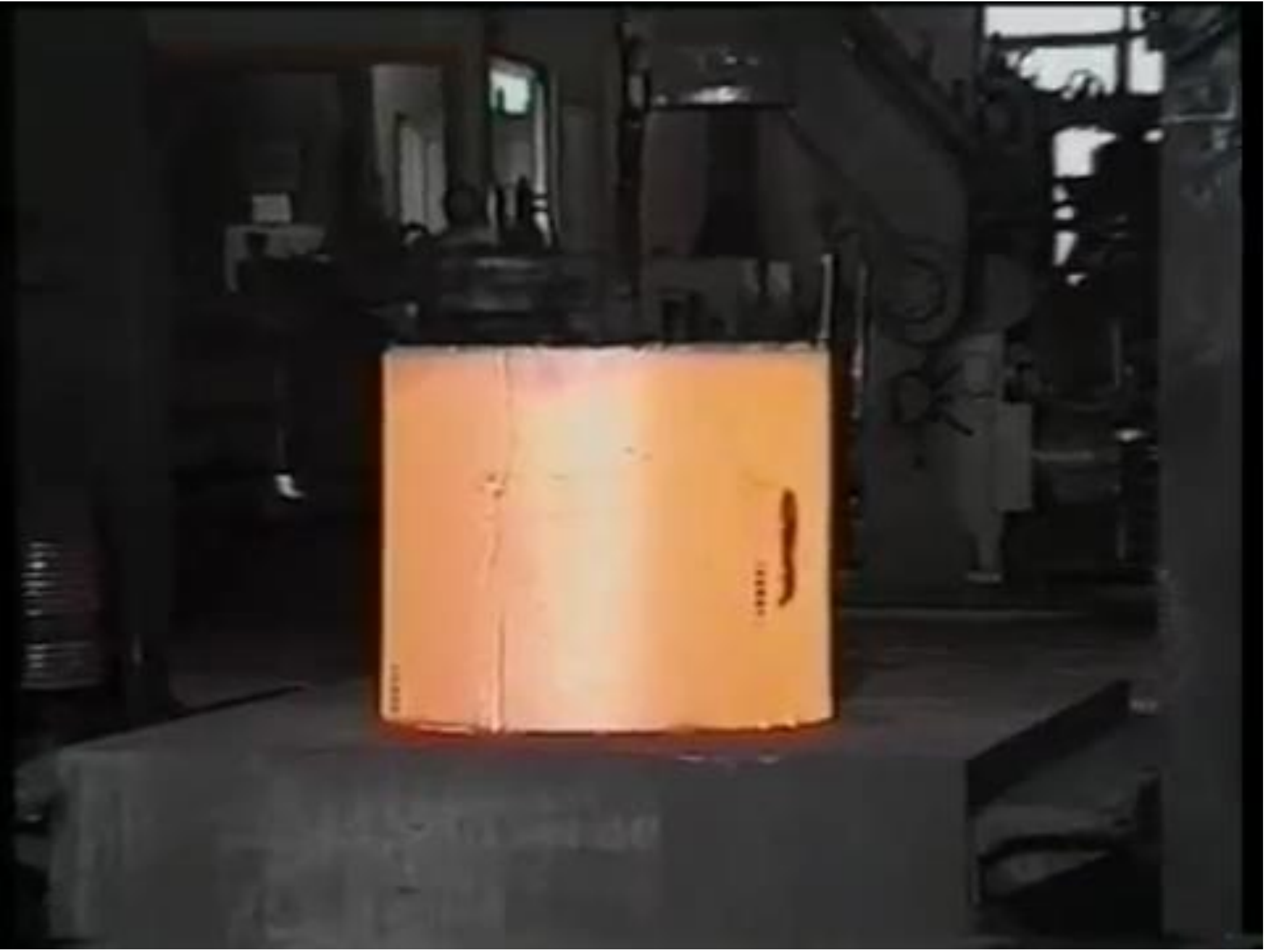
Metal Forming Processes

Sheet Metal-working:

- Also called "**Press-working**".
- Cold working processes.
- Use set of punch and die.
- Performed on metal sheets, strips and coils.
- **Surface area / volume is large.**

Bulk Deformation:

- Compressive deformation force.
- Significant deformations.
- Massive shape changes.
- Starting work shapes include billets and rectangular bars.
- **Surface area / volume is small.**



Classification of bulk (massive) forming processes

Forging

Closed-die forging with flash
Closed-die forging without flash
Coining
Electro-upsetting
Forward extrusion forging
Backward extrusion forging
Hobbing
Isothermal forging
Nosing
Open-die forging
Rotary (orbital) forging
Precision forging
Metal powder forging
Radial forging
Upsetting

Rolling

Sheet rolling
Shape rolling
Tube rolling
Ring rolling
Rotary tube piercing
Gear rolling
Roll forging
Cross rolling
Surface rolling
Shear forming
Tube reducing

Extrusion

Nonlubricated hot extrusion
Lubricated direct hot extrusion
Hydrostatic extrusion

Drawing

Drawing
Drawing with rolls
Ironing
Tube sinking

Reference: ASM Metals Handbook, Vol 14

Classification of sheet metal forming processes

Bending and straight flanging

Brake bending
Roll bending

Surface contouring of sheet

Contour stretch forming (stretch forming)
Androforming
Age forming
Creep forming
Die-quench forming
Bulging
Vacuum forming
Linear stretch forming (stretch forming)
Linear roll forming (roll forming)

Deep recessing and flanging

Spinning (and roller flanging)
Deep drawing
Rubber-pad forming
Marform process
Rubber-diaphragm hydroforming (fluid cell forming or fluid forming)

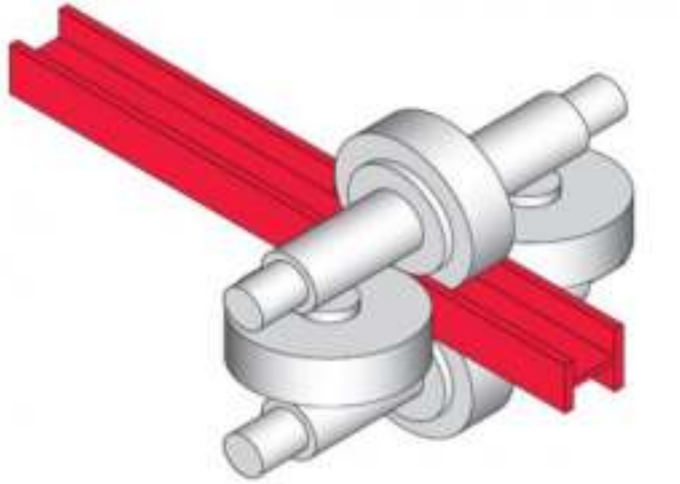
Shallow recessing

Dimpling
Drop hammer forming
Electromagnetic forming
Explosive forming
Joggling

Reference: ASM Metals Handbook, Vol 14

Forming Properties of Metals And Alloys

- Most of the metal forming processes require a combination of material properties for their successful operation.
- The material Properties which are of importance for metal forming are,
  - Yield strength or flow stress.
  - Ductility.
  - Strain hardening.
  - Strain rate sensitivity.
  - Effect of temperature on yield strength and ductility.
  - Effect of hydrostatic pressure on yield strength and ductility.
  - Instability and fracture strength



Stress-strain relationships

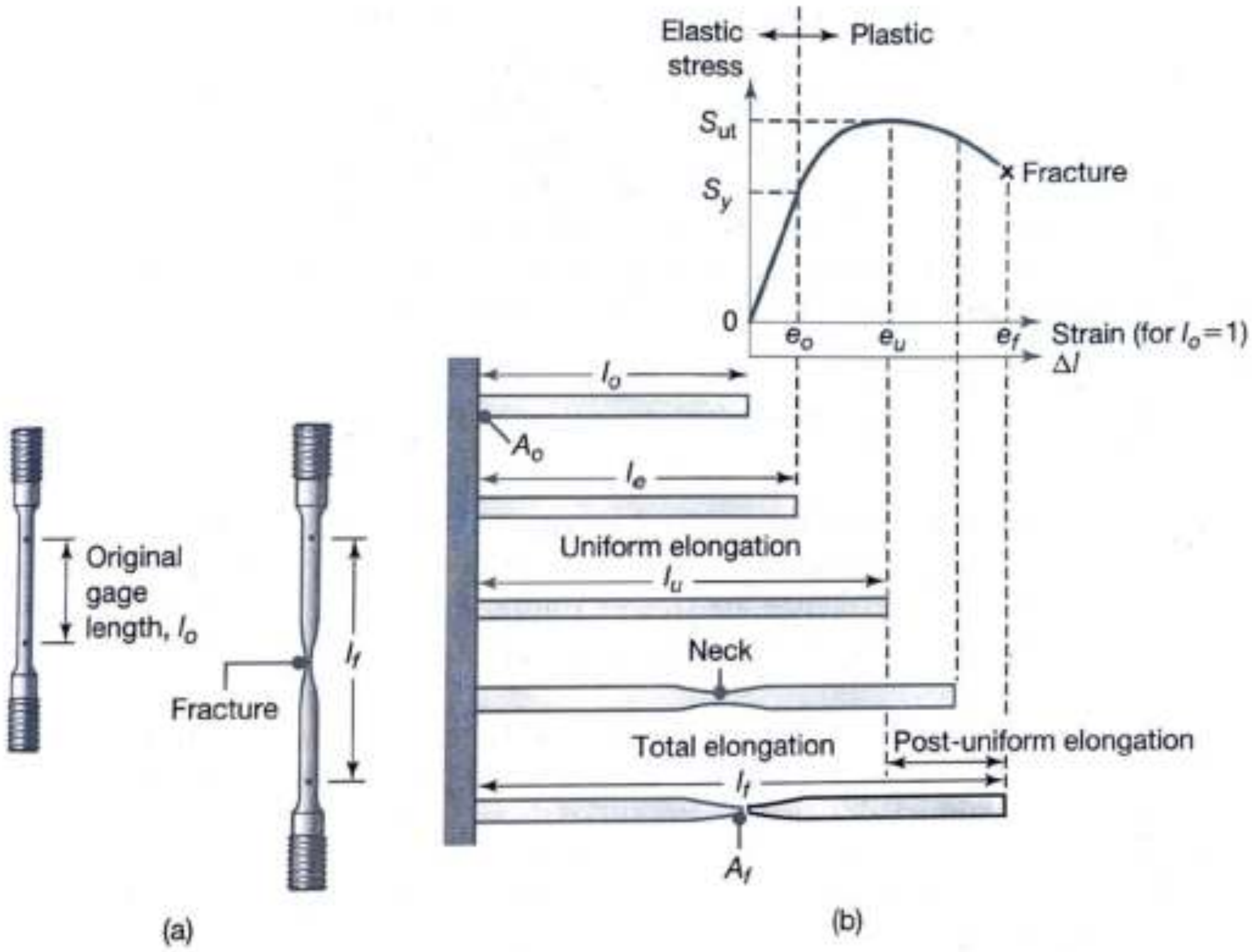


FIGURE 2.2 (a) Original and final shape of a standard tensile-test specimen. (b) Outline of a tensile-test sequence showing different stages in the elongation of the specimen.

Reference: manufacturing processes for engineering materials by Serope Kalpakjian

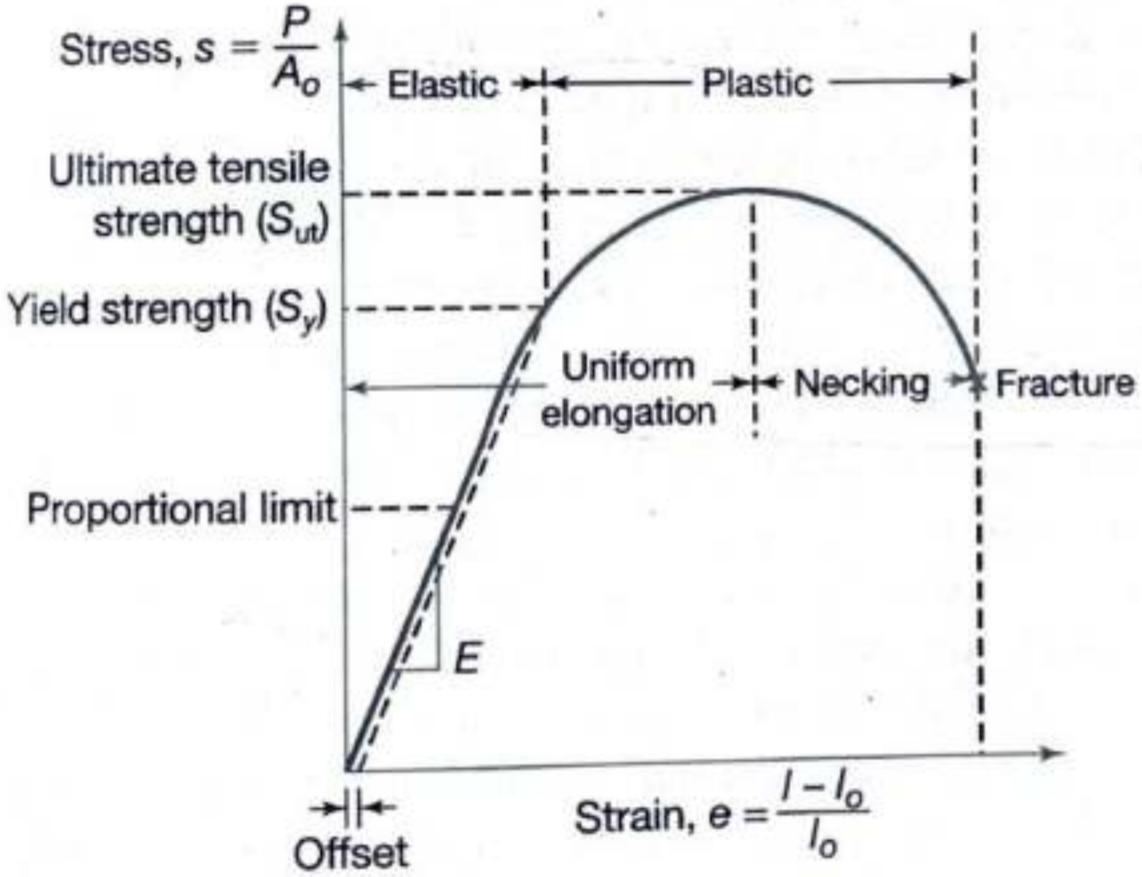


FIGURE 2.3 A typical stress–strain curve obtained from a tension test, showing various features.

Reference: manufacturing processes for engineering materials by Serope Kalpakjian

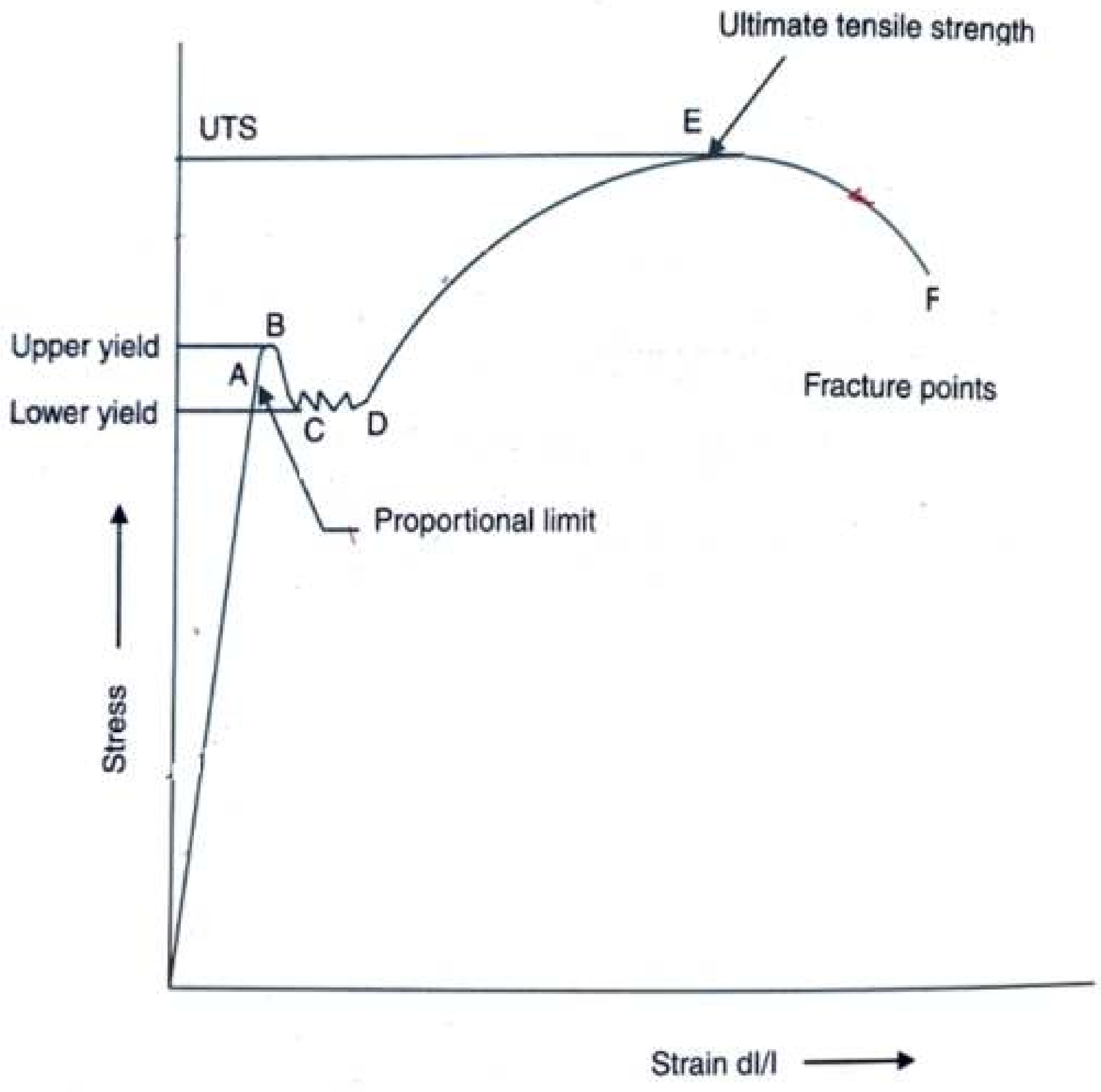


Fig. 1.6. A typical stress-strain curve for mild steel

Reference: Fundamentals of metal forming process, BL Juneja, IIT Delhi

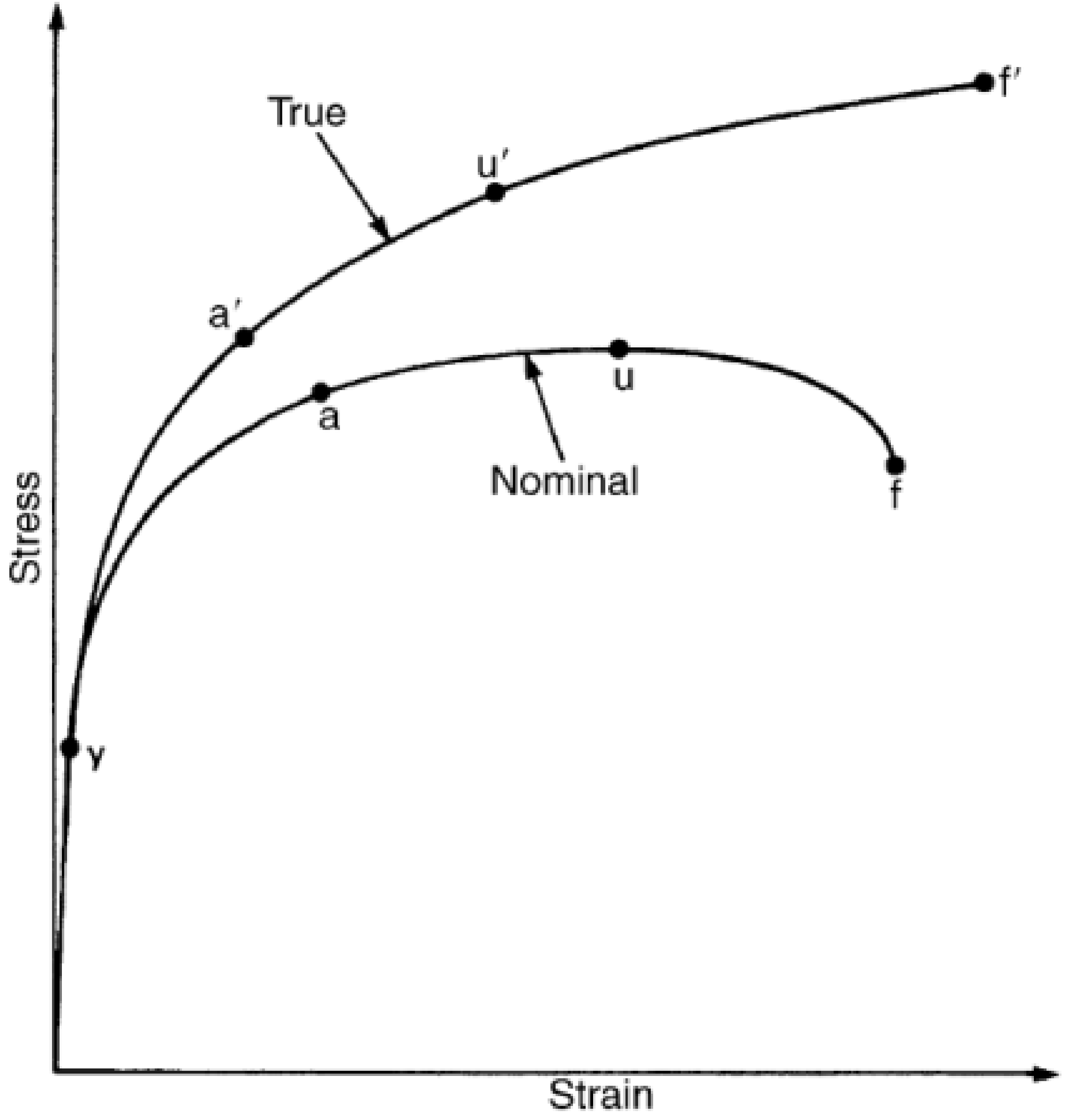


Fig. 3.8 Comparison of engineering and true stress-strain curve. [Hosford & Caddell, 1983]

- True stress is $\sigma = \frac{F}{A}$ where A is the instantaneous area.
- During uniform elongation in tension, for example—the infinitesimal engineering strain, (de), is considered with respect to the original length, l_0, or:

$$de = \frac{dl}{l_o} \rightarrow e = \int_{l_o}^{l_1} \frac{dl}{l_o} = \frac{l_1 - l_o}{l_o}$$

- In True strain change in the length must be related to instantaneous length,

$$d\varepsilon = \frac{dl}{l} \rightarrow \varepsilon = \int_{l_o}^{l_1} \frac{dl}{l} = \ln \frac{l_1}{l_o}$$

$$\varepsilon = \ln \frac{l_1}{l_o} = \ln (e + 1)$$

- Strain rate
  - Depending on the manufacturing operation and the characteristics of the equipment used, a workpiece may be formed at speeds that could range from very low to high.
  - The deformation rate or speed defined in terms of **strain rate.**
  - Within a deforming material, the distribution of velocity components (v_x, v_y, v_z) describes the metal flow in that material.
  - **The strain rates, i.e., the variations in strain with time, are:**

$$\dot{\varepsilon}_x = \frac{\partial \varepsilon_x}{\partial t} = \frac{\partial}{\partial t}\frac{\partial (u_x)}{\partial x} = \frac{\partial}{\partial x}\left(\frac{\partial u_x}{\partial t}\right) = \frac{\partial v_x}{\partial x}$$

Similarly,

$$\dot{\varepsilon}_x = \frac{\partial v_x}{\partial x};\ \dot{\varepsilon}_y = \frac{\partial v_y}{\partial y};\ \dot{\varepsilon}_z = \frac{\partial v_z}{\partial z}$$

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

TABLE 2.3 Typical ranges of strain, deformation speed, and strain rates in metalworking processes.

Process	True strain ϵ	Deformation speed m/s	Strain rate s^{-1}
Cold Working			
Forging, rolling	0.1–0.5	0.1–100	$1–10^3$
Wire and tube drawing	0.05–0.5	0.1–100	$1–10^4$
Explosive forming	0.05–0.2	10–100	$10–10^5$
Hot working and warm working			
Forging, rolling	0.1–0.5	0.1–30	$1–10^3$
Extrusion	2–5	0.1–1	$10^{-1}–10^2$
Machining	1–10	0.1–100	$10^3–10^6$
Sheet metal forming	0.1–0.5	0.05–2	$1–10^2$
Superplastic forming	0.2–3	$10^{-4}–10^{-2}$	$10^{-4}–10^{-2}$

The engineering strain rate, $\dot{e}$, is defined as

$$\dot{e} = \frac{de}{dt} = \frac{d\left(\frac{l - l_o}{l_o}\right)}{dt} = \frac{1}{l_o}\frac{dl}{dt} = \frac{v}{l_o}, \tag{2.16}$$

and the true strain rate, $\dot{\epsilon}$, as

$$\dot{\epsilon} = \frac{d\epsilon}{dt} = \frac{d\left[\ln\left(\frac{l}{l_o}\right)\right]}{dt} = \frac{1}{l}\frac{dl}{dt} = \frac{v}{l}, \tag{2.17}$$

where v is the rate of deformation, for example, the speed of the jaws of the testing machine.

Reference: manufacturing processes for engineering materials by Serope Kalpakjian

- True stress strain curve approximated by the equation

$$\sigma = K\varepsilon^n$$

$$\log \sigma = \log K + n \log \varepsilon$$

n is the strain-hardening exponent.

K is the strength coefficient

σ_f is the flow stress, it defined as the true stress required to continue plastic deformation at a particular true strain ε_1. For strain hardened materials, the flow stress increases with increasing strain.

If there is no strain Harding the flow stress will be equal to the yield strength of the material.

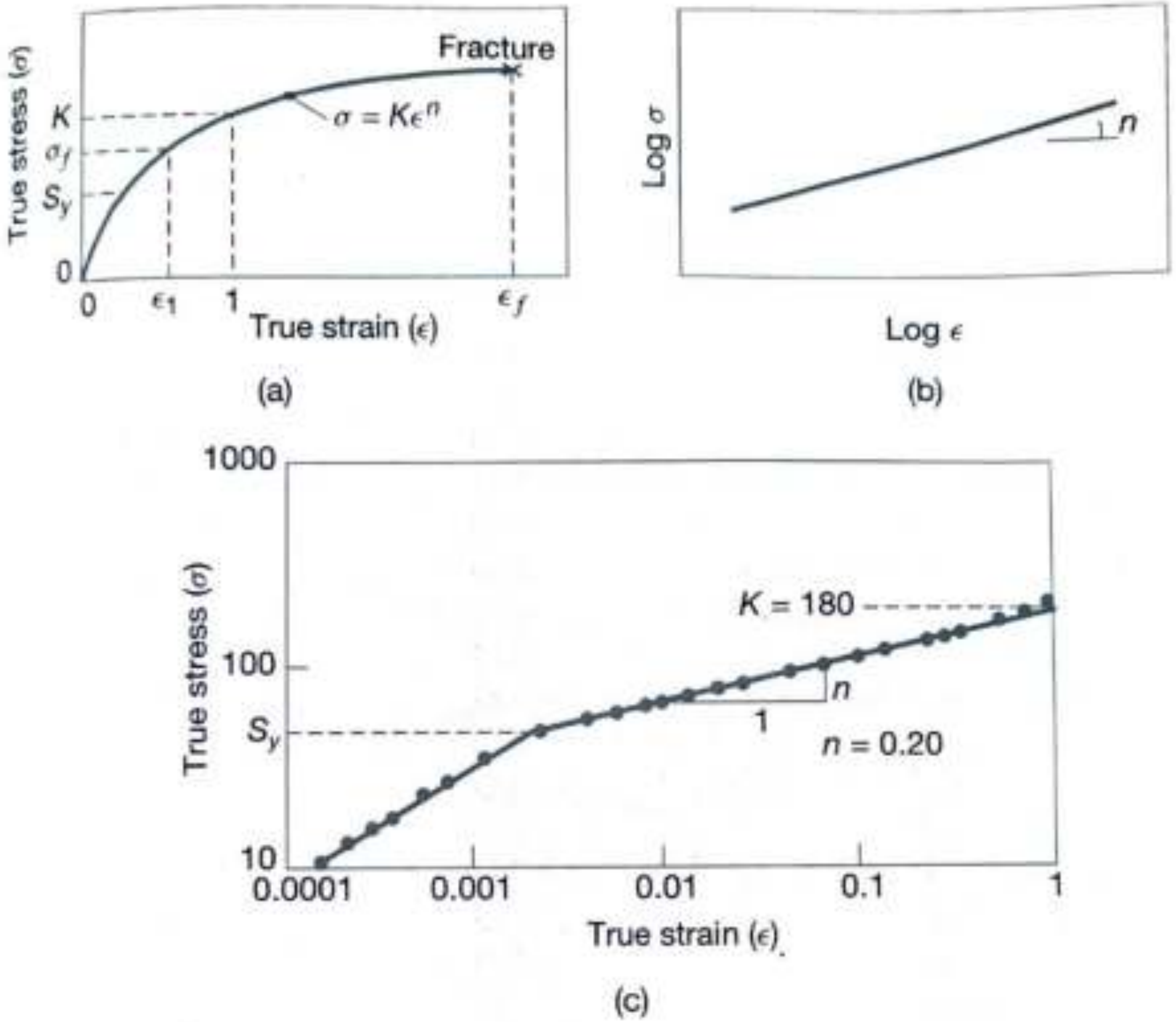


FIGURE 2.5 (a) True stress–true strain curve in tension. Note that, unlike in an engineering stress–strain curve, the slope is always positive and the slope decreases with increasing strain. Although in the elastic range stress and strain are proportional, the total curve can be approximated by the power expression shown. On this curve, S_y is the yield strength and σ_f is the flow stress. (b) True stress–true strain curve plotted on a log-log scale. (c) True stress–true strain curve in tension for 1100-O aluminum plotted on a log-log scale. Note the large difference in the slopes in the elastic and plastic ranges.

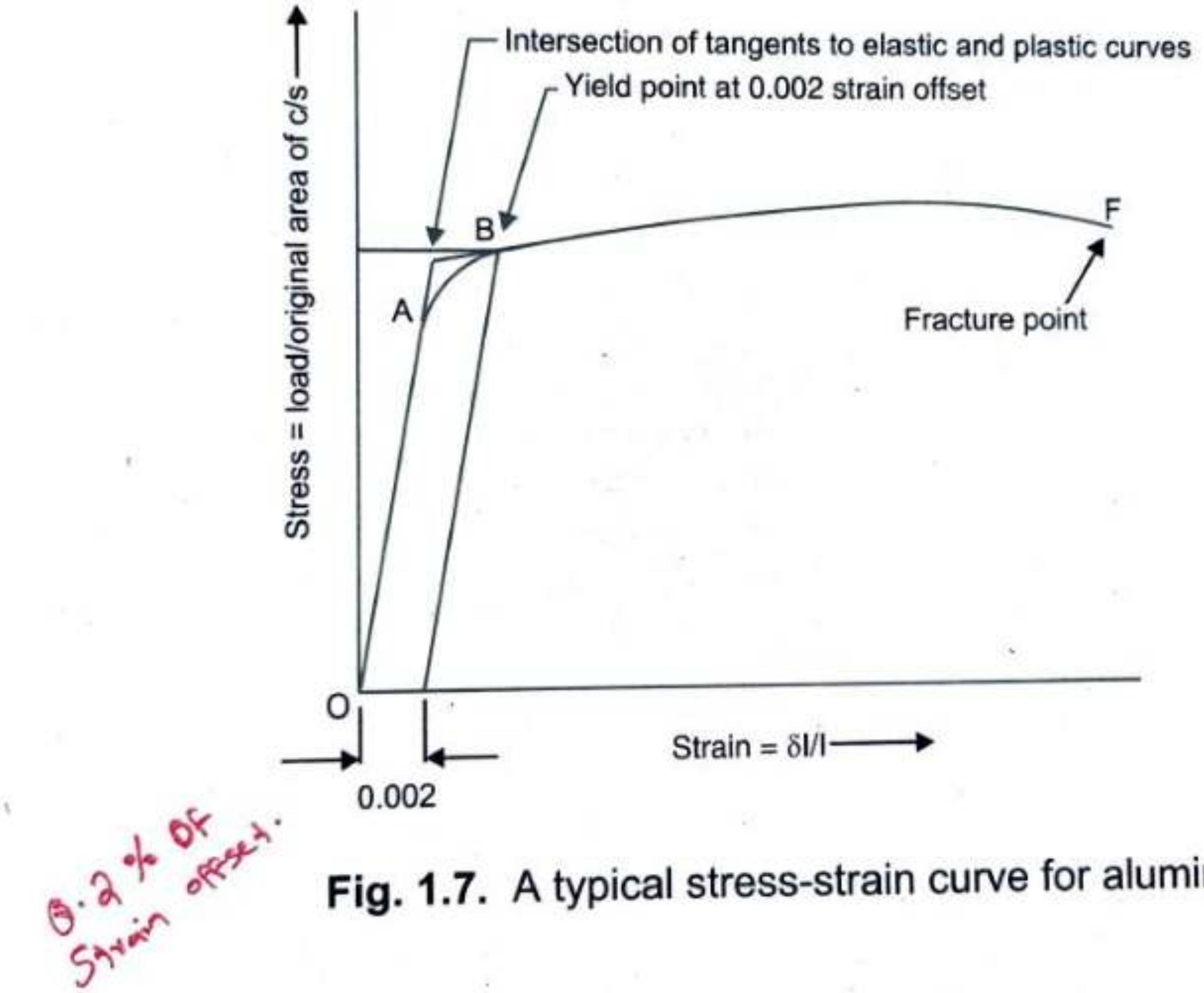


Fig. 1.7. A typical stress-strain curve for aluminum

Reference: Fundamentals of metal forming process, BL Juneja, IIT Delhi

- Strain Hardening Effect in plastic deformation

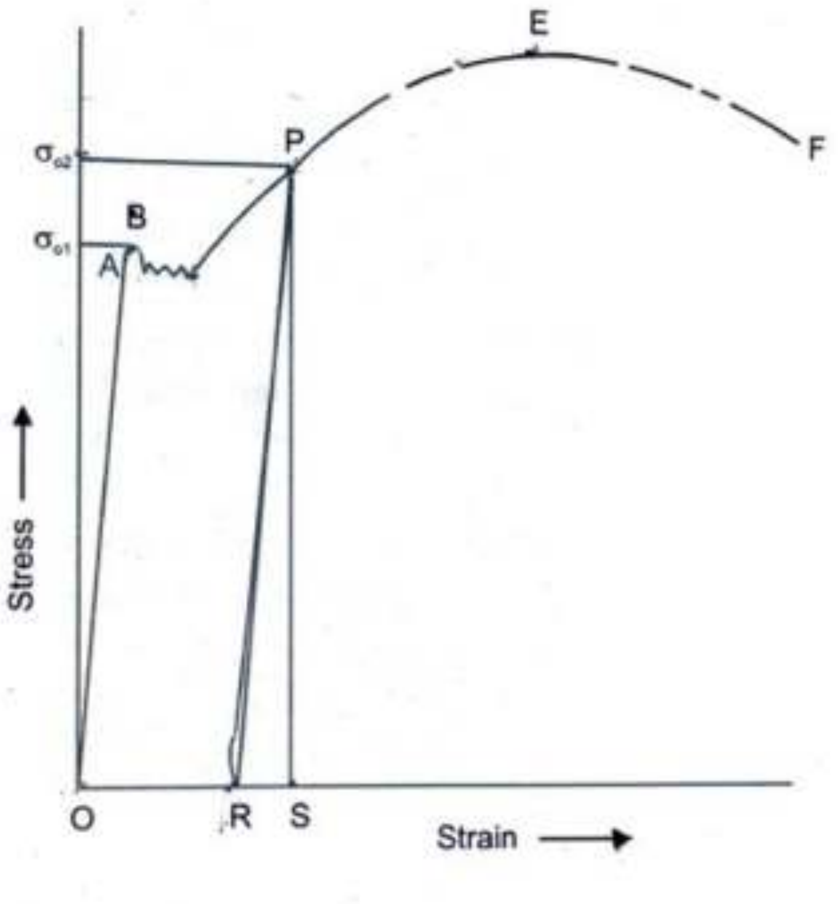
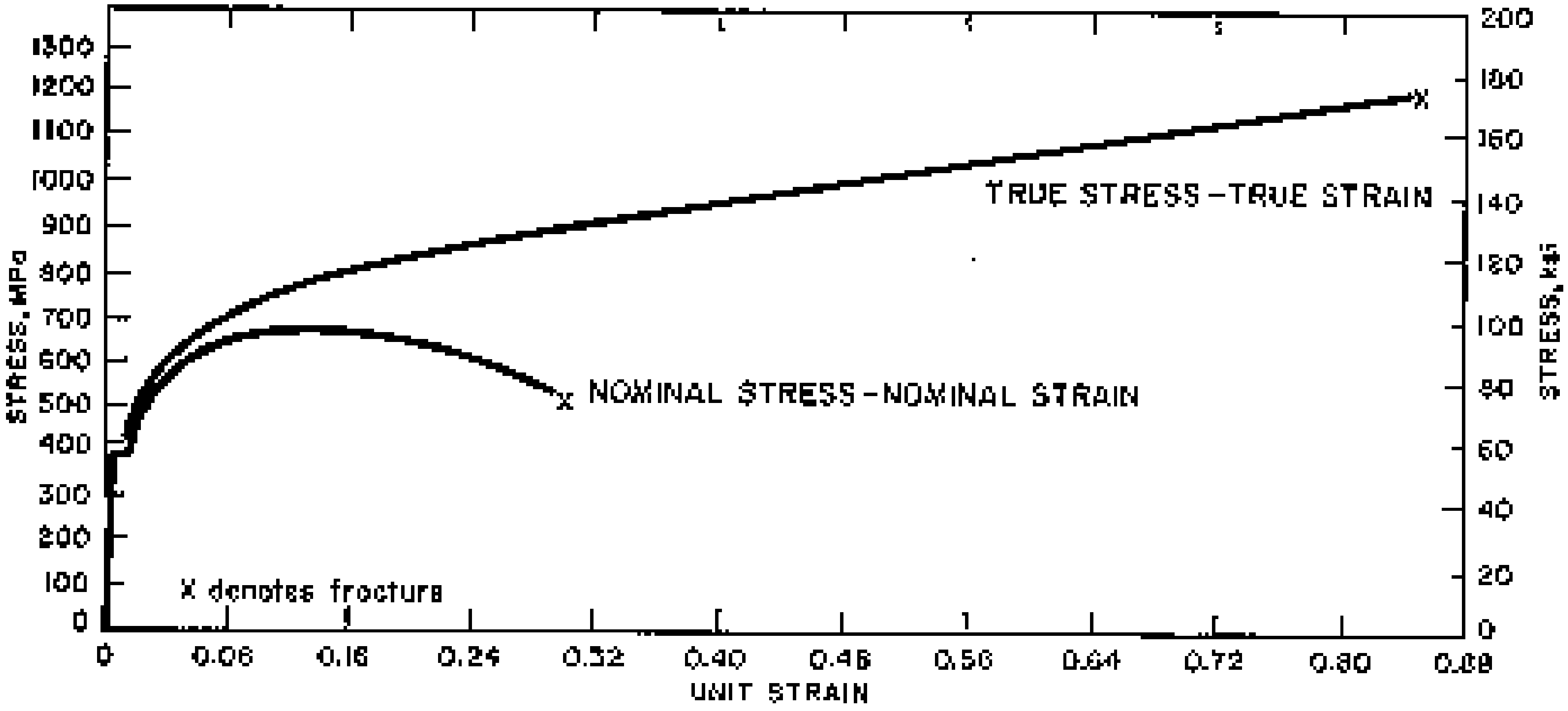


Fig. 1.9. Strain hardening effect

- After suffering a plastic strain represented by OR, the yield strength of the metal has increased from point B to point P (ie, σ_{01} to σ_{02}). This is called strain hardening or work harding

Reference: Fundamentals of metal forming process, BL Juneja, IIT Delhi



ENGINEERING STRESS $$\sigma_E = \frac{P}{A_0}$$

TRUE STRESS $$\sigma_T = \frac{P}{A_i}$$

ELDHO PAUL,Mechanical, MACE

3.State of Stress

- In a deforming object, different states of stress would exist depending on the loading conditions and boundary constraints.
- The state of stress can also be presented in a matrix form, commonly known as stress tensor.

$$\sigma_{ij} = \begin{bmatrix} \sigma_{xx} & \sigma_{yx} & \sigma_{zx} \\ \sigma_{xy} & \sigma_{yy} & \sigma_{zy} \\ \sigma_{xz} & \sigma_{yz} & \sigma_{zz} \end{bmatrix} = \begin{bmatrix} \sigma_{x} & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_{y} & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_{z} \end{bmatrix}$$

Fig. 5.2 Stress tensor

- Normal stress is indicated by σ_{x}
- Shear stress is indicated by τ_{xy}
- The nine stress components then reduce to six independent components.

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

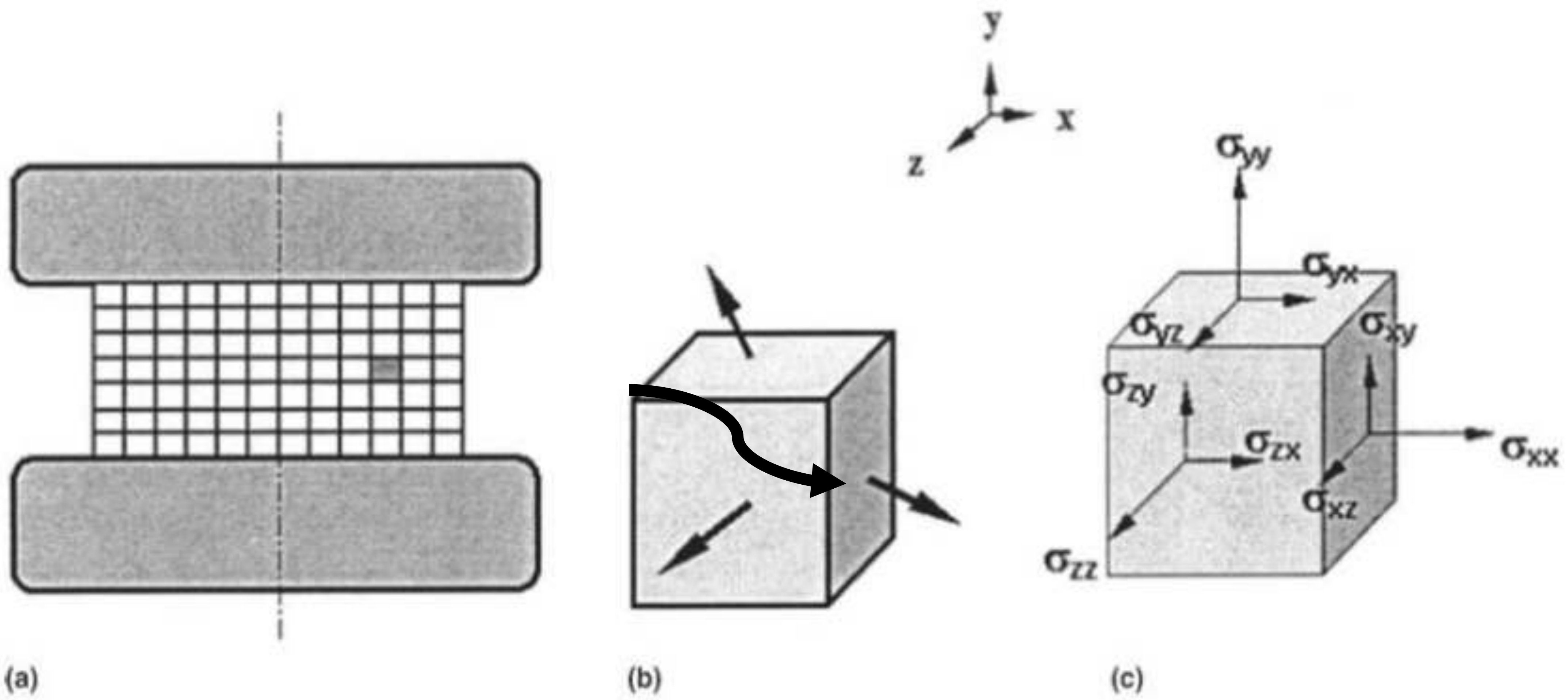


Fig. 5.1 Stress acting on an element. (a) Cylinder upsetting process. (b) Forces acting on an element. (c) Stress components acting on an element

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

- For a general stress state, there is a set of coordinate axes (1, 2, and 3) along which the shear stresses vanish. The normal stresses along these axes, σ_1, σ_2, and σ_3, are called the **principal stresses.**
- The magnitudes of the principal stresses are determined from the following cubic equation.

$$\sigma_i^3 - I_1\sigma_i^2 - I_2\sigma_i - I_3 = 0$$

where

$$I_1 = \sigma_{xx} + \sigma_{yy} + \sigma_{zz}$$

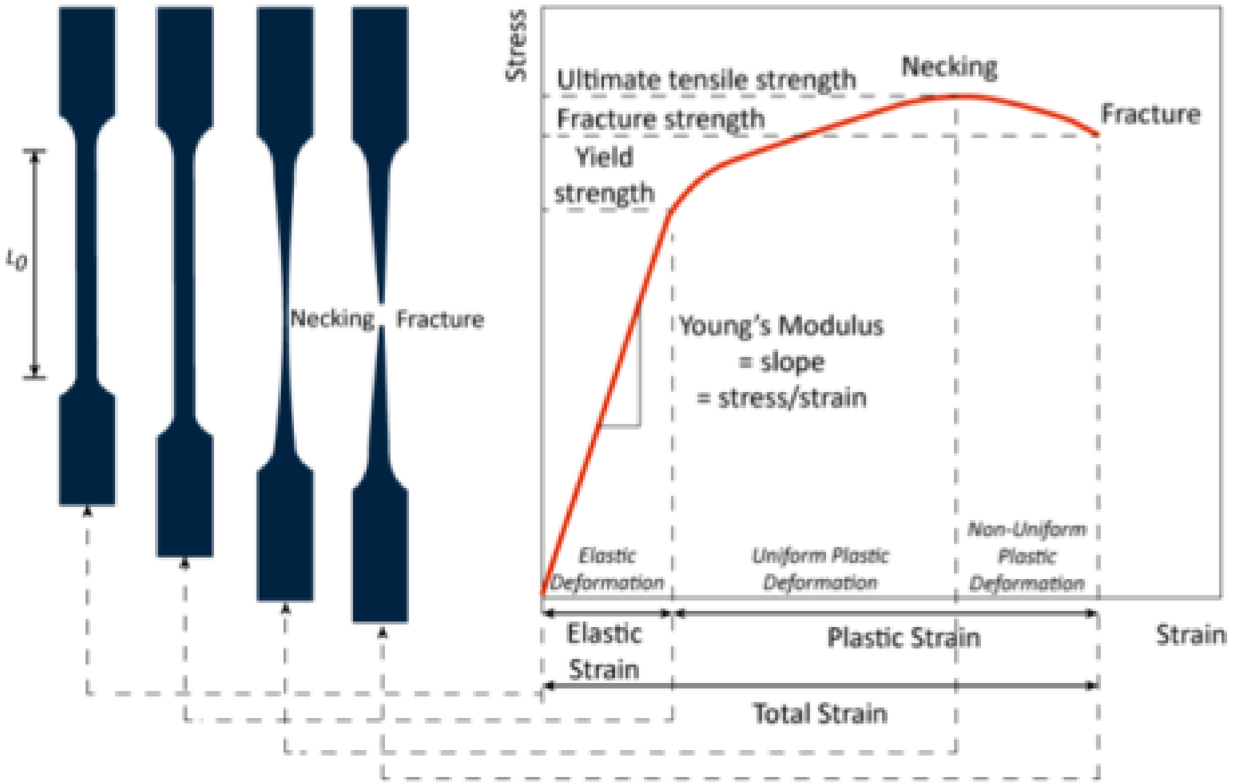
$$I_2 = -\sigma_{xx}\sigma_{yy} - \sigma_{yy}\sigma_{zz} - \sigma_{zz}\sigma_{xx} + \sigma_{xy}^2 + \sigma_{yz}^2 + \sigma_{zx}^2$$

$$I_3 = \sigma_{xx}\sigma_{yy}\sigma_{zz} + 2\sigma_{xy}\sigma_{yz}\sigma_{zx} - \sigma_{xx}\sigma_{yz}^2 - \sigma_{yy}\sigma_{zx}^2 - \sigma_{zz}\sigma_{xy}^2$$

- The three principal stresses(σ_1, σ_2, and σ_3)can only be determined by finding the three roots of the cubic equation.
- The coefficients I_1, I_2, and I_3 are independent of the coordinate system chosen and are hence called invariants.

4.Yield Criteria

- In simple homogeneous (uniaxial) compression or tension, the metal flows plastically when the stress, (σ) reaches the value of the yield or flow stress of material



When material deform plastically under any possible combination of stresses?????

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

Flow stress (σ_0) = $\frac{F}{A}$

where F and A are the instantaneous force and cross-sectional area on which the force acts.

- A yield criterion is a law defining the limit of elasticity or the start of plastic deformation under any possible combination of stresses.
- For isotropic materials, plastic yielding can depend only on the magnitude of the principal stresses.
- There are various yield criteria that have been proposed to date.
- Two major yield criteria that have been used extensively in the analysis of metal forming and forging are,
  - **Tresca or shear stress criterion of yield or plastic flow**
  - **Von Mises or distortion energy criterion of yield or plastic flow**

Von Mises' or distortion energy criterion of yield or plastic flow

$$\sigma_{ij} = \begin{bmatrix} \sigma_x & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z \end{bmatrix}$$

$$= \underbrace{\begin{bmatrix} \sigma_x - \sigma_p & \tau_{yx} & \tau_{zx} \\ \tau_{xy} & \sigma_y - \sigma_p & \tau_{zy} \\ \tau_{xz} & \tau_{yz} & \sigma_z - \sigma_p \end{bmatrix}}_{\text{Deviator part}} + \underbrace{\begin{bmatrix} \sigma_p & 0 & 0 \\ 0 & \sigma_p & 0 \\ 0 & 0 & \sigma_p \end{bmatrix}}_{\text{Hydrostatic Pressure part}}$$

- Stress tensor can decomposed in to Deviator part and Hydrostatic part

Reference: Fundamentals of metal forming process, BL Juneja, IIT Delhi

- **Hydrostatic component** σ_p produces change in the volume of the body. Its value

$$\sigma_p = (\sigma_1 + \sigma_2 + \sigma_3)/3$$

- **Deviator component** is responsible for the change in shape of the body. Hence yield function is a function of components of this part of stress state.

- Out of total energy supplied, one part used to change the volume of the material called volumetric or Hydrostatic part and
- Another part used to distort the shape of the material called Deviator Part.

- **According to Von Mises' or distortion energy criterion,**
- **A Stressed metal body starts to yield or plastically deform when the relationship between the principal stresses and uniaxial yield strength (σ_0) of the material is,**

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_0^2$$

Where σ_1, σ_2, and σ_3, are the principal stresses.

In another form ,

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 6K^2$$

Where K is the yield strength of material in shear (τ_0).

From above two equations

$$K = \tau_0 = \frac{\sigma_0}{\sqrt{3}}$$

Tresca or shear stress criterion of yield or plastic flow

- ***A metal body reaches in the yield point when the maximum shear stress in the body reaches the value equal to the yield strength of the metal in shear.***
- If the stress state is given by three principal stresses σ $_1$, σ $_2$ and σ $_3$ the three maximum shear stress are as follows,

$$\tau_{1max} = \tfrac{1}{2}(\sigma_1 - \sigma_2)$$
$$\tau_{2max} = \tfrac{1}{2}(\sigma_2 - \sigma_3)$$
$$\tau_{3max} = \tfrac{1}{2}(\sigma_3 - \sigma_1)$$

Out of these three we can determine the greatest value of shear stress if we know the relative magnitudes of the principal stresses. Let us take that $\sigma_1 > \sigma_2 > \sigma_3$ then the greatest value of shear stress is given by

$$\tau_{max} = \tfrac{1}{2}(\sigma_1 - \sigma_3)$$

According to Tresca's hypothesis the metal body will be in plastic state if

$$\tfrac{1}{2}(\sigma_1 - \sigma_3) = \tau_0$$

where, τ_0 = yield strength of material in shear.

In a tension test we may take that $\sigma_l \neq 0$, while all other stress components are zero. The yielding occurs when $\sigma_1 = \sigma_0$ = yield strength in tension.

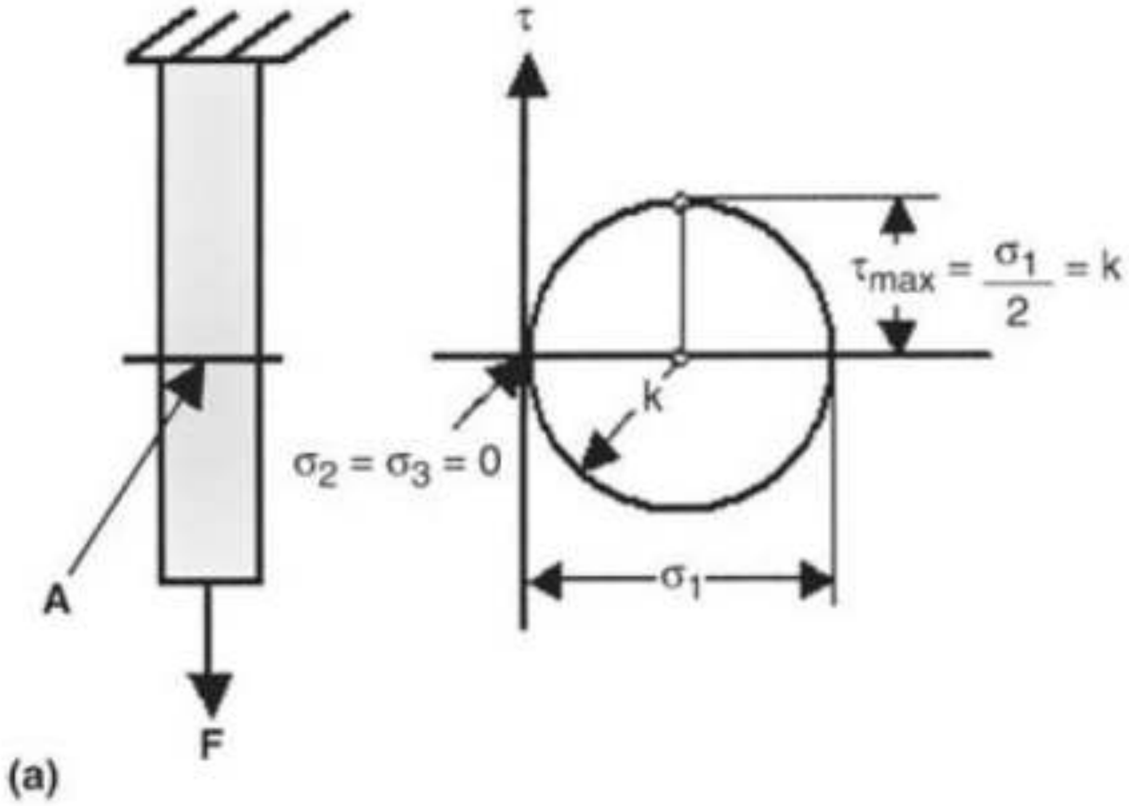


Fig. 5.6 Mohr circles. (a) Uniaxial tension. (b) Uniaxial compression

- In case of uni-axial tension the greatest value of shear stress equal to half of the tensile stress.

$$\text{ie, } \tau_0 = \frac{\sigma_0}{2}$$

Tresca criterion can written in simple form,

$$\frac{\sigma_{max} - \sigma_{min}}{2} = \frac{\sigma_0}{2}$$

Where,

σ_{max} is the maximum principal stress in tri-axial stress system.

σ_{min} is the minimum principal stress in tri-axial stress system.

σ_0 is the uniaxial yield strength.

Comparisons and applications of Yield criteria

- Von Mises yield criterion is found to be suitable for most of the ductile materials used in forming operations. More often in metal forming, this criterion is used for the analysis.
- Metals like aluminum, copper , mild steel experimentally showing obey von mises's criteria.
- The suitability of the yield criteria has been experimentally verified by conducting torsion test on thin walled tube, as the thin walled tube ensures plane stress.
- However, the use of Tresca criterion is found to result in negligible difference between the two criteria.
- Experiments (with combined shear and tension) indicate that the von Mises rule is a better criterion (closer to reality) than Tresca's flow rule.
- **The comparison of Tresca and von Mises criteria can be expressed by superimposing the elliptical yield locus (von Mises) and hexagonal yield locus (Tresca) together as shown in Fig.**

- According to Von Mises' or distortion energy criterion,

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\sigma_0^2$$

Where σ_1, σ_2, and σ_3, are the principal stresses.

This equation represented by a Cylinder surface

- **Generalized equation of Tresca's yield criteria can represented as a Hexagonal prism.**

- Martial will suffer plastic deformation when state of stress point is on the surface of cylinder and stress increment is directed outside the cylinder.
- A similar discussion applies to Tresca's hexagonal prism as well

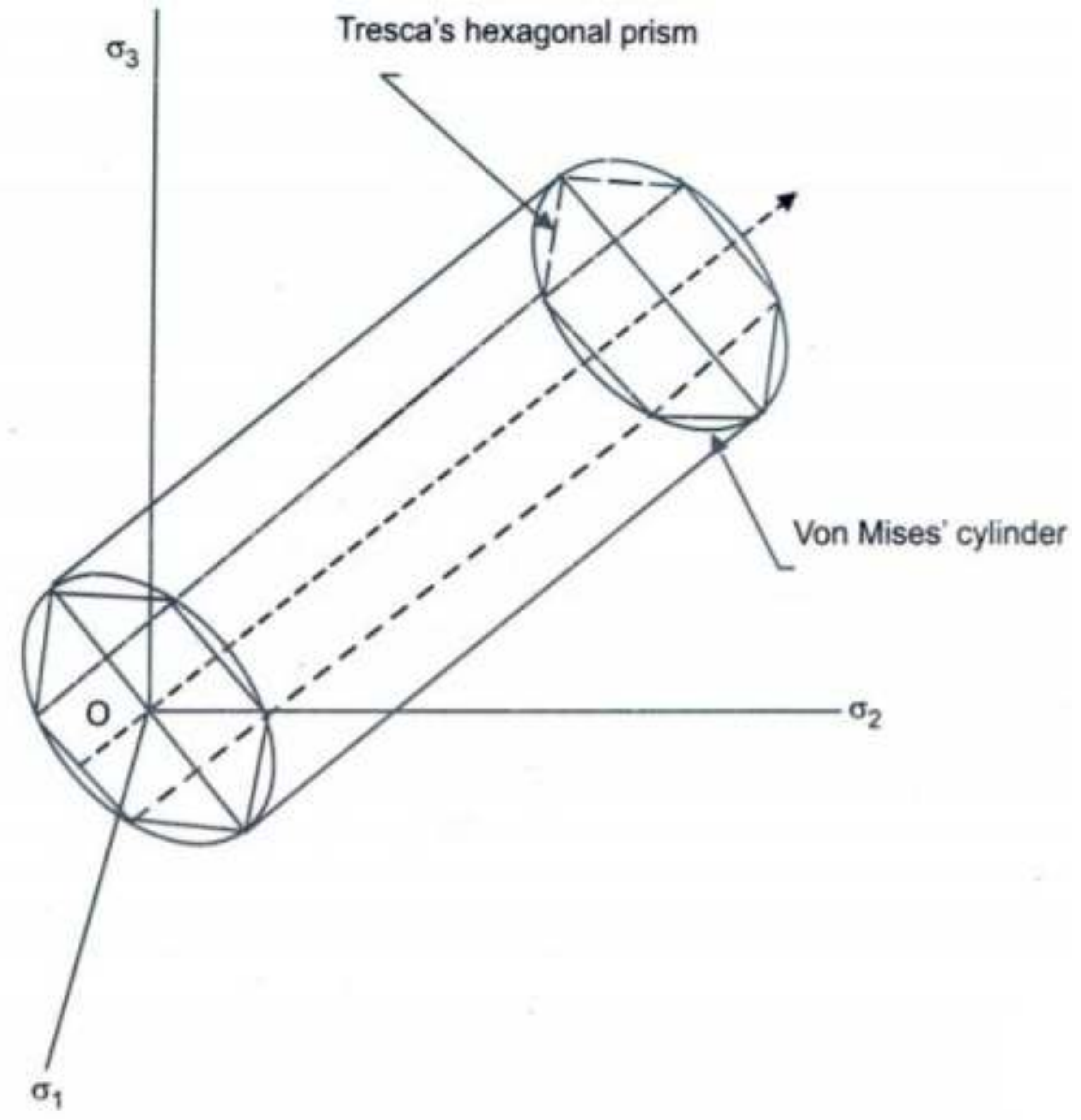


Fig. 4.1. Graphical representation of yield criteria

Reference: Fundamentals of metal forming process, BL Juneja, IIT Delhi

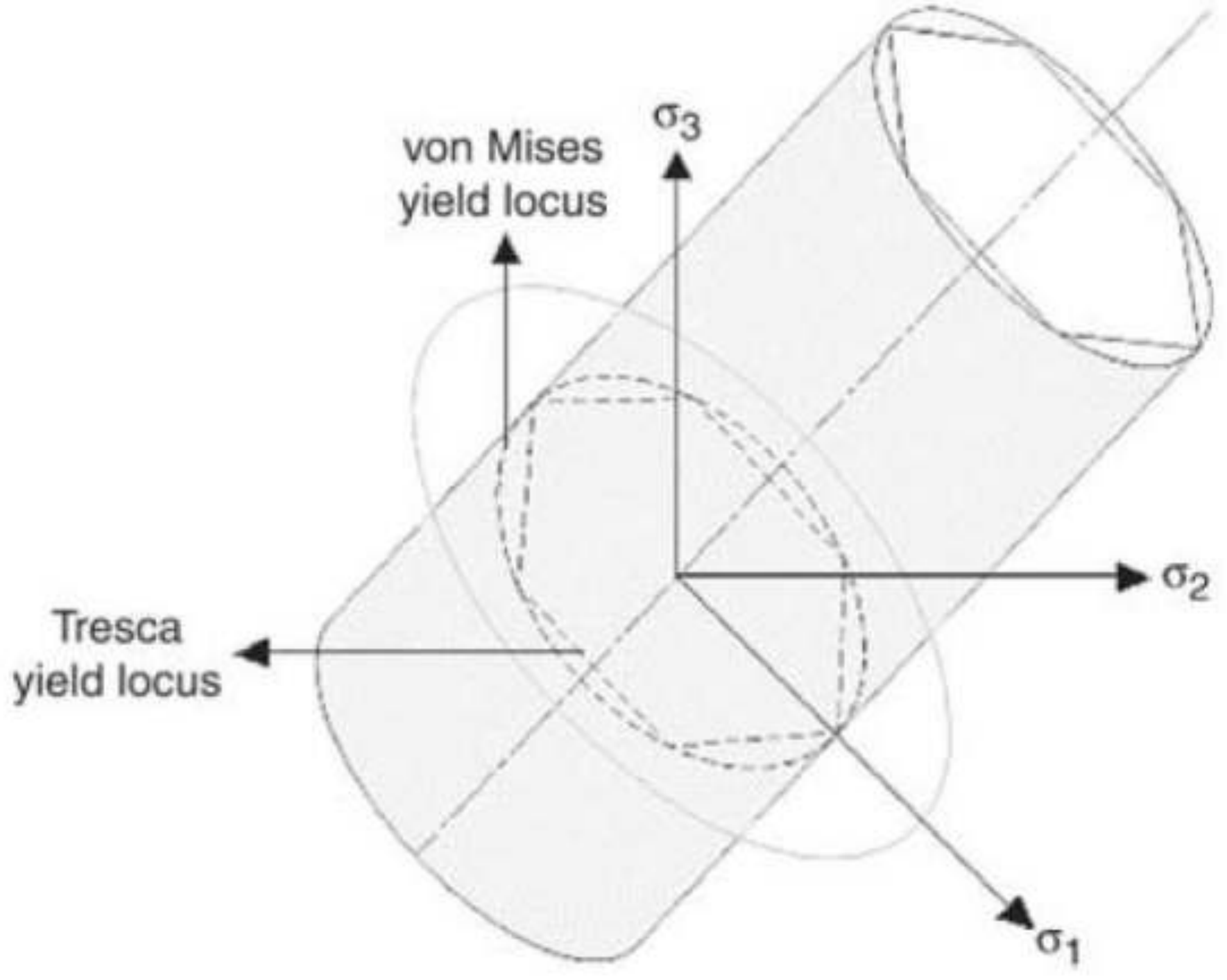
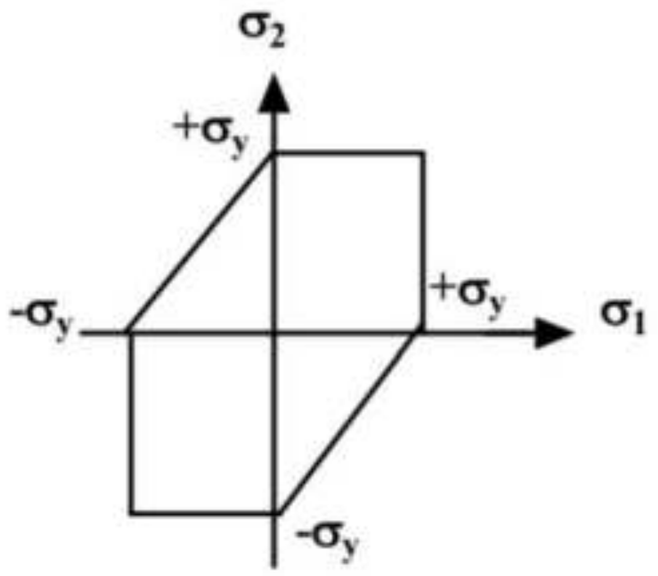


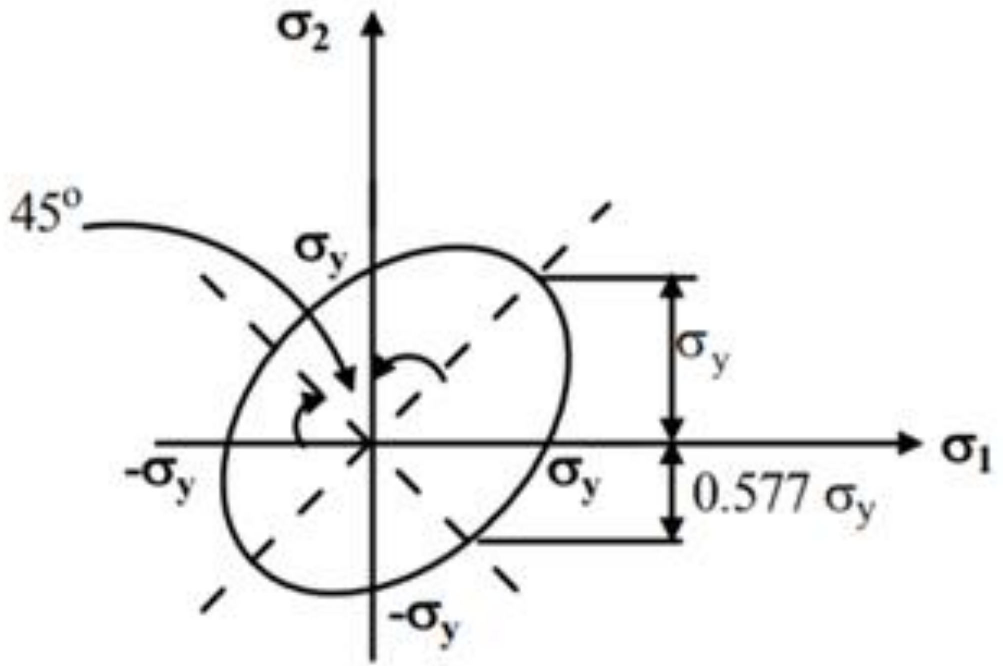
Fig. 5.11 Physical representation of von Mises and Tresca criterion in three dimensions

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

- In plane stress condition ie, $\sigma_3 = 0$,



3.1.4.3.1F- *Yield surface corresponding to maximum shear stress theory*



3.1.4.5.1F- *Yield surface corresponding to von Mises yield criterion.*

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

- Tresca's elongated hexagonal prism inscribed inside Von mises' elongated ellipse in plain stress condition.

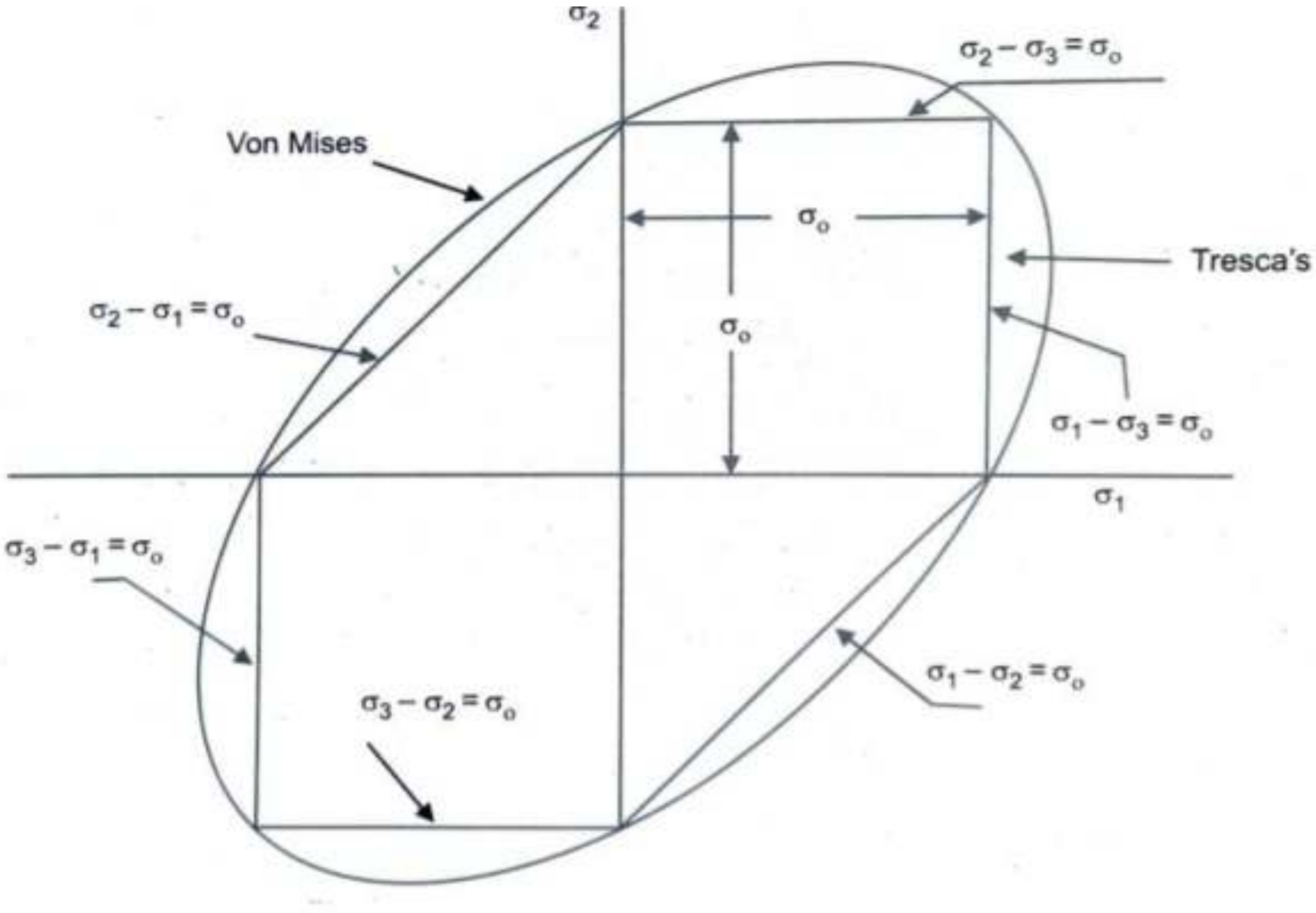


Fig. 4.3. Two-dimensional representations of yield conditions

Reference: Fundamentals of metal forming process, BL Juneja, IIT Delhi

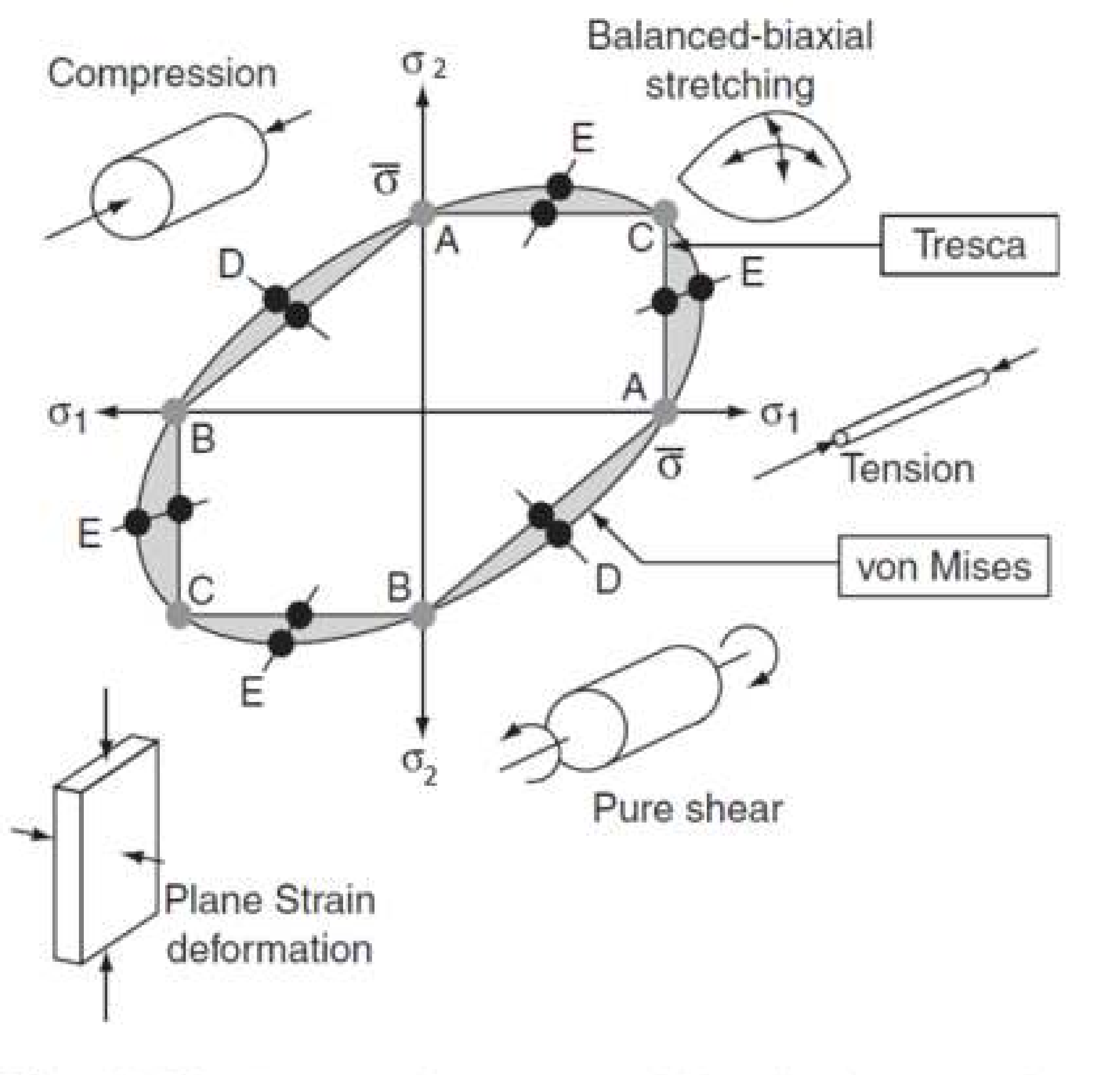


Fig. 5.10 Tresca and von Mises yield loci for the same value of $\bar{\sigma}$, showing several loading paths. Note: $\sigma^2 = 0$.

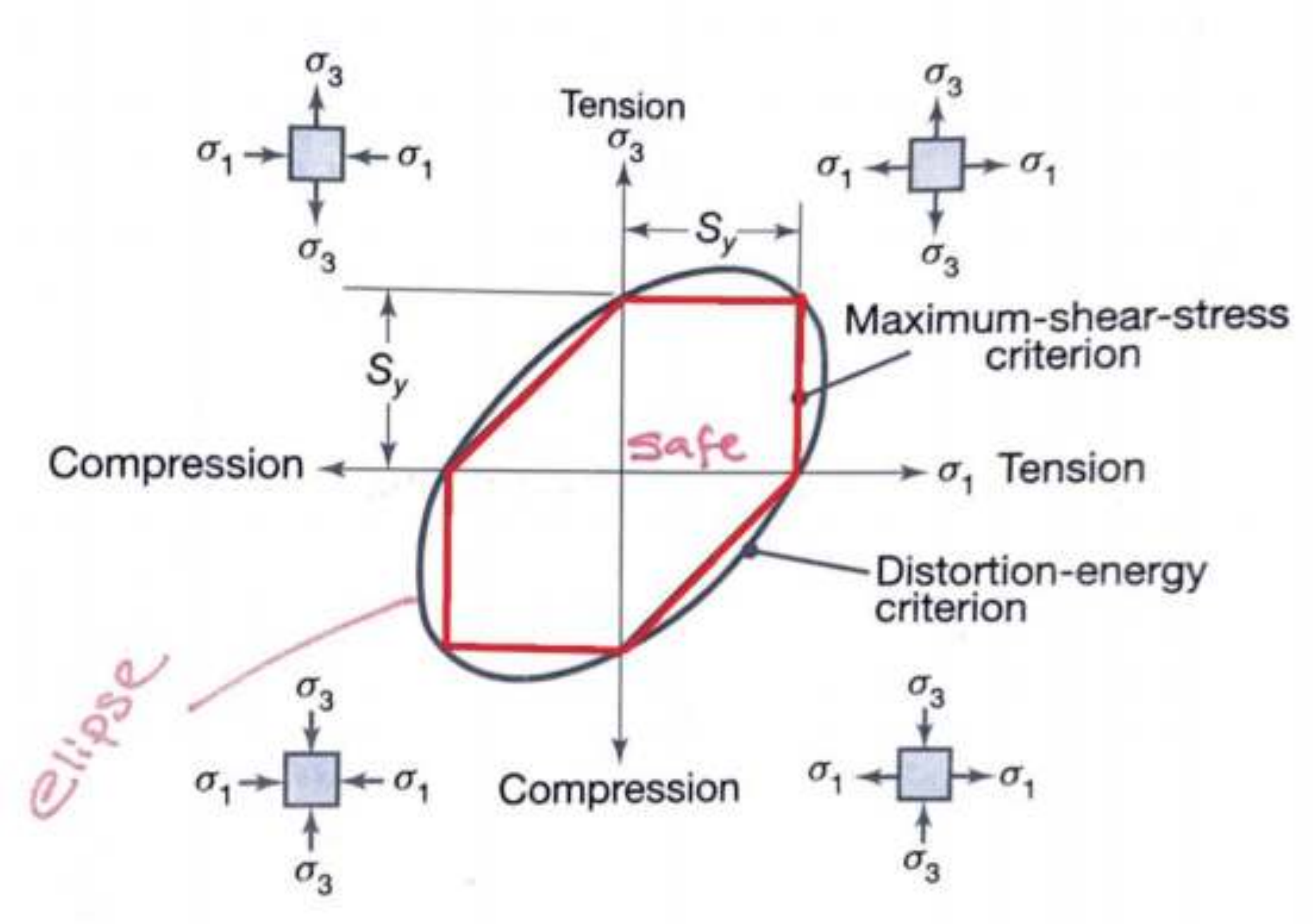


FIGURE 2.32 Plane-stress diagrams for maximum-shear-stress and distortion-energy criteria. Note that $\sigma_2 = 0$.

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

Flow rules

- When the stresses at a given point in the metal reach a certain level, as specified by a flow rule (Tresca or von Mises), then plastic flow, i.e., plastic deformation, starts.
- Similar to the Hooke's law, which gives the relationship between the stress and the corresponding deformation in the elastic range, analysis of plastic deformation requires a certain relation between the applied stresses and strain rates ($\dot{\varepsilon}$),

$$\dot{\varepsilon}_1 = \lambda(\sigma_1 - \sigma_m) \quad \text{(Eq 5.11a)}$$

$$\dot{\varepsilon}_2 = \lambda(\sigma_2 - \sigma_m) \quad \text{(Eq 5.11b)}$$

$$\dot{\varepsilon}_3 = \lambda(\sigma_3 - \sigma_m) \quad \text{(Eq 5.11c)}$$

σ_m is the mean principal stress given by:

$$\sigma_m = \frac{\sigma_1 + \sigma_2 + \sigma_3}{3}$$

- Equations 5.11(a), (b), and (c) are called plasticity equations.
- The variable λ depends on direction of plastic flow, temperature, material, strain, and strain rate.

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

Power and Energy of Deformation

- The plastic deformation processes are irreversible.
- The mechanical energy, consumed during deformation, is transformed largely into heat.
- The following relations, hold here for this homogeneous deformation of a block shown in fig.

$$\varepsilon_h = \varepsilon_1 = \ln \frac{h}{h_o}; \; \dot{\varepsilon}_1 = \frac{V_h}{h}$$

$$\varepsilon_2 = \ln \frac{w}{w_o}; \; \dot{\varepsilon}_2 = \frac{V_w}{w}$$

$$\varepsilon_3 = \ln \frac{l}{l_o}; \; \dot{\varepsilon}_3 = \frac{V_l}{l}$$

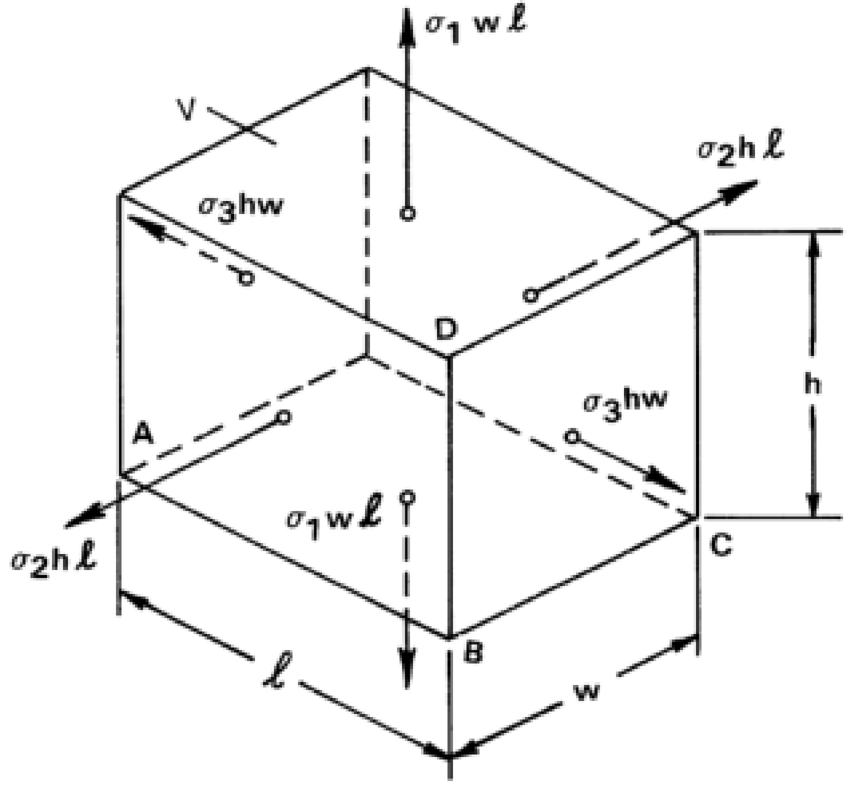


Fig. 5.12 Homogeneous deformation of a block

Refer slide no.24

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

Following Fig.   the instantaneous power of deformation (force times velocity) is given by:

$$P = \sigma_1 wlv_h + \sigma_2 hlv_w + \sigma_3 whv_1$$

$$= \sigma_1 wlh\dot{\varepsilon}_1 + \sigma_2 wlh\dot{\varepsilon}_2 + \sigma_3 wlh\dot{\varepsilon}_3$$

$$= (\sigma_1\dot{\varepsilon}_1 + \sigma_2\dot{\varepsilon}_2 + \sigma_3\dot{\varepsilon}_3)\, V \qquad \text{(Eq 5.14)}$$

where V is the volume of the deforming block. It follows that the energy of deformation, E, is:

$$E = V\int_{t_0}^{t_1} (\sigma_1\dot{\varepsilon}_1 + \sigma_2\dot{\varepsilon}_2 + \sigma_3\dot{\varepsilon}_3)\, dt \qquad (5.15)$$

with $\dot{\varepsilon}\, dt = d\varepsilon$, Eq 5.15 can also be written as:

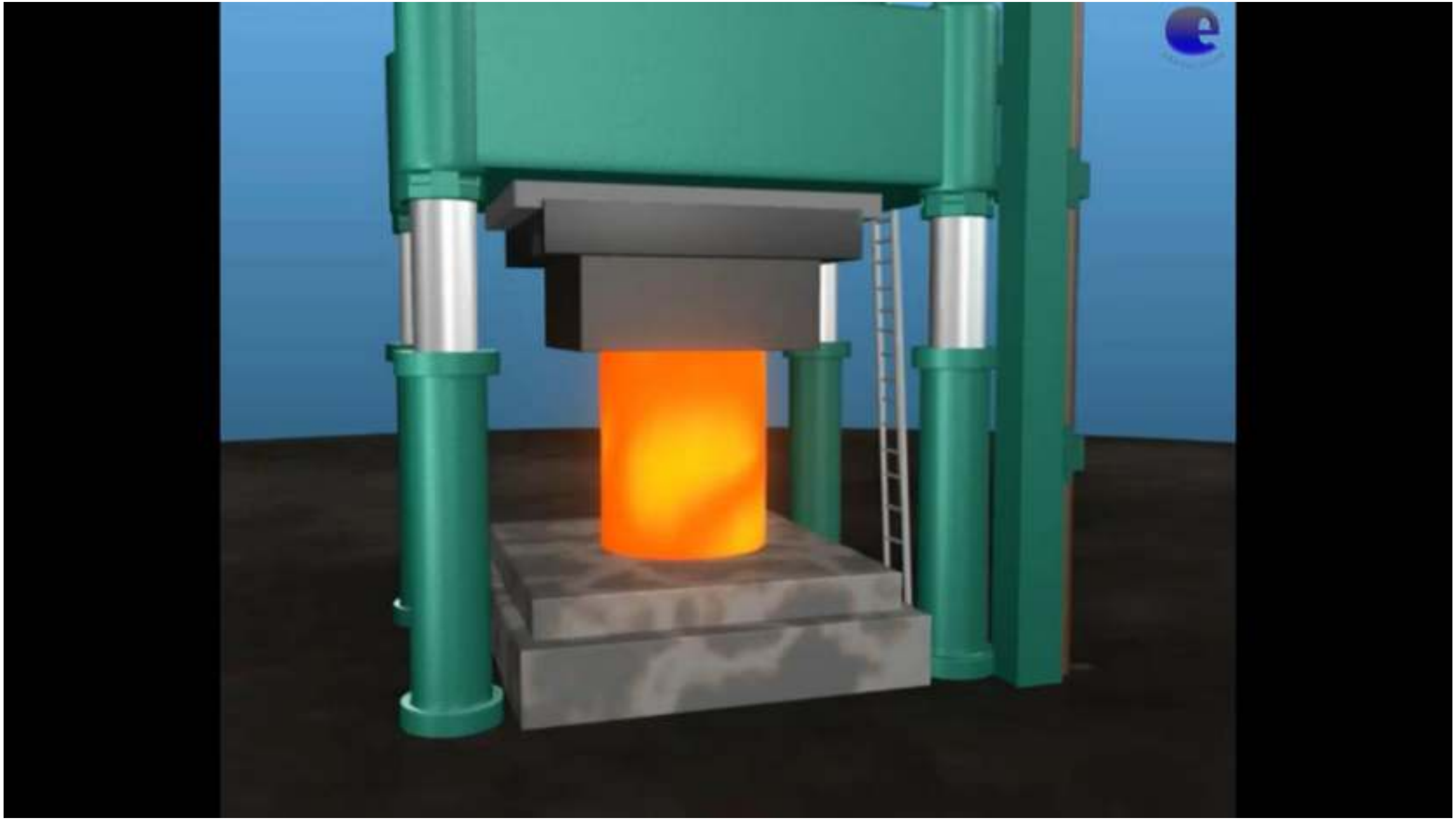
$$E = V\left(\int_0^{\varepsilon_1} \sigma_1 d\varepsilon_1 + \int_0^{\varepsilon_2} \sigma_2 d\varepsilon_2 + \int_0^{\varepsilon_3} \sigma_3 d\varepsilon_3\right) \qquad \text{(Eq 5.16)}$$

Refer slide no.24

Heat generation and heat Transfer in metal forming process

- In metal forming processes, both plastic deformation and friction contribute to heat generation.
- Approximately 90 to 95% of the mechanical energy involved in the process is transformed into heat.
- In some continuous forming operations such as drawing and extrusion, performed at high speeds, temperature increases of several hundred degrees may be involved.
- A part of generated heat remains in the deformed material, another part flows into the undeformed/ less-deformed portion of the material where temperature is lower, while still an additional part may flow into the tooling.
- The temperatures developed during the forging operation influence lubrication conditions, tool life, as well as microstructure and properties of the forged part.

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International



- In metal forming, the magnitudes and distribution of temperatures depend mainly on:
  - The initial workpiece and die temperatures.
  - Heat generation due to plastic deformation and friction at the workpiece/die interface.
  - Heat transfer between the workpiece and dies and between the workpiece and the environment (air or lubricant and coolant, etc.).
- In processes such as forging and extrusion, the average instantaneous temperature in the deforming workpiece, θ_A, can be estimated by,

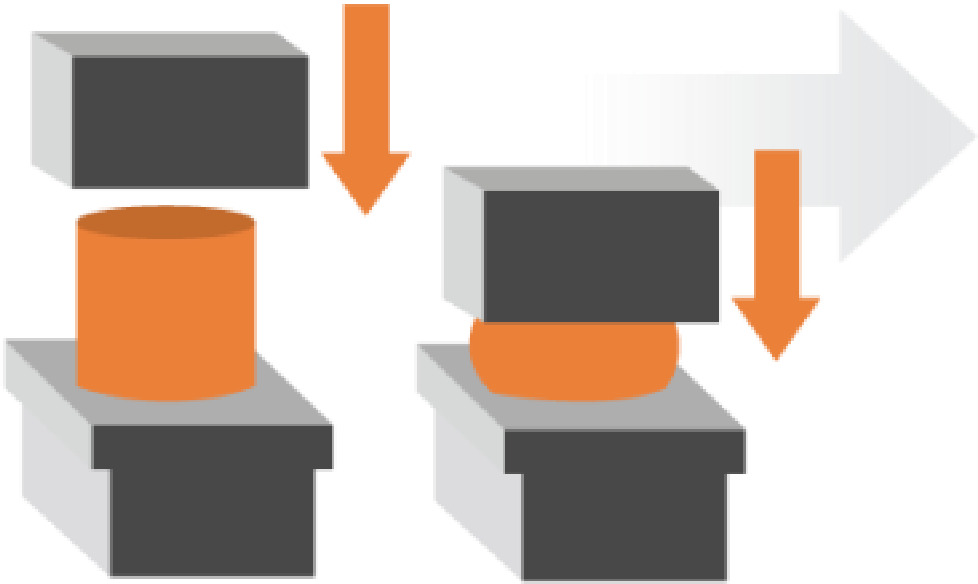
$$\theta_A = \theta_W + \theta_D + \theta_F - \theta_T - \theta_R - \theta_C$$

  - Where θ_w is the initial workpiece temperature, θ_D is the temperature increase due to plastic deformation, θ_F is the temperature increase due to interface friction, θ_T is the temperature drop due to heat transfer into the dies, θ_R is the temperature drop due to radiation to the environment, and θ_c is the temperature drop due to convection to the environment.

The temperature increase due to the deformation, in a time interval Δt, is given by:

$$\theta_D = \frac{A\bar{\sigma}\dot{\bar{\varepsilon}}\Delta t}{c\rho}\beta = \frac{\bar{\sigma}\Delta\bar{\varepsilon}}{Jc\rho}\beta$$

where $\bar{\sigma}$ is the flow stress of the workpiece, $\dot{\bar{\varepsilon}}$ is the effective strain rate, $\Delta\bar{\varepsilon}$ is the effective strain generated during Δt, A is a conversion factor between mechanical and thermal energies, c is the specific heat of the workpiece, ρ is the specific weight of the workpiece, and β is the fraction of deformation energy transformed into heat ($0 \leqslant \beta \leqslant 1$); usually, $\beta = 0.95$.



- The temperature increase due to friction, θ_F, is given by:

$$\theta_F = \frac{Af\bar{\sigma}vF\Delta F}{c\rho\rho_a}$$

where, in addition to the symbols already described, f is the friction factor at the workpiece/tool interface, such that frictional shear stress $\tau = f\bar{\sigma}$, v is the velocity at the workpiece/tool interface, and V_a is the volume of the workpiece which is subject to temperature increase.

Temperatures in Forging Operations

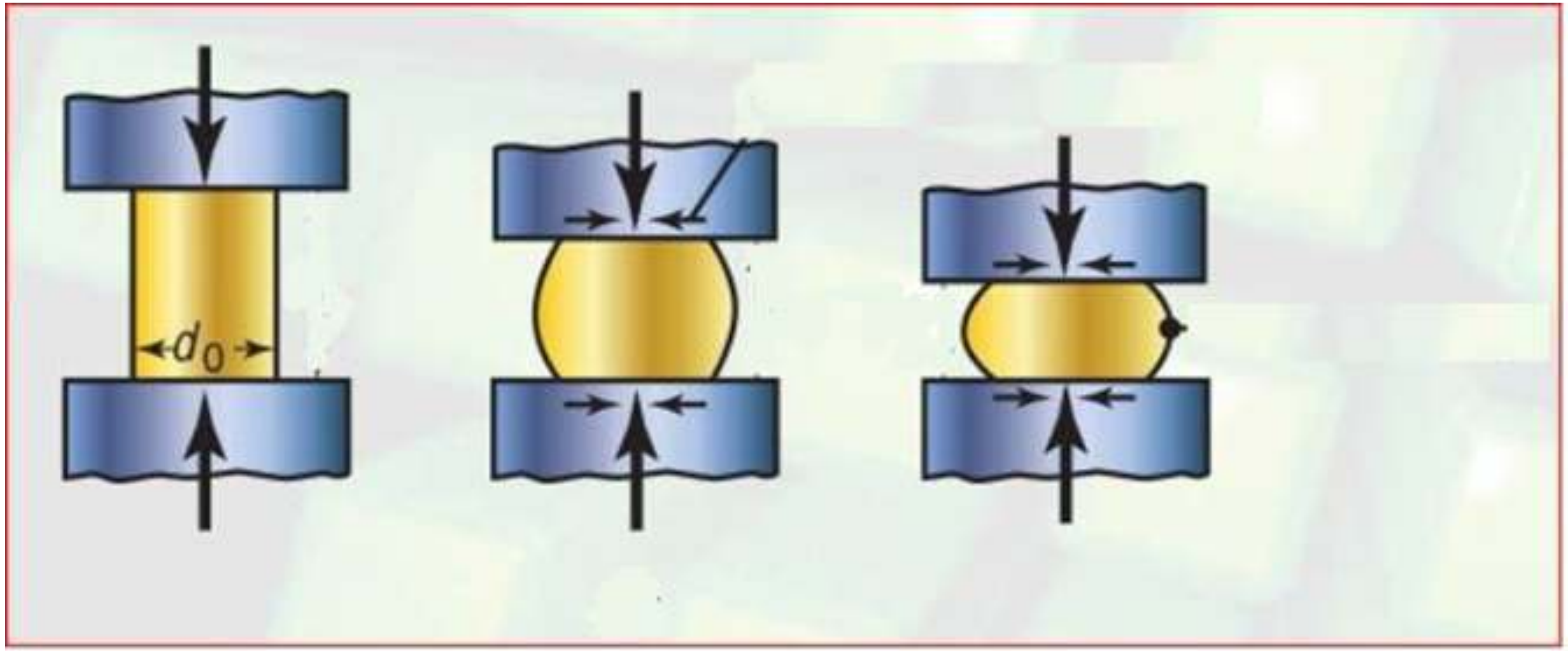
- Forging denotes a family of process by which plastic deformation of the work piece is carried out by compressive forces.
- Parts made by forging –
  - Crank shaft
  - Connecting roads for engine
  - Gears
  - Bolt head
  - Hand tool and other structural components.

- Forging can be carried out at room temperature **called cold forging**
- Or at elevated temperature called **warm and hot forging**

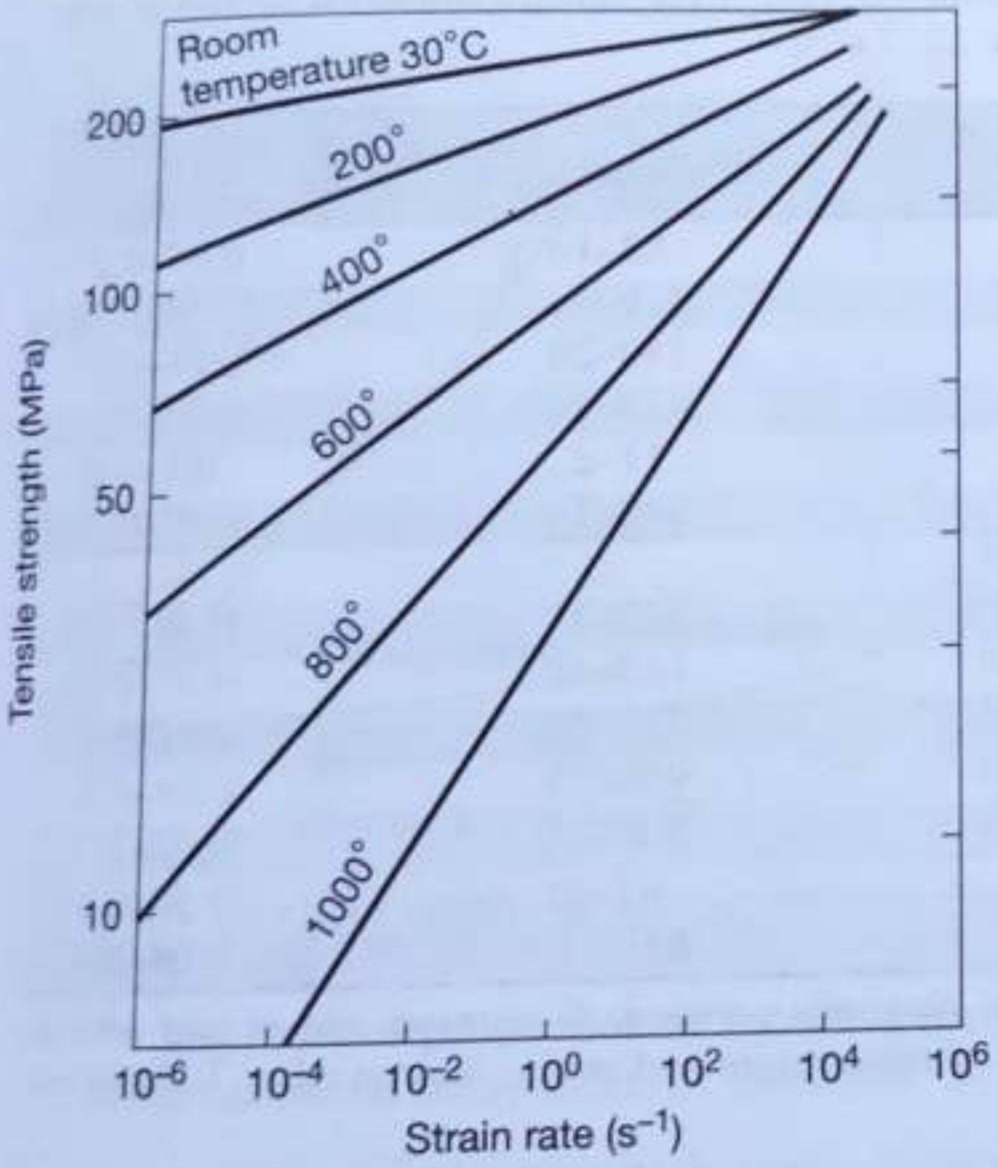
Reference: manufacturing processes for engineering materials by Serope Kalpakjian

- Low yield strength and high ductility is the desirable material properties required for forming. These properties are affected by temperature and rate of deformation (strain rate).
- When the work temperature is raised, ductility is increased and yield strength is decreased. The effect of temperature gives rise to distinctions among cold forming (workpiece initially at room temperature), warm forming (workpiece heated above room temperature, but below the recrystallization temperature of the workpiece material), and hot forming (workpiece heated above the recrystallization temperature).
- For example, the yield stress of a metal increases with increasing strain (deformation) during cold forming.
- In hot forming, however, the yield stress, in general, increases with strain (deformation) rate.

- In forging, the metal flow is non steady state.
- Contact between the deforming metal and the dies is intermittent.
- The length of contact time and the nature of the heat transfer at the die/ material interface influence temperatures very significantly.
- A simple example of an operation involving non-steady-state metal flow is the cold upsetting of a cylinder. Temperatures increase with increasing deformation.



Reference: manufacturing processes for engineering materials by Serope Kalpakjian



Increasing the strain rate increase the strength. Sensitivity of this variation increase with increase in temp.

high temp has high influence on the strain rate

FIGURE 2.10 The effect of strain rate on the ultimate tensile strength of aluminum. Note that as temperature increases, the slope increases. Thus, tensile strength becomes more and more sensitive to strain rate as temperature increases. *Source:* After J.H. Hollomon.

Reference: manufacturing processes for engineering materials by Serope Kalpakjian

- In hot forging operations, the contact time under pressure between the deforming material and the dies is the most significant factor influencing temperature conditions.
- These curves illustrate that, due to strain rate and temperature effects, for the same forging process, different forging loads and energies are required by different machines. For the hammer, the forging load is initially higher due to strain-rate effects, but the maximum load is lower than for either hydraulic or screw presses.
- The reason for this is that in the presses the flash cools rapidly, whereas in the hammer the flash temperature remains nearly the same as the initial stock temperature.
- In hot forging, not only the material and the formed shape but also the type of equipment used (rate of deformation and die chilling effects) determine the metal flow behavior and the forming load and energy required for the process.

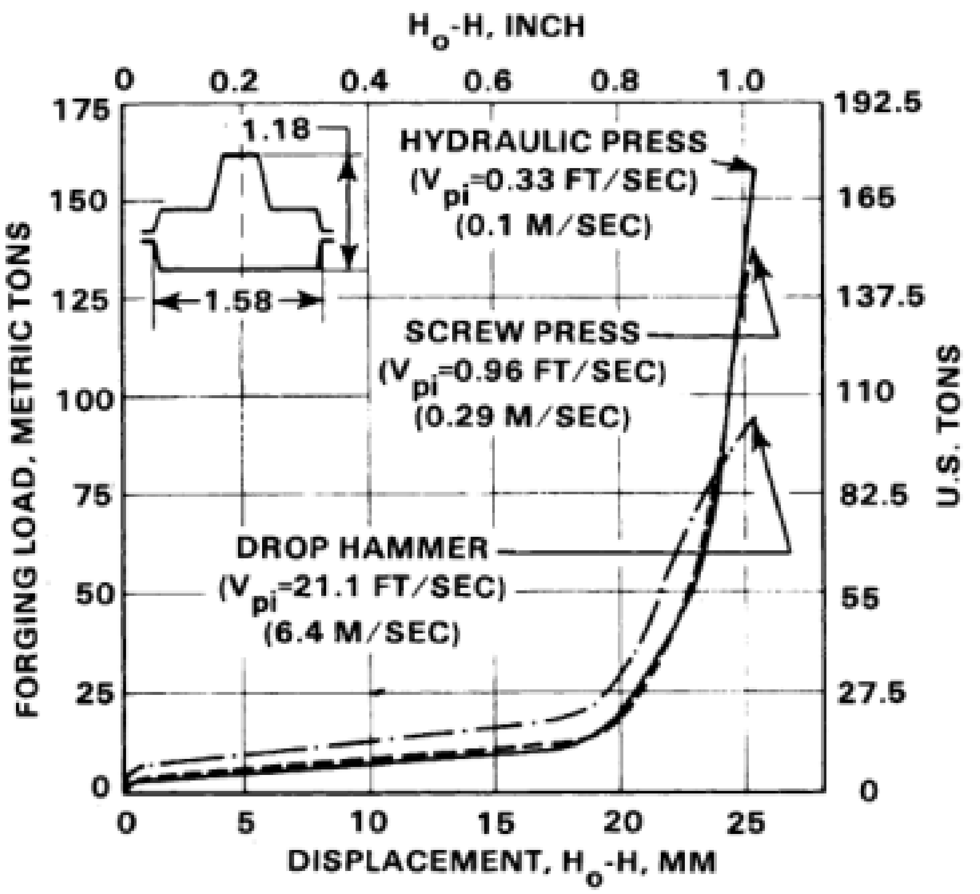


Fig. 6.3 Load-versus-displacement curves obtained in closed-die forging of an axisymmetric steel part (dimensions in inches) at 2012 °F (1100 °C) in three different machines with different initial velocities, $V_{p,i}$. [Altan et al., 1973]

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

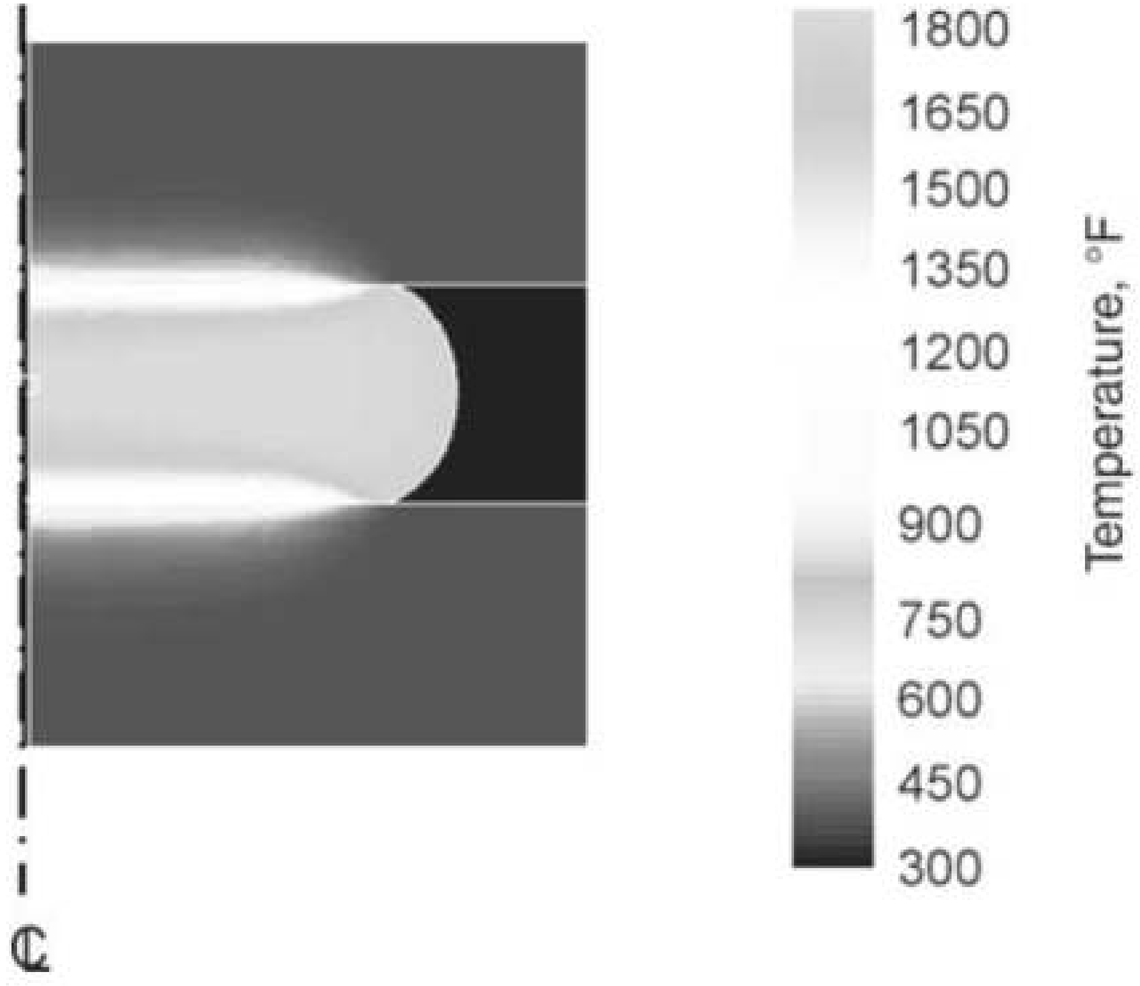
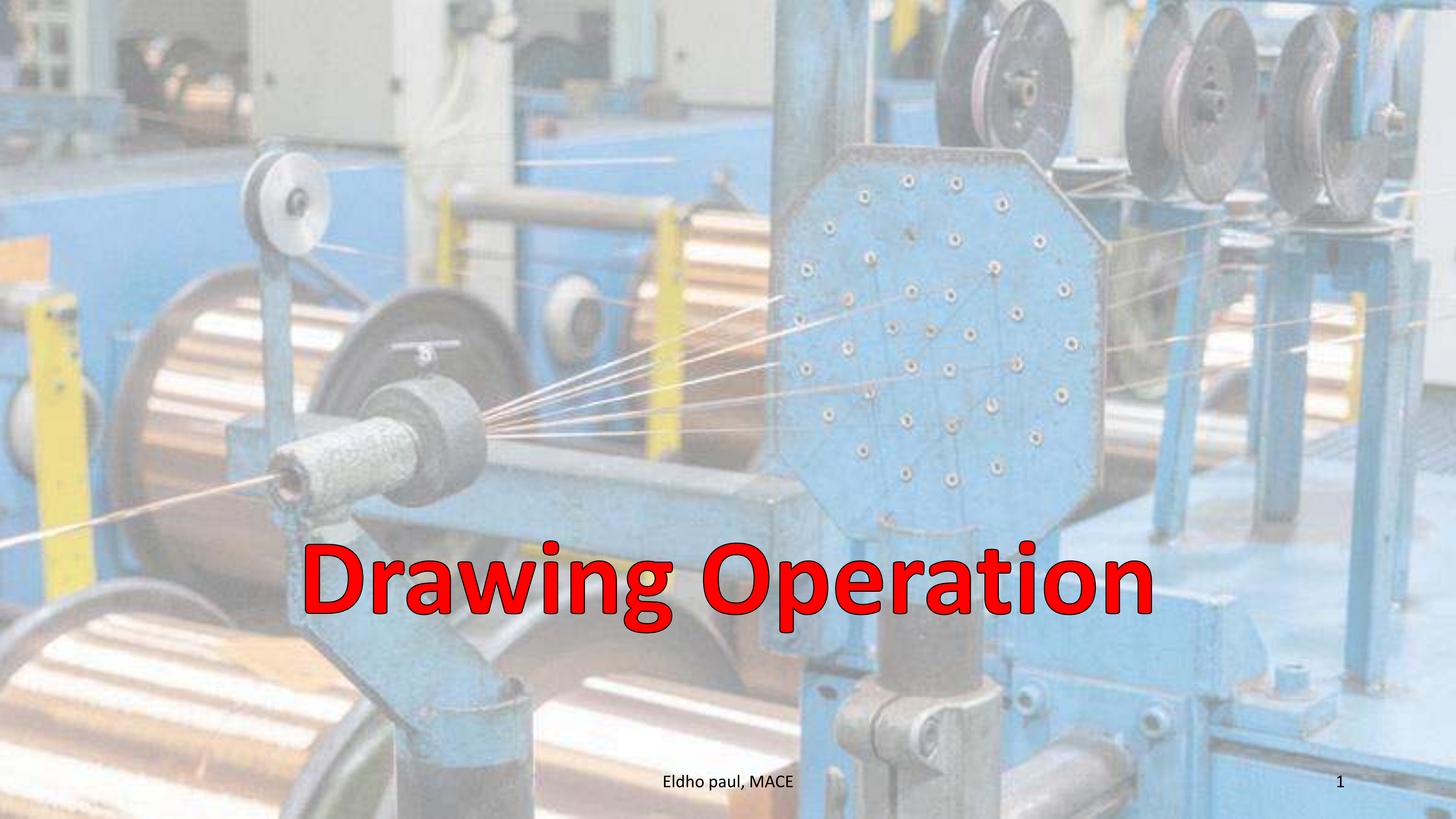


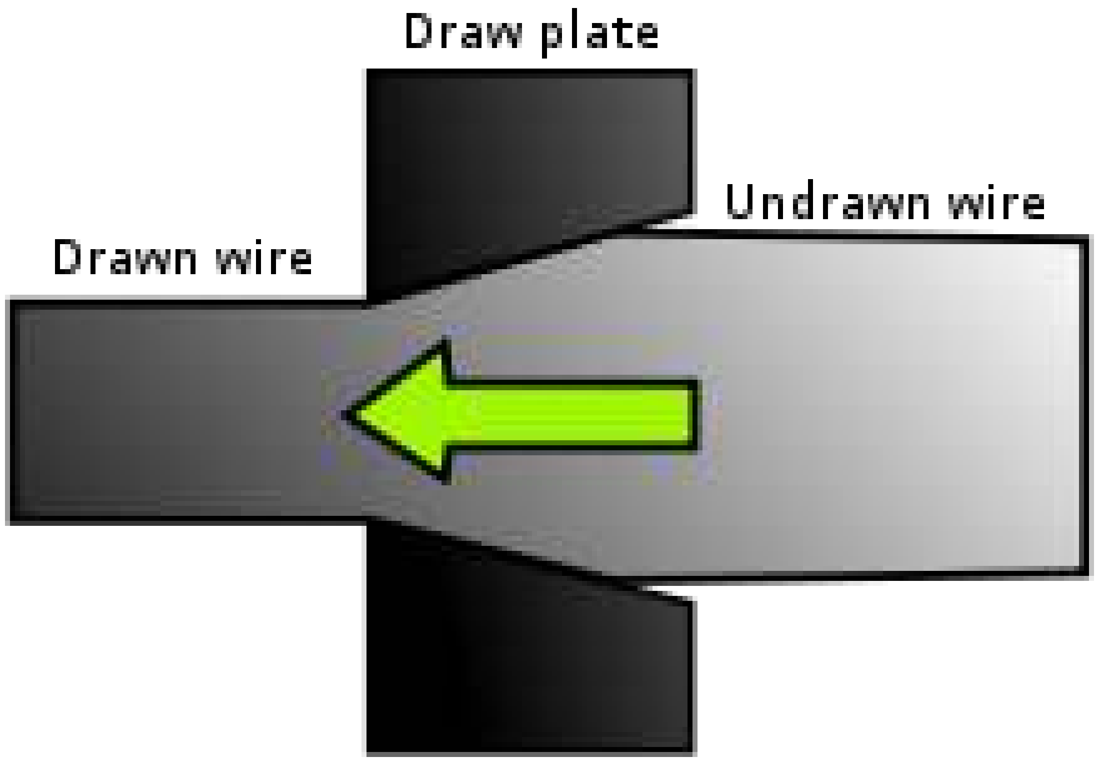
Fig. 6.4 The temperature distribution (in degree Fahrenheit) at the end of a Ti-64 cylinder upset test. The dimension of the cylinder, 1 in. (25 mm) diam by 1.5 in. (38 mm) height; starting temperature of cylinder, 1750 °F (955 °C); starting die temperature, 300 °F (150 °C); total reduction in height, 50%; temperature range of the pancake at the end of upsetting, 1044–1819 °F (560–990 °C); temperature range of the dies at the end of upsetting, 298–723 °F (145–385 °C).

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

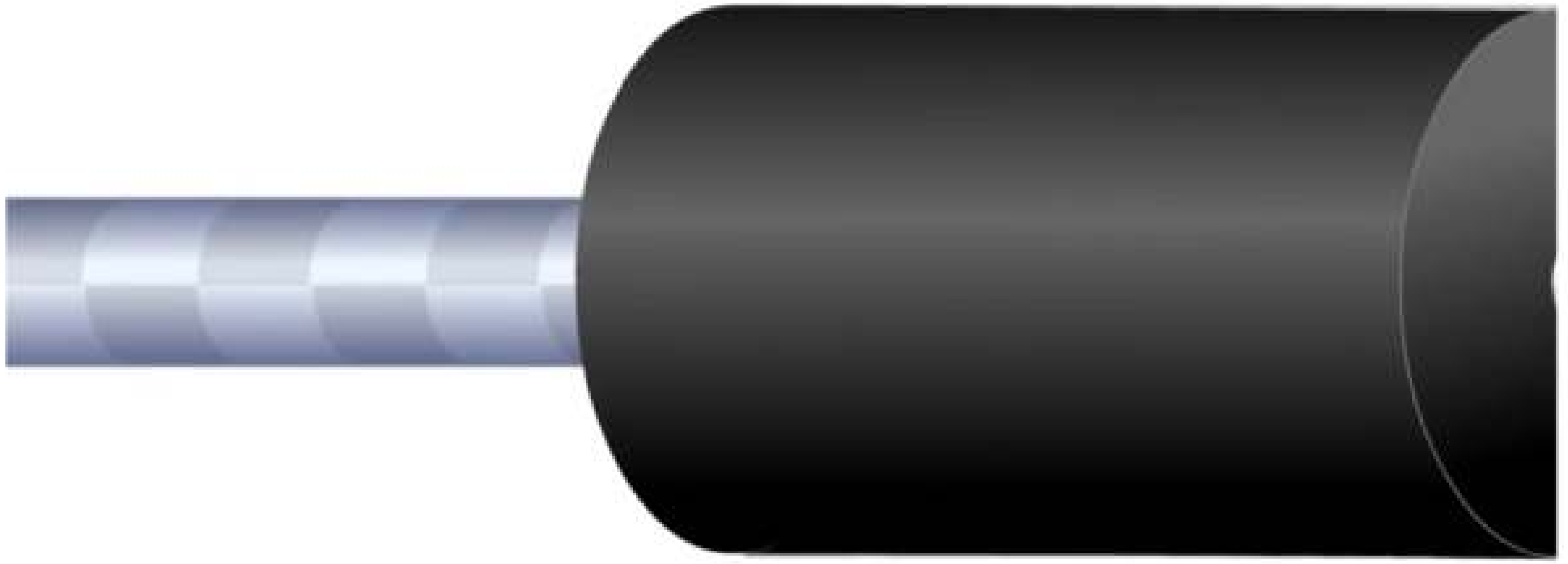
Drawing Operation

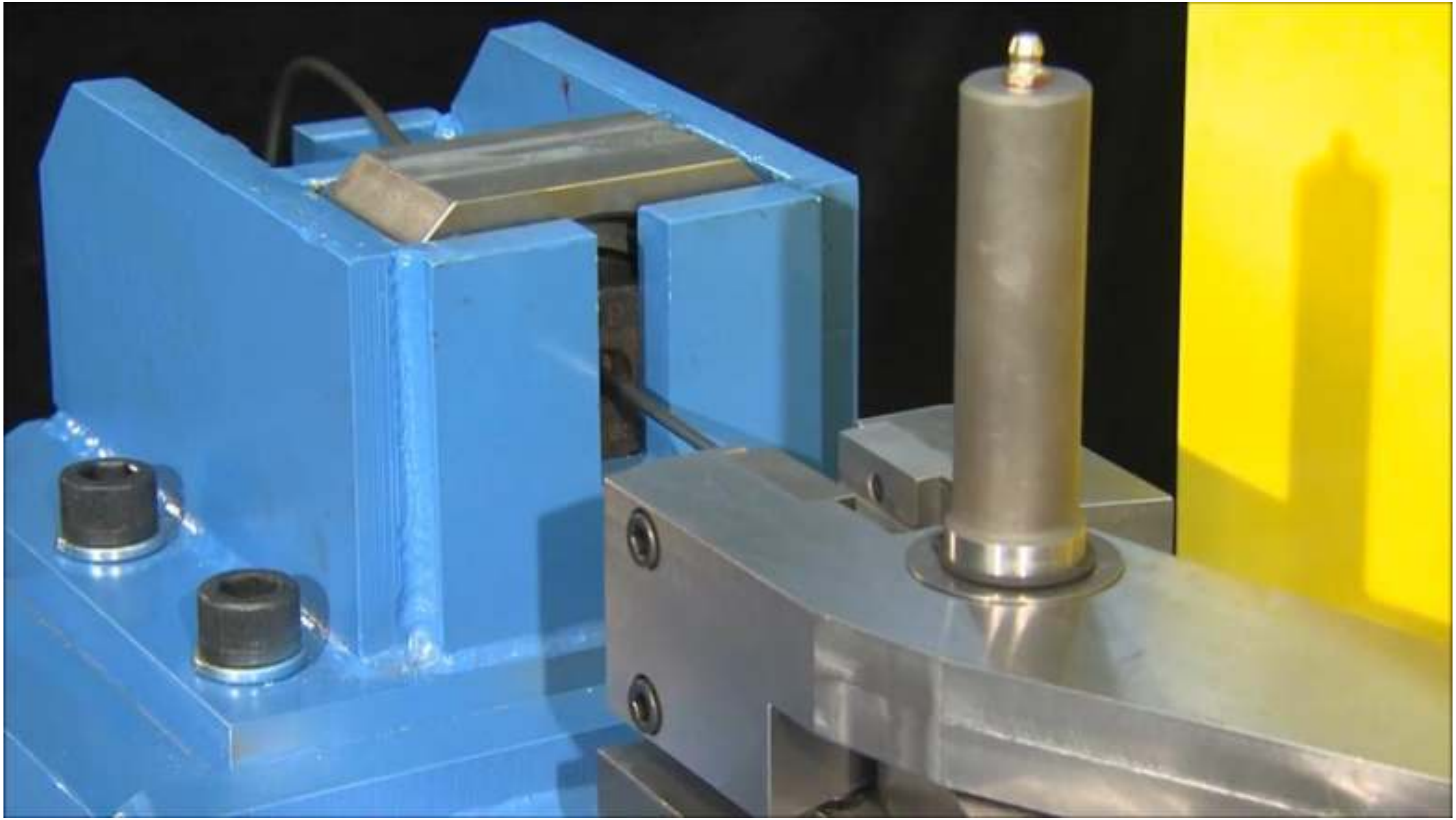


Drawing operation

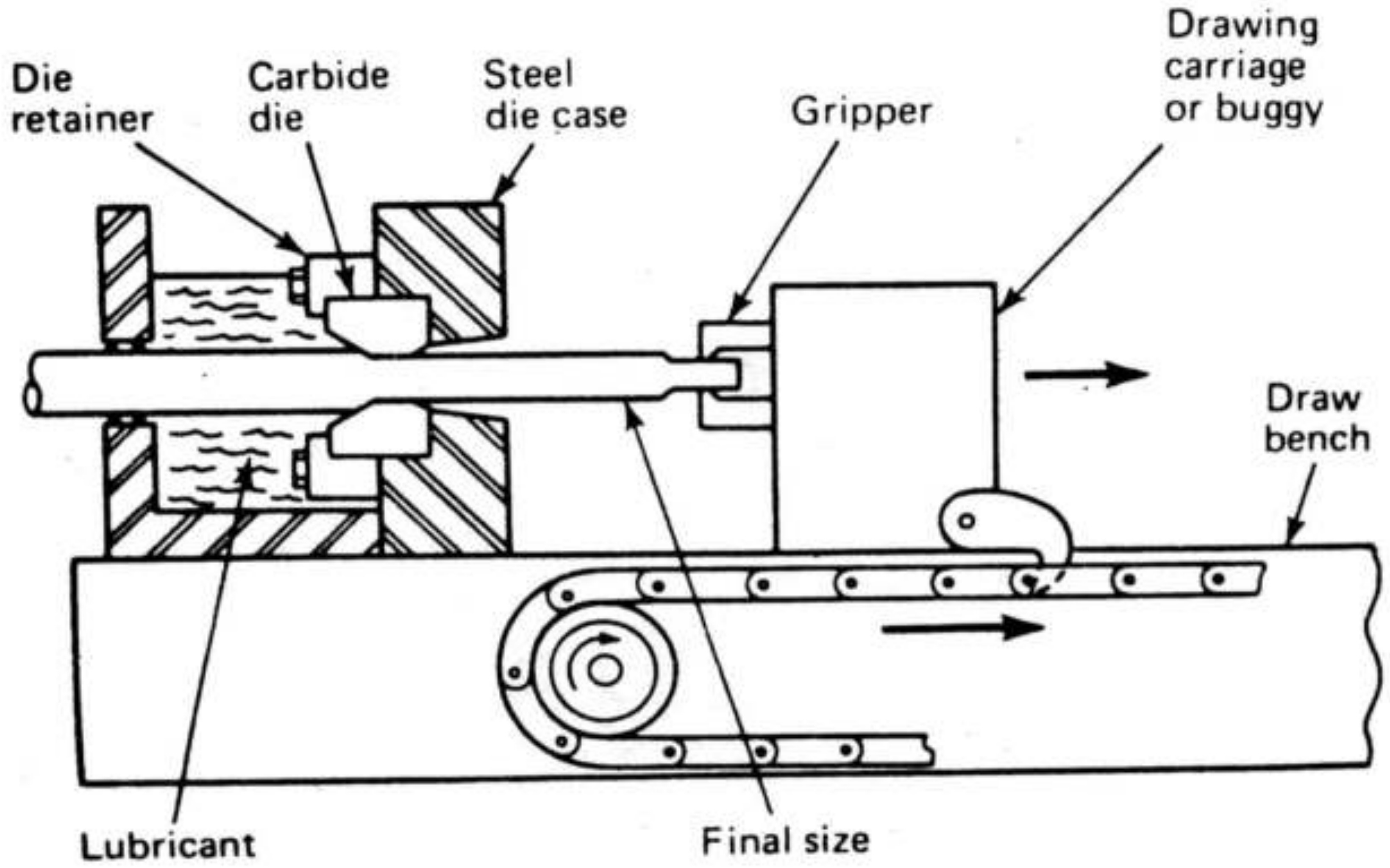


- Drawing is an operation in which the cross-sectional area of a bar or tube is reduced or changed in shape by ***pulling it through a converging die.***
- The drawing process is somewhat similar to extrusion, except that in drawing, the ***bar is under tension, whereas in extrusion it is under compression.***
- Rod and wire drawing produce ***good surface finish*** and dimensional tolerances and do not generally require finishing processes.
- ***Rods*** are used for such applications as shafts, spindles, and structural members, and as the raw material for making fasteners, such as bolts and screws.
- ***Wire and wire products*** have a wide range of applications, such as electrical wiring, cables, springs, musical instruments, paper clips, fencing, welding electrodes, and shopping carts. Wire diameters may be as small as 0.025 mm.



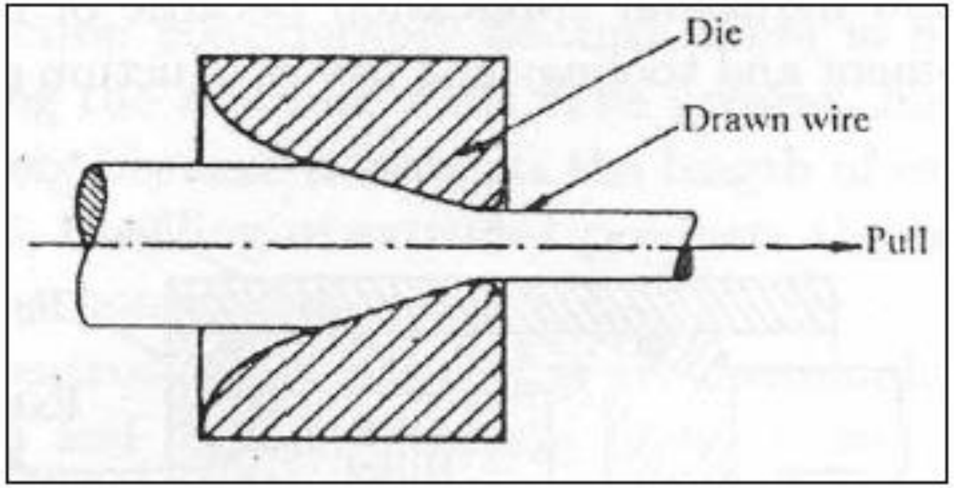


DRAWING OF ROD



- Large quantities of wires, rods, tubes and other sections are produced by drawing process . In this process the material is ***pulled*** through a die in order to reduce it to the desired shape and size.

- In a typical wire drawing operation, once end of the wire is reduced and passed through the opening of the die, gripped and pulled to reduce its diameter.



Mechanics of rod and wire Drawing

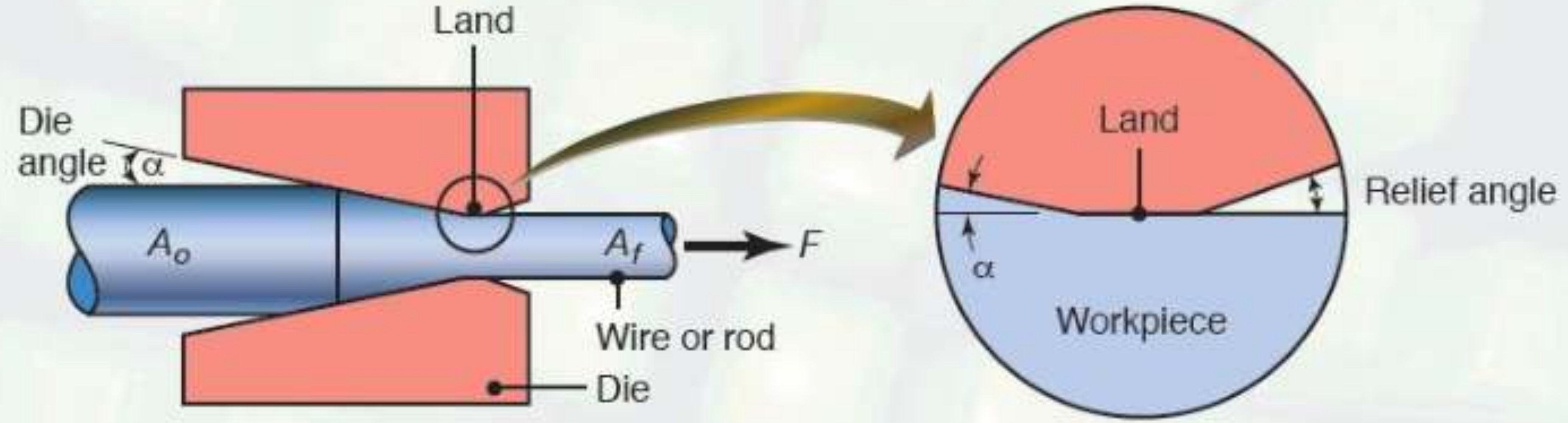


FIGURE 6.60 Variables in drawing round rod or wire.

Ideal deformation

- No friction and redundant work.
- The drawing stress, (σ_d),

$$\sigma_d = \sigma_y In\left(\frac{A_0}{A_f}\right)$$

$$F = A_f X \sigma_d$$

$$F = A_f \, \sigma_y In\left(\frac{A_0}{A_f}\right)$$

- Note that for strain-hardening materials, σ_y, must be replaced by the average flow stress $\bar{\sigma}$,

$$F = A_f \, \bar{\sigma} \, In\left(\frac{A_0}{A_f}\right)$$

Here, $\bar{\sigma} = \frac{K\epsilon^n}{n+1}$

- Note that the higher the reduction in cross-sectional area stronger the material, the higher the drawing force.

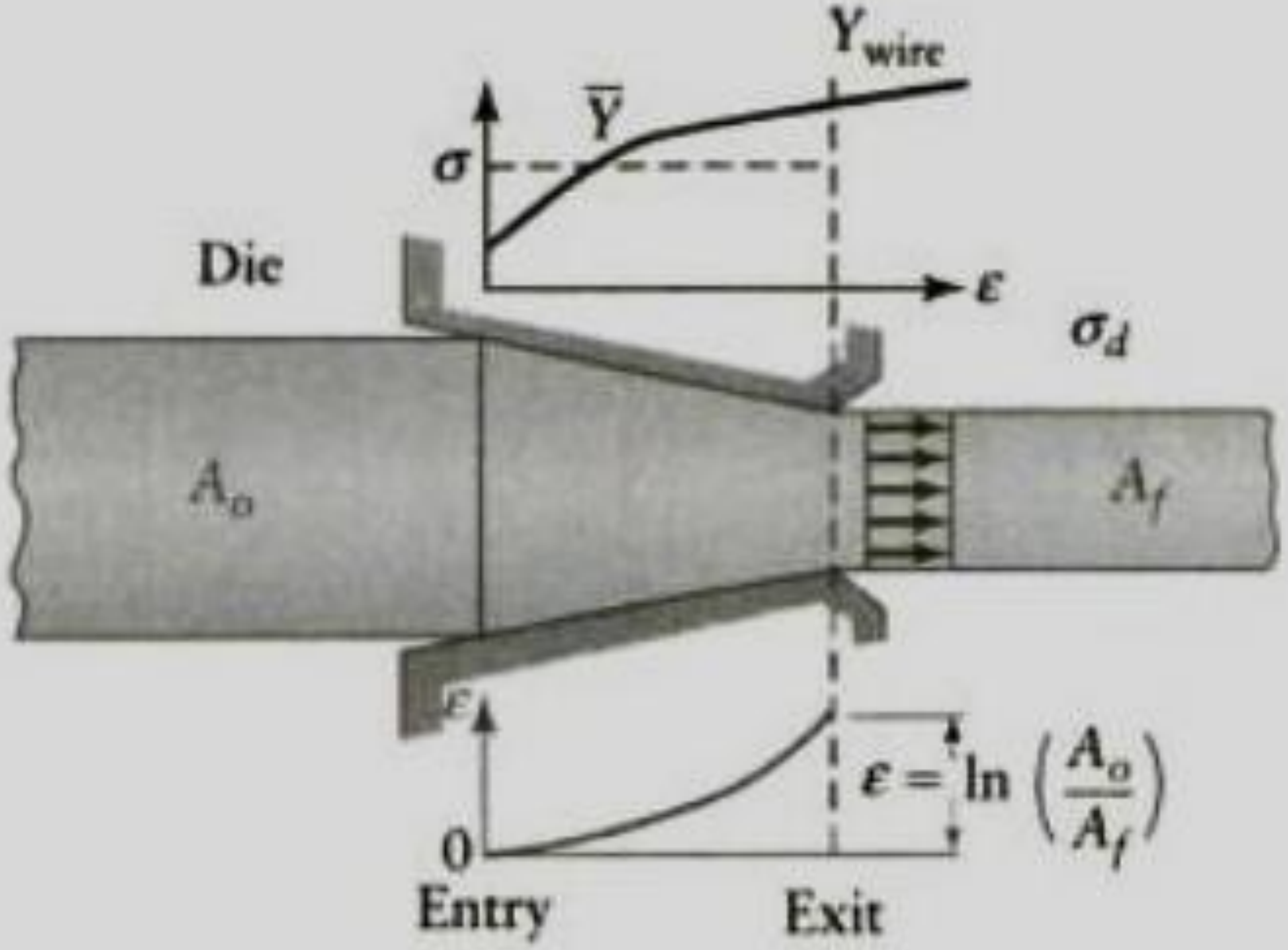


FIGURE 6.63 Variation in strain and flow stress in the deformation zone in drawing. Note that the strain increases rapidly toward the exit. The reason is that when the exit diameter is zero, the true strain reaches infinity. The point Y_{wire} represents the yield stress of the drawn wire.

Ideal deformation and friction

- With friction , But no redundant work.

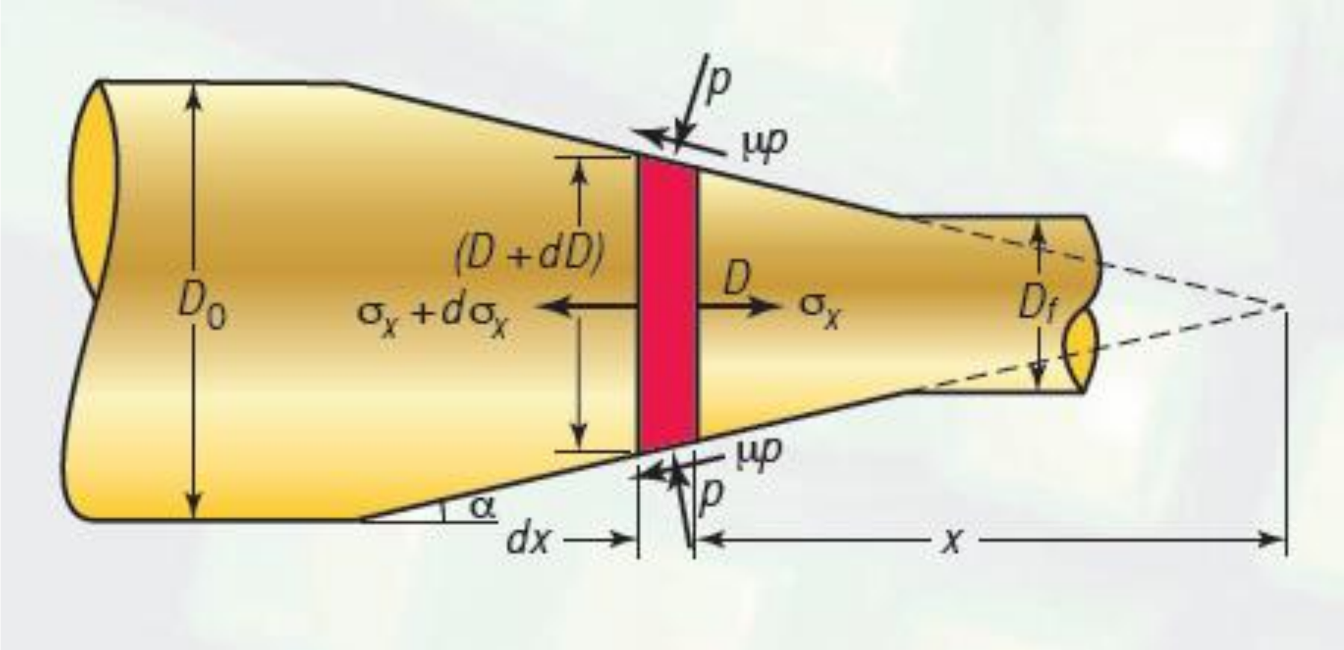


FIGURE 6.61 Stresses acting on an element in drawing of a solid cylindrical rod or wire through a converging conical die.

- Friction at the die-workpiece interface increases the drawing force, because work has to be done to overcome friction.
- Using the slab method of analysis and on an element, drawing stress can calculate as,

$$\sigma_d = \sigma_y \left(1 + \frac{\tan\alpha}{\mu}\right)\left[1 - \left(\frac{A_f}{A_o}\right)^{\mu \cot\alpha}\right]$$

Actual forces

- With friction and redundant work.
- Depending on the die angle and reduction, the material in drawing undergoes inhomogeneous deformation.
- When the redundant work of deformation and friction are included, the expression for the drawing stress becomes,

$$\sigma_d = \bar{\sigma}_f \left\{ \left(1 + \frac{\tan\alpha}{\mu}\right) \left[1 - \left(\frac{A_f}{A_o}\right)^{\mu\cot\alpha} \right] + \frac{4}{3\sqrt{3}} \alpha^2 \left(\frac{1-r}{r}\right) \right\}$$

Where, r is the fractional reduction of area and α is the die angle, in radians.

- The first term in Eq. represents the ***ideal and frictional components*** of work, and the second term represents the ***redundant work component***, which is a function of the die angle.
- The larger the die angle, the greater the inhomogeneous deformation and, hence, the greater the redundant work.

Die pressure

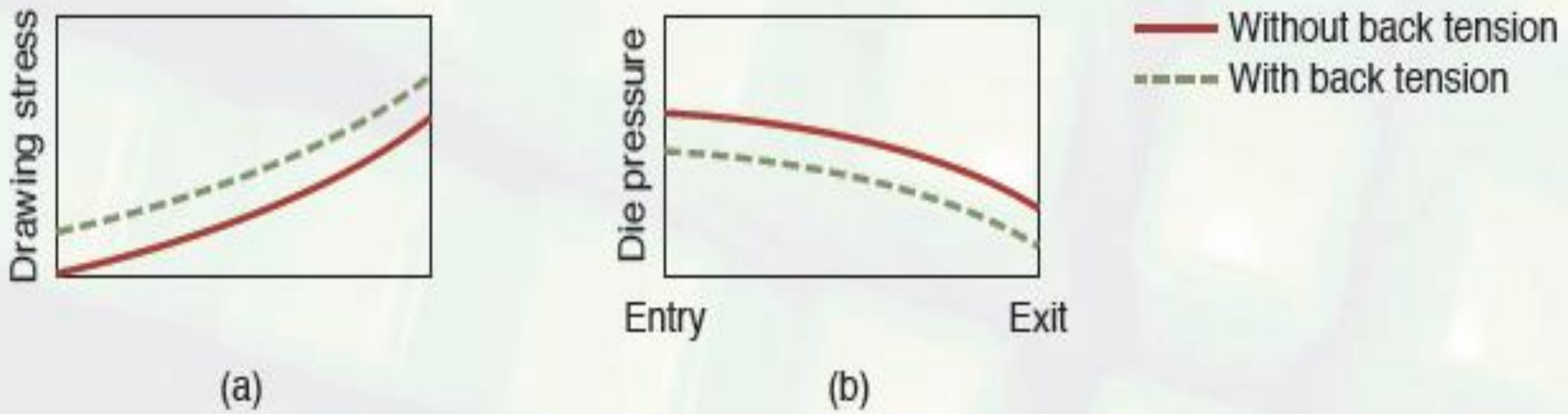


FIGURE 6.62 Variation in the (a) drawing stress and (b) die contact pressure along the deformation zone. Note that as the drawing stress increases, the die pressure decreases (see also yield criteria, described in Section 2.11). Note the effect of back tension on the stress and pressure.

- die pressure *p* along the die contact length can be obtained from,

$$p = \sigma_f - \sigma$$

- where σ is the tensile stress in the deformation zone at a particular diameter, and σ_f is the flow stress of the material at that diameter.

- Note that σ is equal to σ_d at the die exit, and is zero at the die entry. Equation indicates that as the tensile stress increases toward the exit, the die pressure drops toward the exit.

Drawing at elevated temperatures

- Flow stress of metal is a function of the strain rate.
- Average strain rate,

$$\dot{\epsilon} = \frac{6V_o}{D_o} \ln\left(\frac{A_o}{A_f}\right)$$

- After first calculating the average strain rate, the flow stress and the average flow stress, $\overline{\sigma}$, of the material can be calculated and substituted in appropriate equations.

Die angle

- Because of the various effects of the die angle on the three components of work (ideal, friction, and redundant), an optimum die angle at which the drawing force is a minimum.

- ***Optimum angle for the minimum drawing force increases*** with reduction; note also that optimum angles are relatively small.

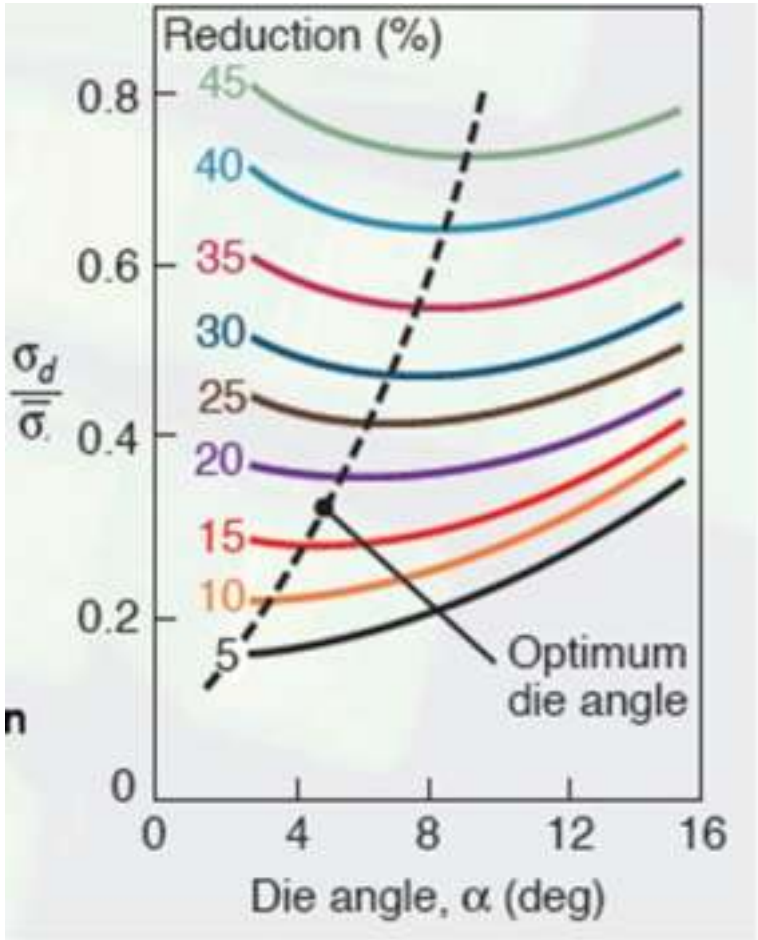


FIGURE 6.63 The effect of reduction in cross-sectional area on the optimum die angle in drawing. *Source:* After J.G. Wistreich.

Maximum reduction per pass for round or rod

- As reduction increases, the drawing stress increases. Obviously, there is a limit to the magnitude of the drawing stress. If it reaches the ***yield stress of the material at the exit***, it will simply continue to yield and fail.
- The limiting situation can be developed based on the fact that, in the ideal case of a perfectly plastic material with a yield stress σ_y , the limiting condition is and therefore,

$$\sigma_d = \sigma_y \ln\left(\frac{A_o}{A_f}\right) = \sigma_y,$$

$$\ln\left(\frac{A_o}{A_f}\right) = 1,$$

and therefore,

$$\frac{A_o}{A_f} = e.$$

Thus, the maximum reduction per pass is given by

$$\frac{A_o - A_f}{A_o} = 1 - \frac{1}{e} = 0.63 = 63\%.$$

- Because of strain hardening, the exiting material will be stronger than the rest of the material in the die gap. Consequently, the ***maximum reduction per pass will increase***.
- Both friction and redundant deformation contribute to an increase in the drawing stress, the ***maximum reduction per pass will be lower than in the ideal case***.
- That is, ***friction and redundant work have a larger effect than strain hardening***.

Drawing of flat strips

- The dies in flat strip drawing are wedge shaped, and there is little or no change in the width of the strip during drawing.
- The drawing process is then somewhat similar to that of rolling wide strips, and hence the process can be considered as a plane-strain problem, especially at large width-to-thickness ratios.
- The drawing stress for the ideal condition is

$$\sigma_d = \sigma'_y \ln\left(\frac{h_o}{h_f}\right)$$

- σ_y' is the flow or yield stress of the material in plain strain.
- h_0 and h_f are the original and final thickness of the strip.

Maximum reduction per pass for flat strip

- By equating the drawing stress to the uniaxial yield stress of the material, because the drawn strip is subjected only to simple simple tension.

$$\sigma_d = \sigma'_y \ln\left(\frac{h_o}{h_f}\right) = \sigma_y, \quad \ln\left(\frac{h_o}{h_f}\right) = \frac{\sigma_y}{\sigma'_y} = \frac{\sqrt{3}}{2}, \quad \text{and} \quad \frac{h_o}{h_f} = e^{\sqrt{3}/2},$$

which reduces to

$$\text{Maximum reduction per pass} = 1 - \frac{1}{e^{\sqrt{3}/2}} = 0.58 = 58\%.$$

Wire drawing

Multistage Wire-drawing Machine

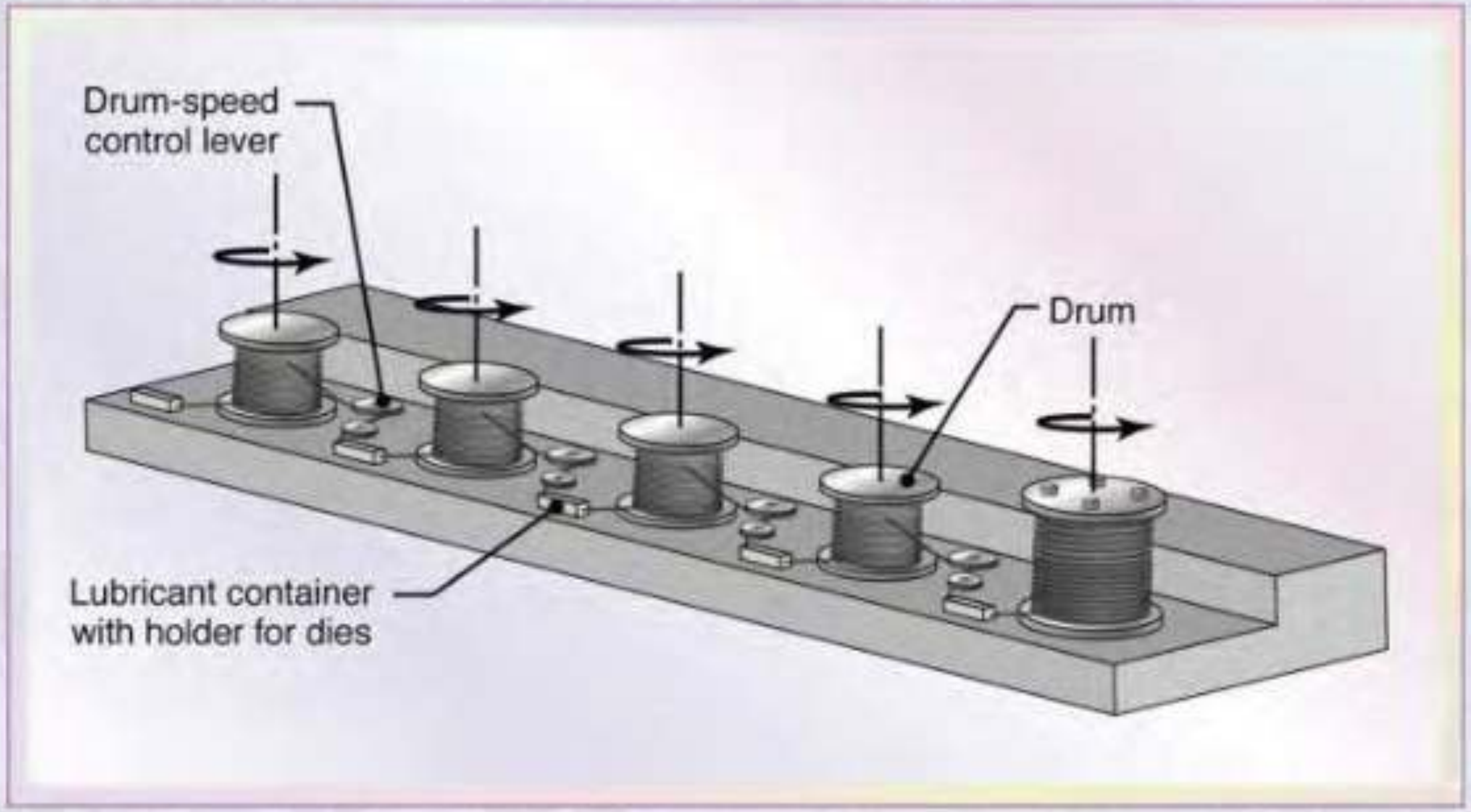


Figure 15.23 Two views of a multistage wire-drawing machine that typically is used in the making of copper wire for electrical wiring. *Source:* After H. Auerswald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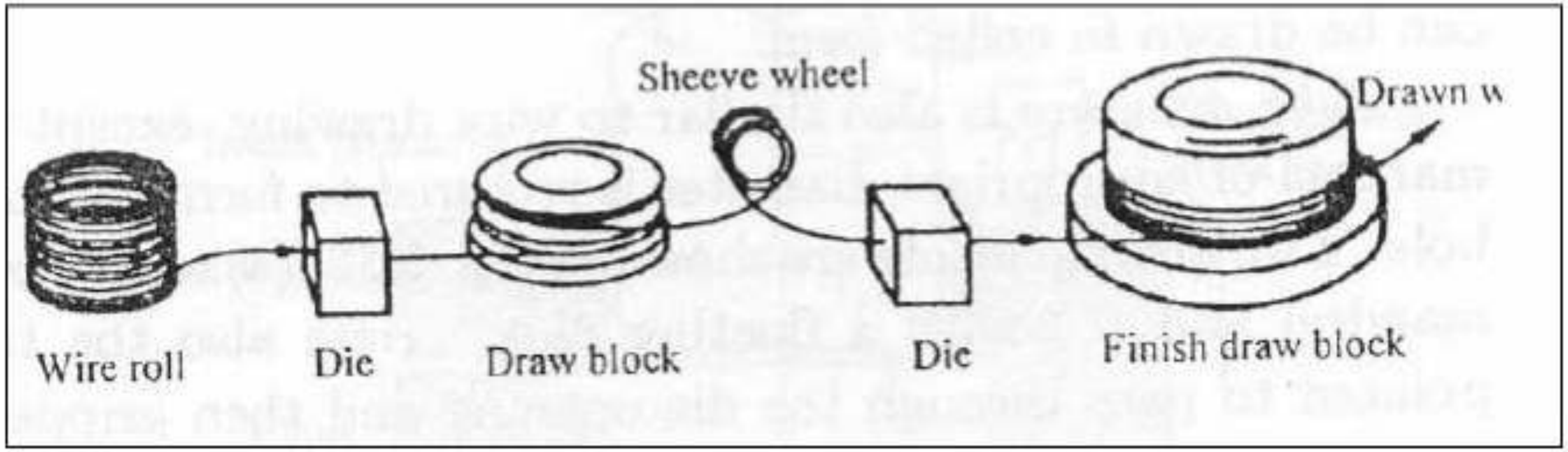
- By ***successive drawing*** operation through dies of reducing diameter the wire can be reduced to a very small diameter.
- ***Annealing*** before each drawing operation permits large area reduction.
- ***Tungsten Carbide dies*** are used to for drawing hard wires, and diamond dies is the choice for fine wires.



Drawing of tubes

- It is similar to wire drawing operation , additionally a mandrel is used for maintaining the required to form the internal hole.
- The process reduces the diameter and thickness of the tube.

FIGURE 6.67 Various methods of tube drawing.

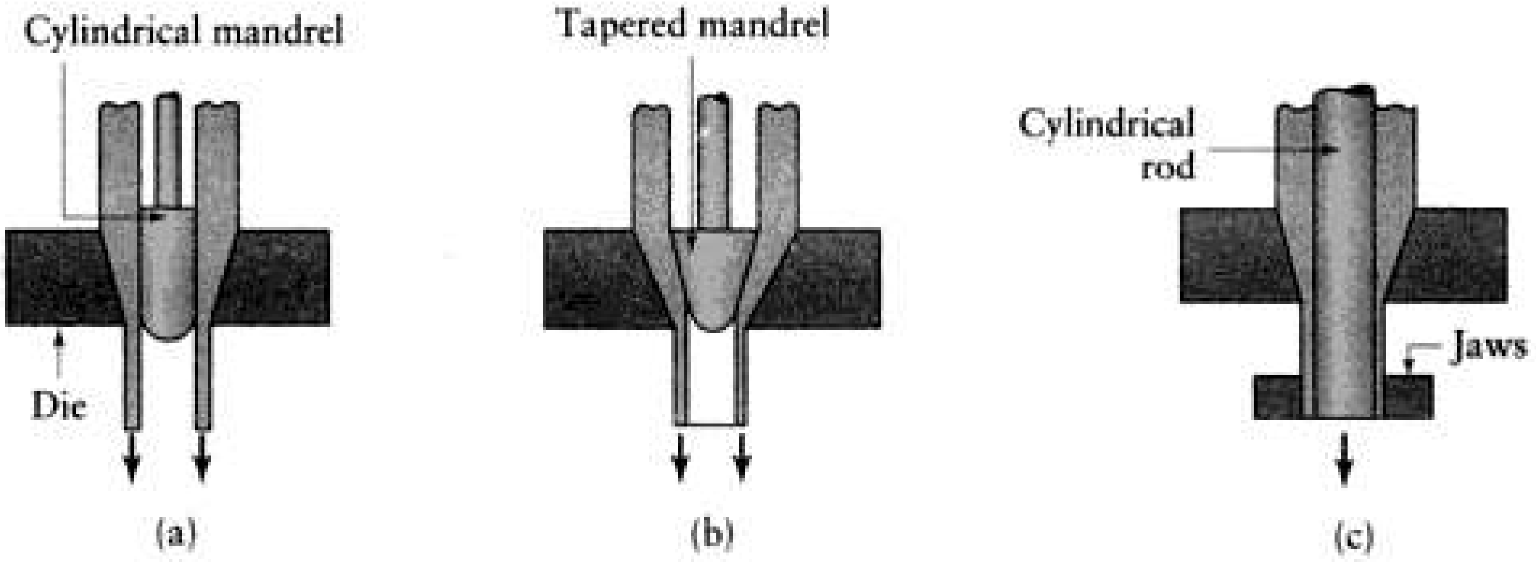
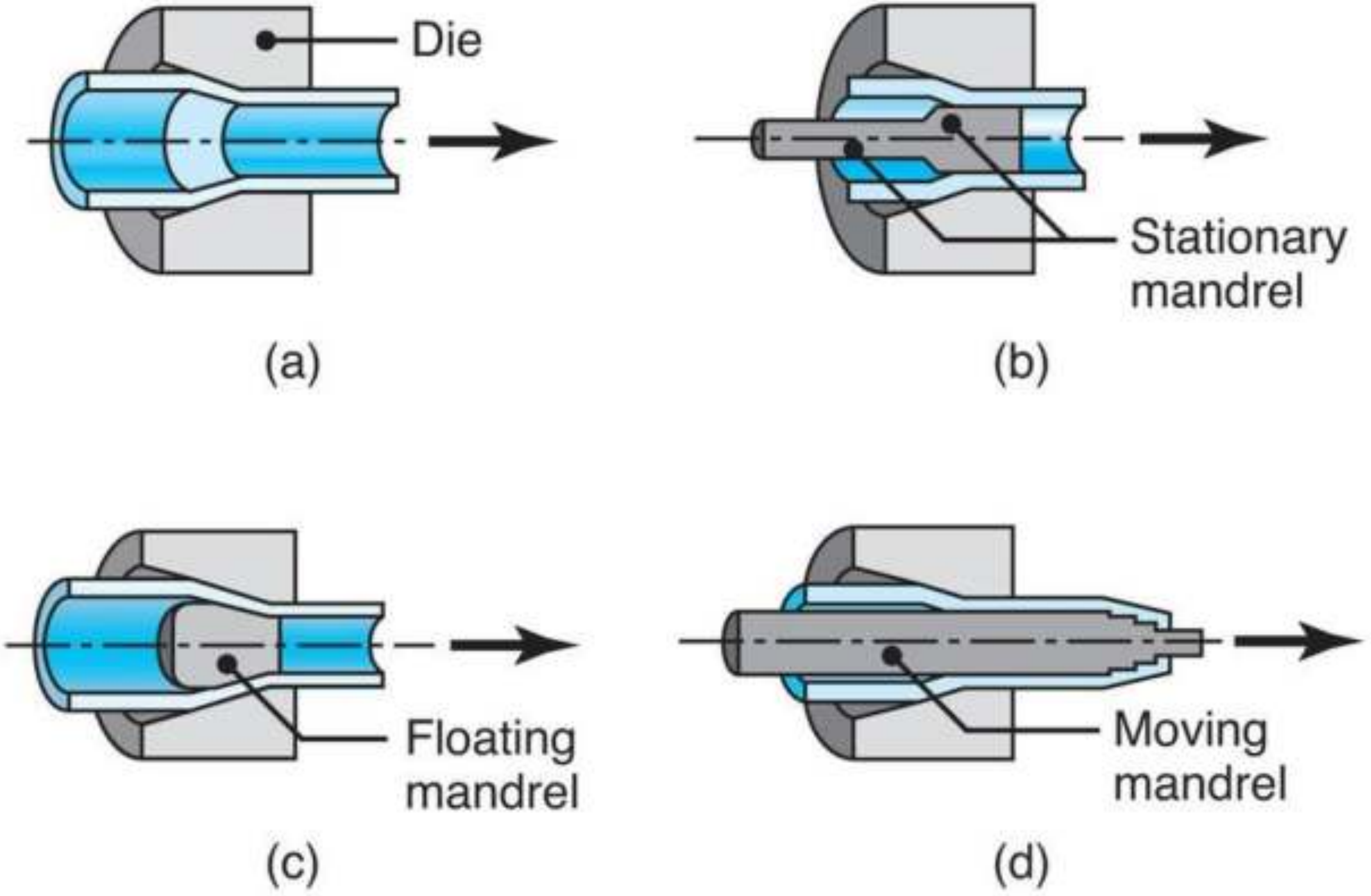


FIGURE 15.21 Examples of tube-drawing operations, with and without an internal mandrel; note that a variety of diameters and wall thicknesses can be produced from the same initial tube stock (which has been made by other processes).



Drawing defects

- Similar to extrusion defects
  1. Internal cracking
     - Tendency for cracking increases with increase in die angle, with decrease in reduction per pass, with friction and with presence of inclusions in the material.
  2. Seams
     - Longitudinal scratches or folds in the material that can open up during subsequent forming operations such as upsetting, heading, thread rolling, or bending of the rod or wire.

- Residual stresses
  - Because of inhomogeneous deformation of cold drawn wire or tube.
  - For light reduction surface residual stresses are compressive improve fatigue life.
  - Residual stresses affect stress corrosion cracking and warping.

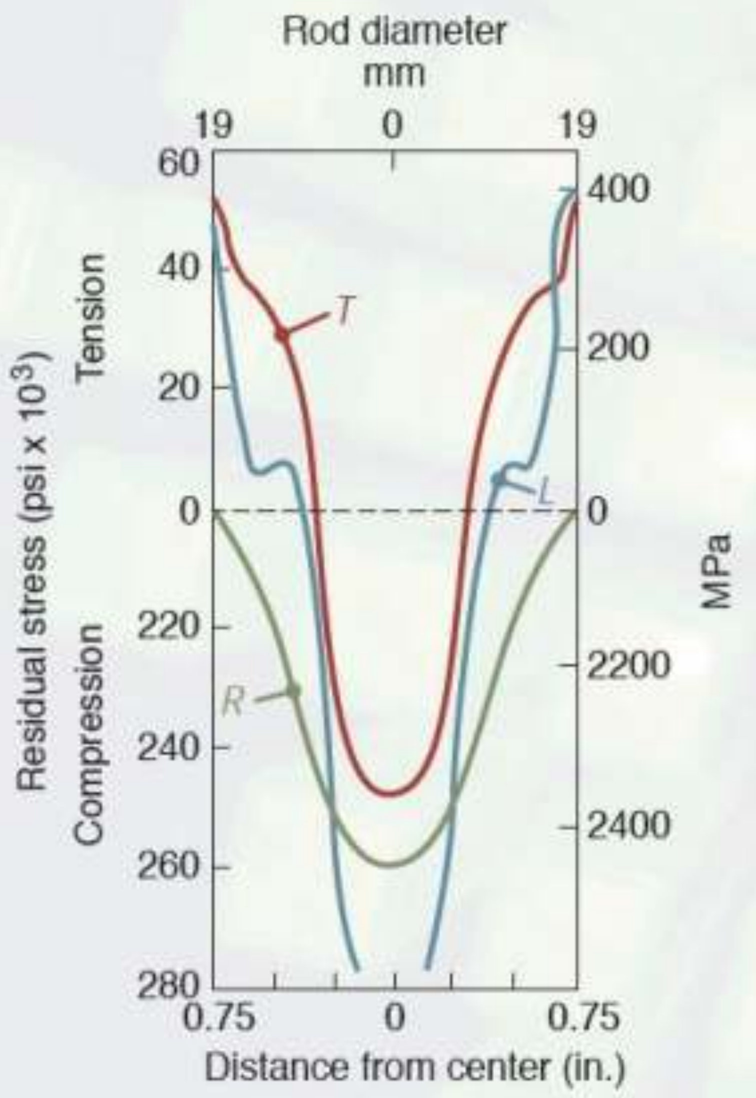


FIGURE 6.65 Residual stresses in cold-drawn 1045 carbon steel round rod: *T* = transverse direction, *L* = longitudinal direction and *R* = radial direction. *Source:* After E.S. Nachtman.

Drawing practices

- A rod or wire is fed into the die by first pointing it by ***swaging*** (i.e., forming the tip of the rod into a conical shape)
- After the rod or wire is placed in the die, the tip is ***clamped*** into the jaws Of the wire-drawing machine, and the rod or wire is drawn continuously through the die.
- In most wire-drawing operations, the wire passes through a series of dies (***tandem drawing***). In order to avoid excessive tension in the exiting wire, it is wound one or two turns around a ***capstan*** between each pair of dies.
- The speed of the capstan is adjusted so that it supplies not only tension, but also a small back tension to the wire entering the next die. Back tension reduces the die pressure and extends die life.

Extruded Channel on a Draw Bench

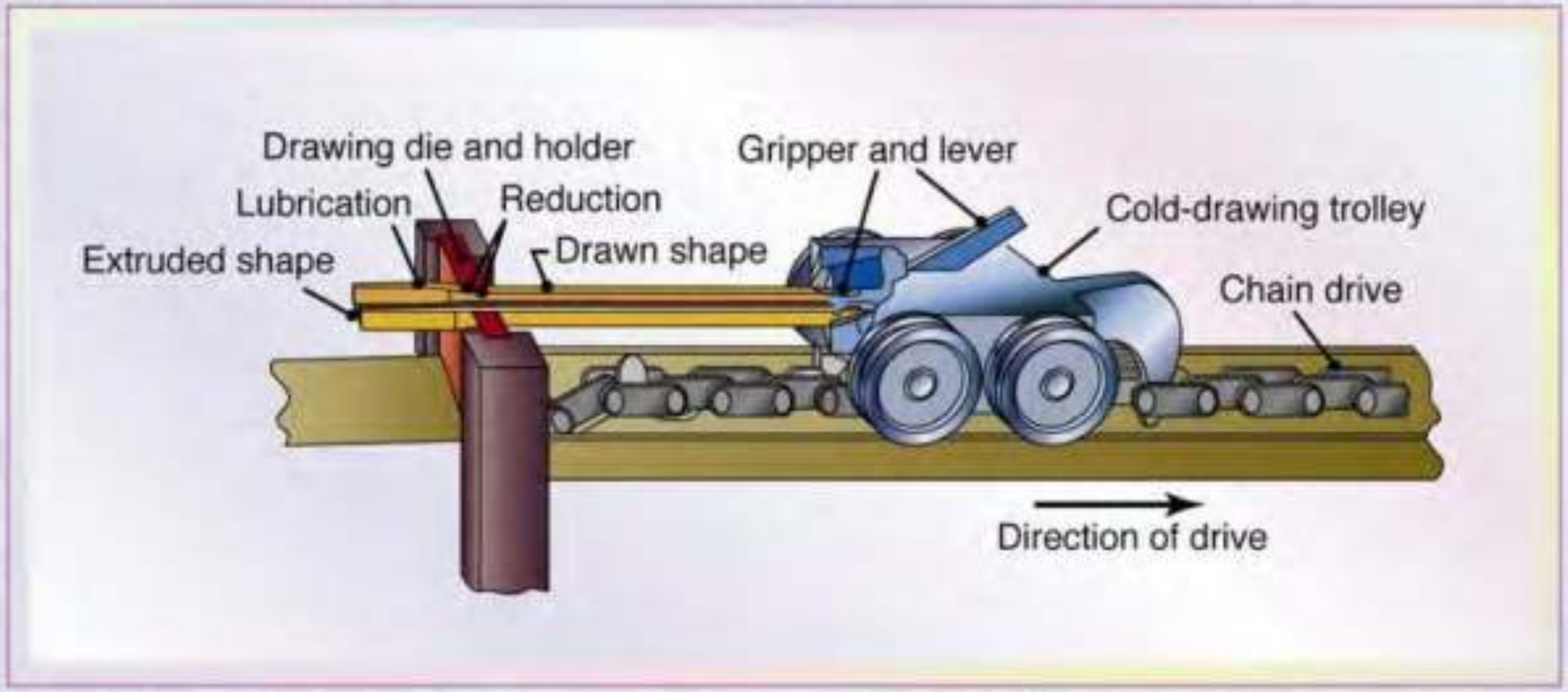
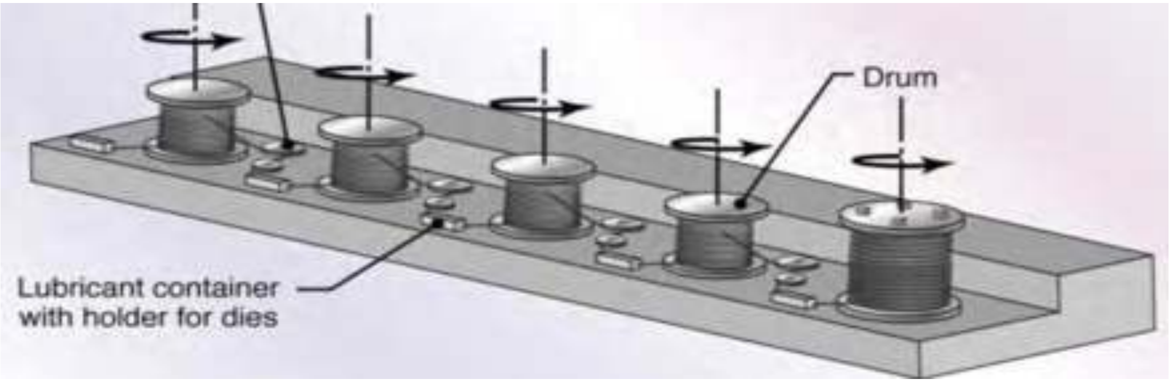
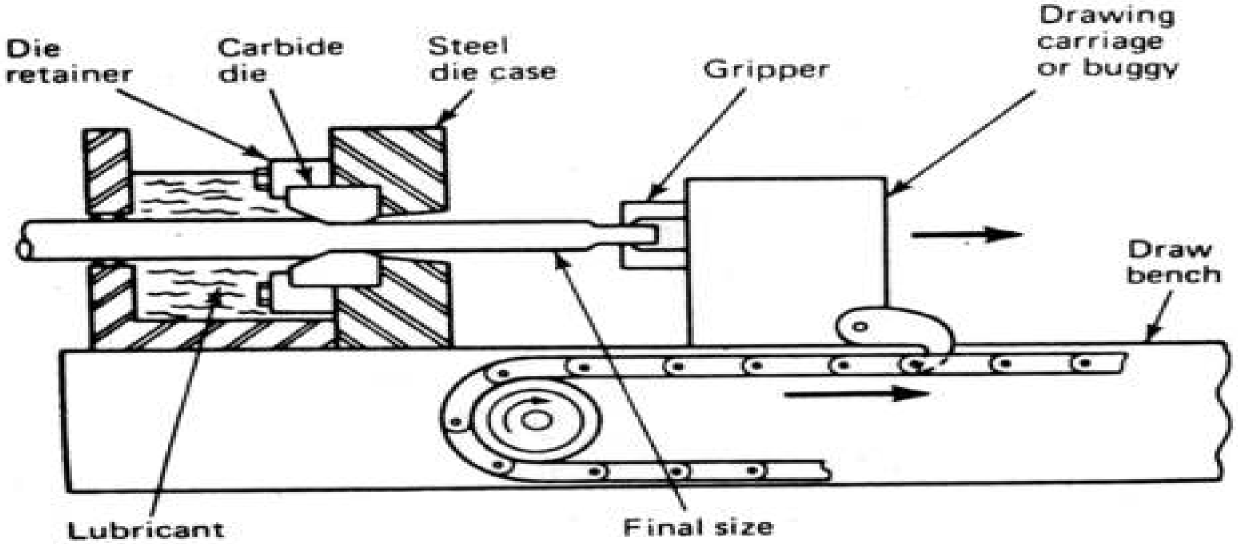


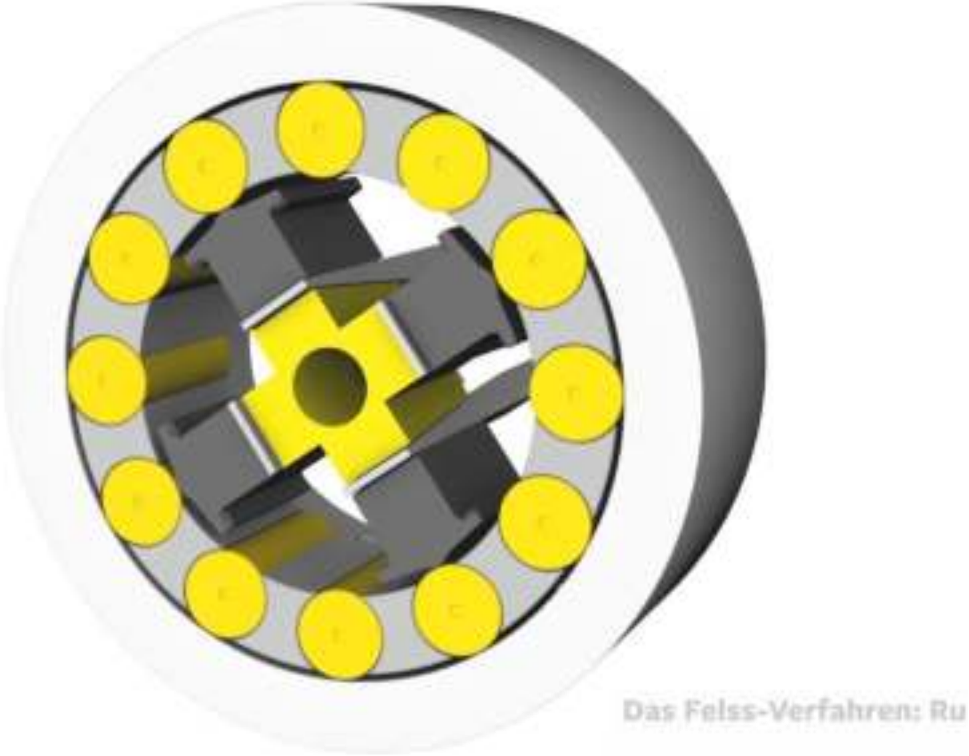
Figure 15.22 Cold drawing of an extruded channel on a draw bench to reduce its cross-section. Individual lengths of straight rods or of cross-sections are drawn by this method. *Source*: Courtesy of The Babcock and

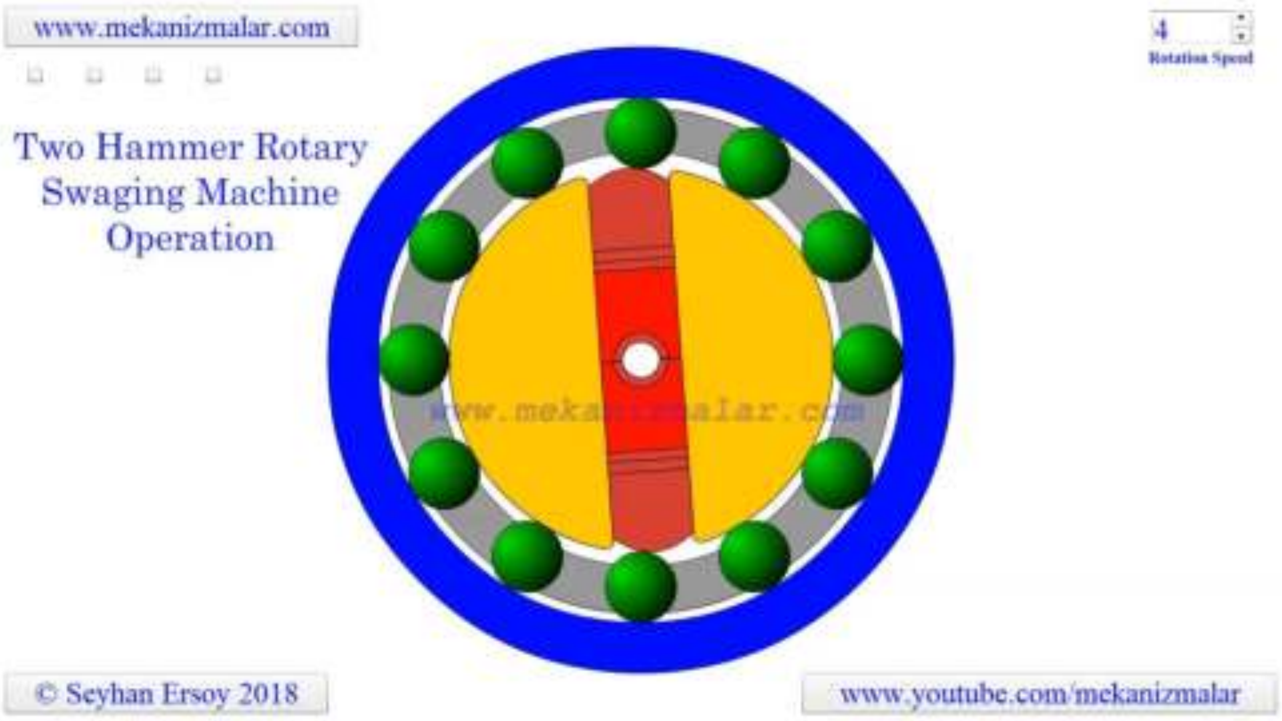

Drum
Lubricant container
with holder for dies


Die
retainer
Carbide
die
Steel
die case
Gripper
Drawing
carriage
or buggy
Draw
bench
Lubricant
Final size

Swaging

- In this process (also known as radial forging, rotary forging, or simply swaging), a solid rod or tube is subjected to ***radial impact forces*** by a set of reciprocating dies of the machine.
- The die movements are obtained by means of a set of ***rollers*** in a cage in an action similar to that of a ***roller bearing***.
- The workpiece is stationary and the dies rotate (while moving radially in their slots), striking the workpiece at rates as high as 20 strokes per second. In die-closing swaging machines, die movements are obtained through the reciprocating motion of wedges.
- **Tube Swaging.** In this process, the internal diameter and/or the thickness of the tube is reduced with or without the use of internal mandrels.


Das Felss-Verfahren: Ru


www.mekanizmalar.com
4
Rotation Speed
Two Hammer Rotary
Swaging Machine
Operation
www.mekanizmalar.com
© Seyhan Ersoy 2018
www.youtube.com/mekanizmalar

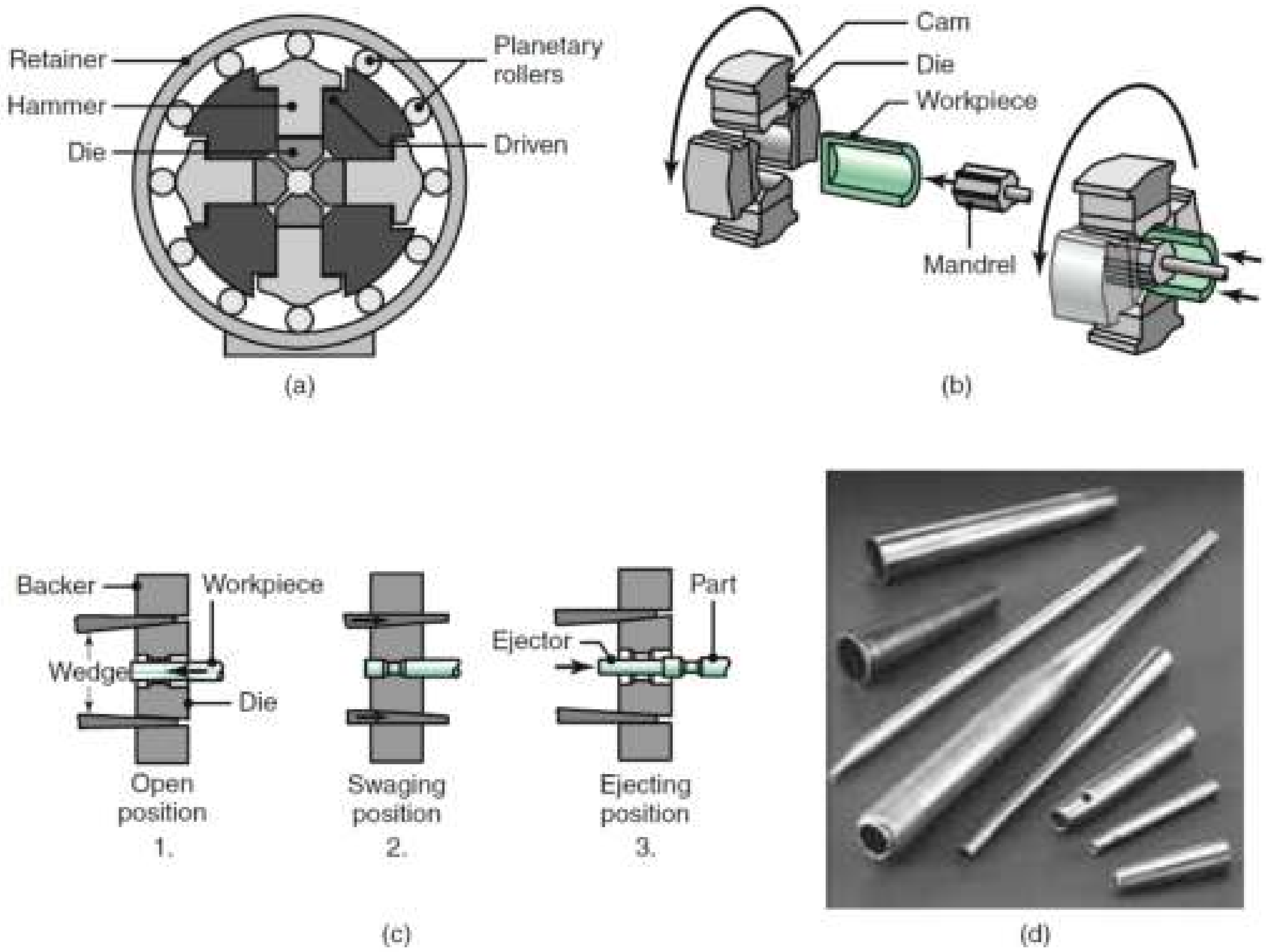


FIGURE 14.14 (a) Schematic illustration of the rotary-swaging process. (b) Forming internal profiles on a tubular workpiece by swaging. (c) A die-closing swaging machine, showing forming of a stepped shaft. (d) Typical parts made by swaging. *Source:* (d) Courtesy of J. Richard Industries.

Application

- Wire drawing is making of steel wires for spring and musical instruments.
- Large cross-sections can drawn at elevated temperatures. In cold drawing, because of strain hardening, intermediate annealing between passes may be necessary to maintain sufficient ductility.
- Steel wires for springs and musical instruments are made by a heat-treatment process that precedes or follows the drawing operation (patenting). These wires have ultimate tensile strengths as high as 4800 MPa (700,000 psi), with tensile reduction Of area Of about 20%.

Thank you…

MODULE 3

METAL ROLLING PROCESS

ELDHO PAUL

Dept. of Mechanical Engineering

MACE Kothamangalam

Content

- Rolling:-
- Principles
- Types of rolls and rolling mills
- Mechanics of flat rolling, roll pressure distribution, neutral point
- Front and back tension
- Torque and power
- Roll forces in hot rolling,
- Friction
- Deflection and flattening, spreading
- Simple problems.
- Rolling defects
- Vibration and chatter
- Flat rolling
- Miscellaneous rolling process: shape, roll forging, ring, thread and gear, rotary tube piercing, tube rolling
- Applications
- Simple problems.

3.1	Rolling:- principles - types of rolls and rolling mills - mechanics of flat rolling, roll pressure distribution, neutral point, front and back tension, torque and power, roll forces in hot rolling, friction, deflection and flattening, spreading -– simple problems.	3	CO4 CO5
3.2	rolling defects-vibration and chatter - flat rolling -miscellaneous rolling process: shape, roll forging, ring, thread and gear, rotary tube piercing, tube rolling - applications – simple problems. (Kalpakjian).	2	CO4
3.3	Plastic deformation of metals - stress-strain relationships- State of stress - yield criteria of Tresca, von Mises, and comparisons - applications.	2	
3.4	Flow rules -power and energy deformations - Heat generation and heat transfer in metal forming process -temperature in forging. (ASM- Taylan Altan).	1	CO4

Course Outcomes - At the end of the course students will be able to

CO 4	Student will estimate the working loads for pressing, forging, wire drawing etc. processes
CO 5	Recommend appropriate part manufacturing processes when provided a set of functional requirements and product development constraints.

1.Introduction

- The manufacture of metal parts and assemblies can be classified, in a simplified manner, into five general areas:
- ***Primary shaping*** processes, such as casting, die casting, and pressing of metal powder. In all these processes, the material initially has no shape but obtains a well-defined geometry through the process.
- ***Metal forming processes*** such as **rolling**, extrusion, cold and hot forging, bending, and deep drawing, where metal is formed by plastic deformation.
- ***Metal cutting processes***, such as sawing, turning, milling and broaching where removing metal generates a new shape.
- ***Metal treatment processes***, such as heat treating, anodizing and surface hardening, where the part remains essentially unchanged in shape but undergoes change in properties or appearance.
- ***Joining processes***, including (a) metallurgical joining, such as welding and diffusion bonding, and (b) mechanical joining, such as riveting, shrink fitting, and mechanical assembly.

Reference: Cold and Hot Forging Fundamentals and Applications, ASM International

Metal forming

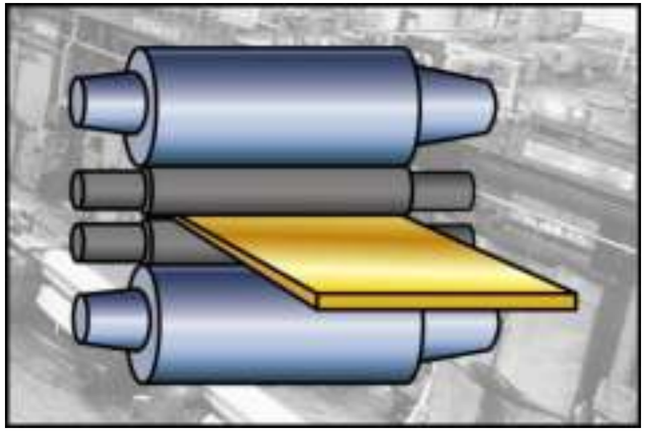
- Forming process make use of suitable stresses like compression, tension, shear or combined stresses to cause plastic deformation of the materials to produce required shapes. In forming, no material is removed i.e. they are deformed and displaced.

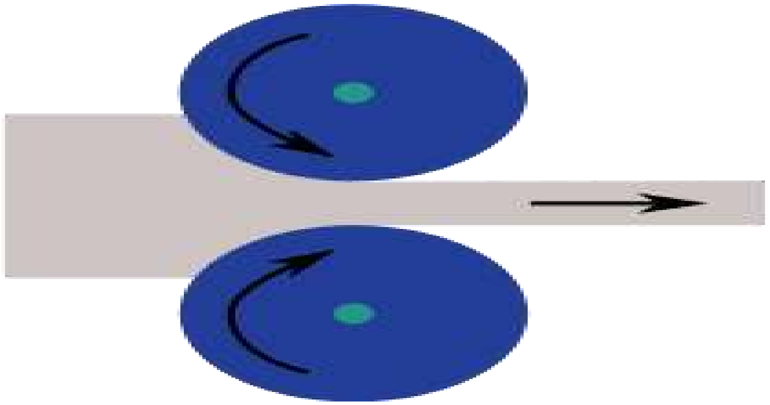
- Recrystallization is a process by which deformed grains are replaced by a new set of undeformed grains that nucleate and grow until the original grains have been entirely consumed.

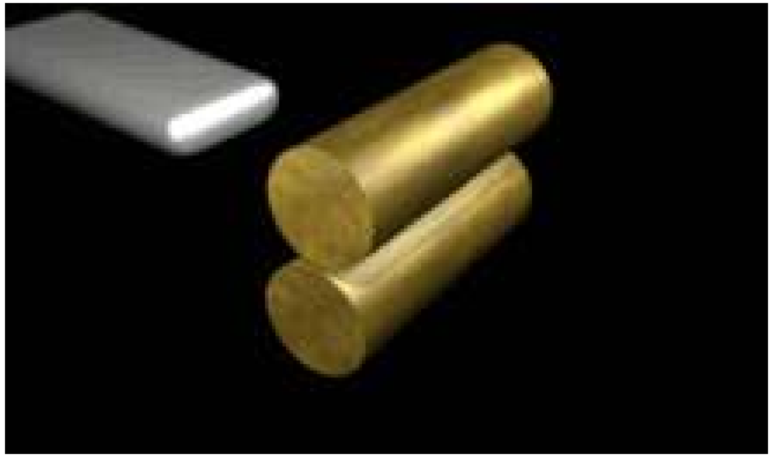
- NOTE: Although the recrystallization temperature for steel is 600^0 C, hot working of steel is carried at 900^0 C-1100^0 C.

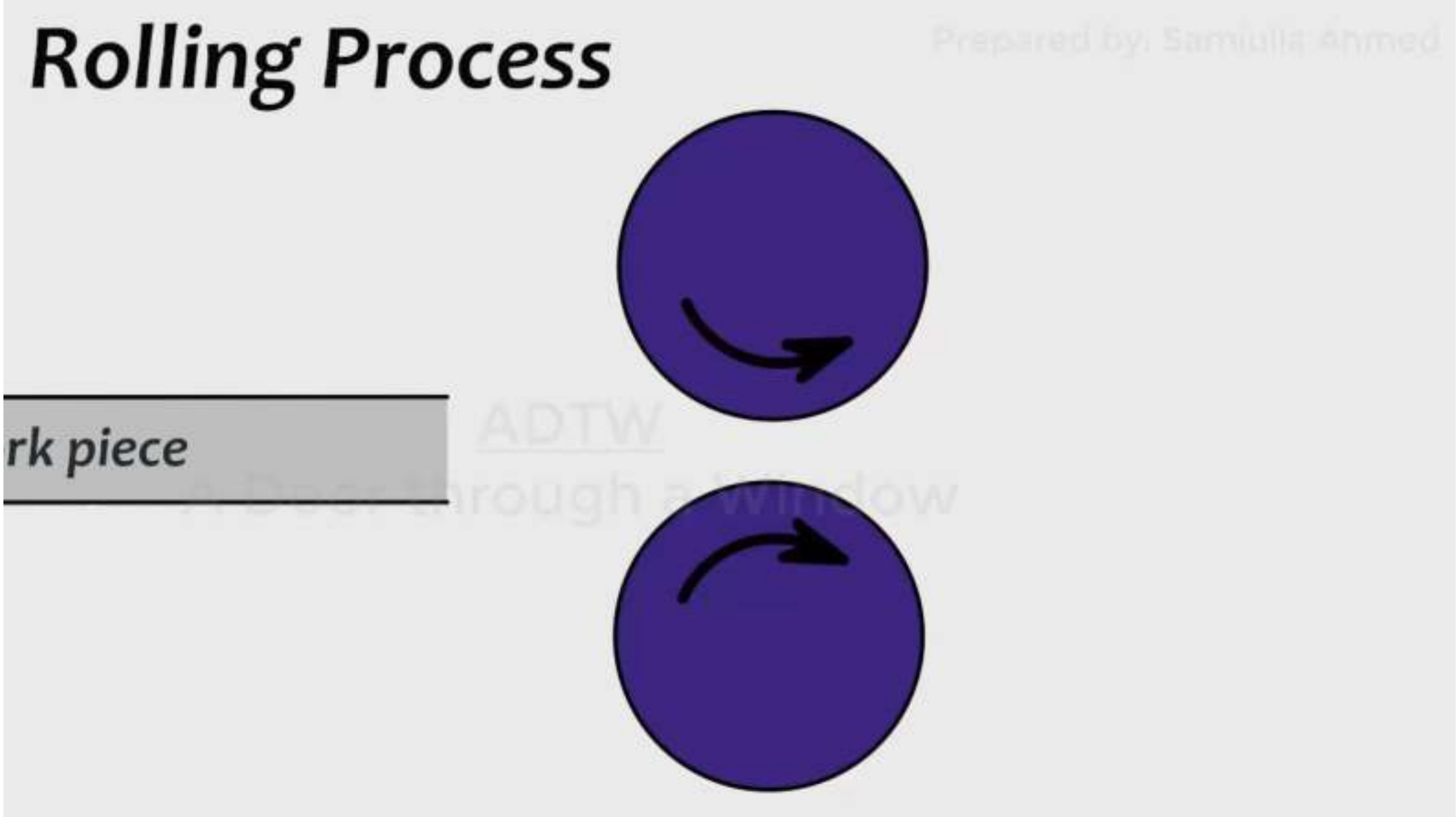
Rolling

- In metalworking, rolling is a metal forming process in which metal stock is passed through one or more pairs of rolls to reduce the thickness and to make the thickness uniform.
- Rolling is classified according to the temperature of the metal rolled.
- If the temperature of the metal is above its recrystallization temperature, then the process is termed as hot rolling.
- If the temperature of the metal is below its recrystallization temperature, the process is termed as cold rolling.

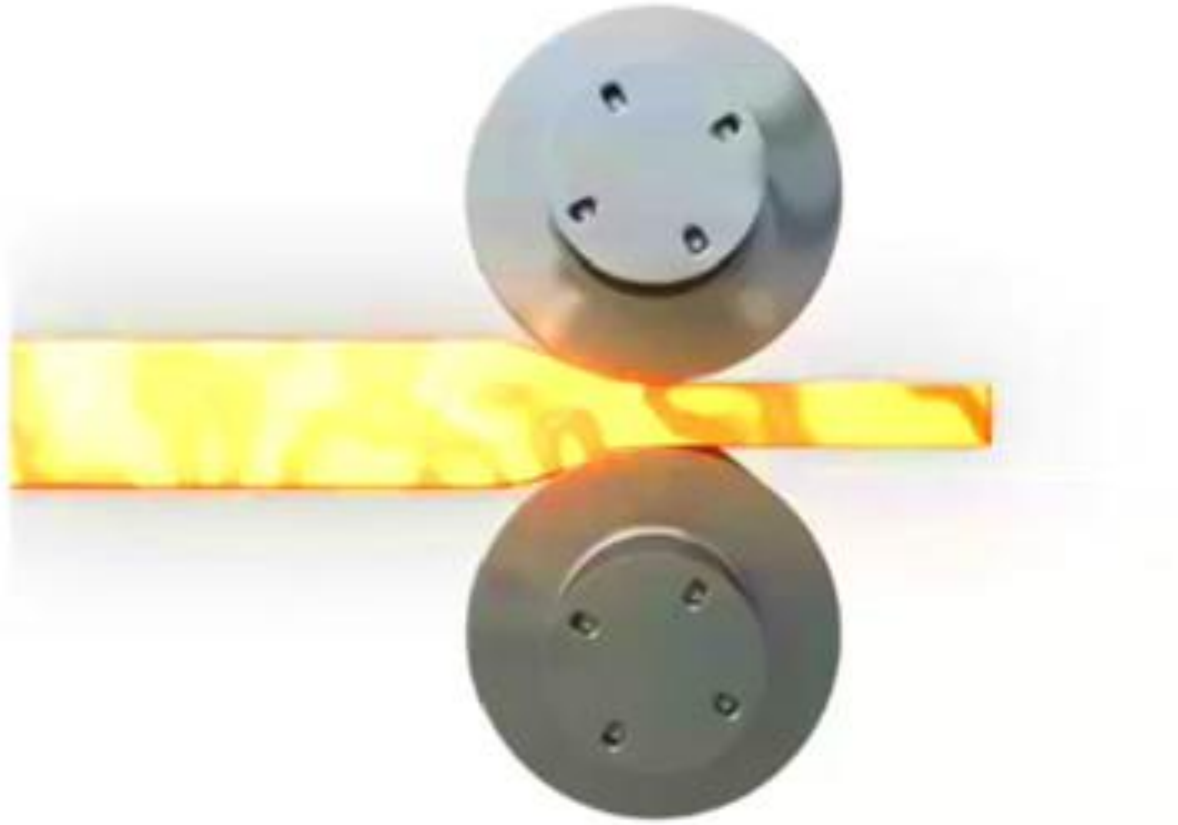


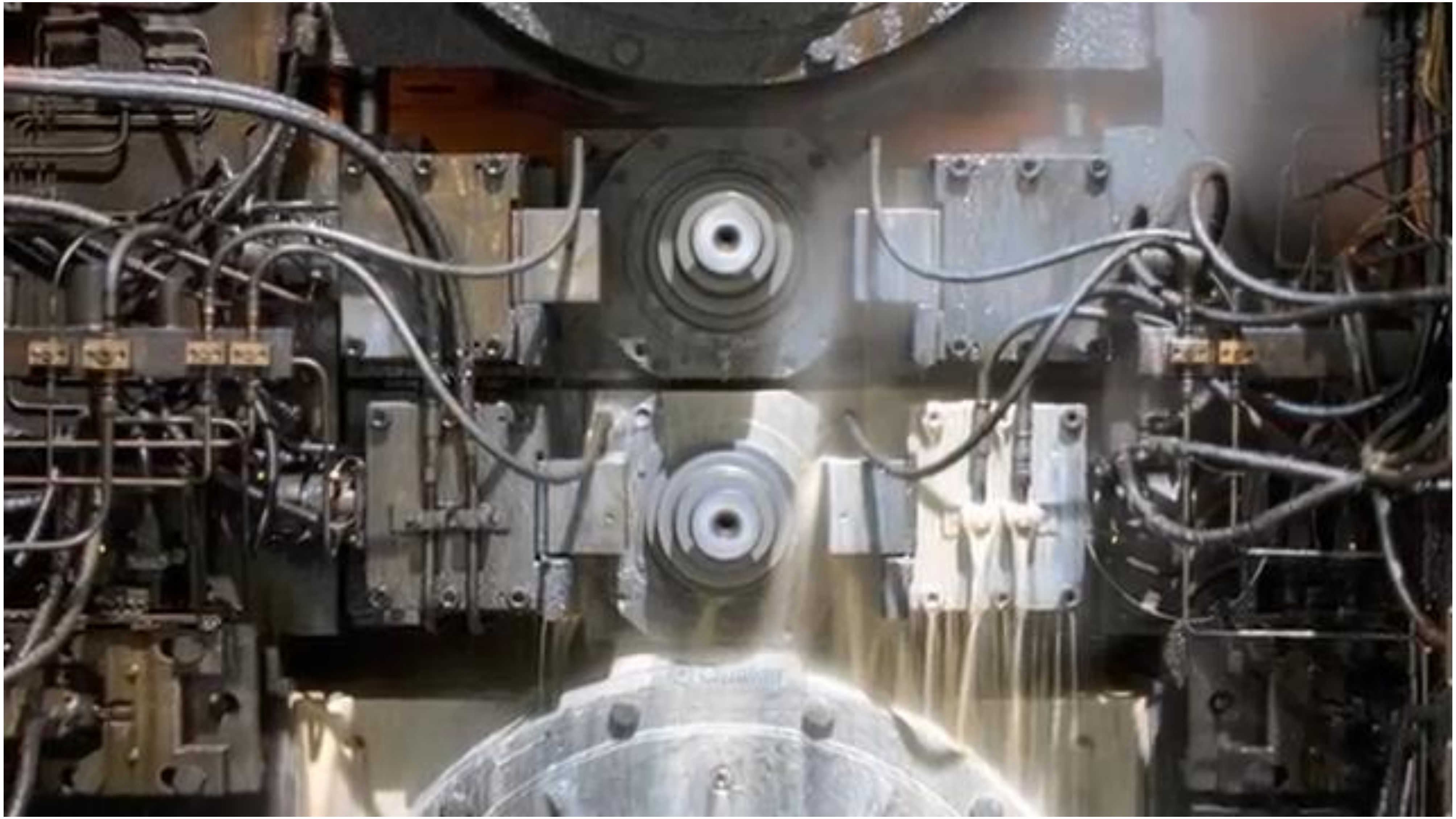





Rolling Process
Prepared by: Samiulla Ahmed
rk piece

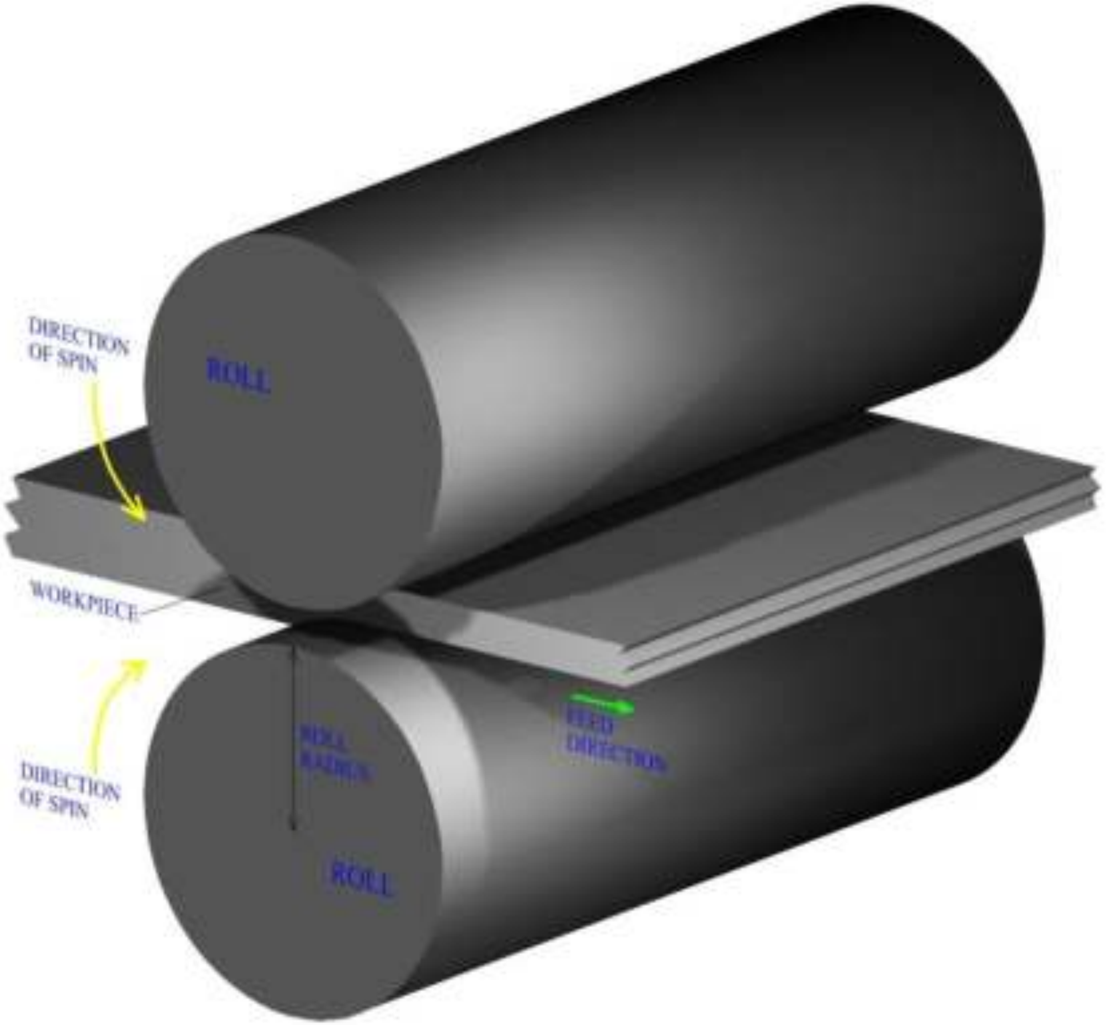
HOT ROLLING

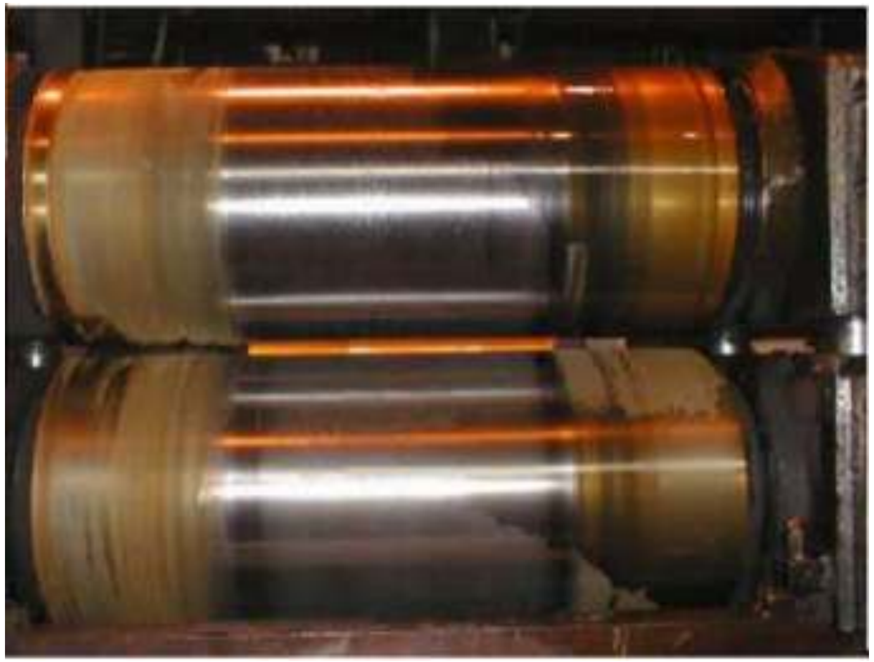




Principles of metal rolling

- Most metal rolling operations are similar in that the work material is plastically deformed by compressive forces between two constantly spinning rolls.
- These forces act to reduce the thickness of the metal and affect its grain structure.
- The reduction in thickness can be measured by the difference in thickness before and after the reduction, this value is called the **draft**.





Terminology

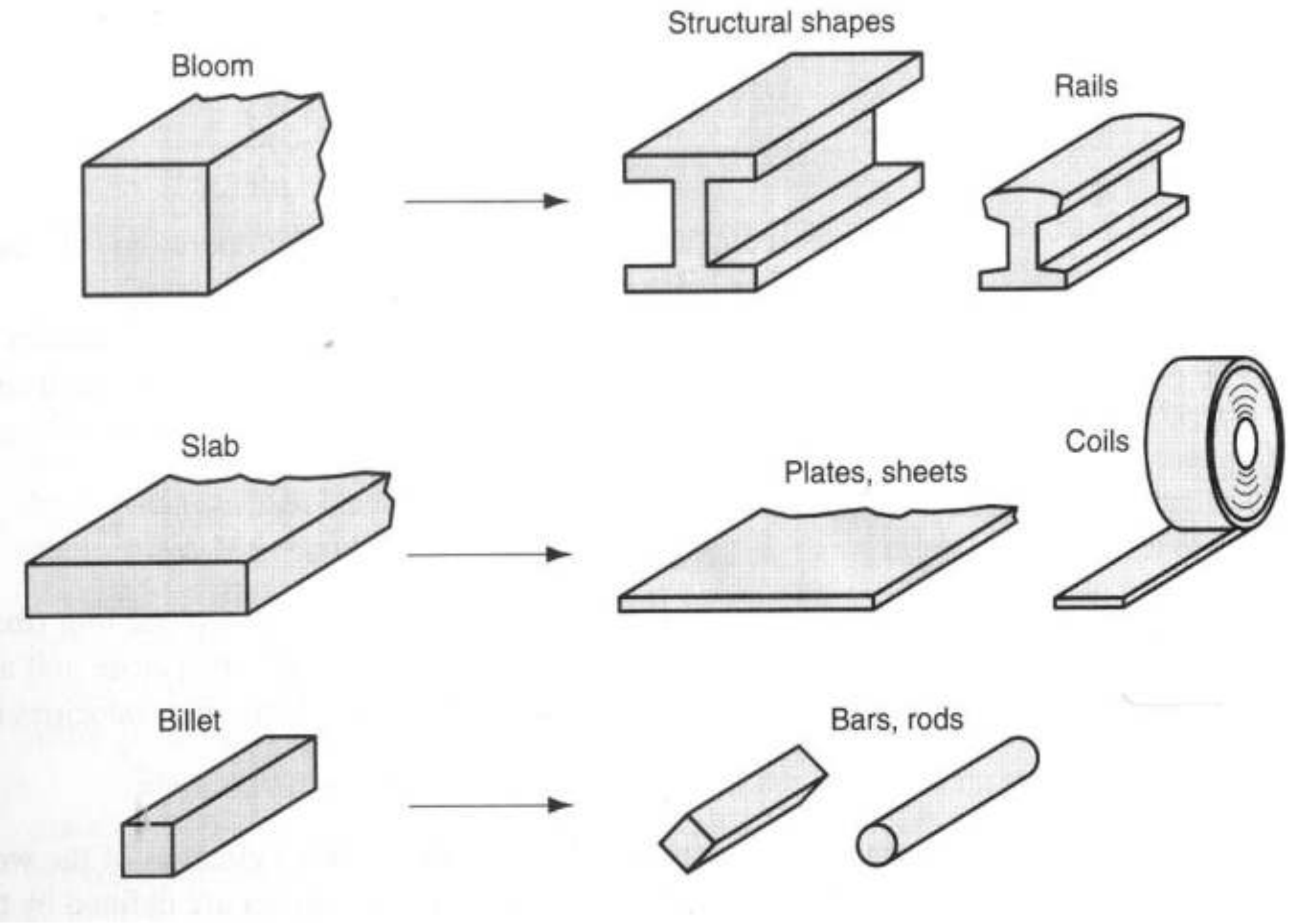
Semi-finished products

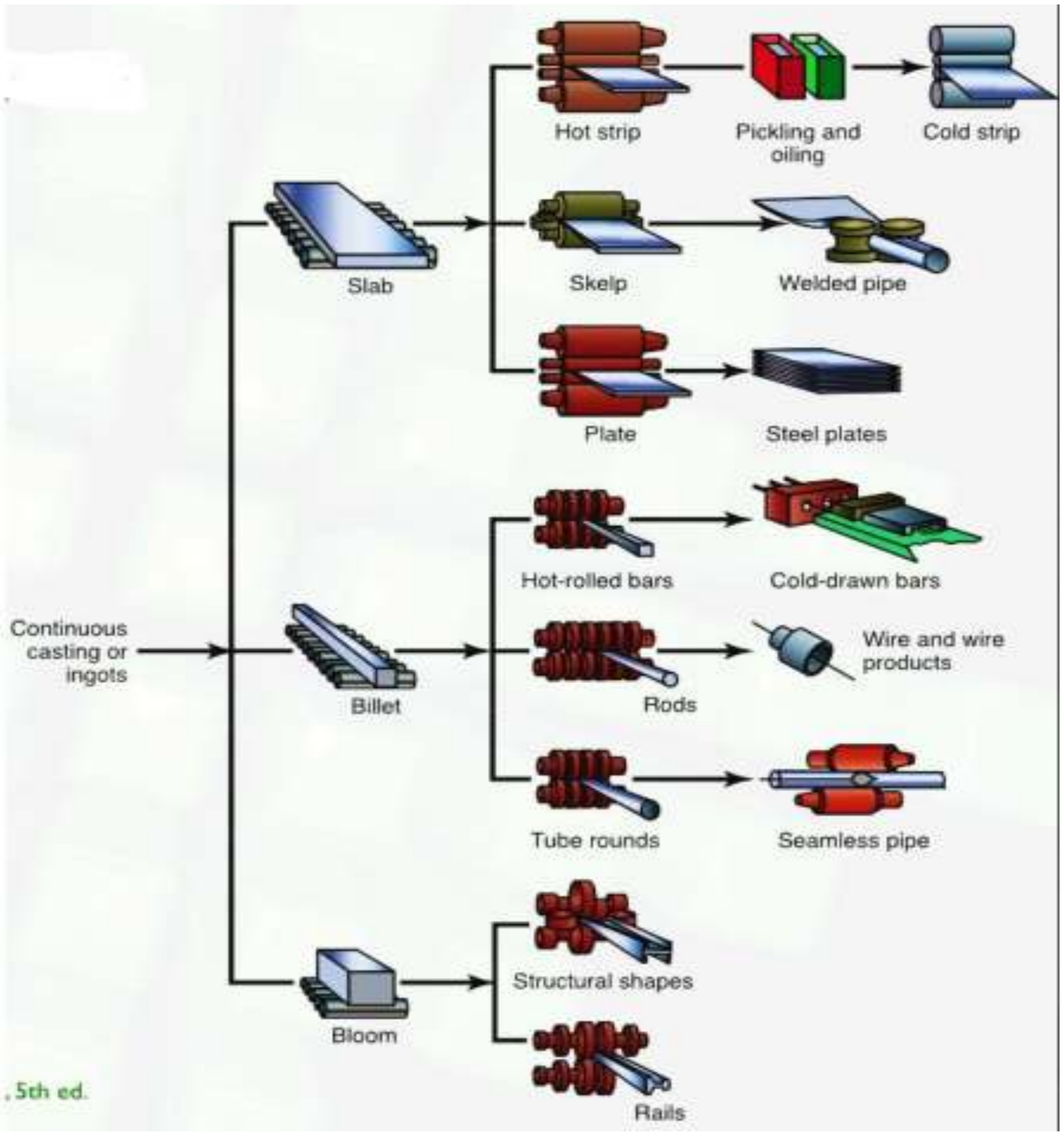
- ***Bloom*** is the product of first breakdown of ingot (cross sectional area > 230 cm^2).
- ***Billet*** is the product obtained from a further reduction by hot rolling (cross sectional area > 40x40 mm^2).
- ***Slab*** is the hot rolled ingot (cross sectional area > 100 cm^2 and with a width ≥ 2 x thickness).

Further rolling steps

Mill products

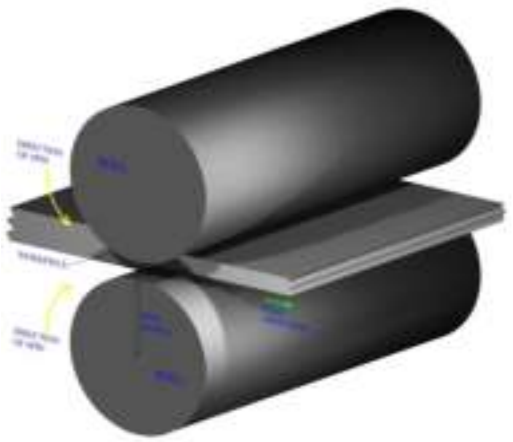
- ***Plate*** is the product with a thickness > 6 mm.
- ***Sheet*** is the product with a thickness < 6 mm and width > 600 mm.
- ***Strip*** is the product with a thickness < 6 mm and width < 600 mm.


Bloom
Structural shapes
Rails
Slab
Plates, sheets
Coils
Billet
Bars, rods

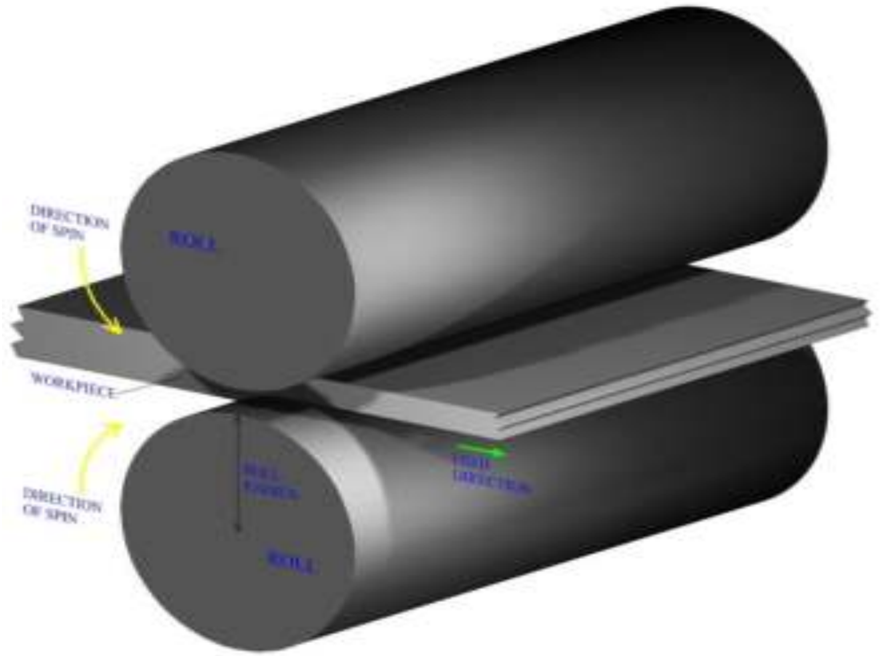


Reference: manufacturing processes for engineering materials by Serope Kalpakjian

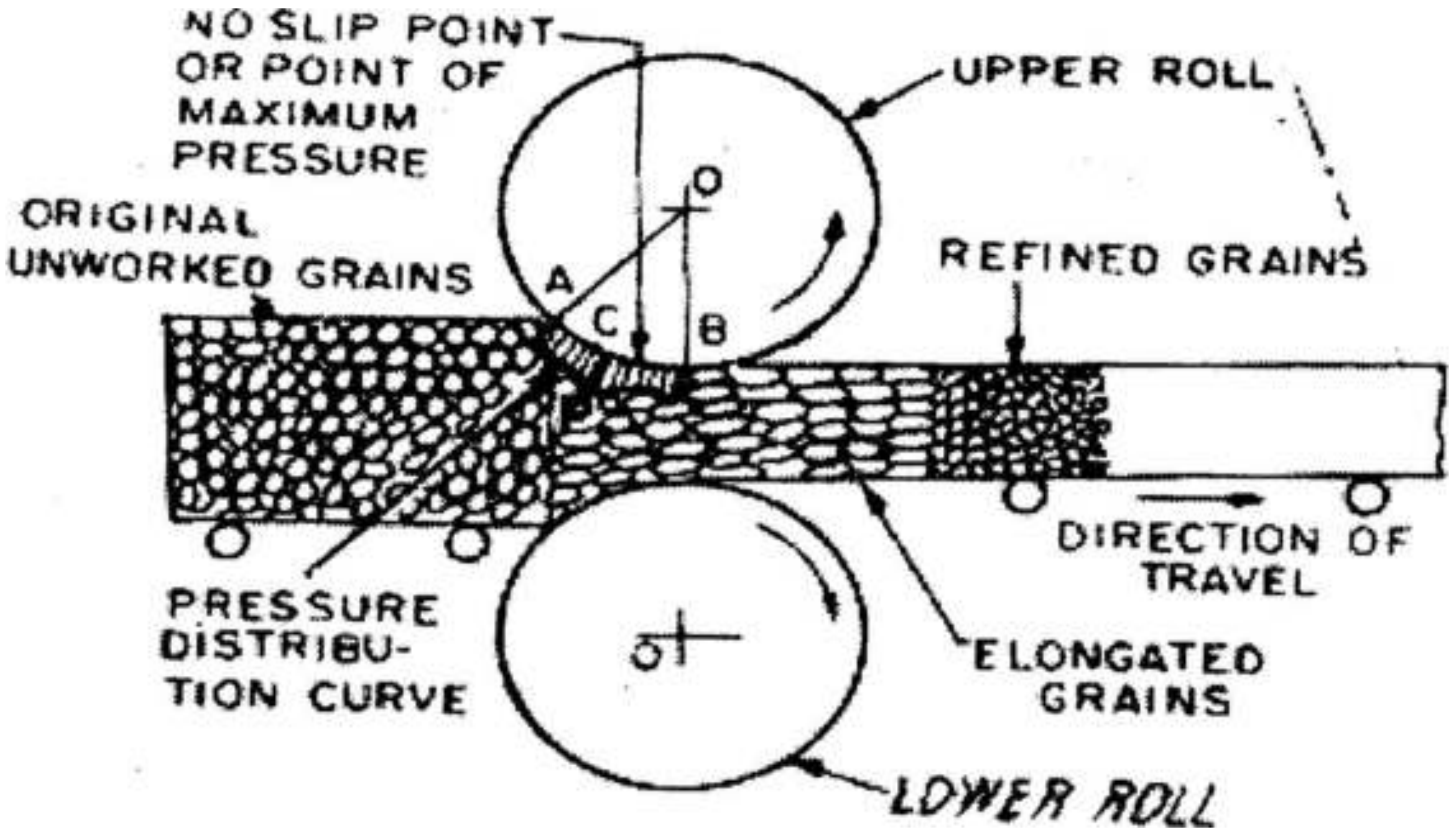
- Rolling process can be defined as: the Bulk deformation process of reducing the thickness or changing the cross-section of a long work-piece by compressive forces applied through a set of rolls (mills).
- When a piece of metal is rolled in between two rolls, the thickness is reduced as a result of the compressive stresses exerted by the rolls and it can be treated as a two-dimensional deformation in the thickness and length directions **neglecting the width direction**.
- This is due to the fact that the length of contact between the rolls and work piece is generally much smaller than the width of the sheet passing through and the undeformed material on both sides of the roll gap is restraining the lateral expansion along the width direction.



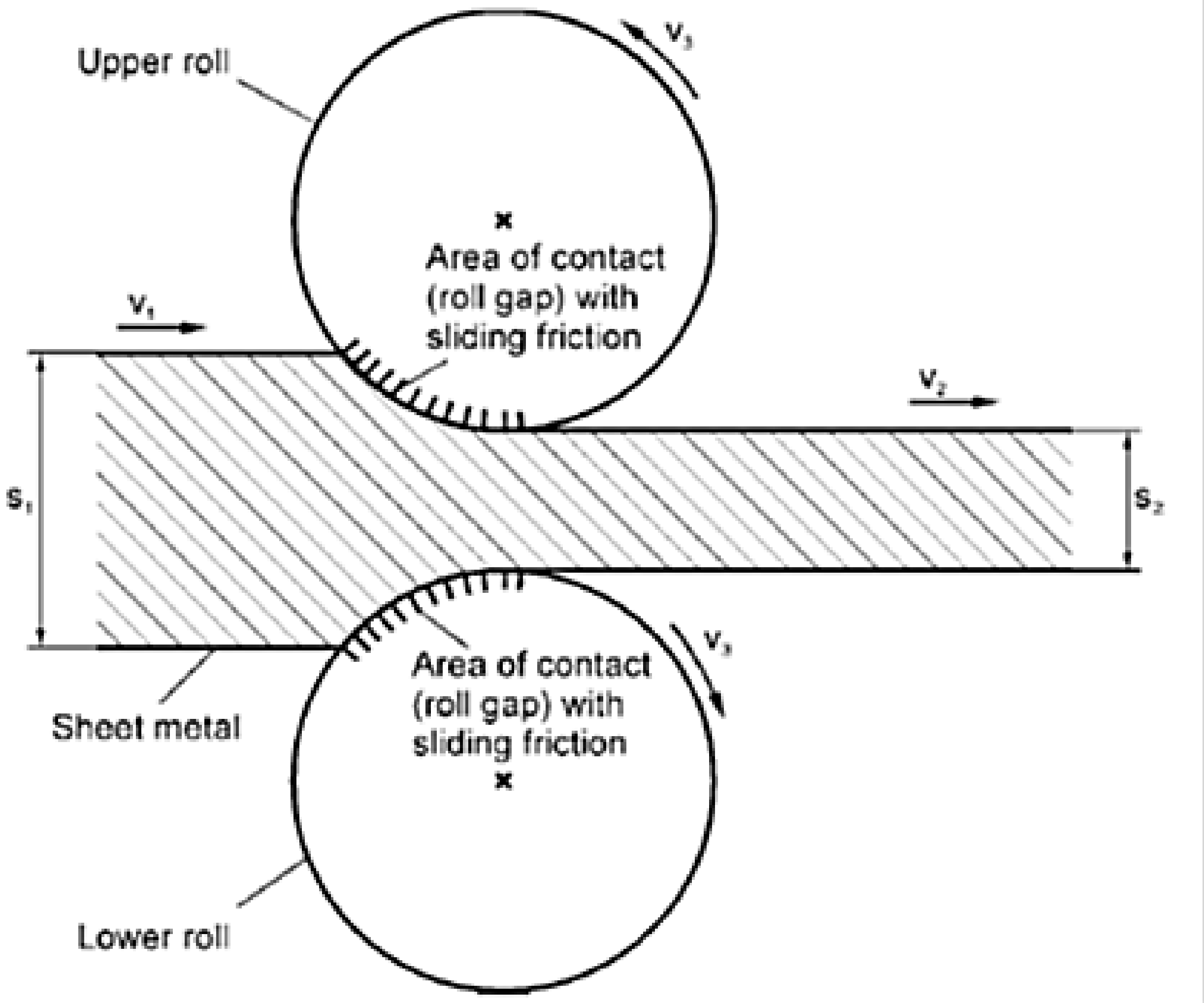
- The metal piece experiences both vertical and horizontal stresses caused by the compressive load from the rolls.
- As the rolls exert a vertical stress on the metal piece, the metal piece exerts the same amount of stress back onto the rolls itself.
- As such the rolls are subjected to elastic deformation due to this stress induced by the workpiece.



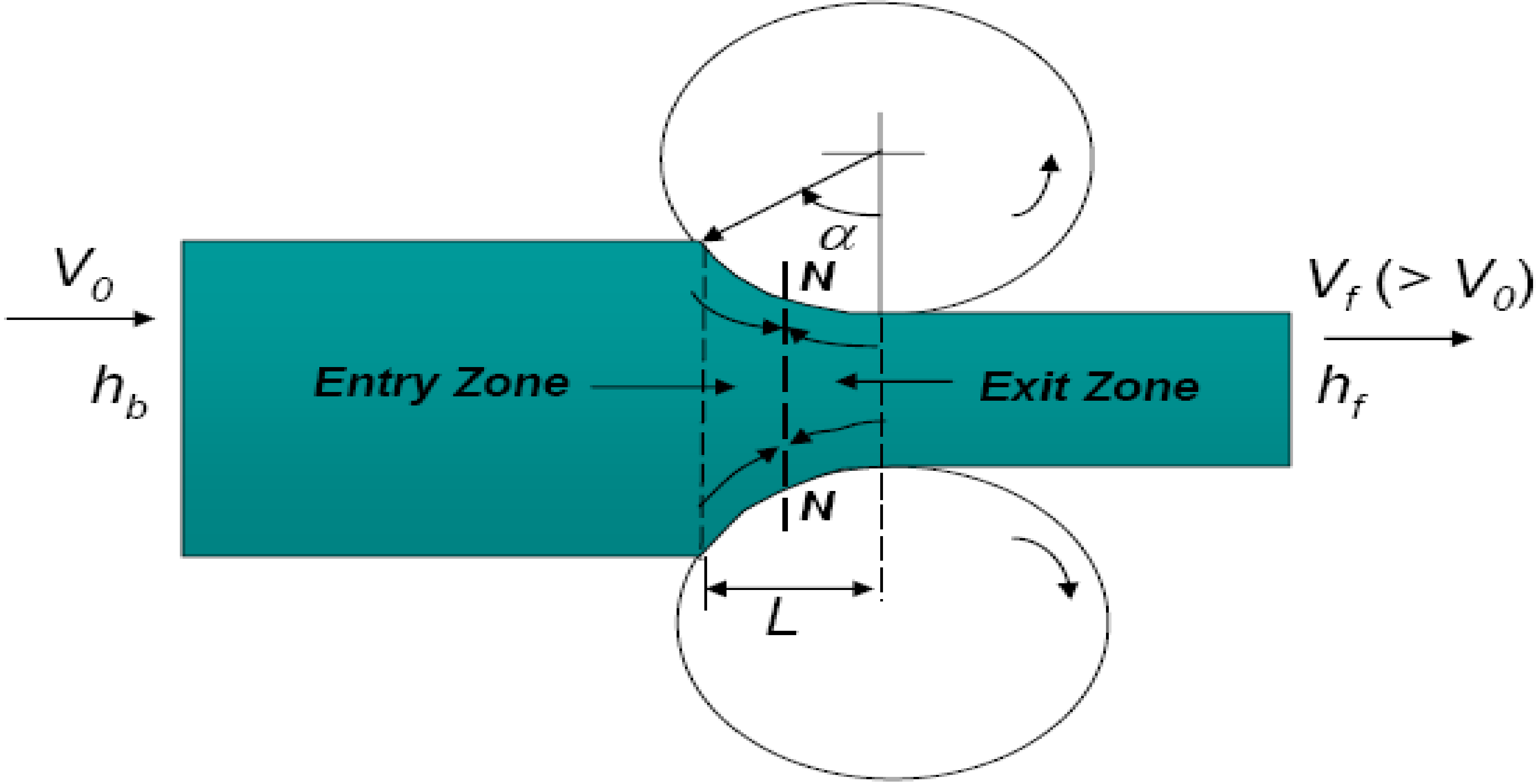
- Rolling basically consists of passing the metal piece through two rolls rotating in opposite directions. The space between the rolls is adjusted to the desired thickness of the rolled section.
- The rolls are in contact with passing metal piece over a sufficient distance represented by the arc AB in the diagram.
- The angle AOB is called Angle of Contact



- The friction between metal piece and rolls provide sufficient grip for the rolls to move the metal piece through the rolls.
- The reduction in thickness increases with coefficient of friction.
- **Friction** is a necessary part of the rolling operation, but too much friction can be detrimental for a variety of reasons.
- It is essential that in a metal rolling process the level of friction between the rolls and work material is controlled, lubricants can help for this.



- The pressure exerted by over the metal by the rolls varies as represented by the pressure distribution curve in the diagram.
- It will be minimum at both the extremities and will be maximum at a point somewhere in the curve.
- The line representing the maximum pressure is called **Neutral or No Slip Line** and the point C is known as **No Slip Point or the Point of Maximum Pressure.**
- At the point C the surface of metal and the roll move at the same speed. Before this point metal moves slower than the rolls. After crossing the rolls metal move at a faster rate



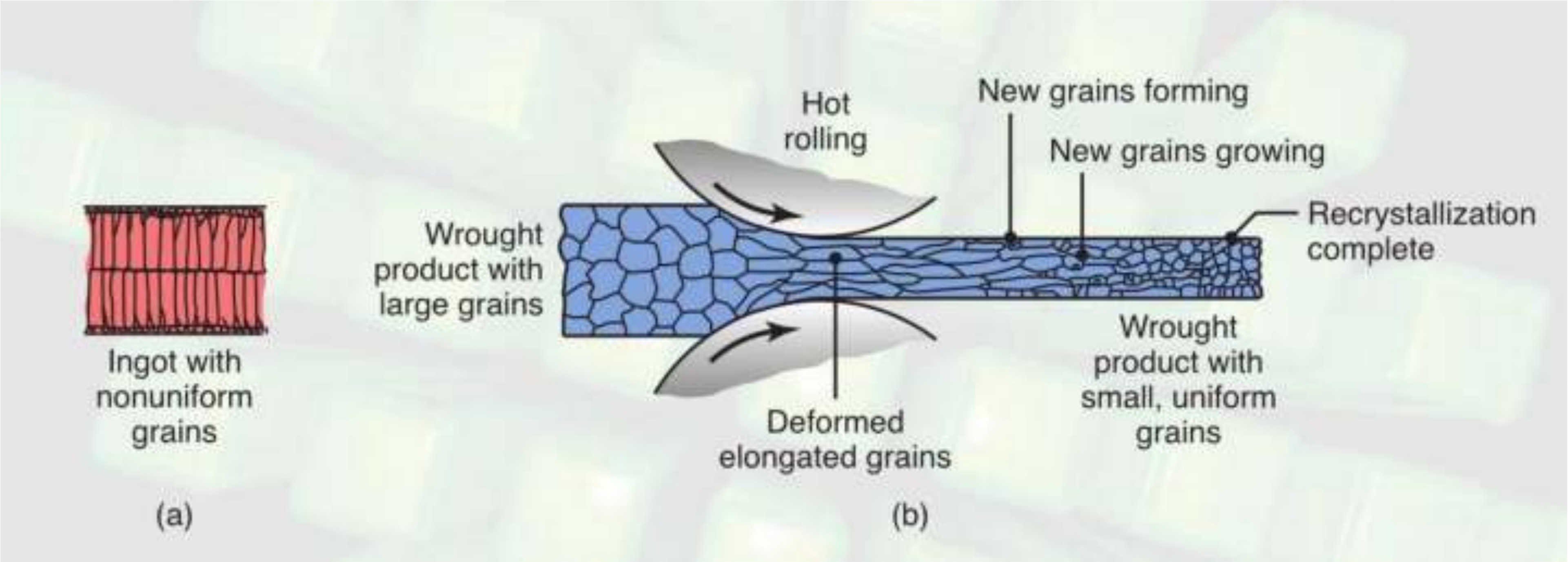
V_o
h_b
α
N
N
Entry Zone
Exit Zone
L
V_f (> V_o)
h_f

Types of Rolling

1. HOT ROLLING

- Hot rolling is a metal working process that occurs above the recrystallization temperature of the material.
- After the grains deform during processing, they recrystallize, which maintains an equiaxed microstructure and prevents the metal from work hardening.
- The starting material is usually large pieces of metal, like semi-finished casting products, such as slabs, blooms, and billets.
- If these products came from a continuous casting operation the products are usually fed directly into the rolling mills at the proper temperature.
- In smaller operations the material starts at room temperature and must be heated.

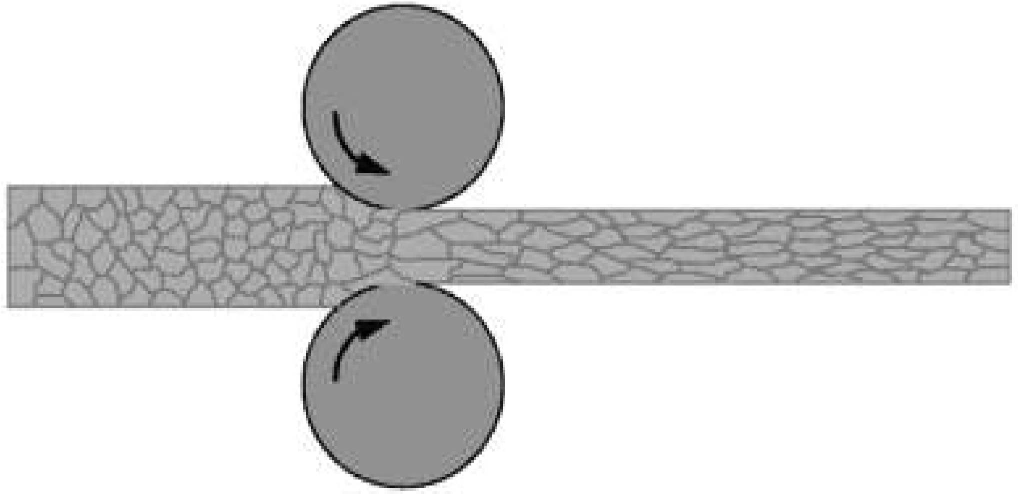
Effects of Hot Rolling



- Changes in the grain structure of cast or of large-grain wrought metals during hot rolling. Hot rolling is an effective way to reduce grain size in metals for improved strength and ductility. Cast structures of ingots or continuous castings are converted to a wrought structure by hot working.

2. COLD ROLLING

- Cold rolling occurs with the metal below its recrystallization temperature (usually at room temperature), which increases the strength via strain hardening up to 20%.
- It also improves the surface finish and holds tighter tolerances Commonly cold-rolled products include sheets, strips, bars, and rods; these products are usually smaller than the same products that are hot rolled.



Cold work being rolled into copper alloy strip.

- Cold rolling cannot reduce the thickness of a work piece as much as hot rolling in a single pass.
- Cold-rolled sheets and strips come in various conditions: full-hard, half-hard, quarter-hard, and skin-rolled.
- Full-hard rolling reduces the thickness by 50%, while the others involve less of a reduction.
- Skin-rolling, also known as a skin-pass, involves the least amount of reduction: 0.5-1%.
- It is used to produce a smooth surface, a uniform thickness.

Hot Rolling

- Metal heated above its recrystallization temperature.
- No strain hardening.
- Co-efficient of friction between the rolls is higher.
- Heavy Reduction in Area is obtained.
- Blow holls and similar defects are removed.
- Roll radius is larger.
- Hot rolled sheets less than 1.25 mm is not economical.
- Residual Stresses are less.

Cold Rolling

- Metal heated below its recrystallization temperature.
- Strain /Work hardening.
- Lesser co-efficient of friction.
- Heavy Reduction in Area not obtained.
- Excessive Cold Rolling generates cracks.
- Roll Radius smaller.
- Thin Sections can be obtained (0.002mm)
- Residual Stresses are more due to deformation of crystals and work hardening effect.

Types of rolls and rolling mills

Rolling Machines

- A wide variety of rolling equipment is available with a number of roll arrangement.
- Small diameter rolls are preferable, because the smaller the radius , the lower the roll force.
- However, small rolls deflect under roll forces and have to be supported by other rollers.

Rolling Mills

Rolling mill is a machine or a factory for shaping metal by passing it through rollers

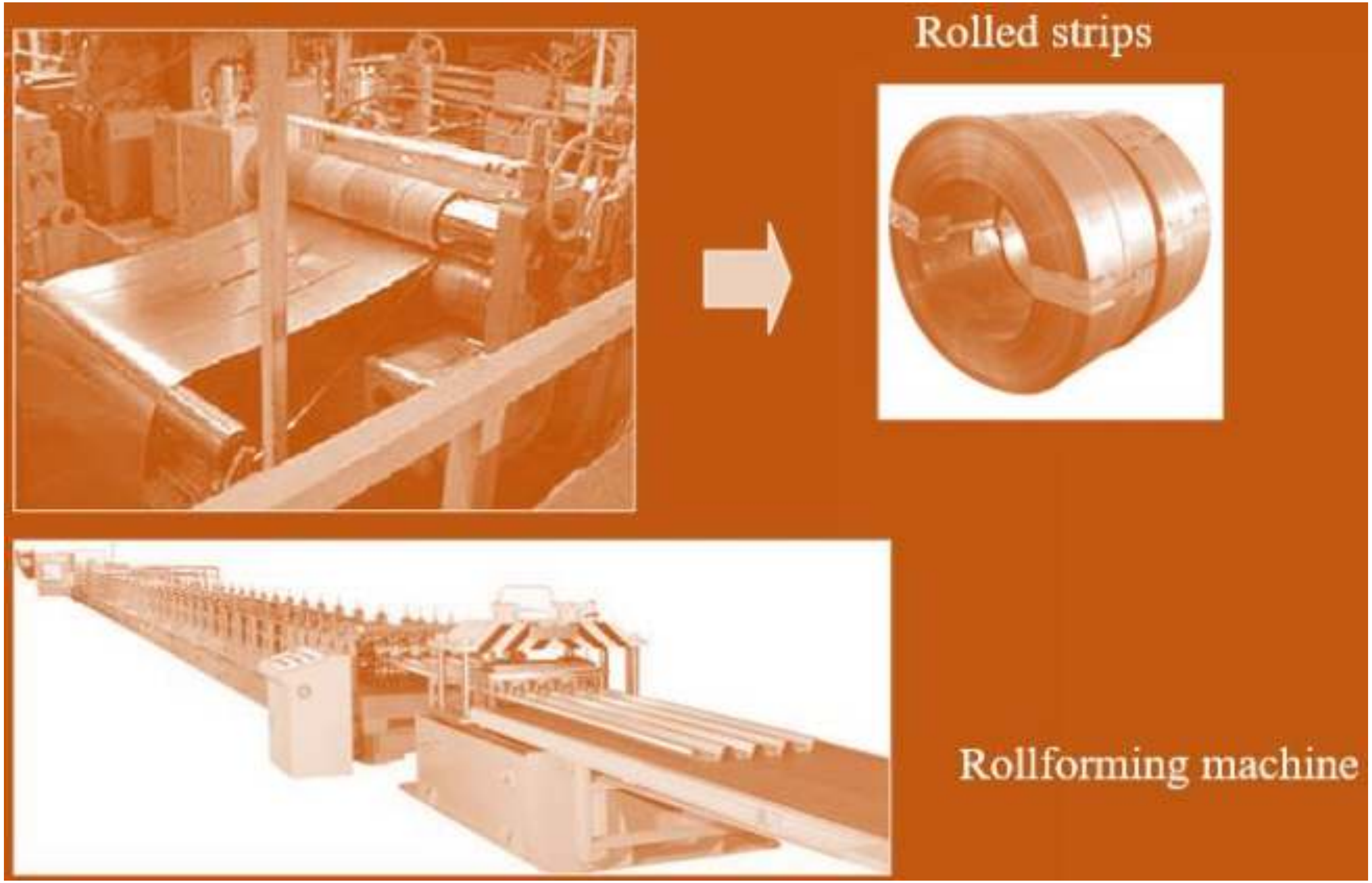
A rolling mill basically consists of

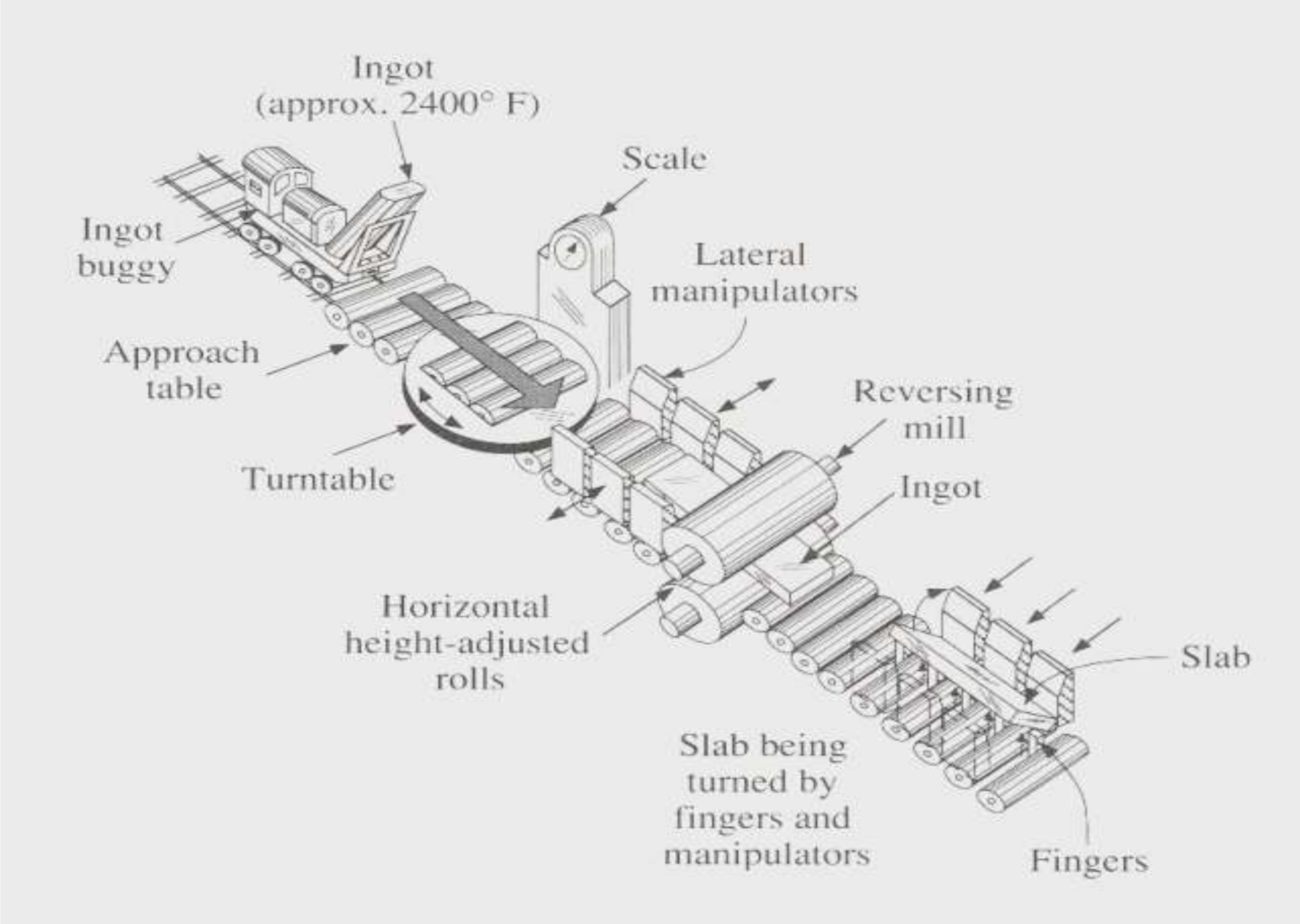
- rolls
- bearings
- a housing for containing these parts
- a drive (motor) for applying power to the rolls and controlling the speed

- Modern rolling mill requires
  - Very rigid construction,
  - Large motors to supply enough power (MN),
  - Successive stands of a large continuous mill,
  - Engineering design,
  - Construction,
  - Huge capital investment,

- Several types of rolling mills and equipment are available with diverse roll arrangements.
- Although the equipment for hot and cold rolling is essentially the same, there are important differences in the roll materials, process parameters, lubricants, and cooling systems.
- The design, construction, and operation of rolling mills require major investments. Highly automated mills produce close tolerance, high quality plates and sheets at high production rates and low cost per unit weight, particularly when integrated with continuous casting.
- Rolling speeds may range up to 40 m/s.
- The width of rolled products may range up to 5 m.
- The basic requirements for roll materials are strength and resistance to wear. Common roll materials are cast iron, cast steel, and forged steel; tungsten carbide is also used for small-diameter rolls, such as the working roll in the cluster mill.

- Sheet Rolling Machine



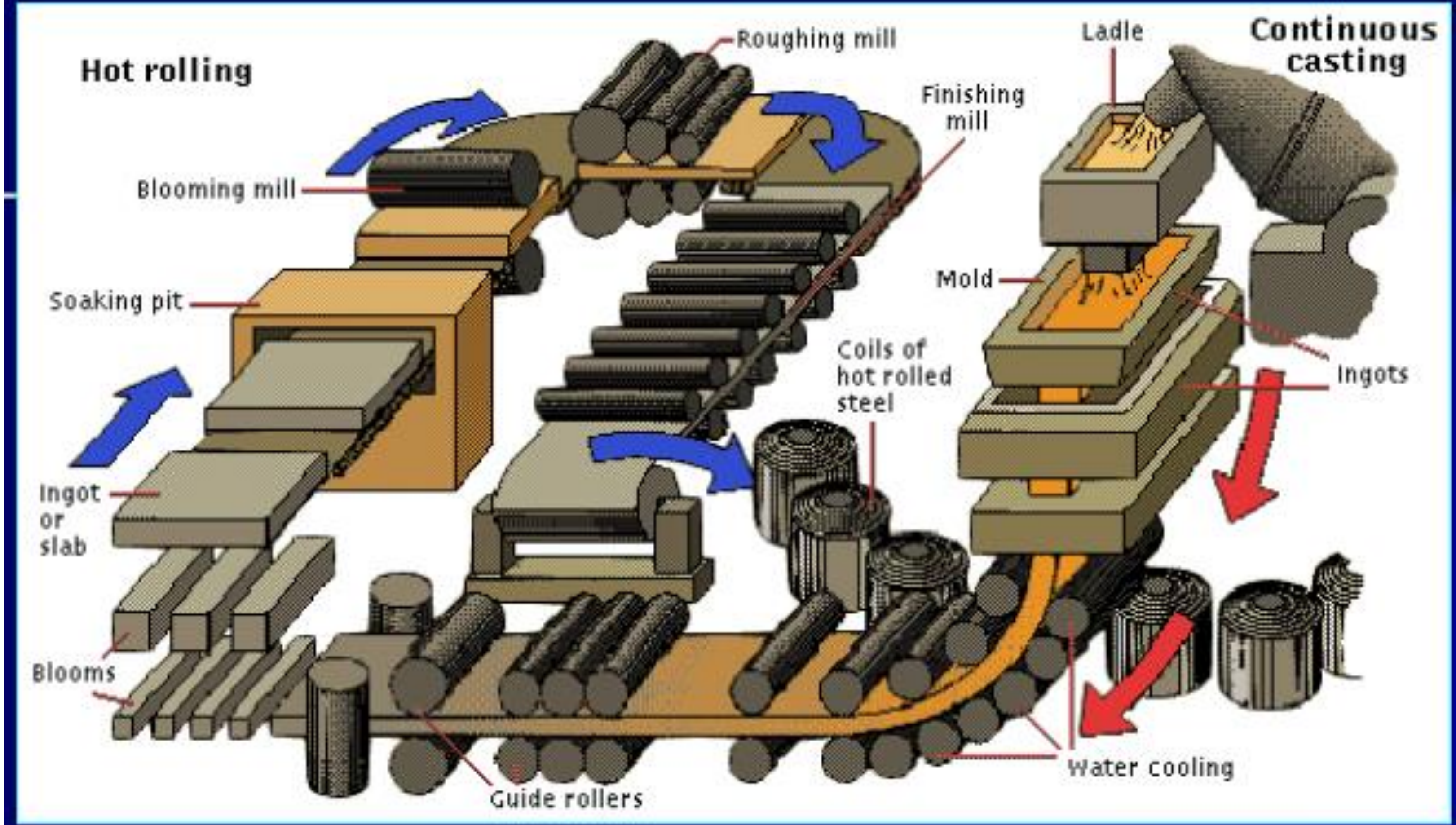


Commercial rolling mill


MACHINERY
TECHNOLOGY


SMS

Continuous casting and hot rolling

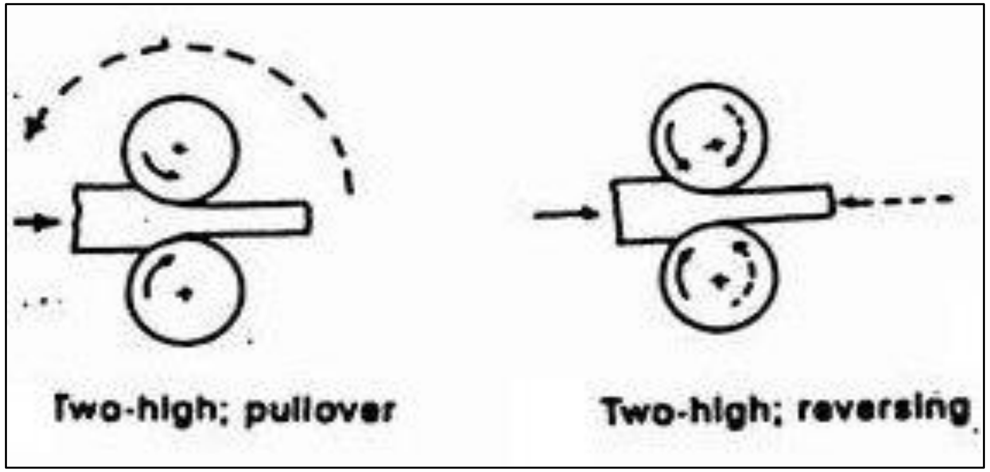


- Metal is ***melted, cast and hot rolled*** continuously through a series of rolling mills within the same process.
- Usually for steel sheet production.

ROLLING MILLS-TYPES

1. Two High Mill

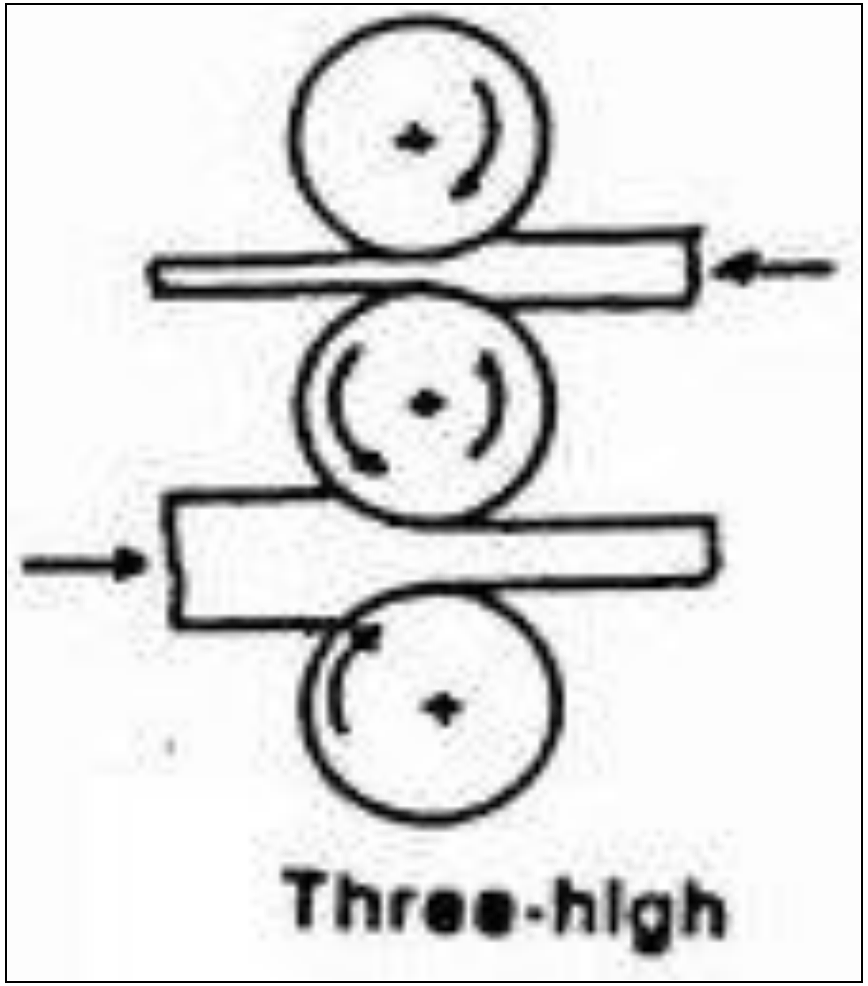
- This is the simplest and most common type of rolling.
- These are further classified as reversing and non reversing mills.
- In non reversing mills, rolls of equal size are rotated only in one direction
- In two high reversing mill the work can be passed to and fro through the rolls by reversing their direction of rotation.
- The space between the rolls can be adjusted by raising or lowering the upper roll.
- Used for hot rolling in initial breakdown passes (primary roughing or cogging mills) on cast ingots or in continuous casting, with roll diameters ranging from 0.6 to 1.4 m.



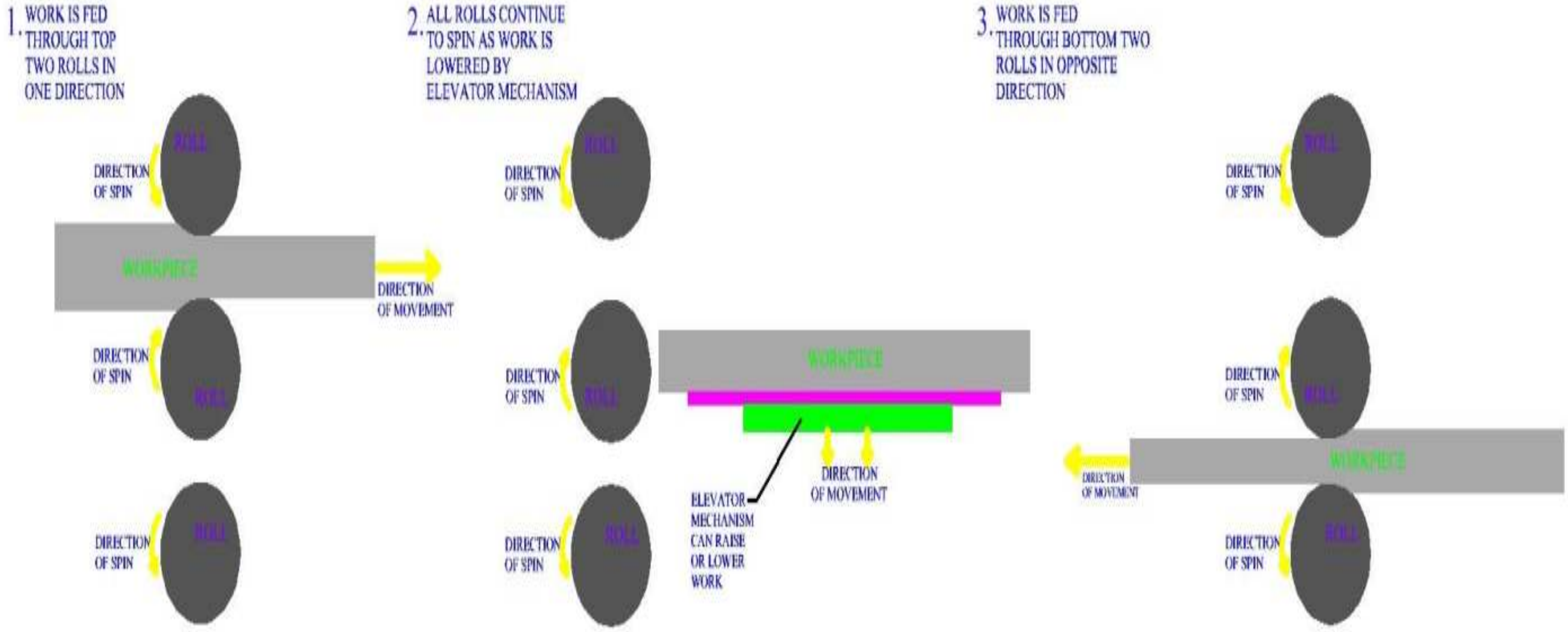

TWO HIGH ROLLING MILL

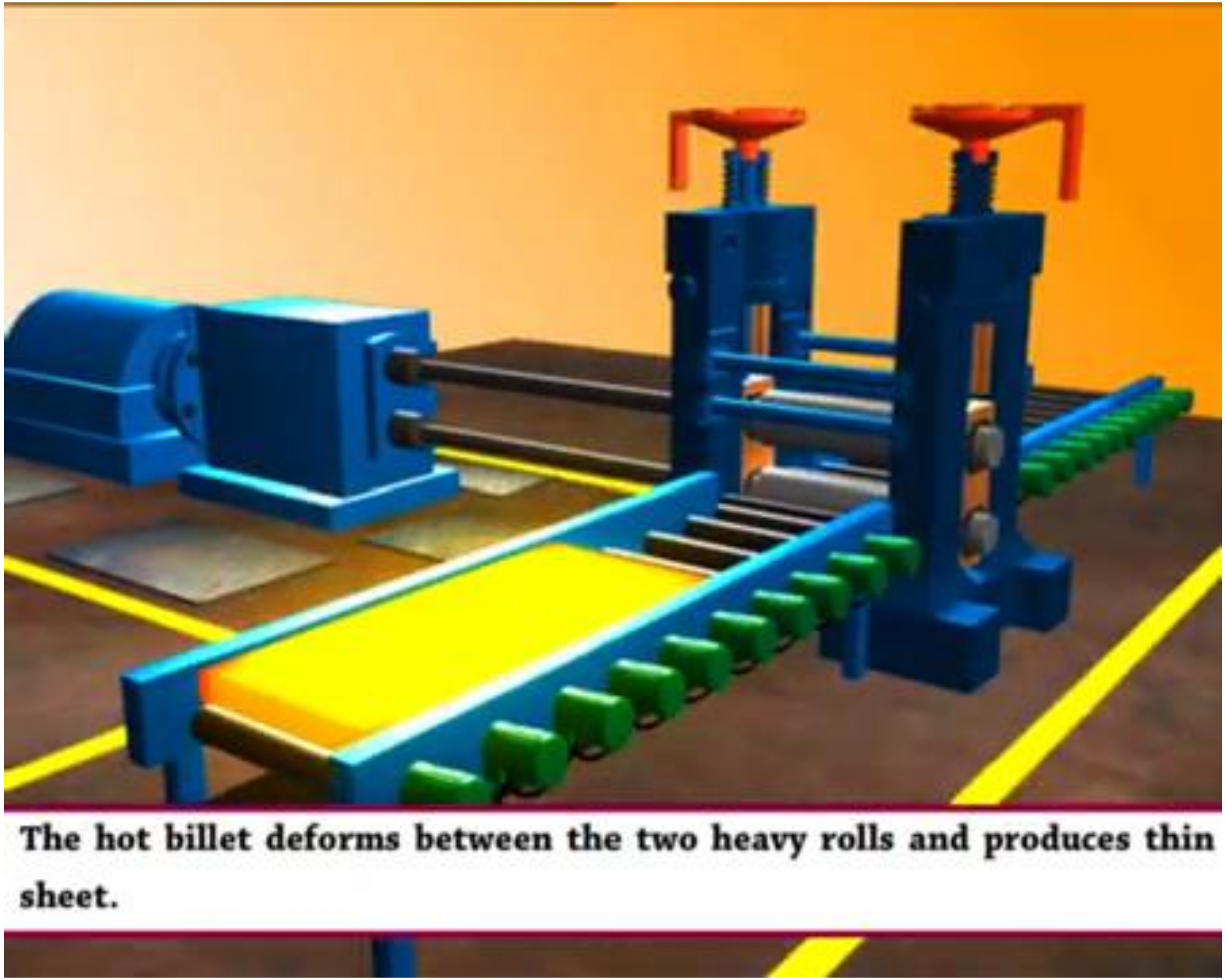
2. Three High Mill

- This consists of three rolls of equal size one above the other. In the upper and lower rolls are power driven, while the middle roll rotates by friction.
- The direction of upper and lower rolls are the same.
- Used for the production of steel shapes such as I-beams, angles, channels etc.
- In the three-high mill (reversing Mill) the direction of material movement is reversed after each pass, using elevator mechanisms and various manipulators. The plate being rolled, which may weigh as much as 160 tons, is raised repeatedly to the upper roll gap, rolled, then lowered to the lower roll gap, rolled, and so on.



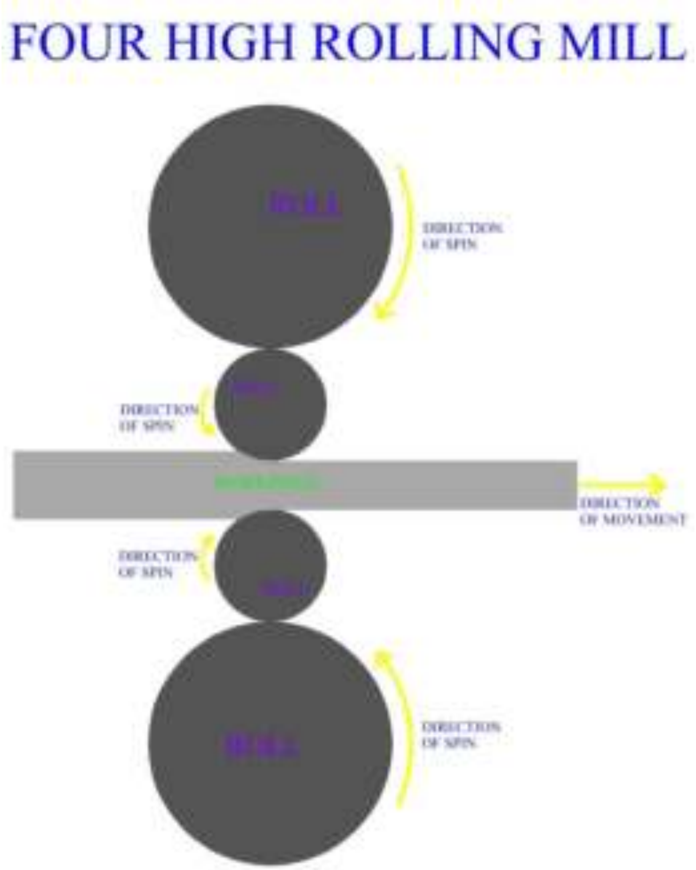
THREE HIGH ROLLING MILL

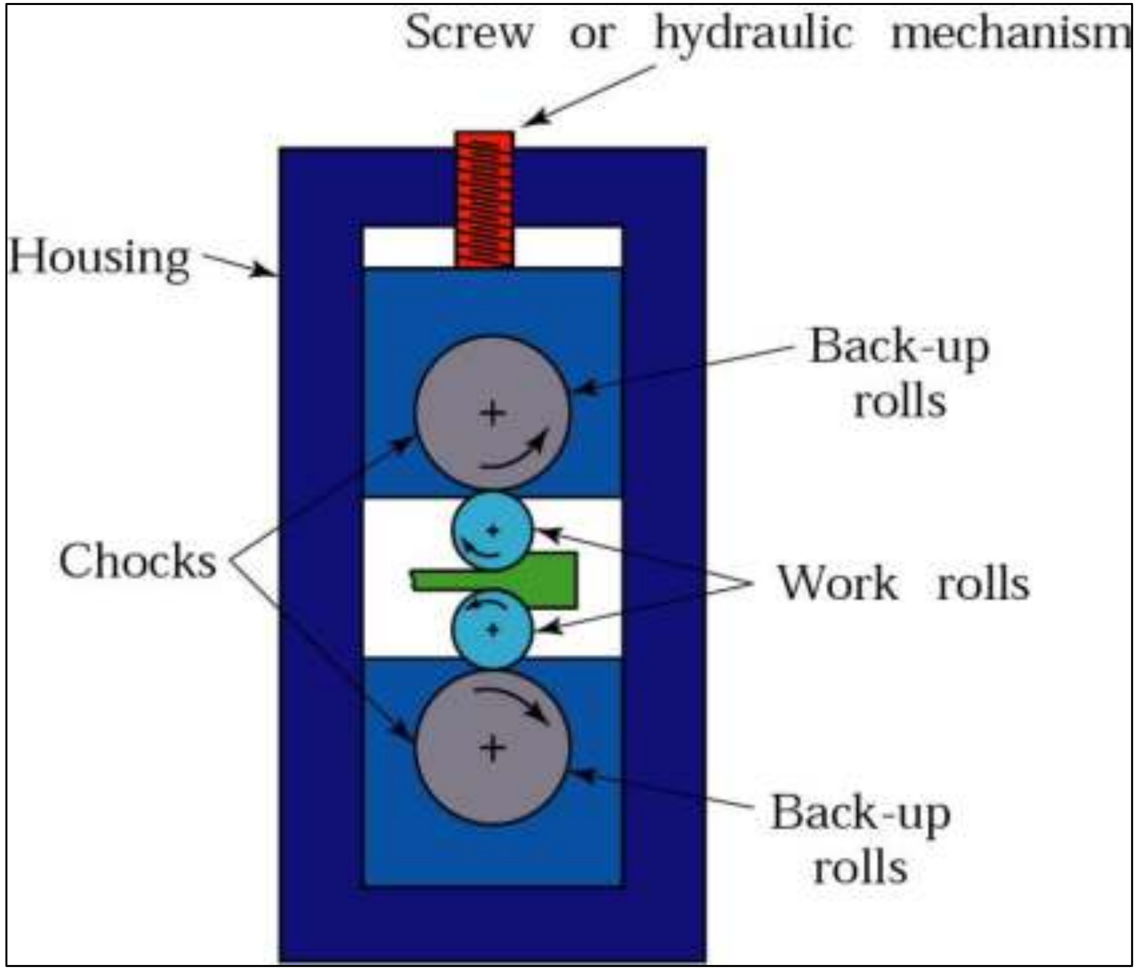



The hot billet deforms between the two heavy rolls and produces thin sheet.

3. Four High Mill

- This consists of two small diameter working rolls and two large diameter backup rolls placed one above the other.
- The larger diameter called as Backup rolls and its function is to prevent the deflection of small rolls
- The smaller rolls are called as Working rolls.
- When worn or broken, small rolls can be replaced at lower cost than can large ones.
- Generally used for sheet rolling
- Used for slab production.
- Are based on the principle that small-diameter rolls lower roll forces (because of small roll strip contact area) and power requirements and reduce spreading.
- Suitable for cold rolling thin sheets of high-strength metals. Common rolled widths in this mill are 0.66 m (26 in.), with a maximum of 1.5 m.



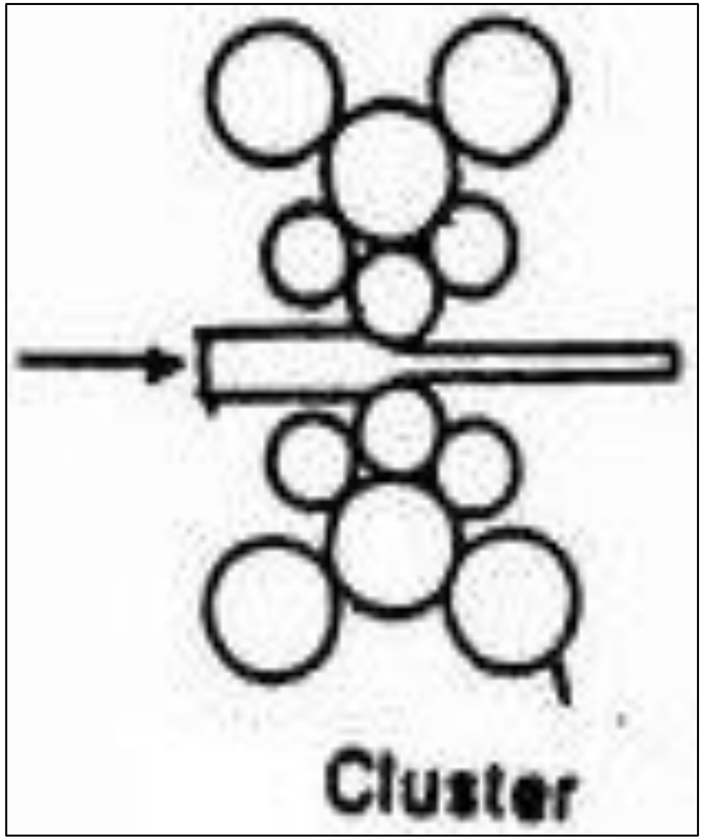


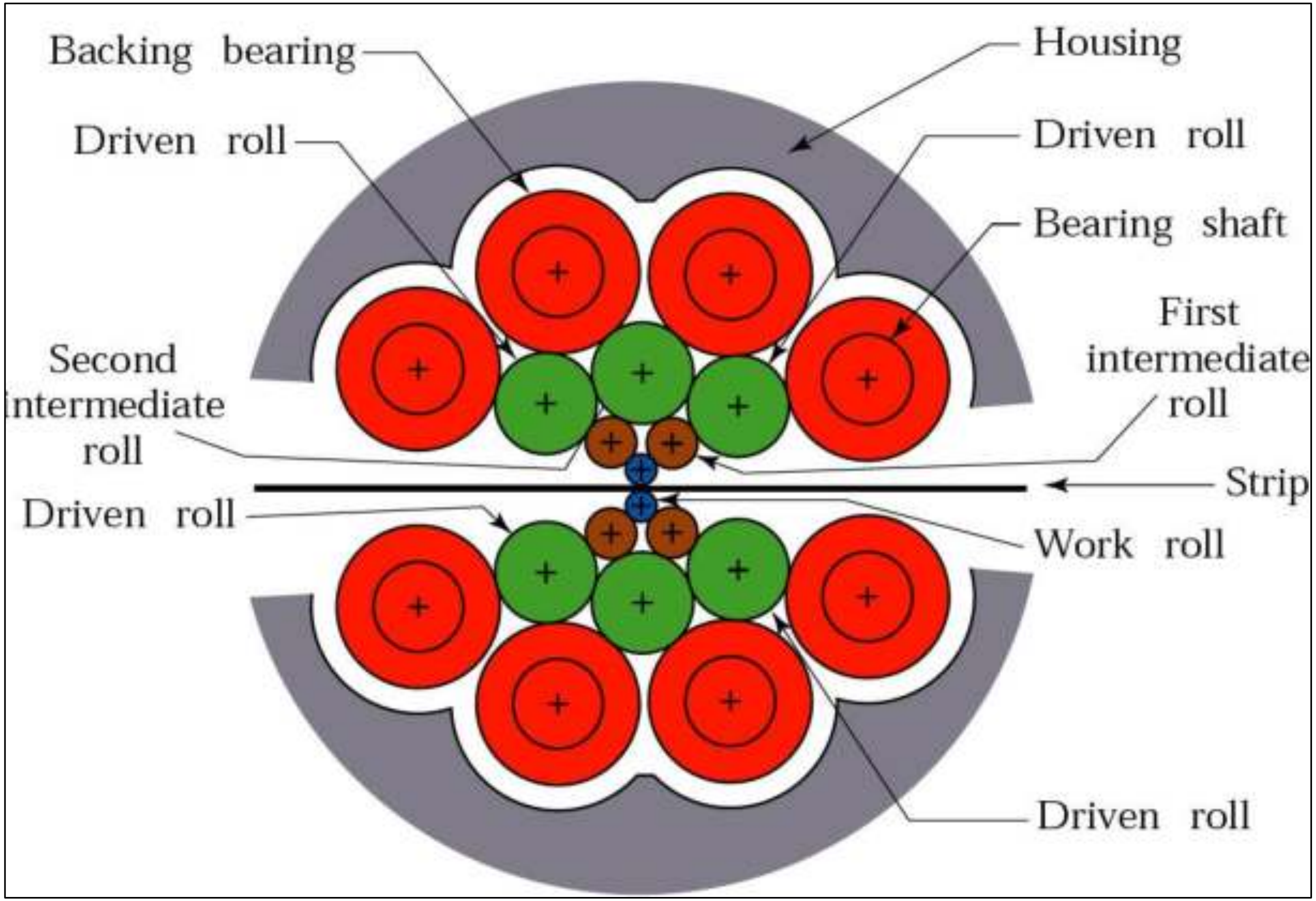
Schematic illustration of a four-high rolling-mill stand, showing its various features. The stiffnesses of the housing, the rolls, and the roll bearings are all important in controlling and maintaining the thickness of the rolled strip.

FOUR HIGH ROLLING MILL

4. Cluster Mill

- Each of the work rolls (which are Power driven) are supported by two backing rolls.
- Used for the production of thin sheet.
- Are based on the principle that small-diameter rolls lower roll forces (because of small roll strip contact area) and power requirements and reduce spreading.

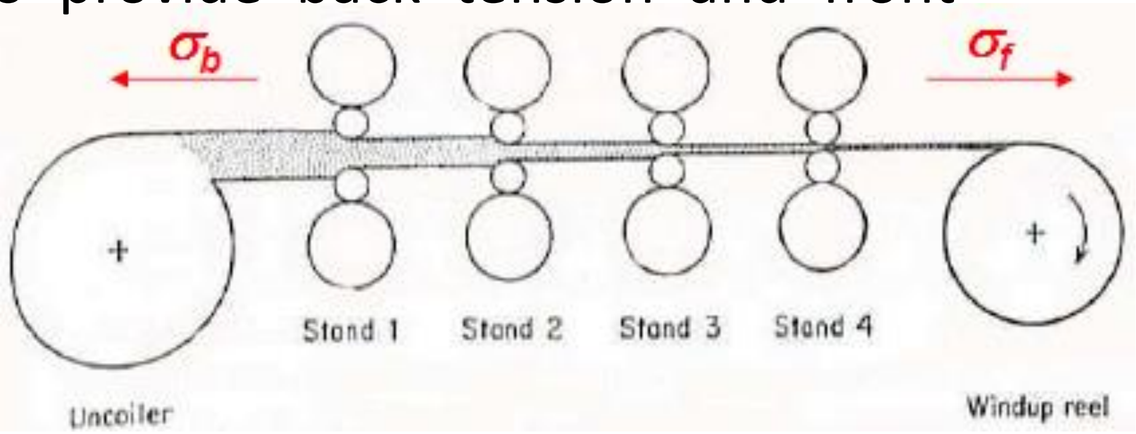


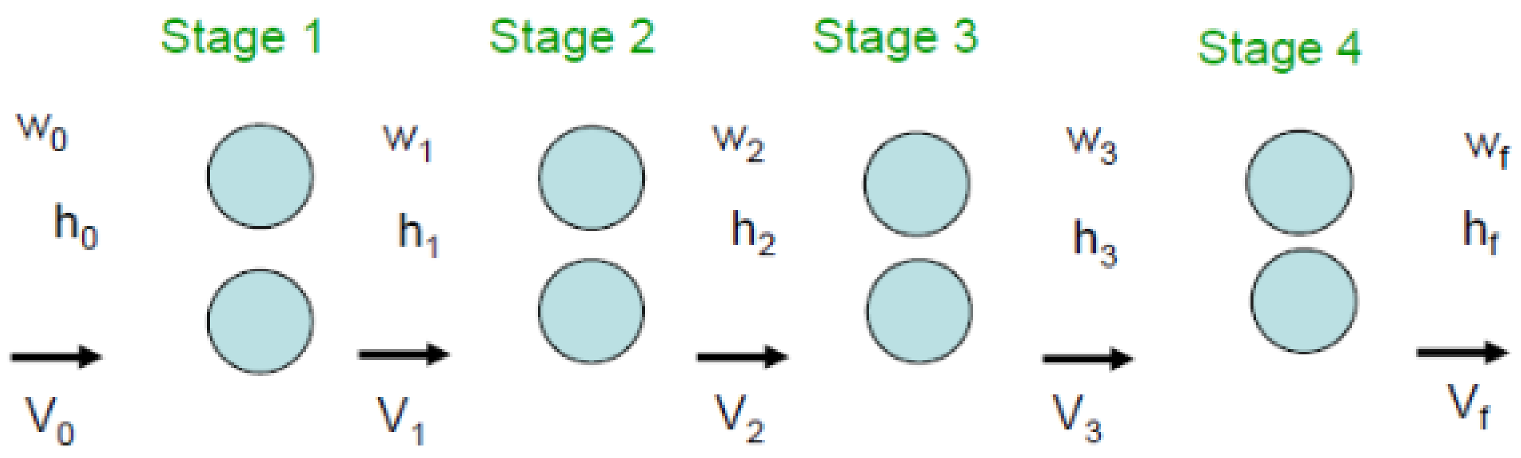


Schematic illustration of cluster (Sendzimir) mill

5. Tandem Mill

- In this, a series of rolling mills are arranged one after the other, to facilitate high production.
- Use a series of rolling mill and each set is called a stand.
- A group of stands is called a train.
- The strip will be moving at different velocities at each stage in the mill.
- The speed of each set of rolls is synchronised so that the input speed of each stand is equal to the output speed of preceding stand.
- The uncoiler and windup reel not only feed the stock into the rolls and coiling up the final product but also provide back tension and front tension to the strip.





Volume conserved

$$h_0 V_0 w_0 = h_1 V_1 w_1 = h_2 V_2 w_2 = h_3 V_3 w_3 = h_f V_f w_f$$

Rolling schedules

Equal drafts

$$h_0 - h_1 = h_1 - h_2 = h_2 - h_3 = h_3 - h_f$$

Equal strains

$$\ln \frac{h_0}{h_1} = \ln \frac{h_1}{h_2} = \ln \frac{h_2}{h_3} = \ln \frac{h_3}{h_f}$$

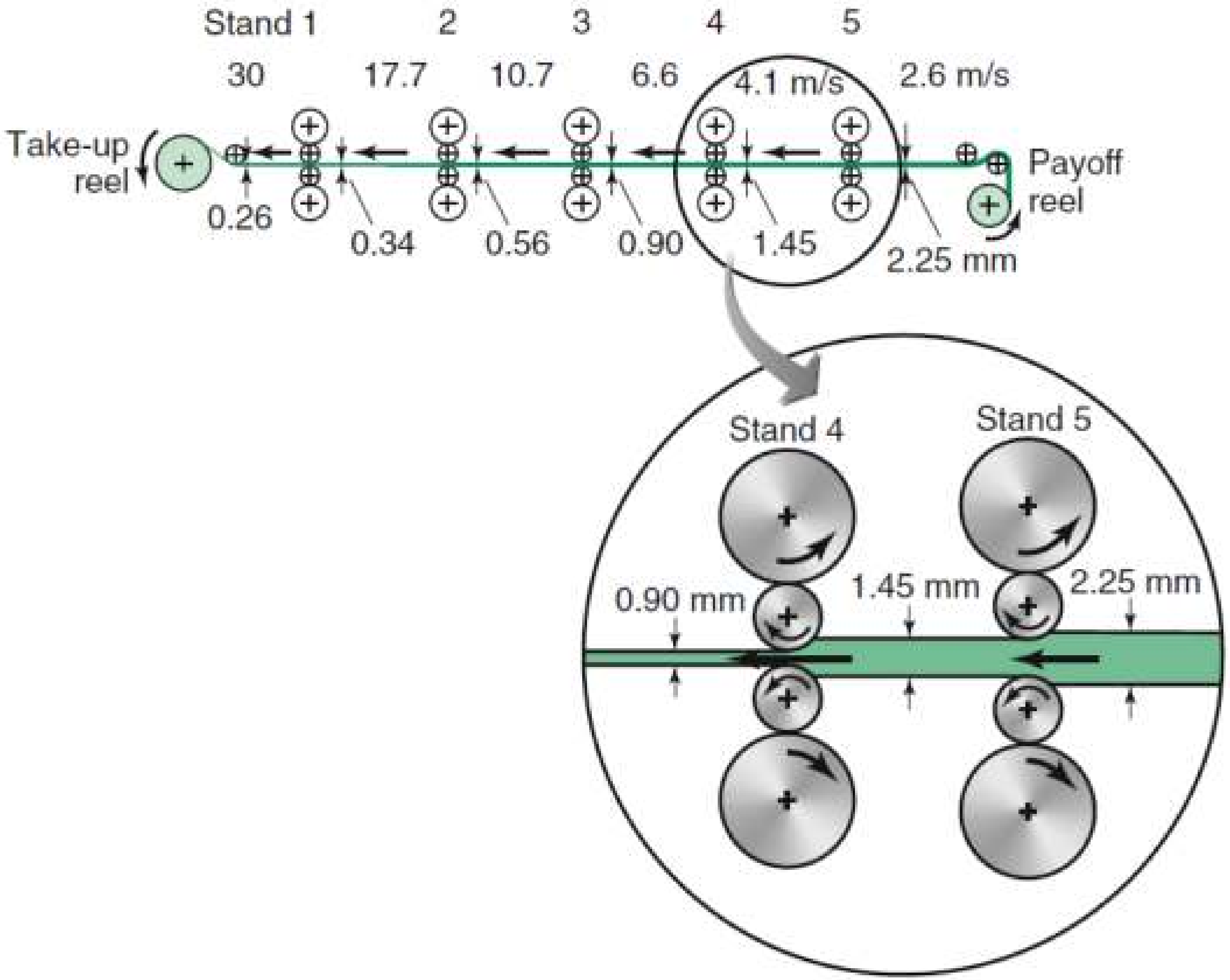
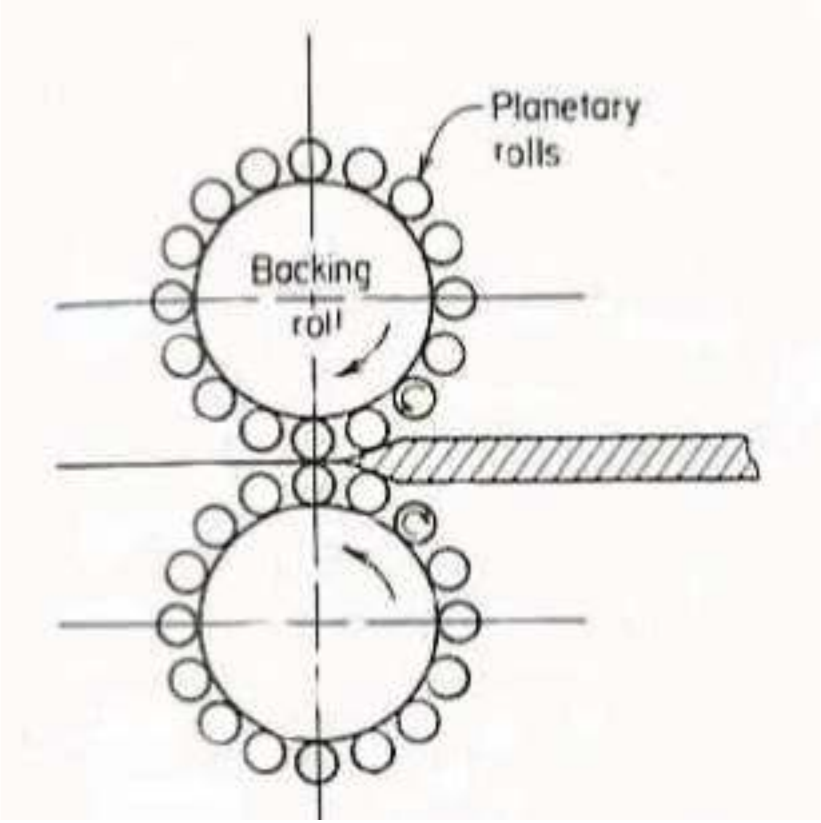


FIGURE 13.11 An example of a tandem-rolling operation.

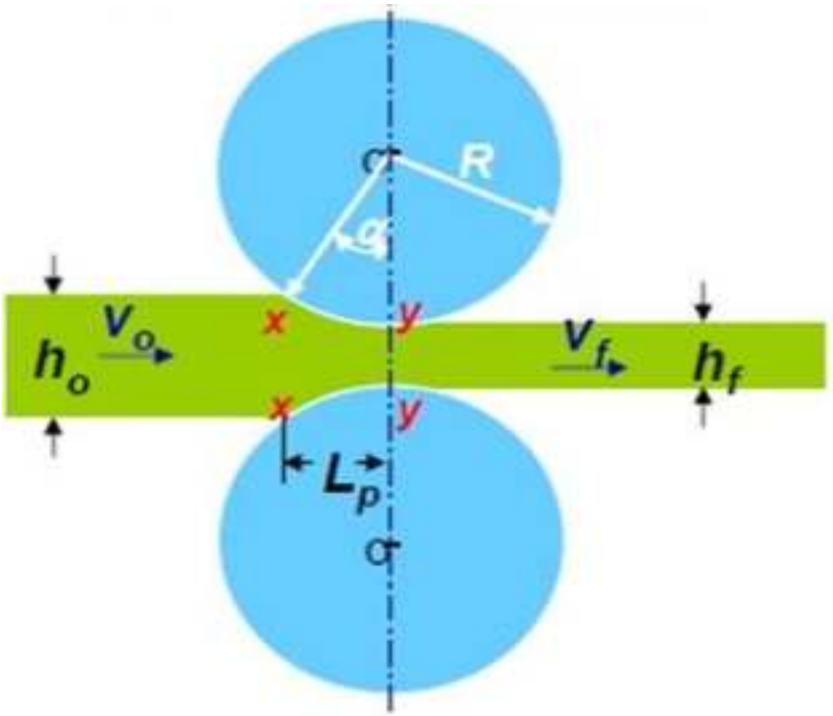
7. Planetary Mills

- Consist of a pair of heavy backing rolls surrounded by a large number of planetary rolls.
- Each planetary roll gives an almost constant reduction to the slab as it sweeps out a circular path between the backing rolls and the slab. As each pair of planetary rolls ceases to have contact with the work piece, another pair of rolls makes contact and repeat that reduction.
- The overall reduction is the summation of a series of small reductions by each pair of rolls. Therefore, the planetary mill can not reduces a slab directly to strip in one pass through the mill.
- The operation requires feed rolls to introduce the slab into the mill.

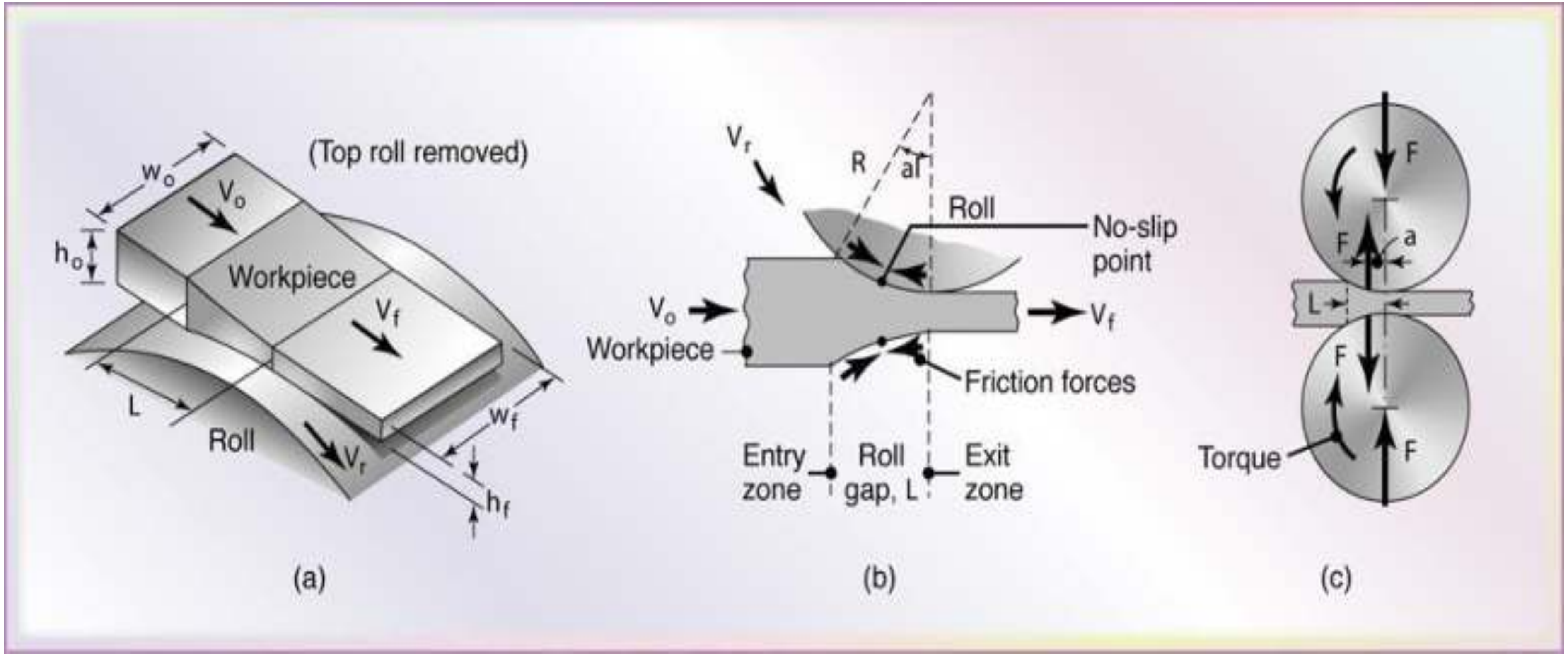


Fundamental concept of metal rolling

- Assumptions
  - The arc of contact between the rolls and the metal is a part of a circle.
  - The coefficient of friction, μ, is constant in theory, but in reality μ varies along the arc of contact.
  - The metal is considered to deform plastically during rolling.
  - The volume of metal is constant before and after rolling. In practical the volume might decrease a little bit due to close-up of pores.
  - The velocity of the rolls is assumed to be constant.
  - The metal only extends in the rolling direction and no extension in the width of the material.
  - The cross sectional area normal to the rolling direction is not distorted.

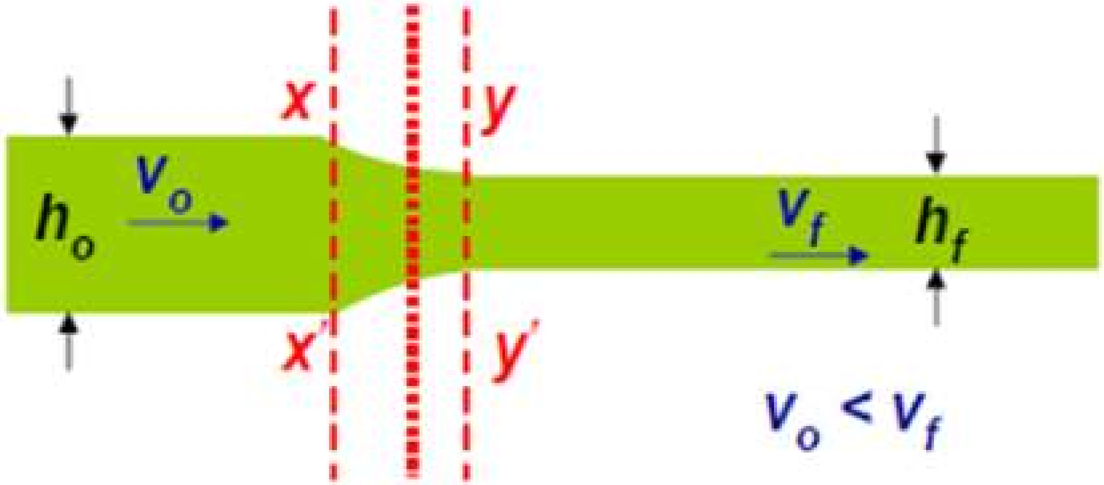


Mechanics of flat rolling



(a) Schematic illustration of the flat-rolling process.
(b) Friction forces acting on strip surfaces.
(c) Roll force, F, and the torque, T, acting on the rolls. The width of the strip, w, usually increases during rolling

- Flat rolling is the most basic form of rolling with the starting and ending material having a rectangular cross-section.
- The material is fed in between two *rollers*, called *working rolls*, that rotate in opposite directions.
- The gap between the two rolls is less than the thickness of the starting material, which causes it to deform.
- The decrease in material thickness causes the material to elongate.
- The friction at the interface between the material and the rolls causes the material to be pushed through.

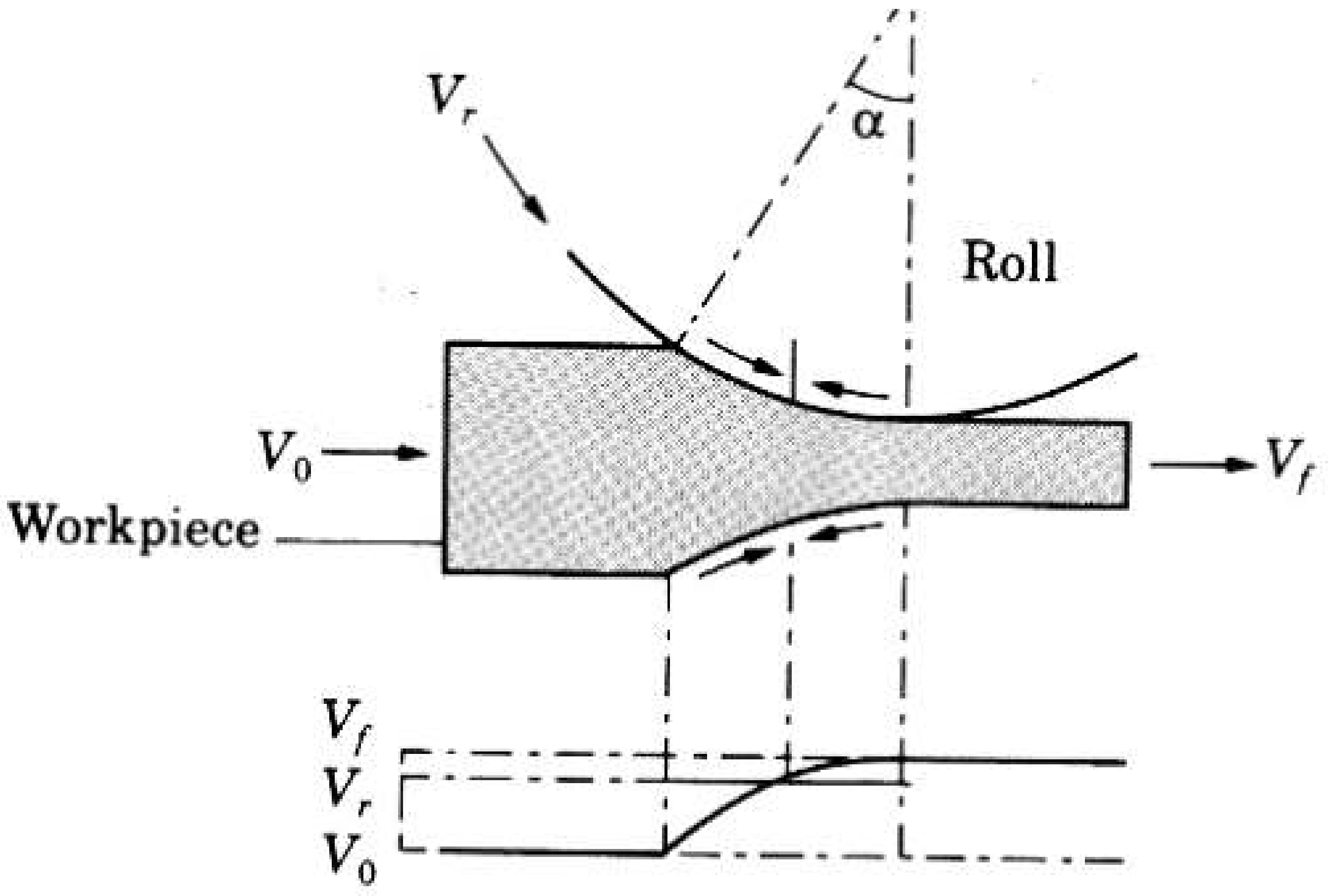


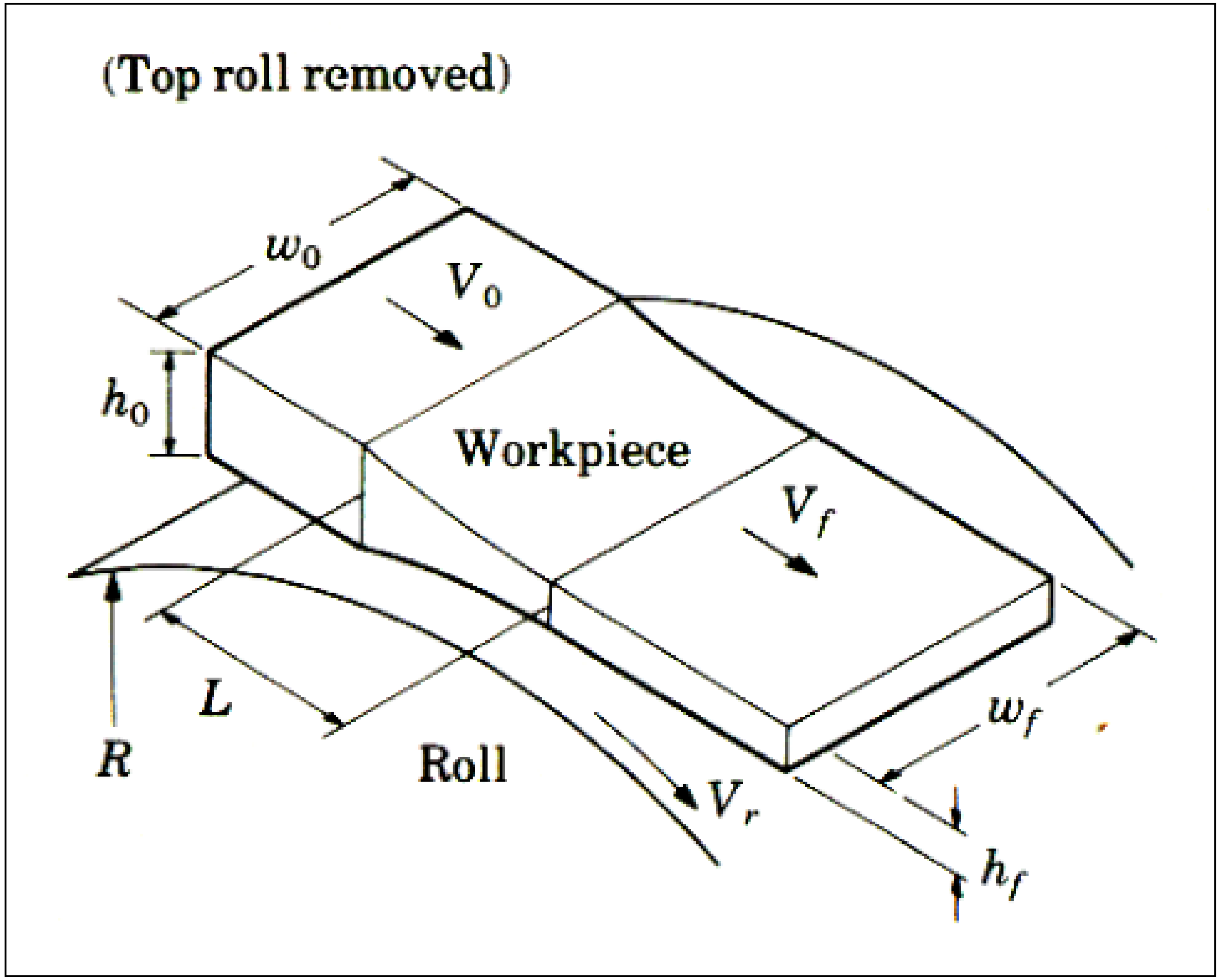
- A metal sheet with a thickness h_0 enters the rolls at the entrance plane with a velocity V_o.
- It passes through the roll gap and leaves the exit plane with a reduced thickness h_f and at a velocity V_f.
- Given that there is no increase in width, the vertical compression of the metal is translated into an elongation in the rolling direction.
- Since there is no change in metal volume at a given point per unit time (**volume rate of metal flow constant**) throughout the process, therefore,

$$h_0 V_0 w_0 = h_f V_f w_f$$

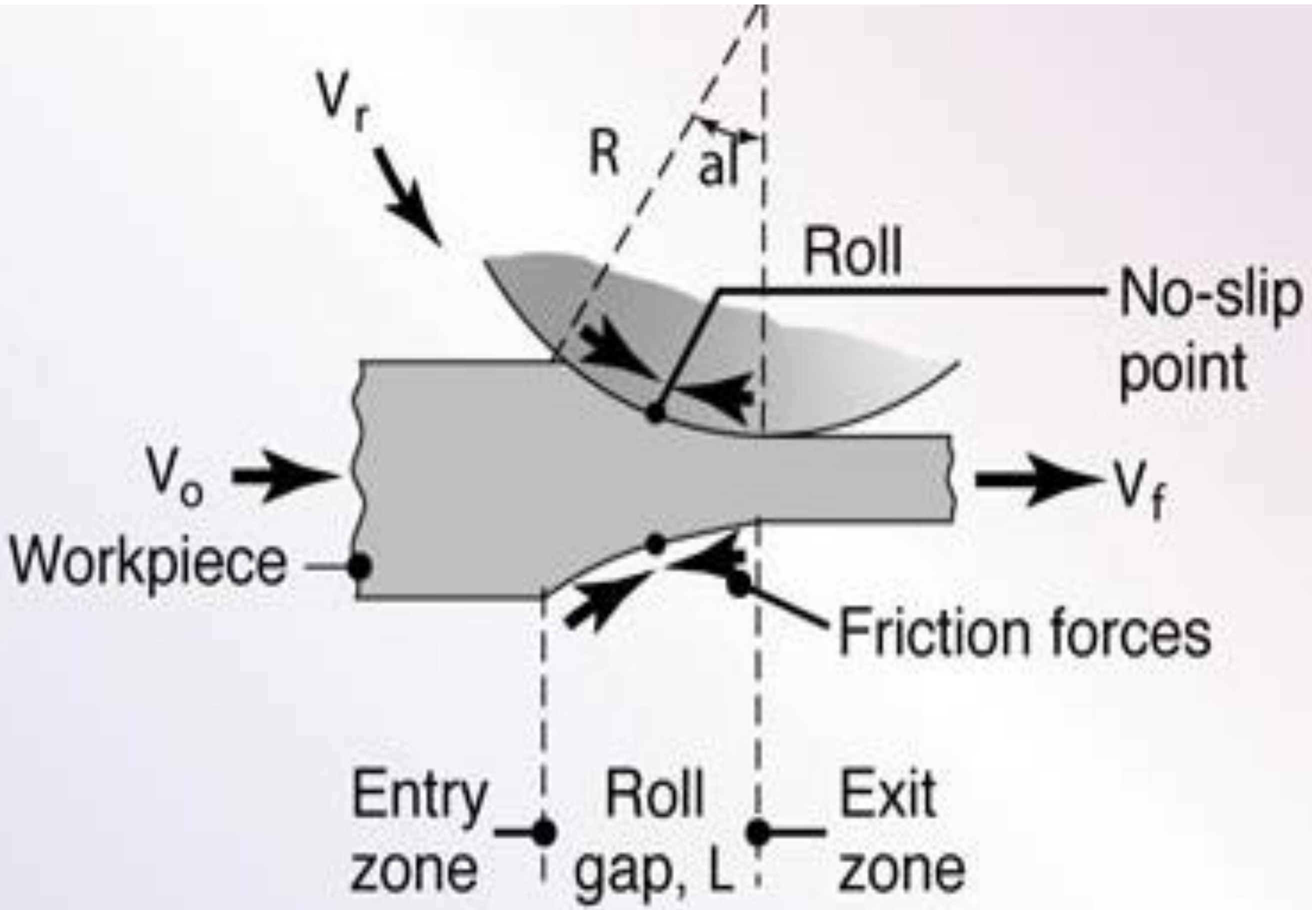
- When $h_0 > h_f$, we then have $V_0 < V_f$
- The velocity of the sheet must steadily increase from entrance to exit such that a vertical element in the sheet remain undistorted.

- Because velocity of roller (V_r) is constant along the roll gap, but strip velocity increases as it passes through the roll gap, sliding occurs between the roll and the strip.
- But at one point along the arc of contact, however the two velocities are the same.
- This point is called **Neutral point or no slip point.**
- **To the left of this point , the roll moves faster than the w/p.**
- **And to the right the w/p moves faster than the roll.**



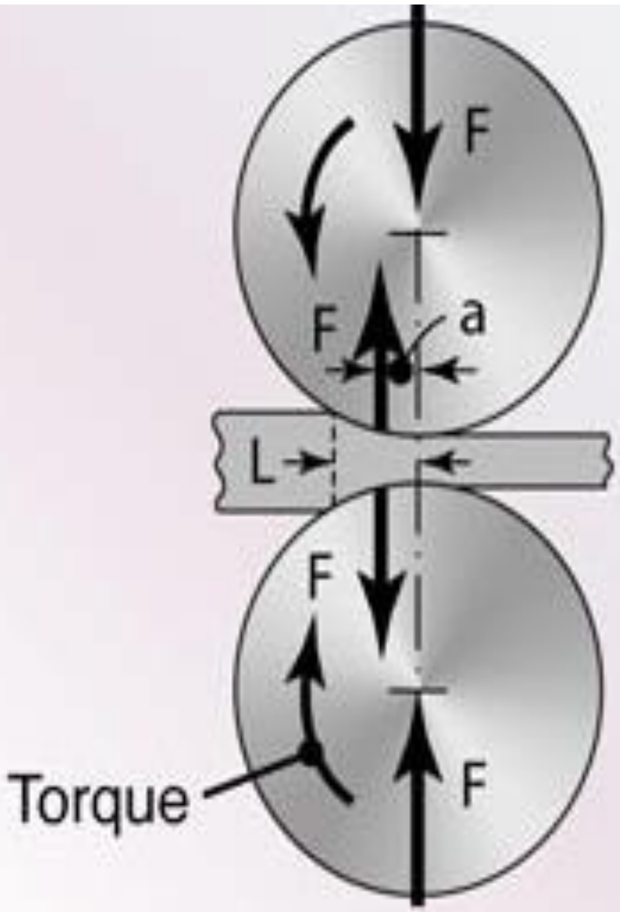


Schematic Illustration of the Flat-Rolling Process



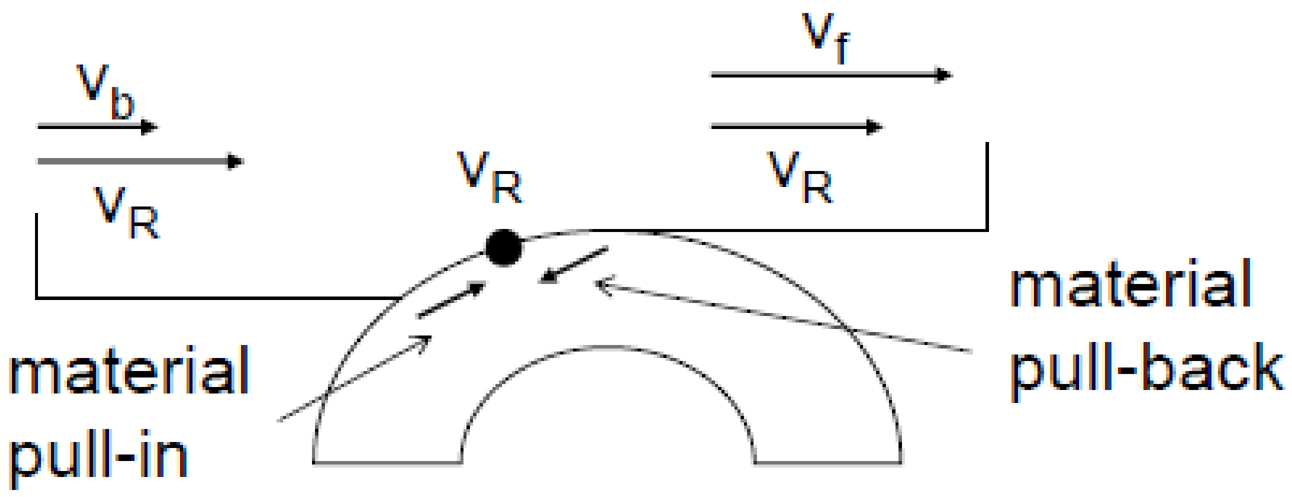
V_r
R
al
Roll
No-slip point
V_o
Workpiece
V_f
Friction forces
Entry zone
Roll gap, L
Exit zone
F
F
a
L
F
F
Torque

(b)

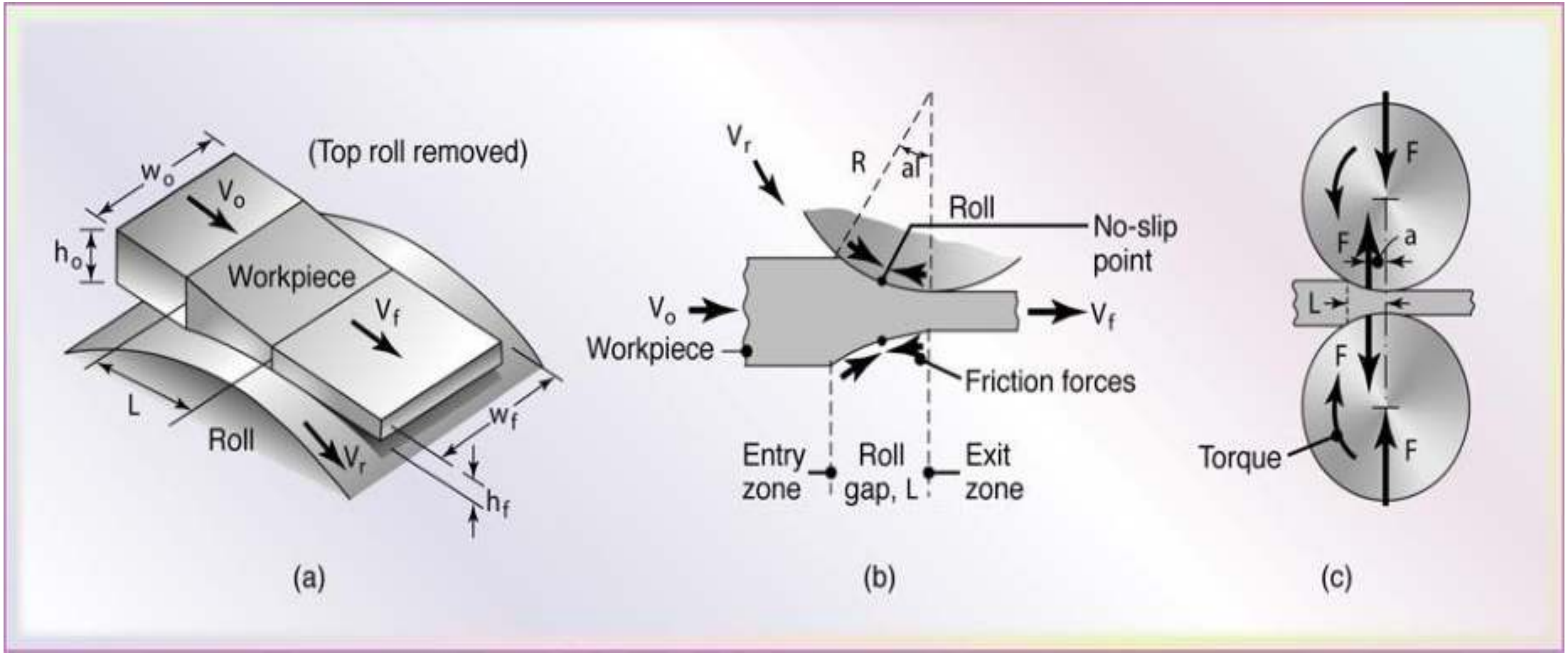

(c)

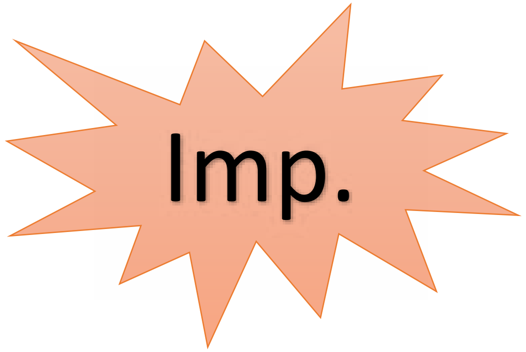
Zero slip (neutral) point

- Entrance: material is pulled into the nip
  - roller is moving faster than material
- Exit: material is pulled back into nip
  - roller is moving slower than material



- The amount of deformation possible in a single pass is limited by the friction between the rolls.
- The final product is either sheet or plate, with the former being less than 6 mm (0.24 in) thick.
- Lubrication is often used to keep the work piece from sticking to the rolls.


(Top roll removed)
w_o
V_o
h_o
Workpiece
V_f
L
Roll
V_r
w_f
h_f
(a)
V_r
R
a
Roll
No-slip
point
V_o
V_f
Workpiece
Friction forces
Entry
zone
Roll
gap, L
Exit
zone
(b)
F
F
a
L
F
F
Torque
(c)


Imp.

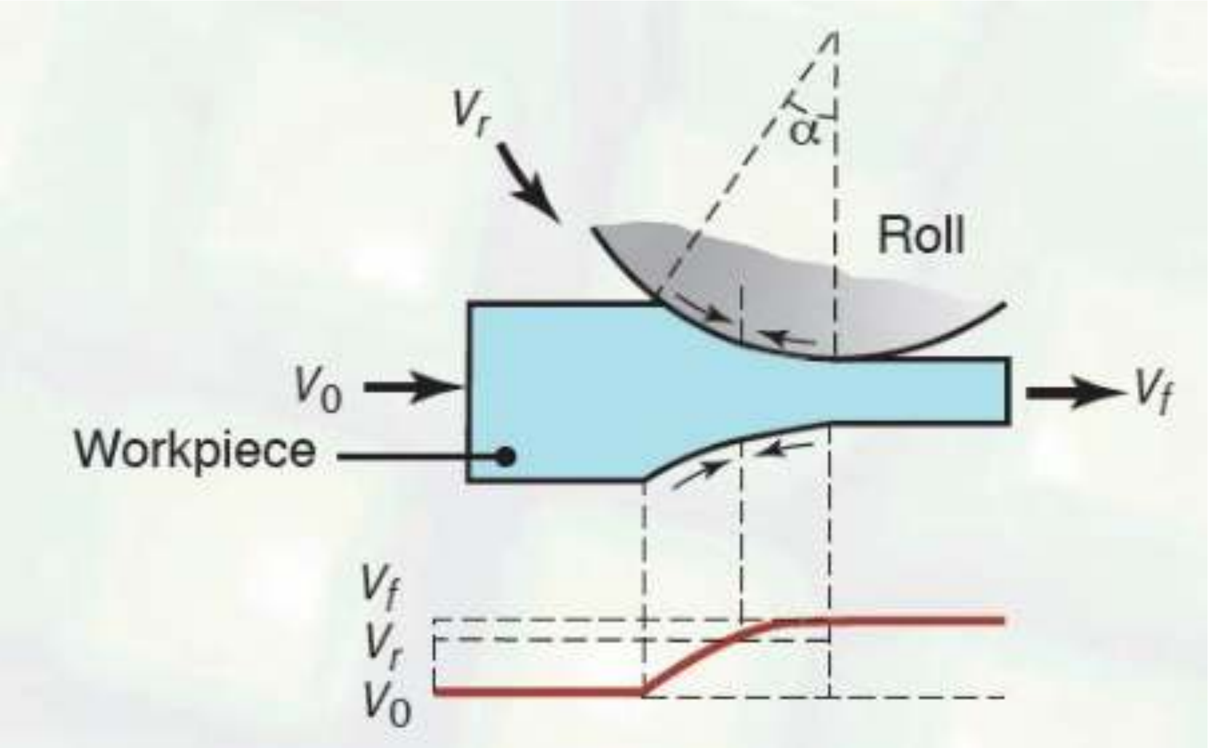
- Because of the relative motion at the interface, the frictional forces(which oppose motion) act on the strip surface in the direction shown in fig(b).
- In rolling frictional force on the left of the neutral point must be grater than the frictional force on the right.
- This difference yields a net frictional force to the right , which makes rolling operation possible by pulling the strip into the roll gap.
- The net frictional force and the surface velocity of the roll must be in the same direction in order to supply work to the system.
- Therefore, the neutral point should be located towards the exit in order to satisfy these requirements.

Forward Slip

- The forward slip in strip rolling was defined as the relative difference between the roll surface speed and strip exit speed.

- Forward slip. In rolling is defined in terms of the exit velocity of the strip V_f and the surface speed of the roll V_r as:

$$FORWARD\ SLIP = \frac{Vf - Vr}{Vr}$$



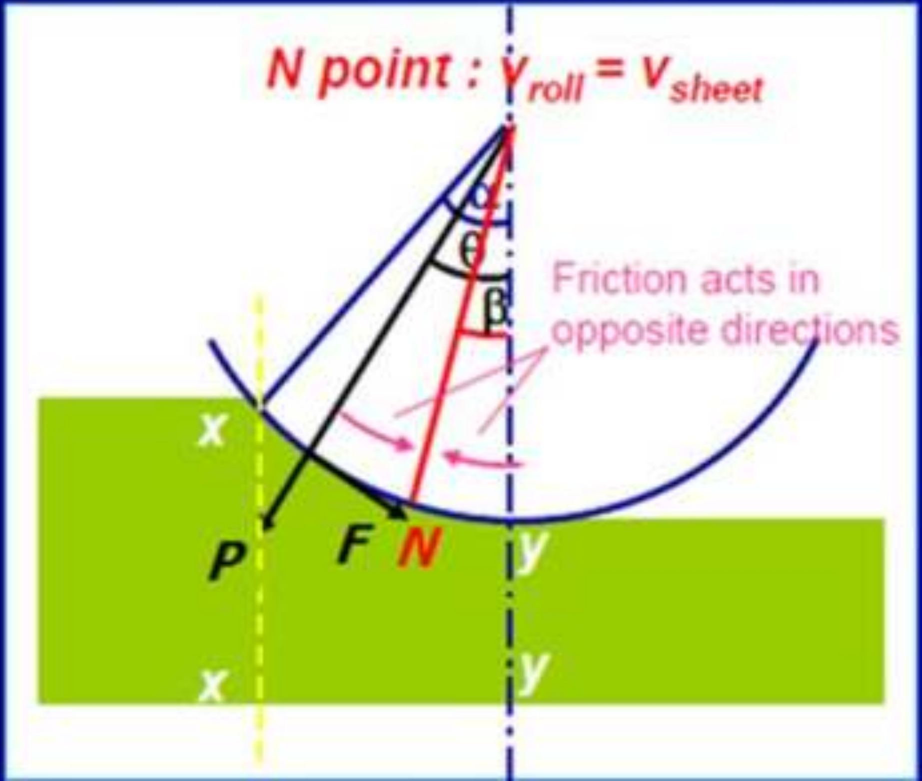
Relative Velocity Distribution between Roll and Strip Surfaces

- At only one point along the surface of contact between the roll and the sheet, two forces act on the metal: 1) ***a radial force*** ***P*** and 2) ***a tangential frictional force*** ***F***.

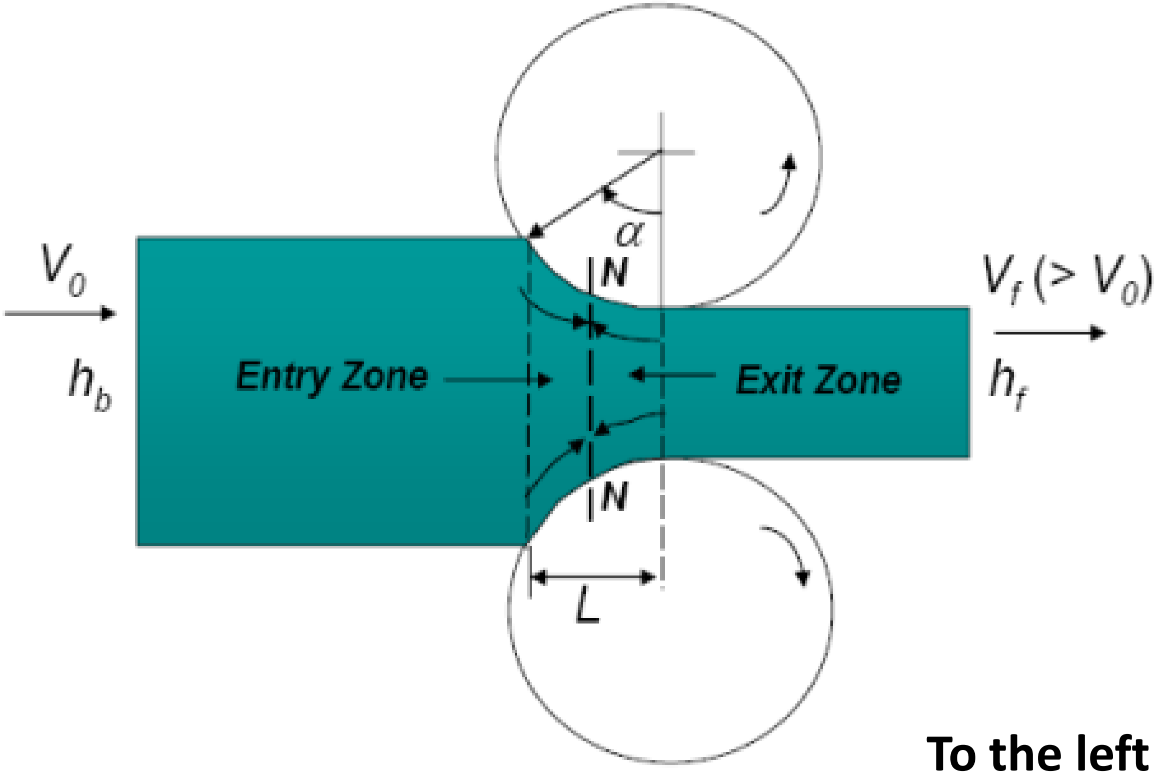
- If the surface velocity of the roll v_r equal to the velocity of the sheet, this point is called ***neutral point*** or ***no-slip point***. For example, point ***N***.

- Between the entrance plane (***xx***) and the neutral point the sheet is moving slower than the roll surface, and the ***tangential frictional force***, ***F***, act in the direction (*see Fig*) to draw the metal into the roll.

- On the exit side (***yy***) of the neutral point, the sheet moves faster than the roll surface. The direction of the frictional fore is then ***reversed*** and oppose the delivery of the sheet from the rolls.



Roll Pressure Distribution



V_0 = input velocity

V_f = final or output velocity

R = roll radius

h_b = back height

h_f = output or final thickness

α = angle of bite

N-N = neutral point or no-slip point

L = Roll Gap

To the left of the Neutral Point:

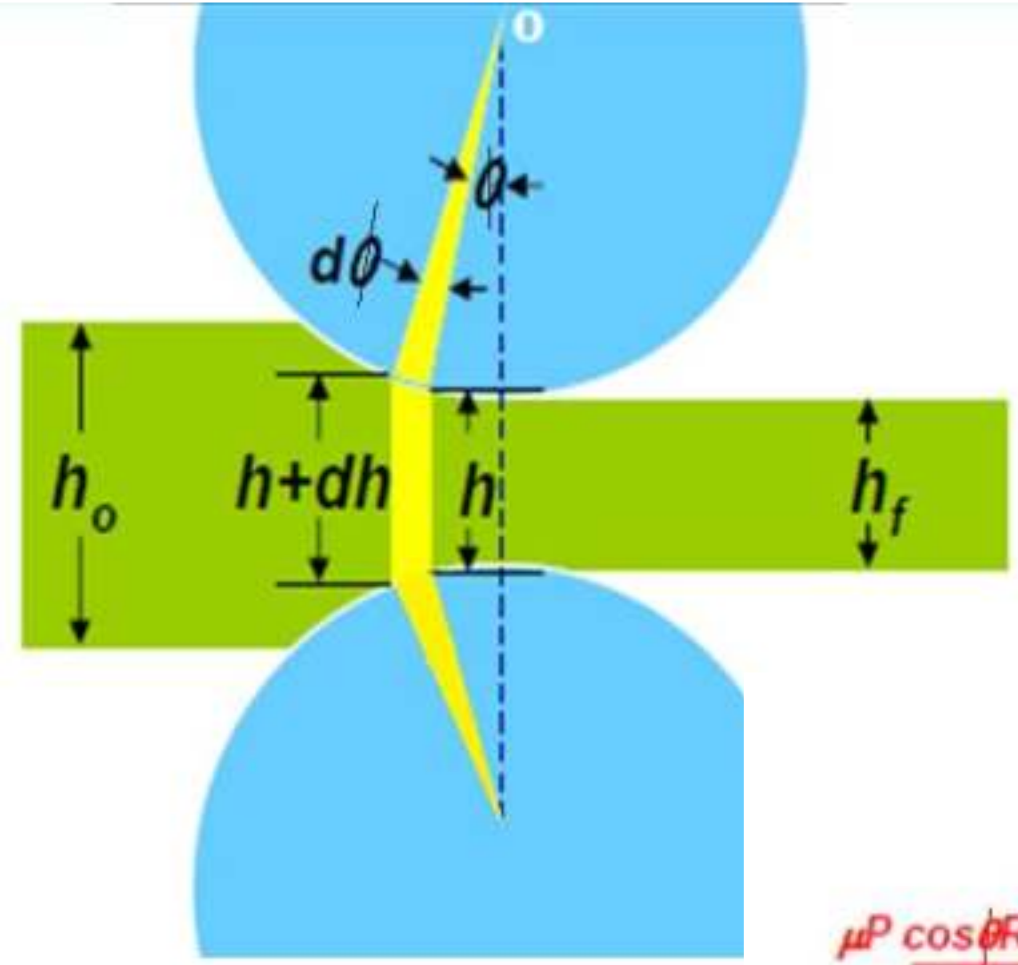
Velocity of the strip < Velocity of the roll

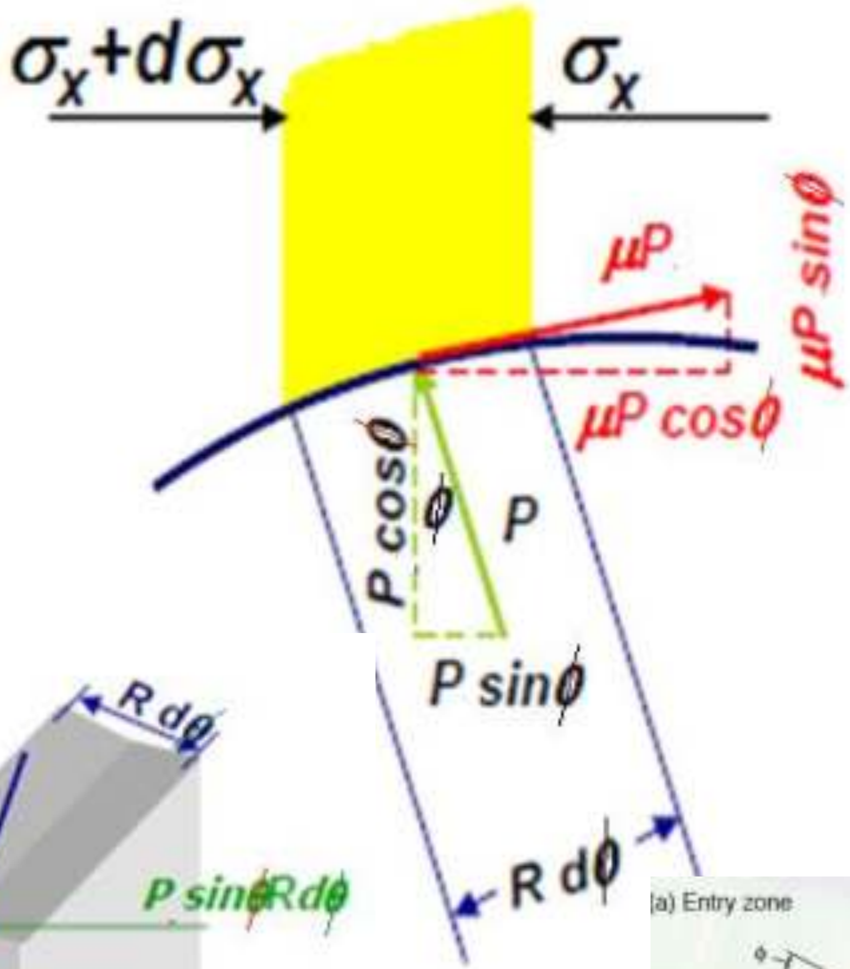
To the right of the Neutral Point:

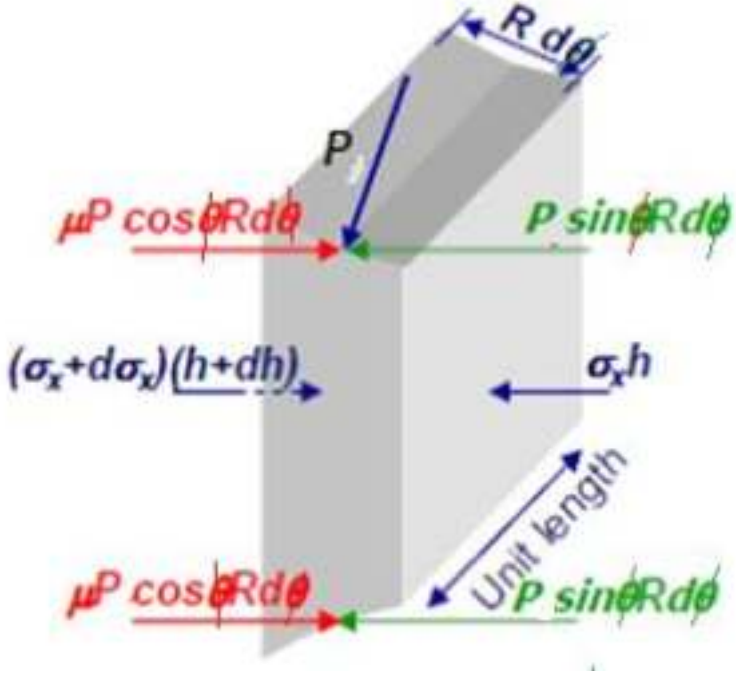
Velocity of the strip > Velocity of the roll

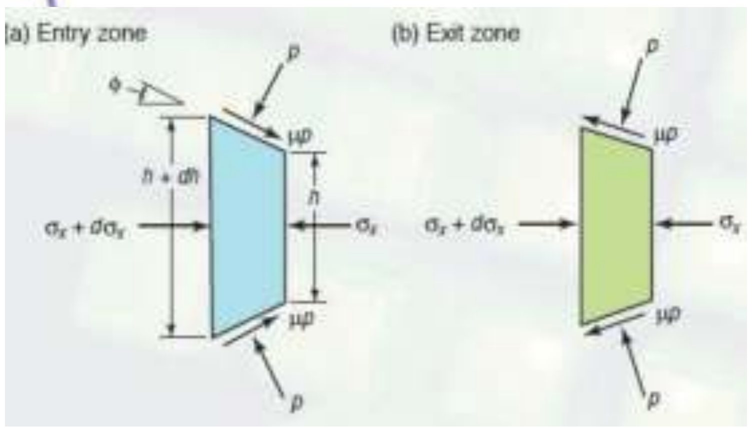
Slab analysis of plain-strain rolling

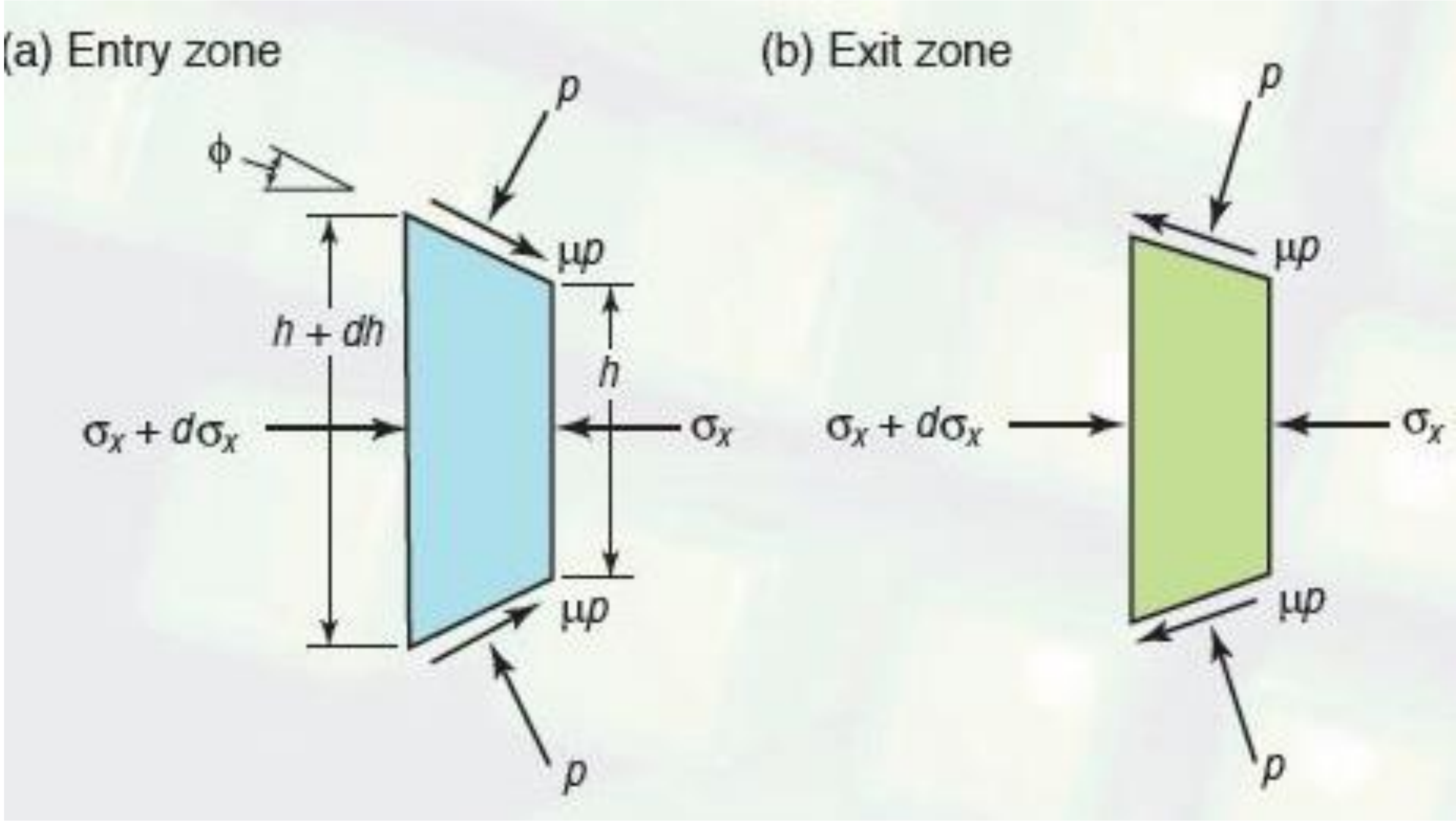
- The calculation of forces and stress or pressure distribution in rolling is done by slab analysis of plain-strain rolling.
- Using the slab method of analysis for plane strain the stresses in rolling can be analyze.
- In slab method of analysis we take an element from the workpiece and identify all the stresses acting on the element (including frictional force).
- Then analysis of the element is by balancing the horizontal forces.
- The stresses acting on an element in the entry and exit zones, respectively, are shown in Fig.
- Note that the only difference between the two elements is the **direction of the friction force.**
- In cold rolling, the material at the **exit is strain hardened**, and thus the **flow stress at the exit is higher than that at the entry**.


O
ϕ
dϕ
h_o
h+dh
h
h_f


σx+dσx
σx
μP
μP sinϕ
μP cosϕ
P cosϕ
ϕ
P
P sinϕ
R dϕ


R dϕ
P
μP cosϕRdϕ
P sinϕRdϕ
(σx+dσx)(h+dh)
σxh
Unit length
μP cosϕRdϕ
P sinϕRdϕ


(a) Entry zone
(b) Exit zone
ϕ
p
μp
h + dh
h
σx + dσx
σx
μp
p
p
μp
σx + dσx
σx
μp
p



The stresses acting on an element in the entry and exit zones. Here only difference between the two elements is the direction of the friction force

- From the equilibrium of the horizontal forces on the element shown in fig.

$$(\sigma_x + d\sigma_x)(h + dh) - 2pR\, d\phi \sin\phi - \sigma_x h \pm 2\mu pR\, d\phi \cos\phi = 0. \qquad \text{Eq---- (1)}$$

- Simplifying and ignoring the second—order terms, this expression reduces to,

$$\frac{d(\sigma_x h)}{d\phi} = 2pR(\sin\phi \mp \mu\cos\phi). \qquad \text{Eq---- (2)}$$

- In rolling practice, the bite angle α is typically only a few degrees; hence, it can be assumed that sin ø = ø and cos ø =1

$$\frac{d(\sigma_x h)}{d\phi} = 2pR(\phi \mp \mu) \qquad \text{Eq---- (3)}$$

- Because the angles involved are very small, p can be assumed to be a principal stress. The other **principal stress is σ_x**. The relationship between these two principal stresses and the **flow stress σ_f**, of the material is given,

$$p - \sigma_x = \frac{2}{\sqrt{3}}\sigma_f = \sigma_f'. \qquad \text{Eq---- (4)}$$

  - According to Von Mises yield criterion in plain strain condition (Reference given in next slide).

Plastic deformation in plane strain

Here, one principal strain is zero. Let this be ε_3. Then $\delta\varepsilon_3 = 0$.

From the Levy-Mises equation,

$$\frac{\delta\varepsilon_1}{\sigma_1 - \frac{1}{2}(\sigma_2+\sigma_3)} = \frac{\delta\varepsilon_2}{\sigma_2 - \frac{1}{2}(\sigma_3+\sigma_1)} = \frac{\delta\varepsilon_3}{\sigma_3 - \frac{1}{2}(\sigma_1+\sigma_2)} \neq 0$$

It follows that $\sigma_3 = \frac{1}{2}(\sigma_1+\sigma_2)$ in order to avoid $\frac{\delta\varepsilon_1}{\sigma_1 - \frac{1}{2}(\sigma_2+\sigma_3)} = 0$

Hence σ_3 is the mean of σ_1 and σ_2. By convention we define $\sigma_1 > \sigma_2$ $\sigma_1 > \sigma_3 > \sigma_2$. Therefore the maximum shear stress in the σ_1- σ_2 plane is at 45° to the axes and has magnitude $\frac{\sigma_1-\sigma_2}{2}$.

If we now examine the Tresca and von Mises yield criteria, we find:

- Tresca $\frac{\sigma_1-\sigma_2}{2}$ = k = $\frac{Y}{2}$ (k = shear yield stress and Y = uniaxial yield stress)
- von Mises $(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2 = 6k^2 = 2Y^2$

$$\text{If } \sigma_3 = \frac{1}{2}(\sigma_1+\sigma_2),\ \frac{3}{2}(\sigma_1-\sigma_2)^2 = 6k^2 = 2Y^2$$

$$\Rightarrow (\sigma_1-\sigma_2) = 2k = \frac{2Y}{\sqrt{3}}$$

Flow stress = Y= σ_f

Reference : Von Mises yield criterion in **plain strain condition**. Here Y is the flow stress

Therefore, if we have plane strain, the Tresca yield criterion and the von Mises yield criterion have the same result expressed in terms of k. It is unnecessary to specify which criterion we are using, provided we use k.

- Rewriting Eq.3 based on Yield criterion.

$$\frac{d\left[\left(p-\sigma_f'\right)h\right]}{d\phi}=2pR\left(\phi\mp\mu\right),\qquad \text{Eq---- (5)}$$

or

$$\frac{d}{d\phi}\left[\sigma_f'\left(\frac{p}{\sigma_f'}-1\right)h\right]=2pR\left(\phi\mp\mu\right),\qquad \text{Eq---- (6)}$$

which, upon differentiation, becomes

$$\sigma_f'h\frac{d}{d\phi}\left(\frac{p}{\sigma_f'}\right)+\left(\frac{p}{\sigma_f'}-1\right)\frac{d}{d\phi}\left(\sigma_f'h\right)=2pR\left(\phi\mp\mu\right).\qquad \text{Eq---- (7)}$$

- For a **strain hardened material** flow stress σ_f depend on the strain. If reduction in thickness (h) decreased (or strain increased) then flow stress σ_f also will increase.
- So the product of σ'_f **and h can be assumed to be a constant**

So in eq. 7 $$\frac{d}{d\phi}\left(\sigma_f'h\right)\approx 0$$

Eq.(7) after simplification,

$$\frac{\frac{d}{d\phi}\left(\frac{p}{\sigma_f'}\right)}{\frac{p}{\sigma_f'}} = \frac{2R}{h}(\phi \mp \mu).$$

Eq---- (8)

Letting h_f be the final thickness of the strip being rolled,

$$h = h_f + 2R(1 - \cos\phi),$$

or, approximately,

$$h = h_f + R\phi^2.$$

Eq---- (9)

Substituting this expression for h in Eq. (8) and integrating,

$$\ln\frac{p}{\sigma_f'} = \ln\frac{h}{R} \mp 2\mu\sqrt{\frac{R}{h_f}}\tan^{-1}\sqrt{\frac{R}{h_f}}\phi + \ln C$$

or

$$p = C\sigma_f'\frac{h}{R}e^{\mp\mu H},$$

Eq---- (10)

where

$$H = 2\sqrt{\frac{R}{h_f}}\tan^{-1}\left(\sqrt{\frac{R}{h_f}}\phi\right)$$

Eq---- (11)

- At the entry, ø = α (angle of bite) hence H= H_0 with ø replaced by α.
- At the exit, ø = 0, so that p= $\boldsymbol{\sigma'_f}$

NP SLIDE Slide 78

- In entry zone,

$$C = \frac{R}{h_f} e^{\mu H_i}$$

- So eq.10 in **entry zone becomes**,

$$p = \sigma'_f \frac{h}{h_o} e^{\mu(H_o - H)}.$$

Eq---- (12)

Roll entrance to neutral point:

- In exit zone,

$$C = \frac{R}{h_f},$$

- So eq.10 in **exit zone becomes**,

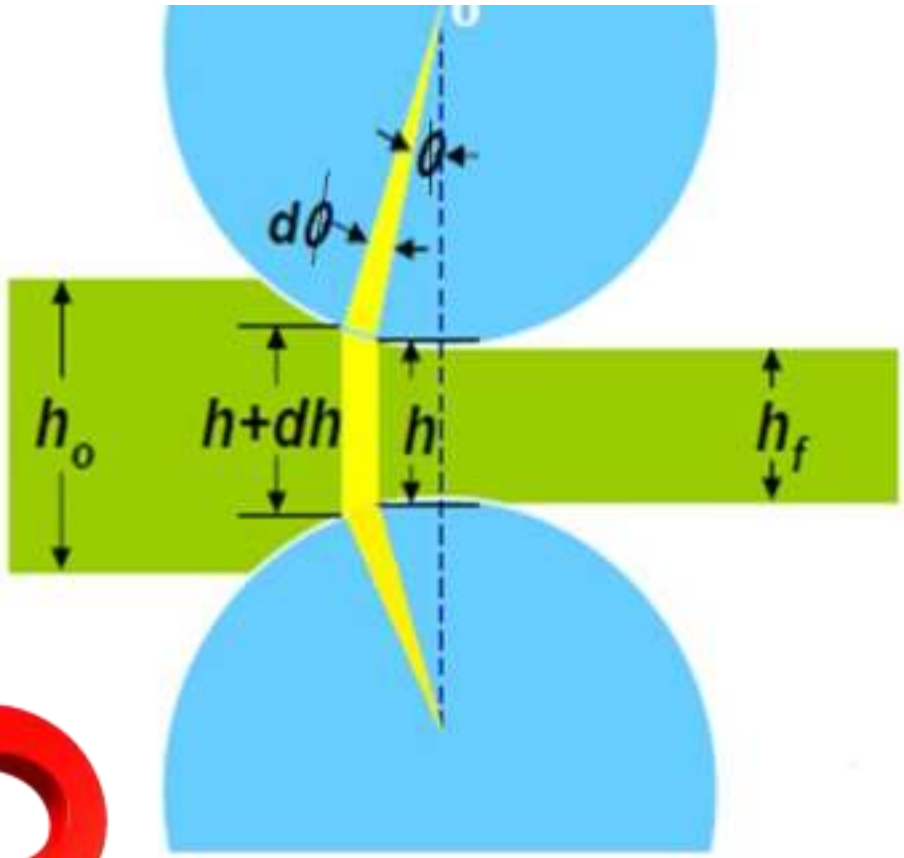
$$p = \sigma'_f \frac{h}{h_f} e^{\mu H}.$$

Eq---- (13)

Neutral point to roll exit:

Conclusion from eq.12 and 13.

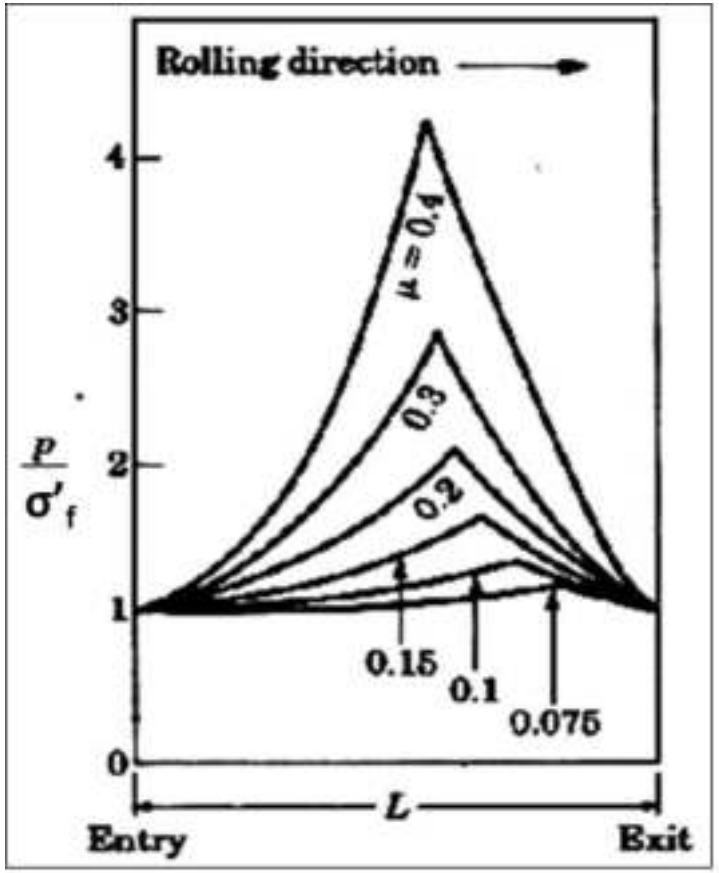
- Note that the pressure **p** at any location in the roll gap is a function of **h** and its angular position **ø** along the arc of contact.
- Pressure increases with **increasing h**.
- These expressions also indicate that,
- The pressure increases with increasing the **strength of the material**.
- Pressure increases with **increasing of coefficient of friction.**
- Pressure increases with **increasing R/hf ratio.**

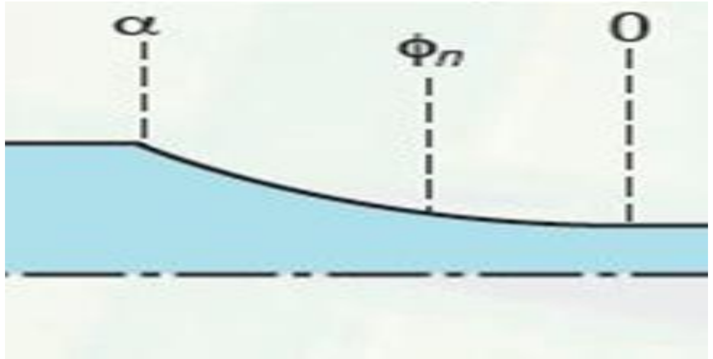


Why we use small diameter roll for rolling???

Pressure distribution in the roll gap as a function of the coefficient of friction.(Friction Hill)

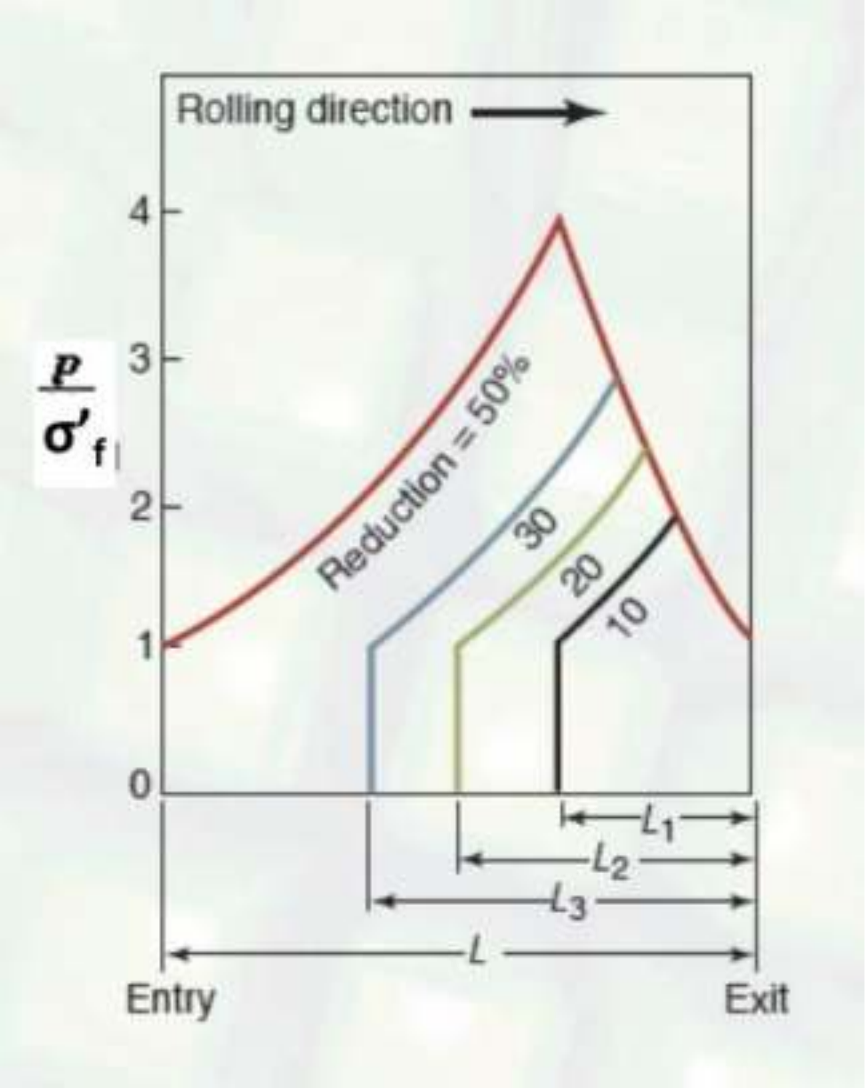
- The dimensionless theoretical pressure distribution in the roll gap is shown in Fig.
- Note that, as friction increases. The neutral point shifts toward the entry.
- Without friction, the rolls slip and the neutral point **shifts completely to the exit.**
- As reduction increases, the length of contact in the roll gap increases, which in turn reduces the **peak pressure.**
- The curves shown are theoretical; actual pressure distributions, as determined experimentally, have smoother curves with their peaks rounded off.



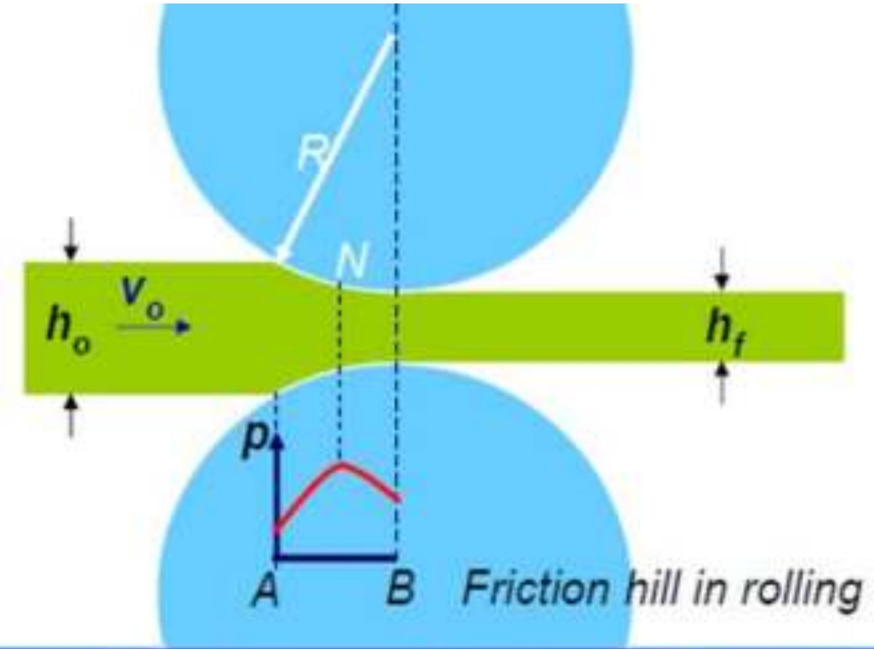


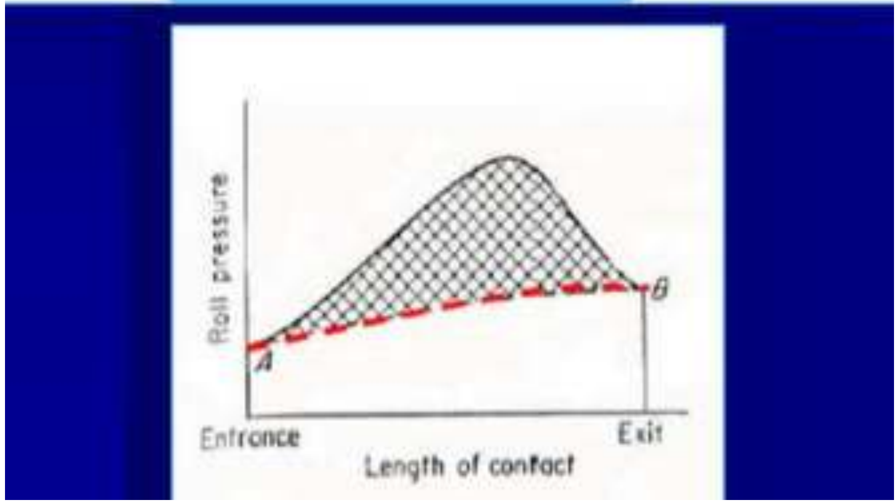
Pressure distribution in the roll gap as a function of reduction in thickness

- As reduction increases, the length of **contact in the roll gap increases**, which, in turn, increases the peak pressure.
- The curves shown in Fig. are theoretically derived; actual pressure distributions, as determined experimentally, are smoother, with rounded peaks.
- The increase in the area under the curves with increasing reduction in thickness , thus increasing the roll force.



- The distribution of roll pressure along the arc of contact shows that the pressure rises to a maximum at the neutral point and then falls off.
- The pressure distribution does not come to a sharp peak at the neutral point, which indicates that the **neutral point is not really a line on the roll surface but an area.**
- The area under the curve is proportional to the rolling load.
- The area in shade represents the force required to overcome frictional forces between the roll and the sheet.
- The area , under the dashed line AB represents the force required to deform the metal in plane homogeneous compression.





Determination of the Neutral Point

- Determined simply by equating the roll pressures at the entry and exit zone(by equating Eqs.12 and 13). Slide 71

At Neutral Point, H → H_n

$$\frac{h_o}{h_f} = \frac{e^{\mu H_o}}{e^{2\mu H_n}} = e^{\mu(H_o - 2H_n)},$$

$$\frac{h_0}{h_f} = e^{\mu(H_0 - 2H_n)}$$

At Neutral Point,

$$H_n = \frac{1}{2}\left(H_0 - \frac{1}{\mu} ln \frac{h_0}{h_f}\right)$$

Eq---- (14)

$$\emptyset_n = \sqrt{\frac{h_f}{R}} \tan\left(\sqrt{\frac{h_f}{R}} . \frac{H_n}{2}\right)$$

Front and Back Tension

- The roll force, F or Pressure P, can be reduced mainly by, Slide 84 Slide 71

  (a) Lowering friction;
  (b) Using rolls with smaller radii;
  (c) Taking smaller reductions per pass; and
  (d) Raising the workpiece temperature.

- When a **tensile stress is applied to a strip**, the yield strength normal to the strip surface decreases, and thus the roll pressure and force decrease.
- Another particularly effective method is to reduce the **apparent compressive yield strength** of the material by applying longitudinal tension.
- In practice, tensile forces in rolling can be applied either at the **entry (back tension, p_b) or at the exit (front tension, p_f)** of the strip, or both.

- Eq. 12 and 13 can be modified by include the effect of tension for entry and exit zone.

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$$\text{Entry zone: } p = \left(\sigma_f' - p_b\right)\frac{h}{h_o}e^{\mu(H_o - H)}$$

Eq---- (15)

$$\text{Exit zone: } p = \left(\sigma_f' - p_f\right)\frac{h}{h_f}e^{\mu H}.$$

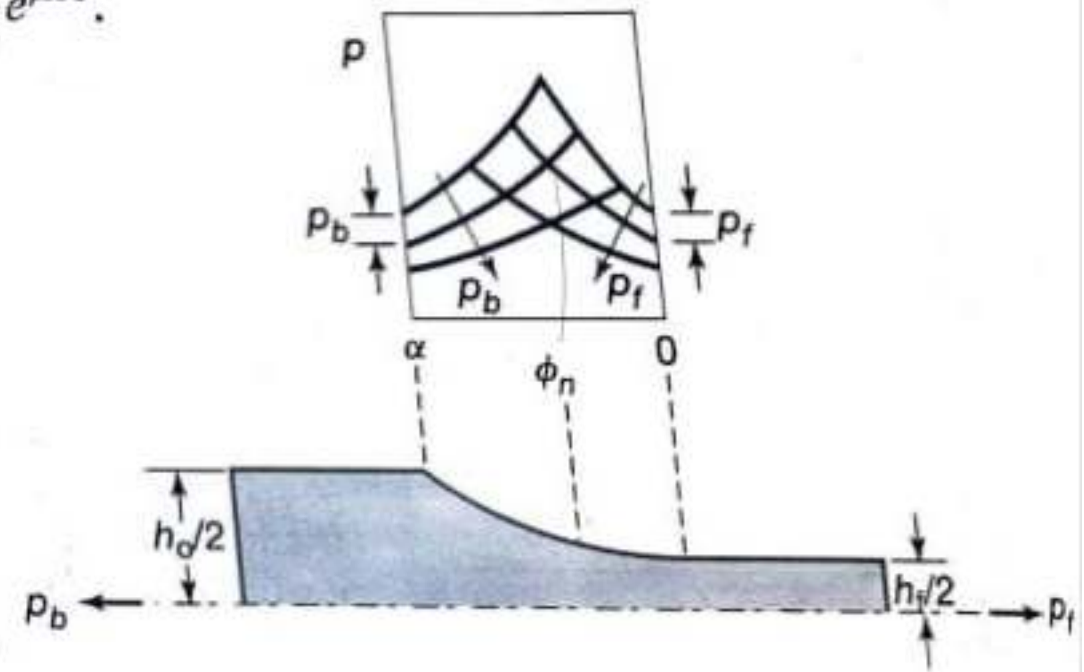
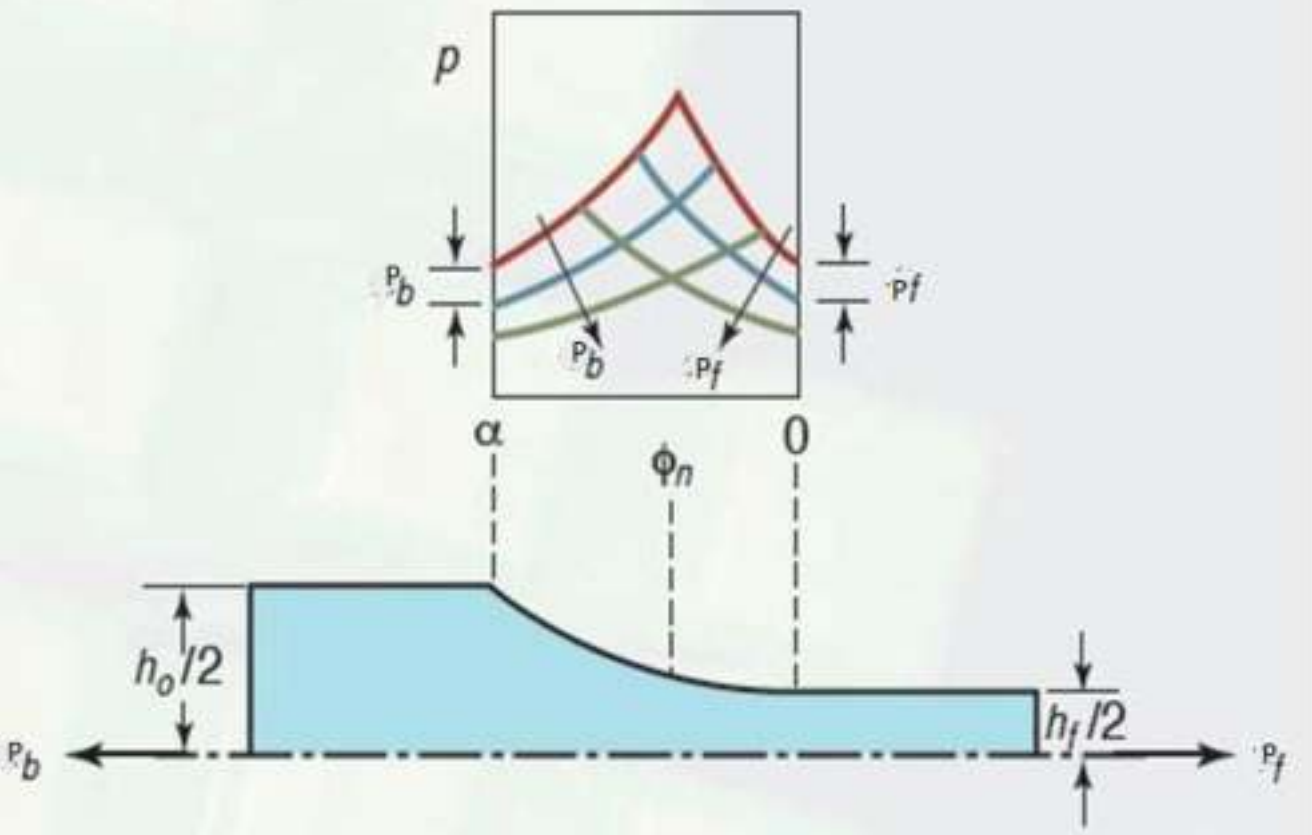


FIGURE 6.33 Pressure distribution as a function of front and back tension in rolling. Note the shifting of the neutral point and the reduction in the area under the curves (hence reduction in the roll force) as tensions increase.

Entry zone: $p = \left(\sigma_f' - p_b\right) \frac{h}{h_o} e^{\mu(H_o - H)}$

Exit zone: $p = \left(\sigma_f' - p_f\right) \frac{h}{h_f} e^{\mu H}.$



Pressure distribution as a function of front and back tension in rolling. Note the shifting of the neutral point and the reduction in the area under the curves (hence reduction in the roll force) as tensions increase.

- Depending on the relative magnitudes of the tensile stresses applied the **neutral point may shift**, as shown in Fig.
- As expected, this shift then affects the pressure distribution, torque, and power requirements.
- Tensions are particularly important in **rolling thin, high-strength materials, because such materials require high roll forces**.
- Front tension in practice is typically controlled by the torque on the **coiler(delivery reel),** around which the rolled sheet is coiled. Back tension is controlled by a braking system in the uncoiler (payoff reel).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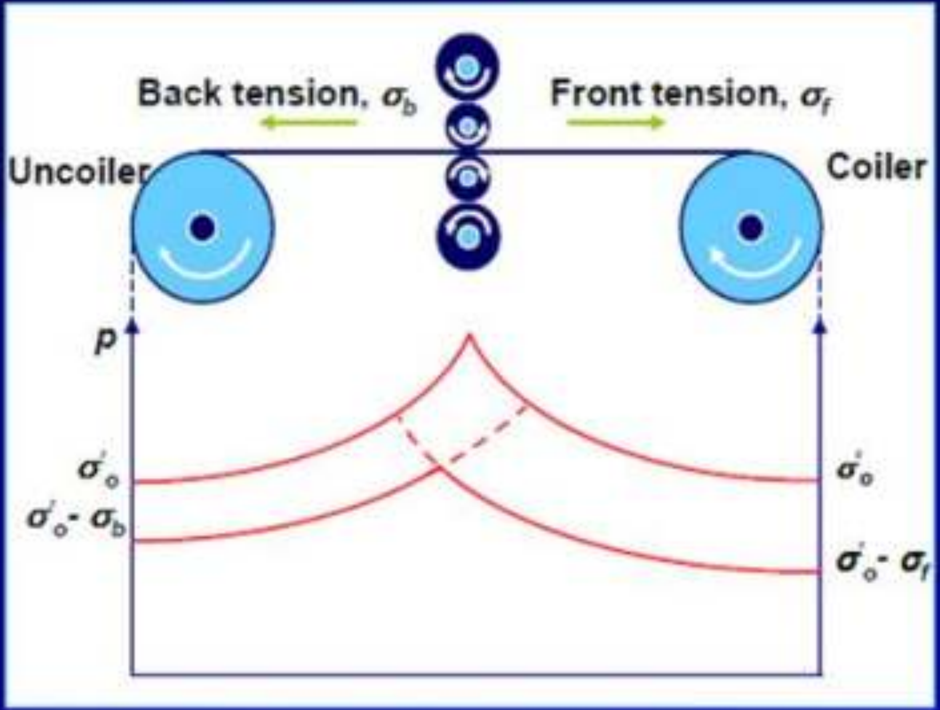
Back and front tensions in sheet

- The presence of back and front tensions in the plane of the sheet reduces the rolling load.
- **Back tension** may be produced by controlling the speed of the uncoiler relative to the roll speed.
- **Front tension** may be created by controlling the coiler.
- **Back tension** is ~ twice as effective in reducing the rolling load ***P*** as front tension.
- The effect of sheet tension on reducing rolling pressure ***p*** can be shown simply by

$$p = \sigma_o' - \sigma_h = \frac{2}{\sqrt{3}}\sigma_f - \sigma_h \quad ...Eq.11$$

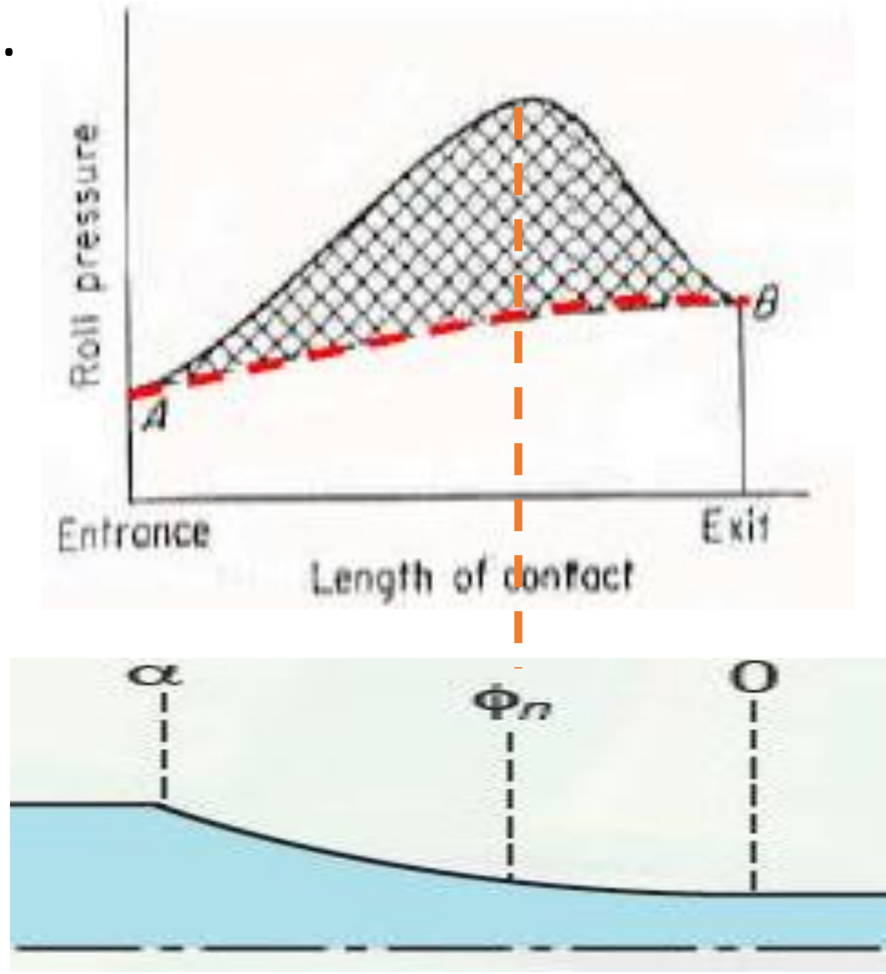


- If a high enough **back tension** is applied, the neutral point moves toward the roll exit –> rolls are moving faster than the metal.
- If the **front tension** is used, the neutral point will move toward the roll entrance.

Where σ_h = horizontal sheet tension.

Roll Forces or load calculation

- The **area in shade** represents the force required to overcome **frictional forces** between the roll and the sheet.
- The area **under the dashed line** AB represents the force required to deform the metal in plane homogeneous compression.



The area under the pressure-contact length curves, multiplied by the strip width, *w, is the roll force, F, on the strip.*

This force can be expressed as:

$$F = \int_{0}^{\phi_n} \omega.p.R.d\phi + \int_{\phi_n}^{\alpha} w.p.R.d\phi$$ Eq---- (16)

- A **simple method** of calculating the roll force is to multiply the contact area by an average contact stress, $P_{av.}$

$$F = L.w.p_{average}$$ Eq---- (17)

where L is the length of contact and can be approximated as the **projected length**.

$$L = \sqrt[2]{R.\Delta h}$$

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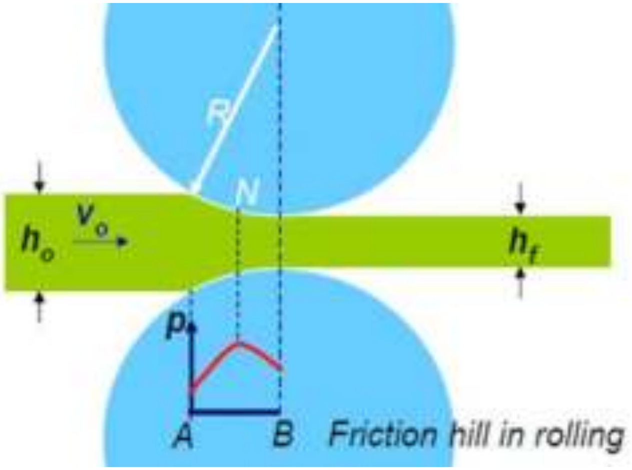
Eq---- (18)

$$\Delta h = h_0 - h_f$$



where R is the roll radius and Δh is the difference between the original and final thicknesses of the strip (called draft).

Roll diameter ⇧ Rolling load ⇧

- The magnitude of P_{av} depends on the h/L ratio, where **h** is now the average thickness of the strip in the roll gap.

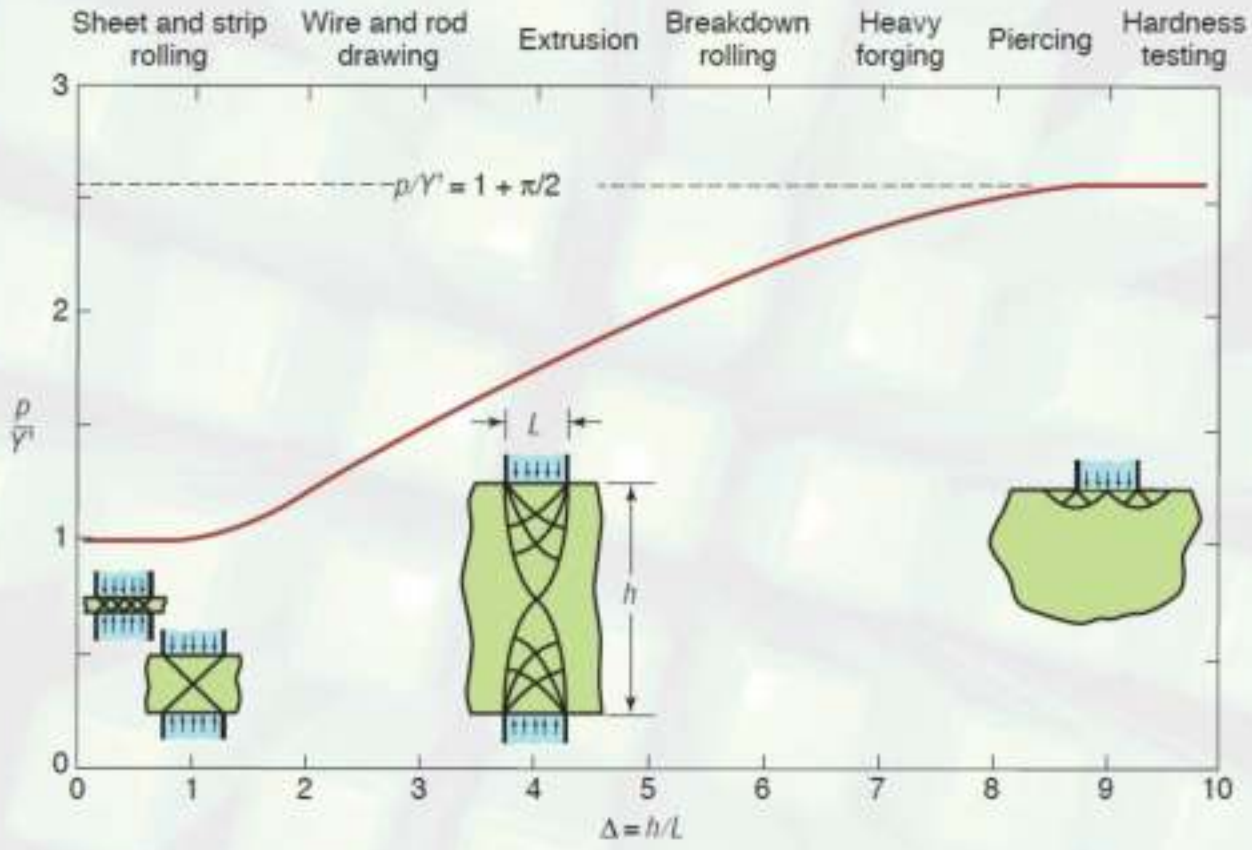


FIGURE 6.12 Die pressure required in various metalworking operations and under *frictionless* plane-strain conditions, as obtained by the slip-line analysis. Note that the magnitude of the die-workpiece contact area is an important factor in determining pressures. *Source:* After W.A. Backofen.

- For **large h/L ratios**, the rolls will act in a manner similar to **indenters in a hardness test**. **Friction is not significant**.
- In such case eq.17 can use to calculate the roll force.

- For **small h/L ratios, friction is predominant.**
- In such case eq.17 modified with P $_{average}$,

$$p_{average} = \left(1 + \frac{\mu . L}{2.h_{average}}\right) \quad \text{Eq---- (19)}$$

$$F = Lw\left(1 + \frac{\mu . L}{2.h_{average}}\right) \quad \text{Eq---- (20)}$$

- **In Cold rolling For strain—hardening materials**, the appropriate flow stresses must be calculated and used to calculate **Roll force F**.
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- Eq.17 modified in low friction condition as,

$$F = Lw\sigma'_f \qquad \text{Eq---- (21)}$$

where σ'_f is the average flow stress in plain strain of the material in the roll gap.

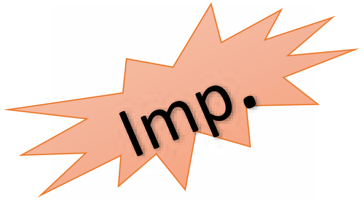
- Eq.17 modified in high friction condition as,

$$F = Lw\sigma'_f \left(1 + \frac{\mu L}{2h_{av}}\right) \qquad \text{Eq---- (22)}$$

$$p_{average} = \begin{cases} \sigma'_f & \text{, Low frictional conditions, Large } \dfrac{h}{L} \text{ Ratio.} \\ \sigma'_f \left(1 + \dfrac{\mu . L}{2 . h_{average}}\right) & \text{, Higher frictional conditions, Small } \dfrac{h}{L} \text{ Ratio} \end{cases}$$

Where σ'_f is the average flow stress in plane strain of the material in the roll gap.

The roll force F can be reduced by various means, such



1. A lower friction
2. Smaller roll radii
3. Smaller reductions, and
4. Higher work piece temperatures
5. Reduce the plain compressive yield stress of the material by applying longitudinal tension.

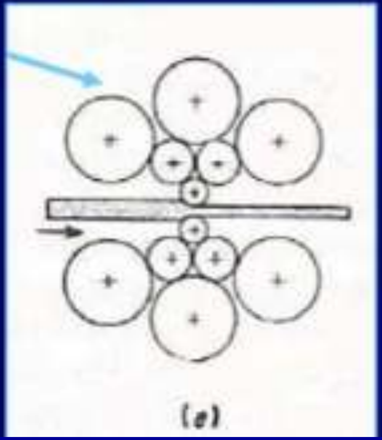
•Therefore the ***rolling load*** F increases with the roll radius $R^{1/2}$, depending on the contribution from the friction hill.

• The ***rolling load*** also increases as the sheet entering the rolls becomes thinner (due to the term e^Q).

• At one point, ***no further reduction in thickness*** can be achieved if the deformation resistance of the sheet is greater than the roll pressure. The rolls in contact with the sheet are both severely elastically deformed.

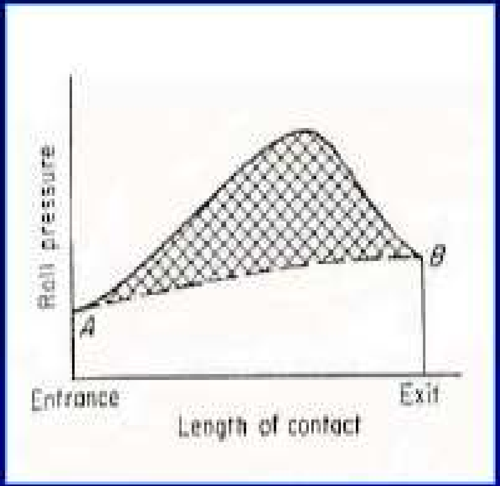
• ***Small-diameter rolls*** which are properly stiffened against deflection by backup rolls can produce a greater reduction before roll flattening become significant and no further reduction of the sheet is possible.

Backup rolls



Example: the rolling of aluminium cooking foil. Roll diameter < 10 mm with as many as 18 backing rolls.

• *Frictional force* is needed to pull the metal into the rolls and responsible for a large portion of the rolling load.



• *High friction results in high rolling load, a steep friction hill and great tendency for edge cracking.*

• The friction varies from point to point along the contact arc of the roll. However it is very difficult to measure this variation in μ, all theory of rolling are forced to assume a *constant coefficient of friction*.

• For cold-rolling with lubricants, $\mu \sim 0.05 - 0.10$.
• For hot-rolling , $\mu \sim 0.2$ up to sticky condition.

Roll Torque and Power

- **Torque** is the measure of the force applied to a member to produce rotational motion.
- **Power** is applied to a rolling mill by applying a torque to the rolls and by means of strip tension.
- The power is spent principally in four ways

    1) The energy needed to deform the metal.

    2) The energy needed to overcome the frictional force.

    3) The power lost in the pinions and power transmission system.

    4) Electrical losses in the various motors and generators.

- Remarks: Losses in the windup reel and uncoiler must also be considered.

Roll Torque and Power

- The roll torque T for each roll can be calculated analytically from the expression,

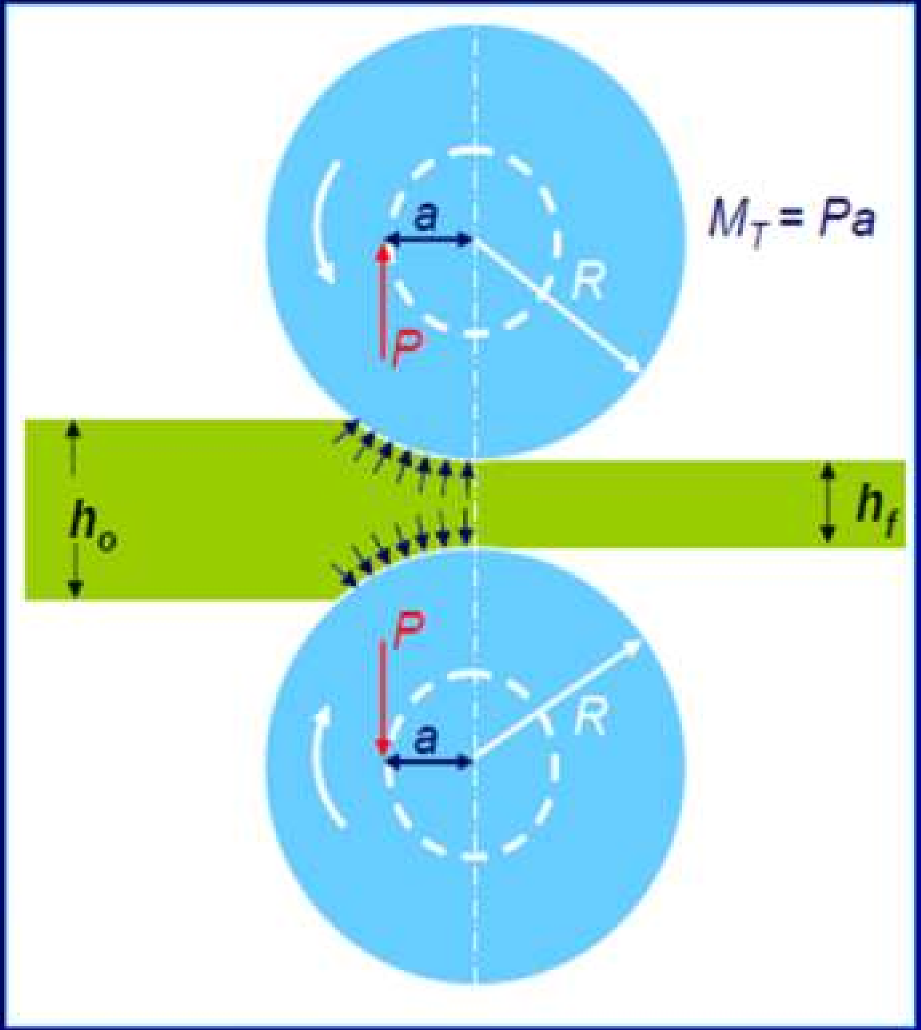
$$T = \int_{\phi_n}^{\alpha} w\mu p R^2 \, d\phi - \int_{0}^{\phi_n} w\mu p R^2 \, d\phi \qquad \text{Eq---- (23)}$$

(entry zone) (exit zone)

The ***total rolling load*** is distributed over the ***arc of contact*** in the typical friction-hill pressure distribution.

However the total rolling load can be assumed to be concentrated at ***a point along the act of contact at a distance*** ***a*** from the line of centres of the rolls.

The ratio of the moment arm ***a*** to the projected length of the act of contact L_p can be given as



Schematic diagram illustrating roll torque

Roll Torque and Power

- The torque in rolling can also be estimated by assuming that the roll force F, acts in the **middle of the arc of contact** (that is, a length of action of 0.5L), and that this force is perpendicular to the plane of the strip.
- Using this assumption, Torque per roll is then,

$$T = \frac{FL}{2} \qquad \text{Eq---- (24)}$$

- The power required **per roll** is

$$\text{Power} = T\omega = \frac{FL\omega}{2} = \frac{\pi FLN}{60} \qquad \text{Eq---- (25)}$$

Where $\omega = 2\pi N$ and

N is the revolutions per minute of the roll

Power in watt

F in Newton

L in meters

$$\text{Power per roll} = \frac{\pi FLN}{33000}\ in\ hp \qquad \text{Eq---- (26)}$$

Roll Force in hot Rolling

- In hot working processes, the flow stress for hot-rolling is a function of both **temperature and strain rate(speed of rolls).**
- The calculation of forces and torque in hot rolling presents two difficulties

  determining (a) the strain rate sensitivity of materials at elevated temperatures;

  - (b) the **coefficient of friction,μ,** at elevated temperatures.
- The average strain rate, $\dot{\varepsilon}$, in flat rolling can be obtained by dividing the strain by the time required for an element to undergo this strain in the roll gap.

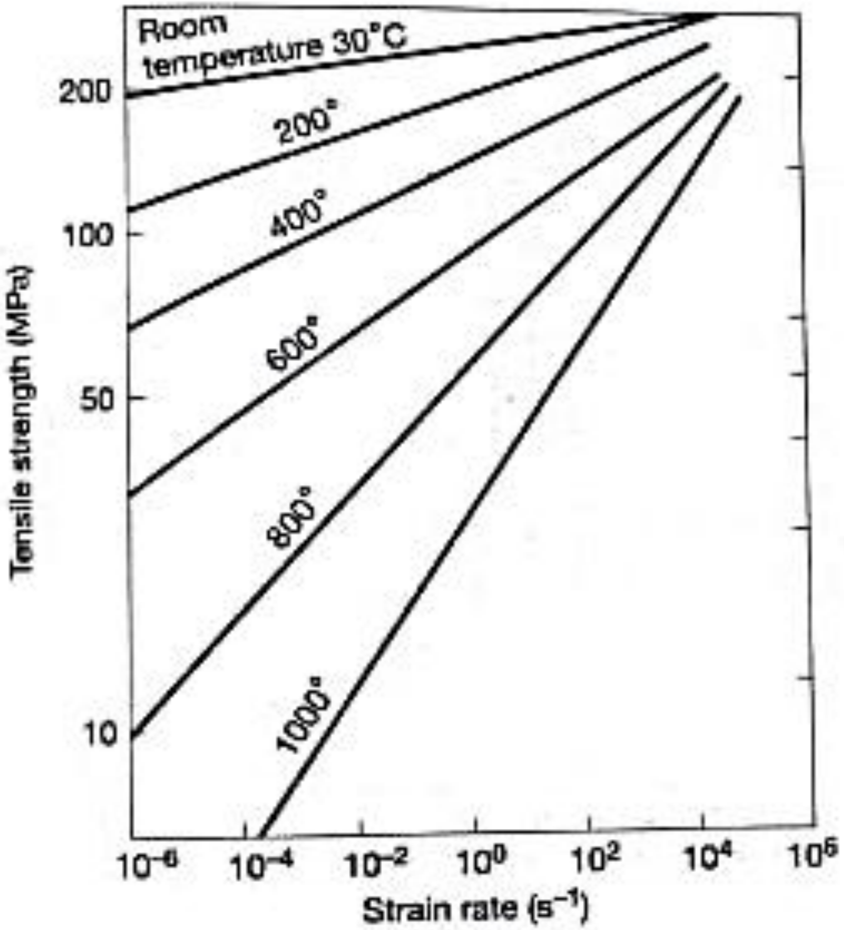
$$\dot{\epsilon} = \frac{V_r}{L} \ln\left(\frac{h_o}{h_f}\right) \qquad \text{Eq---- (27)}$$

- Flow stress corresponds to this strain rate is,

$$\sigma_f' = C\,\dot{\varepsilon}^m \qquad \text{Eq---- (28)}$$

C is the strength coefficient

m is the strain rate sensitivity exponent



- Increasing the strain rate increase the strength.
- Sensitivity of this variation increase with increase in temp.
- high temp has high influence on the strain rate.

FIGURE 2.10 The effect of strain rate on the ultimate tensile strength of aluminum. Note that as temperature increases, the slope increases. Thus, tensile strength becomes more and more sensitive to strain rate as temperature increases. *Source:* After J.H. Hollomon.

- Then substitute flow stress eq.28 in equation for roll force ie, eq.21 or 22

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- After substitution,

eq.21 becomes

$$F = Lw\bar{\sigma}'_f$$

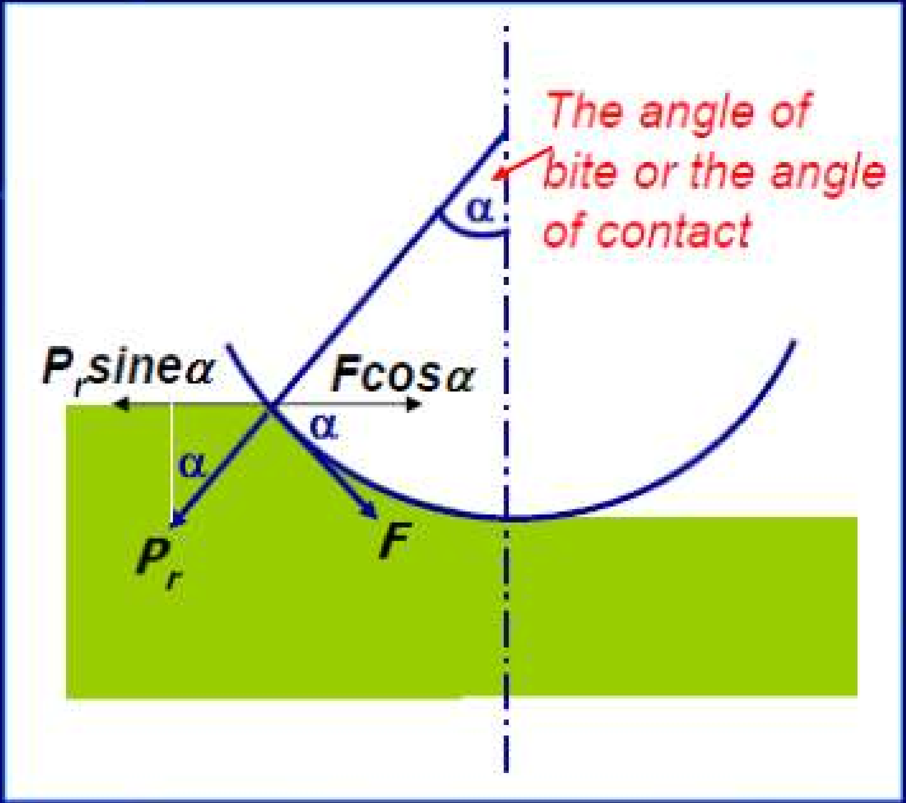
where, $\sigma_f' = C\,\dot{\varepsilon}^m$

eq.22 becomes

$$F = Lw\bar{\sigma}'_f\left(1 + \frac{\mu L}{2h_{av}}\right)$$

where, $\sigma_f' = C\,\dot{\varepsilon}^m$

Roll bite condition



For the workpiece to enter the throat of the roll, the component of the ***friction force*** must be ***equal to or greater*** than the ***horizontal component of the normal force***.

$$F\cos\alpha \geq P_r \sin\alpha$$

$$\frac{F}{P_r} \geq \frac{\sin\alpha}{\cos\alpha} \geq \tan\alpha$$

But we know $F = \mu P_r$

Therefore $\mu = \tan\alpha$ ...*Eq.5*

F is a tangential friction force

P_r is radial force

- If ***$\tan\alpha > \mu$***, the workpiece cannot be drawn.
- If ***$\mu = 0$***, rolling cannot occur.

The maximum value of the angle α called angle of acceptance ,

$\alpha_{max} = \tan^{-1}\mu$.

If α_{max} is larger than this value, the roll begins to slip, because the friction is not high enough to pull the material through the roll gap

Therefore ***Free engagement*** will occur when $\mu > \tan \alpha$

Increase the effective values of μ, for example grooving the rolls parallel to the roll axis.

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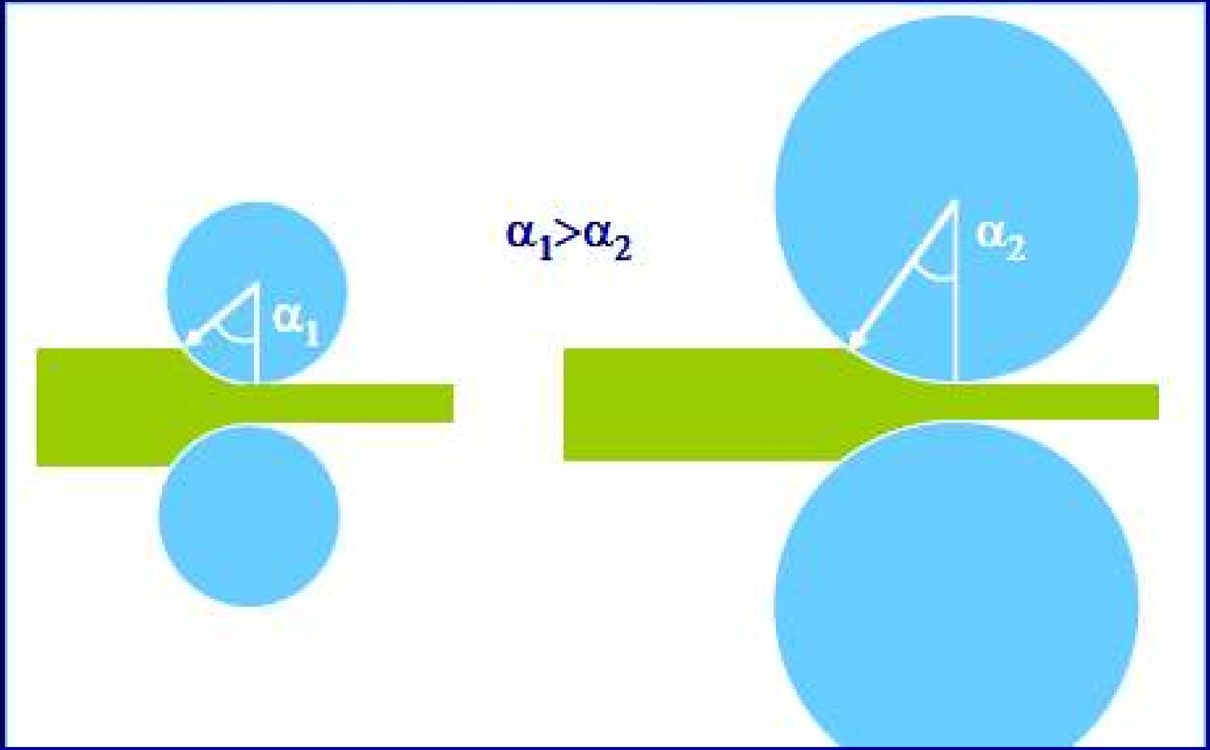
Using big rolls to reduce $\tan \alpha$ or if the roll diameter is fixed, reduce the h_o



The maximum reduction

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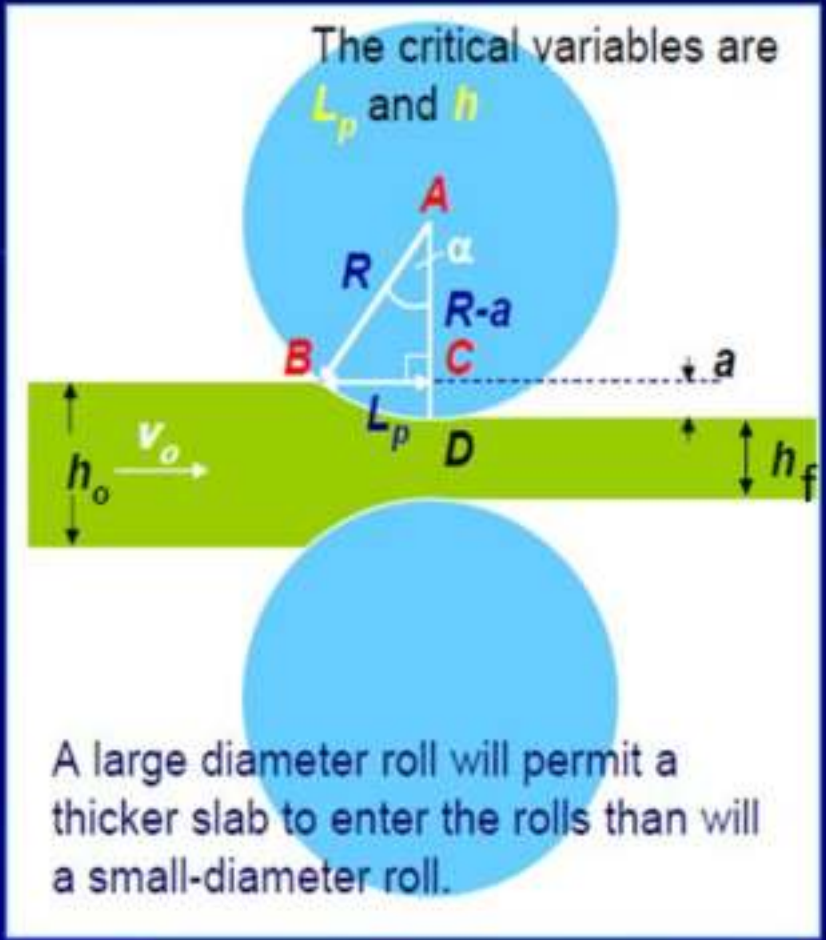


From triangle **ABC**, we have

$$R^2 = L_p^2 + (R-a)^2$$

$$L_p^2 = R^2 - (R^2 - 2Ra + a^2)$$

$$L_p^2 = 2Ra - a^2$$

As **a** is much smaller than **R**, we can then ignore **a²**.

$$L_p \approx \sqrt{2Ra} \approx \sqrt{R\Delta h}$$

Where $\Delta h = h_o - h_f = 2a$

$$\mu = \tan\alpha = \frac{L_p}{R - \Delta h/2} \approx \frac{\sqrt{R\Delta h}}{R - \Delta h/2} \approx \sqrt{\frac{\Delta h}{R}}$$

⇒ $$(\Delta h)_{max} = \mu^2 R$$

Roll Deflection

- Because of the forces acting on them, rolls undergo changes in shape during rolling. Just as a straight beam deflects under a transverse load, roll forces tend to bend the rolls elastically during rolling.
- As expected, the **higher the elastic modulus of the roll material**, the smaller the roll deflection.
- Roll forces tend to bend the rolls resulting in a strip that is thicker at its **Center than at its edges (crown).**
- One method for avoiding this problem is to grind the roll in such a way that its diameter at the center is slightly larger than at the edges. This **curvature is known as camber**.
- In sheet metal rolling practice, the camber is typically less than 0.50 mm on the roll diameter.

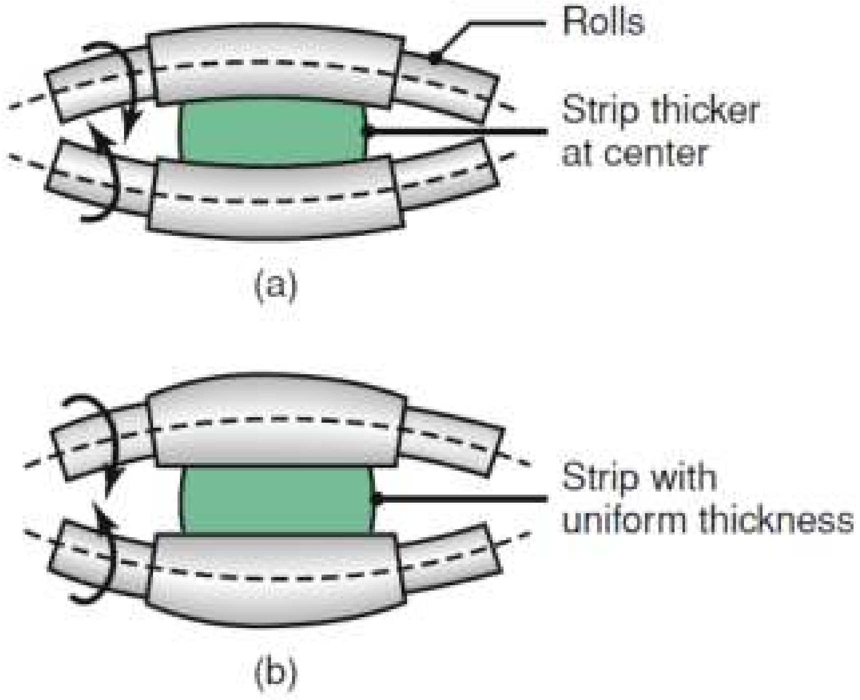
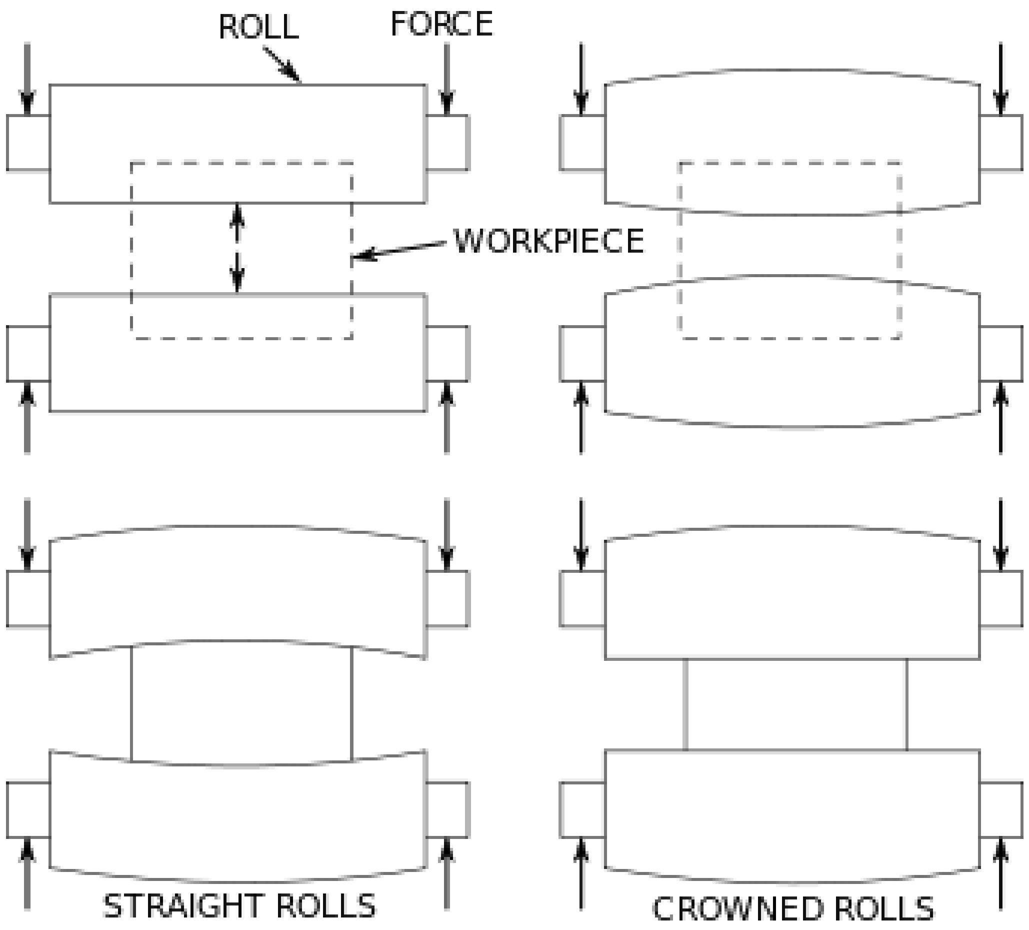


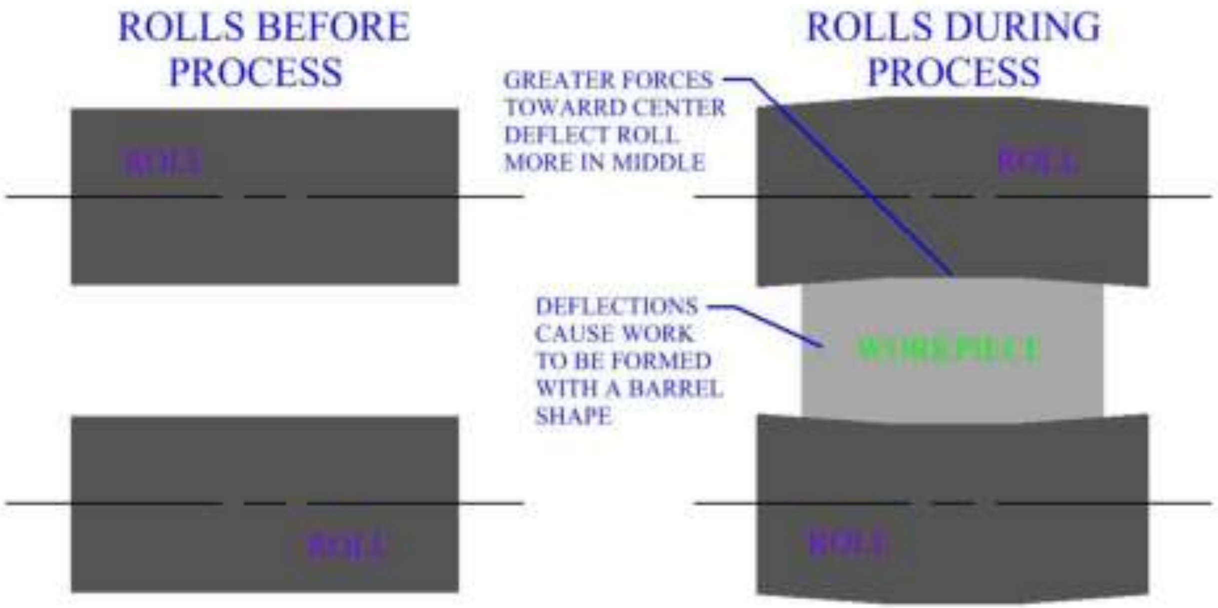
FIGURE 13.4 (a) Bending of straight cylindrical rolls caused by roll forces. (b) Bending of rolls ground with camber, producing a strip with uniform thickness through the strip width. Deflections have been exaggerated for clarity.

Roll Deflection

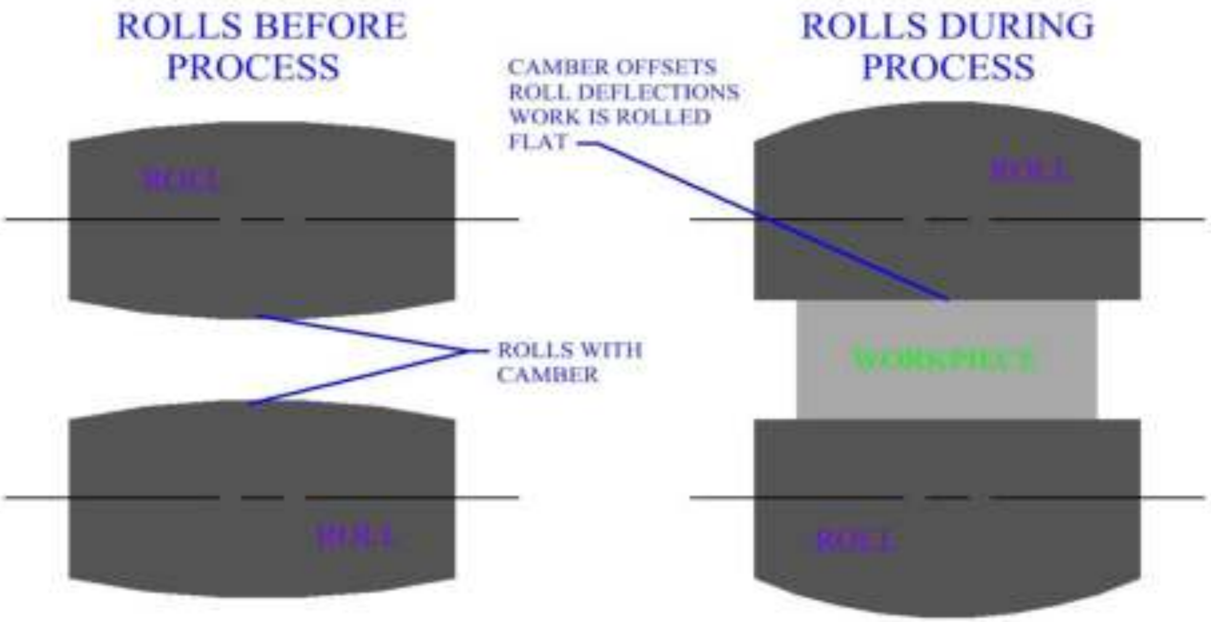
- To reduce the effects of deflection, the rolls also can be subjected to **external bending by applying moments at their bearings**.
- In addition, in **hot rolling** or because of heat generation, rolls can become slightly barrel shaped. **Known as thermal camper.**
- This effect can be controlled by varying the **location of the coolant on the rolls along their axial direction**. When designed properly, such rolls produce flat strips.
- however, a particular camber is correct only for a **certain load and width of strip**.



ROLL DEFLECTIONS IN FLAT ROLLING CAUSING A BARRELING EFFECT

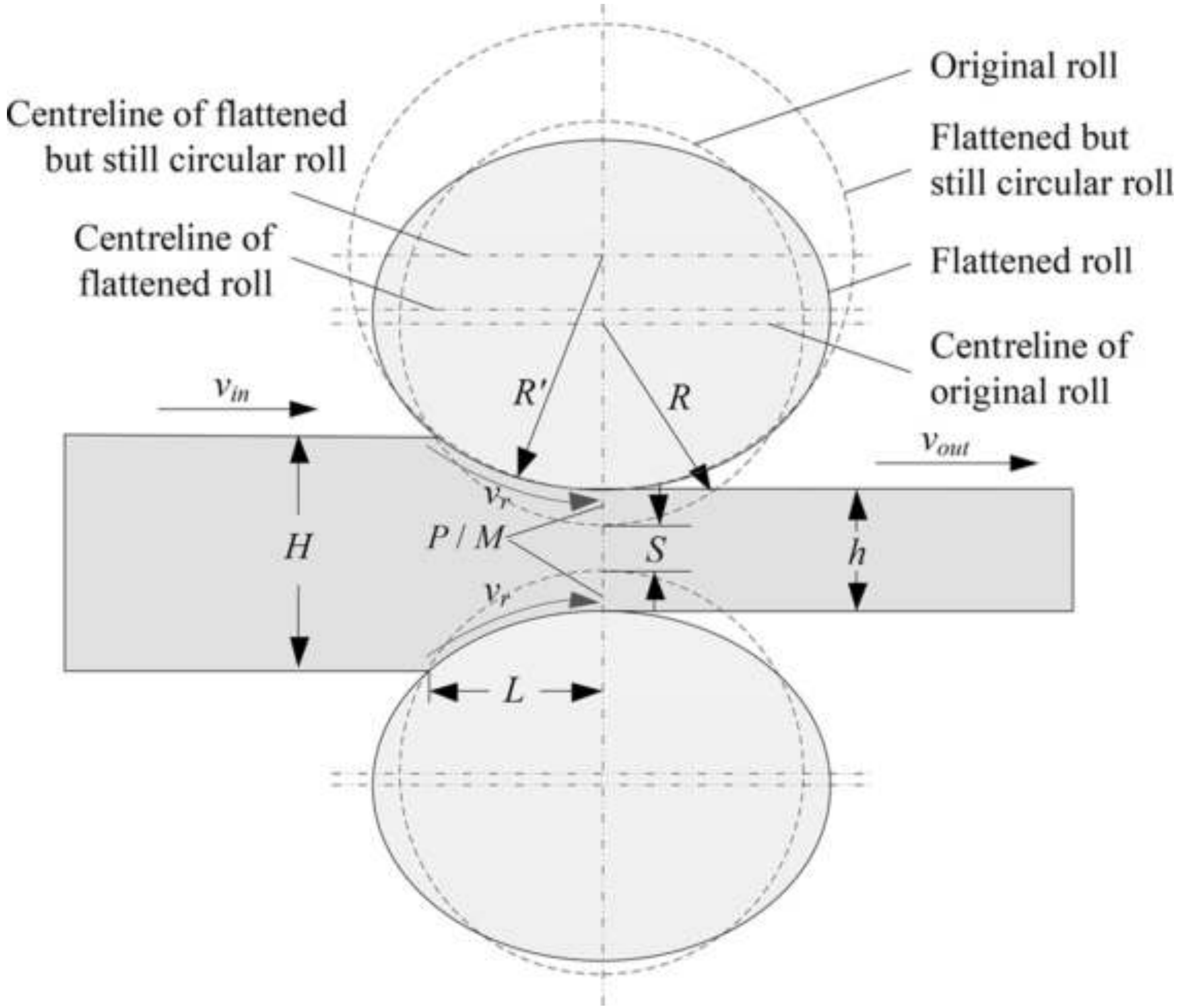


ROLLS WITH CAMBER PRECISELY ELIMINATE ROLL DEFLECTIONS



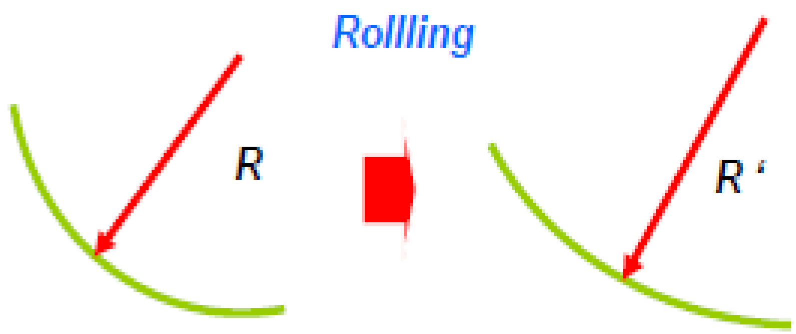
Roll Flattening

- Roll forces also tend to **flatten the rolls elastically**, much like the flattening of vehicle tires on roads.
- Flattening increases the roll's radius, resulting in a **larger contact area for the same reduction in thickness**, and increasing the roll force, F.
- Because of the **combined effects of flattening and the friction hill**, reductions in thickness of thin sheets is very difficult to obtain with large work rolls.
- The usual solution is to roll thin workpieces using a **backing roll arrangement**.



Original roll
Centreline of flattened but still circular roll
Flattened but still circular roll
Centreline of flattened roll
Flattened roll
Centreline of original roll
v_{in}
R'
R
v_{out}
v_r
H
P / M
S
h
v_r
L

- The rolls flatten in the region where they contact the workpiece. The radius of the curvature is increased R -> R' (Roll Flattening).
- According to analysis by Hitchcock,



$$R' = R\left(1 + \frac{CF'}{h_o - h_f}\right),$$

where the value of C is 2.3×10^{-2} mm^2/kN for steel rolls and 4.57×10^{-2} for cast-iron rolls, and F' is the **roll force per unit width** of strip, expressed in kN/mm. The higher the elastic modulus of the roll material, the less the roll distorts. The magnitude of R' cannot be calculated directly from Eq. because the roll force is itself a function of the roll radius; the solution is then obtained iteratively. Note that R in all previous equations should be replaced by R' when significant roll flattening occurs.

Spreading

- In rolling plates and sheets with high width-to-thickness ratios, the width of the strip remains effectively ***constant during rolling (Plain strain condition)***.
- However, with smaller ratios (such as a strip with a square cross section), its width increases significantly as it passes through the rolls.
- This ***increase in width is called spreading***. In the calculation of the roll force, the width w is taken as an average width.
- In metal rolling operations, the plastic deformation causing a reduction in thickness will also cause an increase in the ***width of the part***, this is called *spreading*.

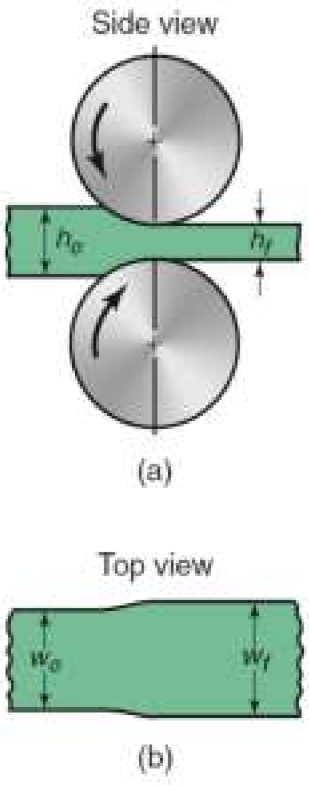
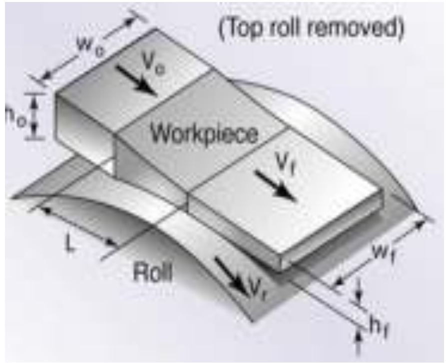
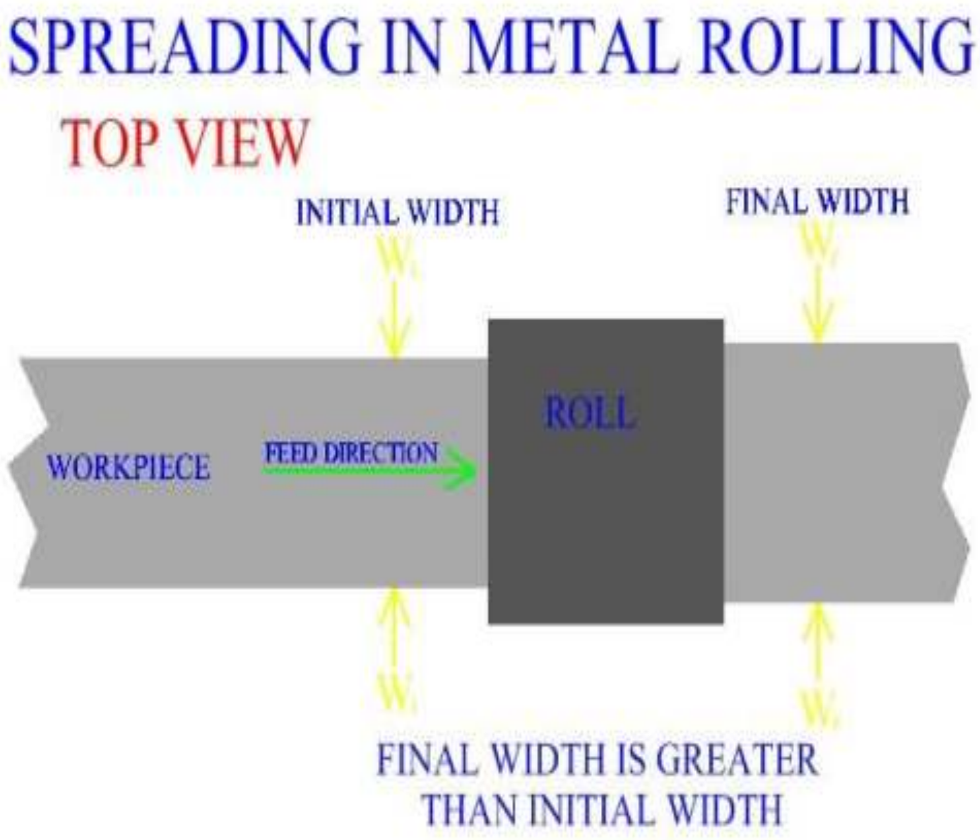


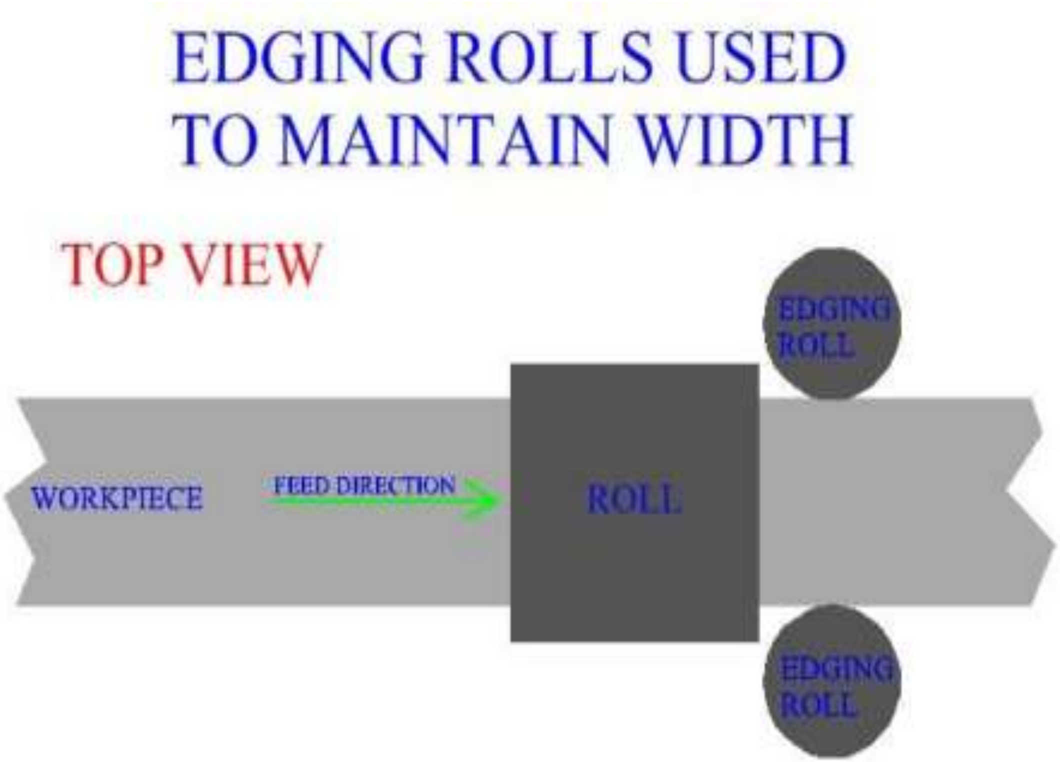
FIGURE 13.5 Spreading in flat rolling. Note that similar spreading can be observed when dough is rolled with a rolling pin.



- *Spreading increases* with
  - ***Decreasing width-to-thickness ratio*** of the entering strip (because of reduction in the width constraint.
  - ***Increasing friction***, and
  - ***Decreasing ratio of the roll radius to the strip thickness***. The last two effects are due to the increased longitudinal constraint of the material flow in the roll gap.
- Spreading can be prevented also by using ***additional rolls (with vertical axes)*** in contact with the edges of the rolled product in the roll gap (edger mills), thus providing a physical constraint to spreading.



- In cases of low width to thickness ratios, such as a bar with a square cross section, spreading can be an issue.
- Vertical rolls can be employed to edge the work and maintain a constant width.



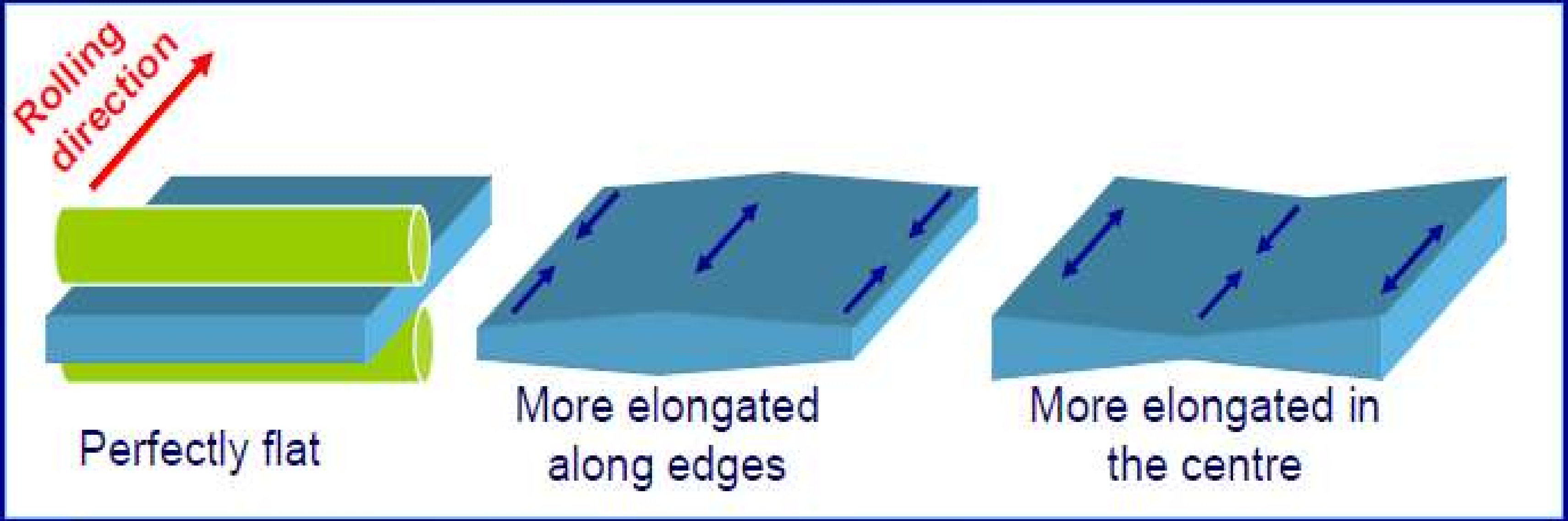
Defects in Rolling

- Defects may be on the ***surfaces of the rolled*** plates and sheets, or they may be ***structural defects within*** the material.
- In hot rolling, if the temperature of the work piece is not uniform the flow of the material will occur more in the warmer parts and less in the cooler.
- If the temperature difference is great enough ***cracking and tearing*** can occur.
- Surface defects may result from inclusions and impurities in the material, scale, rust, dirt, roll marks, and other causes related to the prior treatment and working of the material.
- Torch (scarfing), is a preconditioning process to ***remove scale*** from the surfaces of some hot rolled product.

Flatness

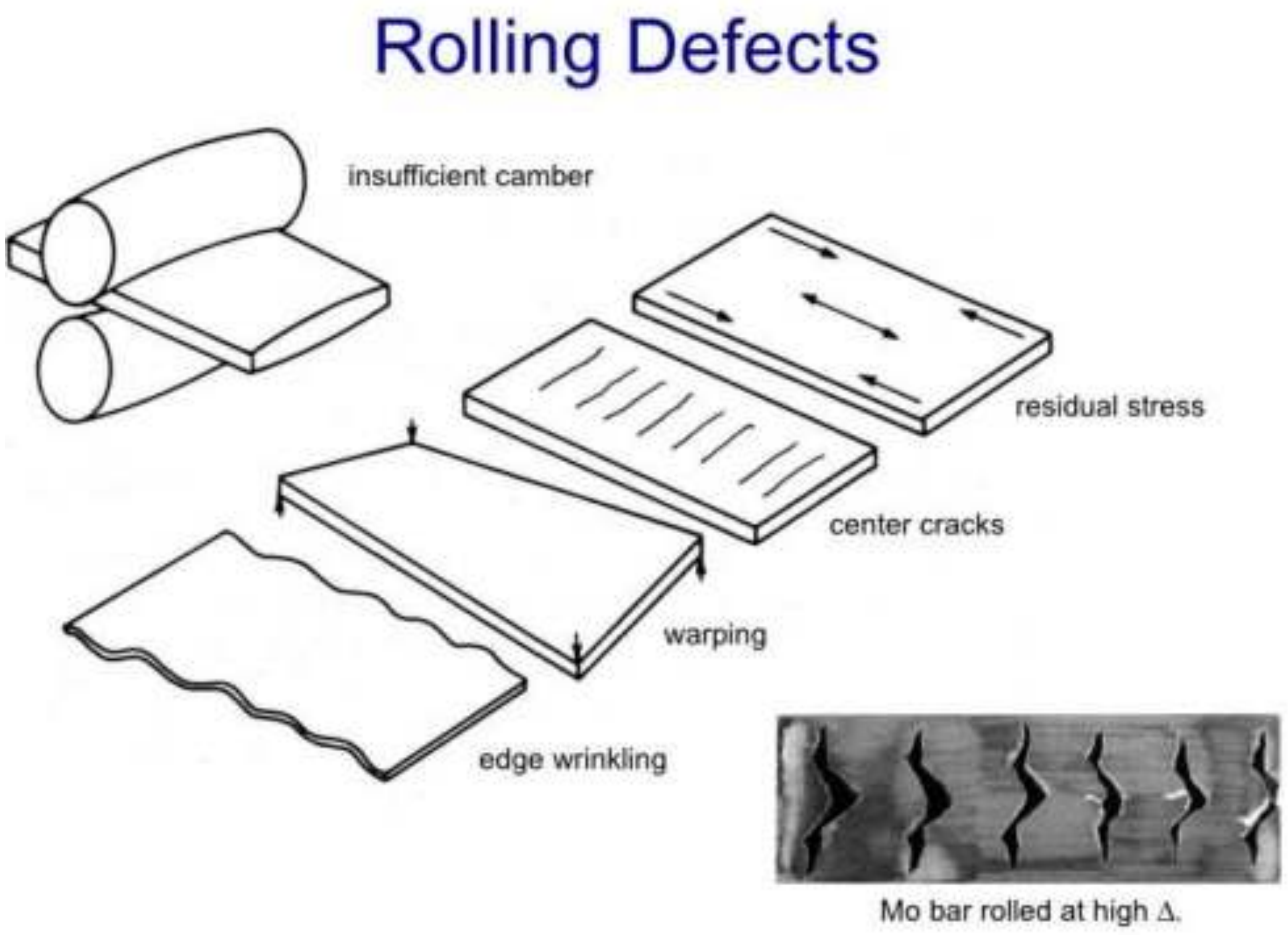
• The ***roll gap*** must be perfectly parallel to produce sheets/plates with equal thickness at both ends.

• The rolling speed is very sensitive to *flatness*. A difference in elongation of one part in 10,000 between different locations in the sheet can cause waviness.



Possible defects when Rolling with insufficient camber

- Thicker centre means the edges would be plastically elongated more than the centre, normally called long edges.
- This induces the ***residual stress pattern of compression at the edges and tension along the centre line.***
- This can cause **centre line cracking (c)** **warping (d)** or **edge wrinkling or crepe-paper effect or Wavy edge (e)**.

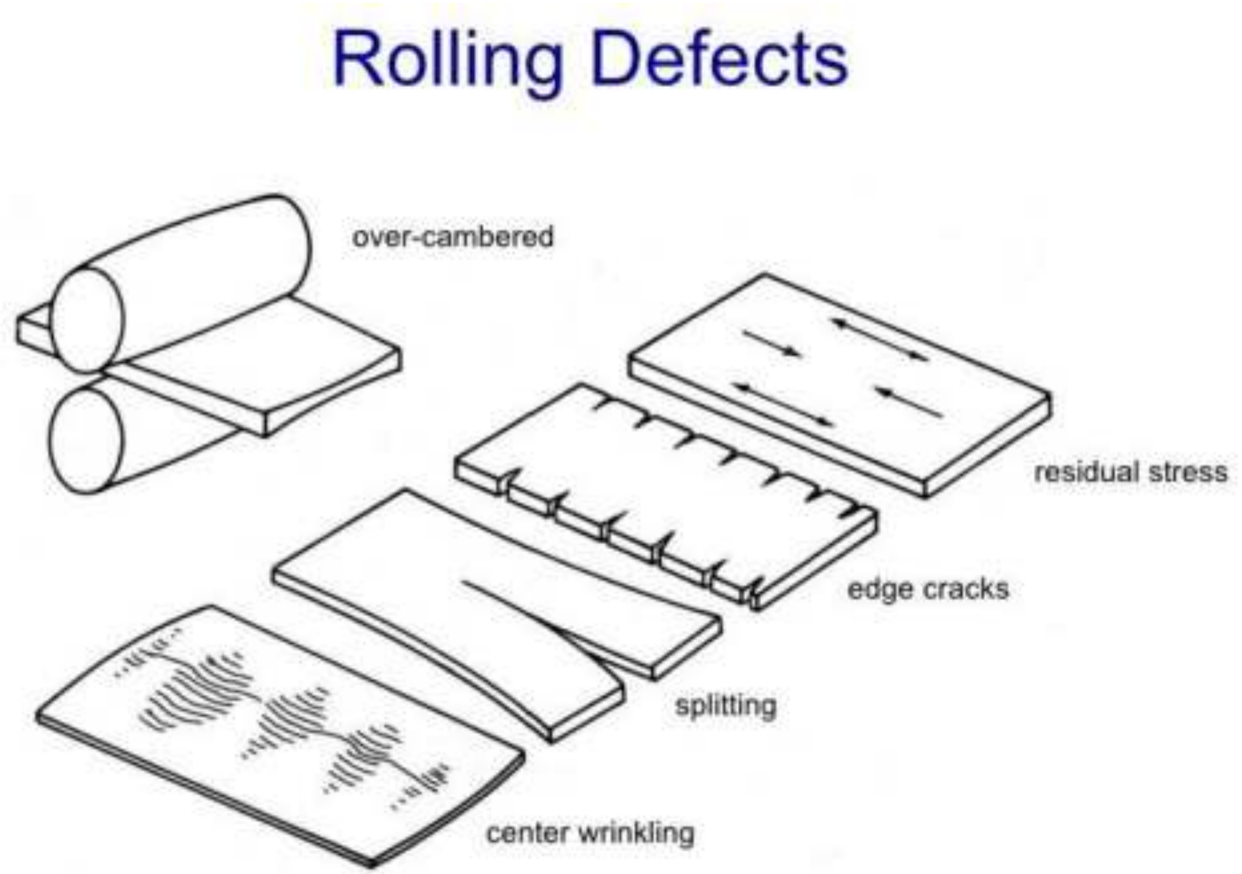


Wavy Edges

- Wavy edges are caused by bending of the rolls, the edges of the ***strip are thinner than at the center***. Because the edges elongates more than the center and are restrained by the bulk of the material from expanding freely, they buckle.

Possible effects when rolls are over-cambered.

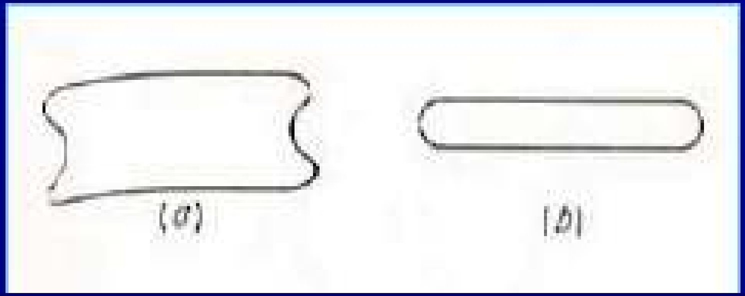
- Thicker edges than the centre means the centre would be plastically elongated more than the edges, resulting in lateral spread.
- The residual stress pattern is now ***under compression in the centerline and tension at the edges***.
- This may cause ***edge cracking (c)***, ***centre splitting (d)***, ***centerline wrinkling(e)***

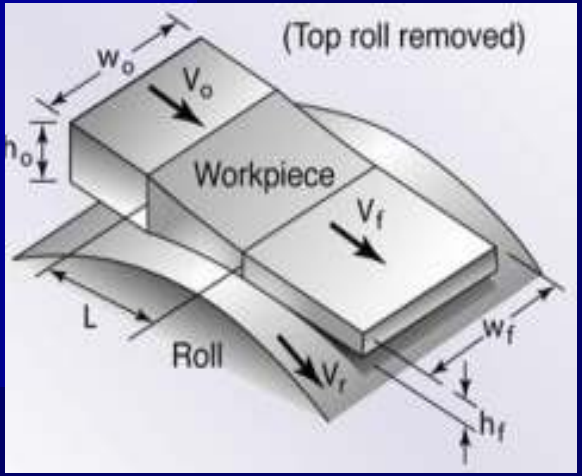


- ***Edging*** can also be caused by inhomogeneous deformation in the thickness direction.

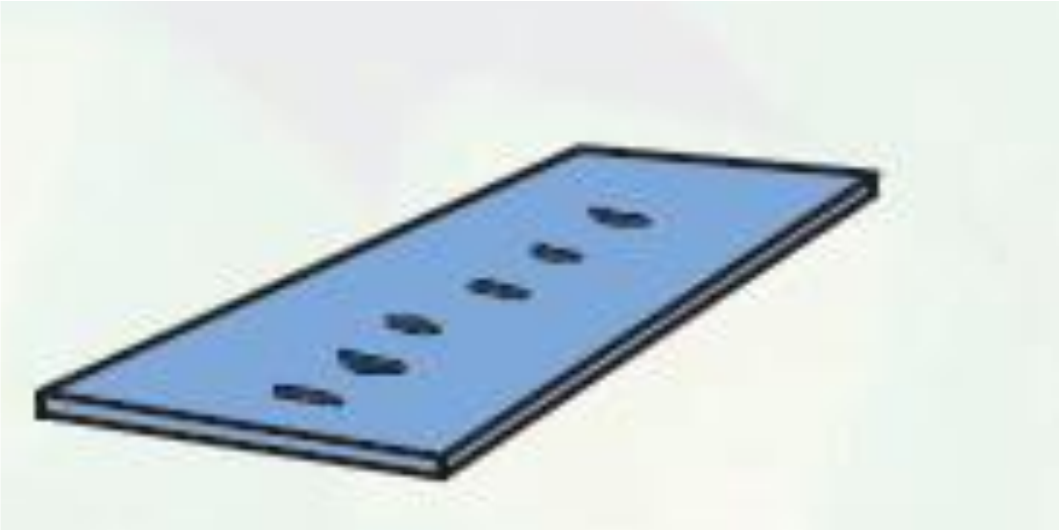
- If only the surface of the workpiece is deformed (as in a light reduction on a thick slab), the edges are concaved (a). The ***overhanging material*** is not compressed in the subsequent step of rolling, causing this area under tensile stress and leading to ***edge cracking***. This has been observed in initial breakdown of hot-rolling when $h/L_p > 2$

- With heavy reduction, the centre tends to expand more laterally than the surface to produced ***barrelled edges*** (b). This causes secondary tensile stresses by barrelling, which are susceptible to ***edge cracking***.





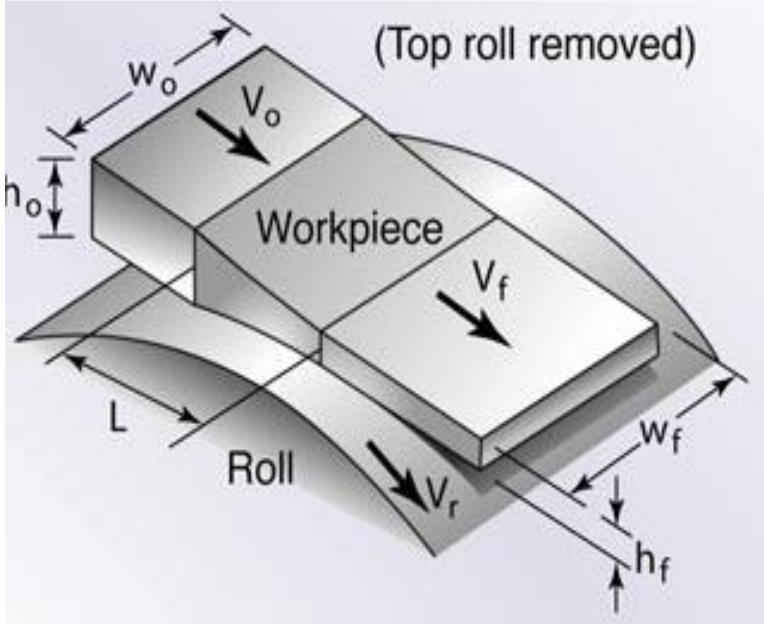
Edge cracks due to barrelling

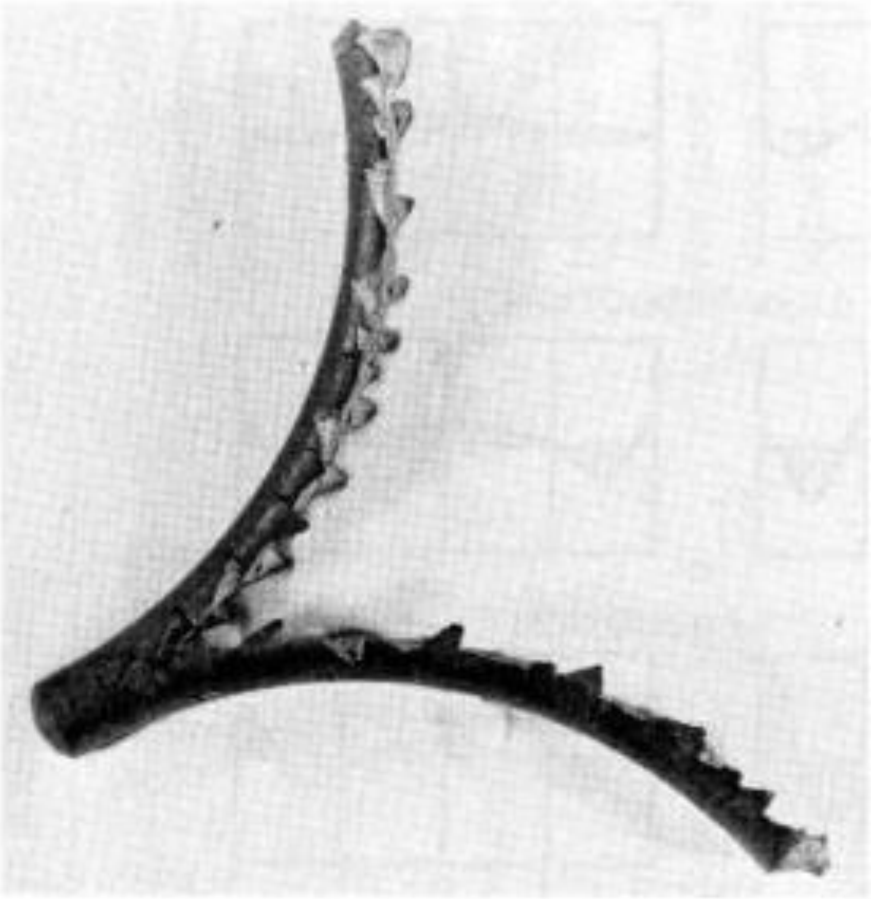


Zipper cracks in the center of strip due to low ductility

Alligatoring

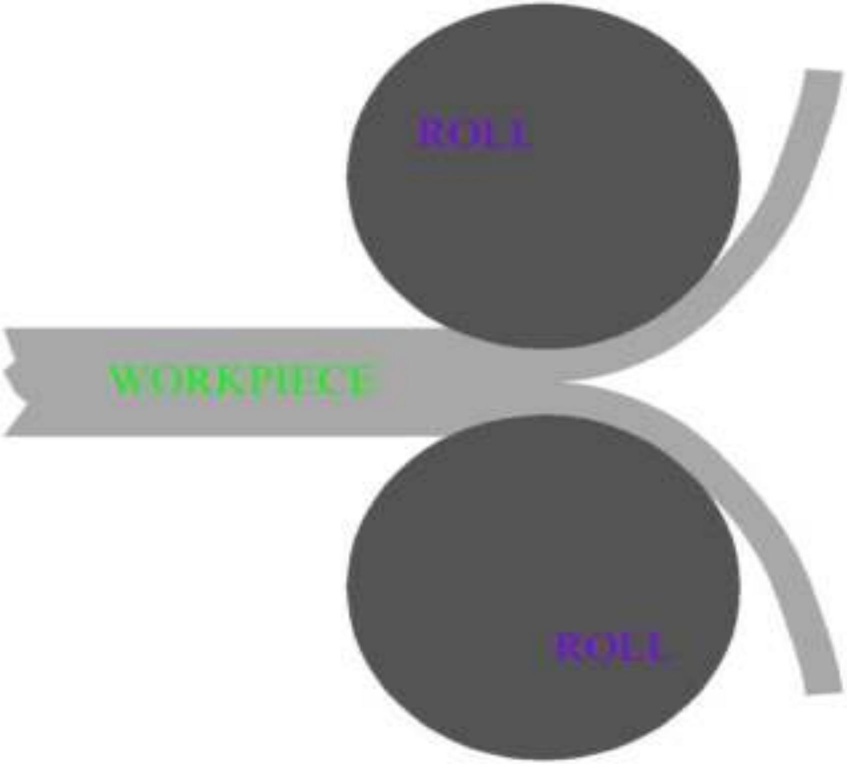
- Alligatoring is a complex phenomenon resulting from **inhomogeneous deformation** of the material during rolling or defects in the original cast ingot, such as pipes.
- Alligatoring will occur **when lateral spread is greater in the centre than the surface** (surface in tension, centre in compression) and with the presence of metallurgical weakness along the centre line.
- Here the work being rolled ***actually splits in two during the process***. The two parts of the work material travel in opposite directions relative to their respective rolls.





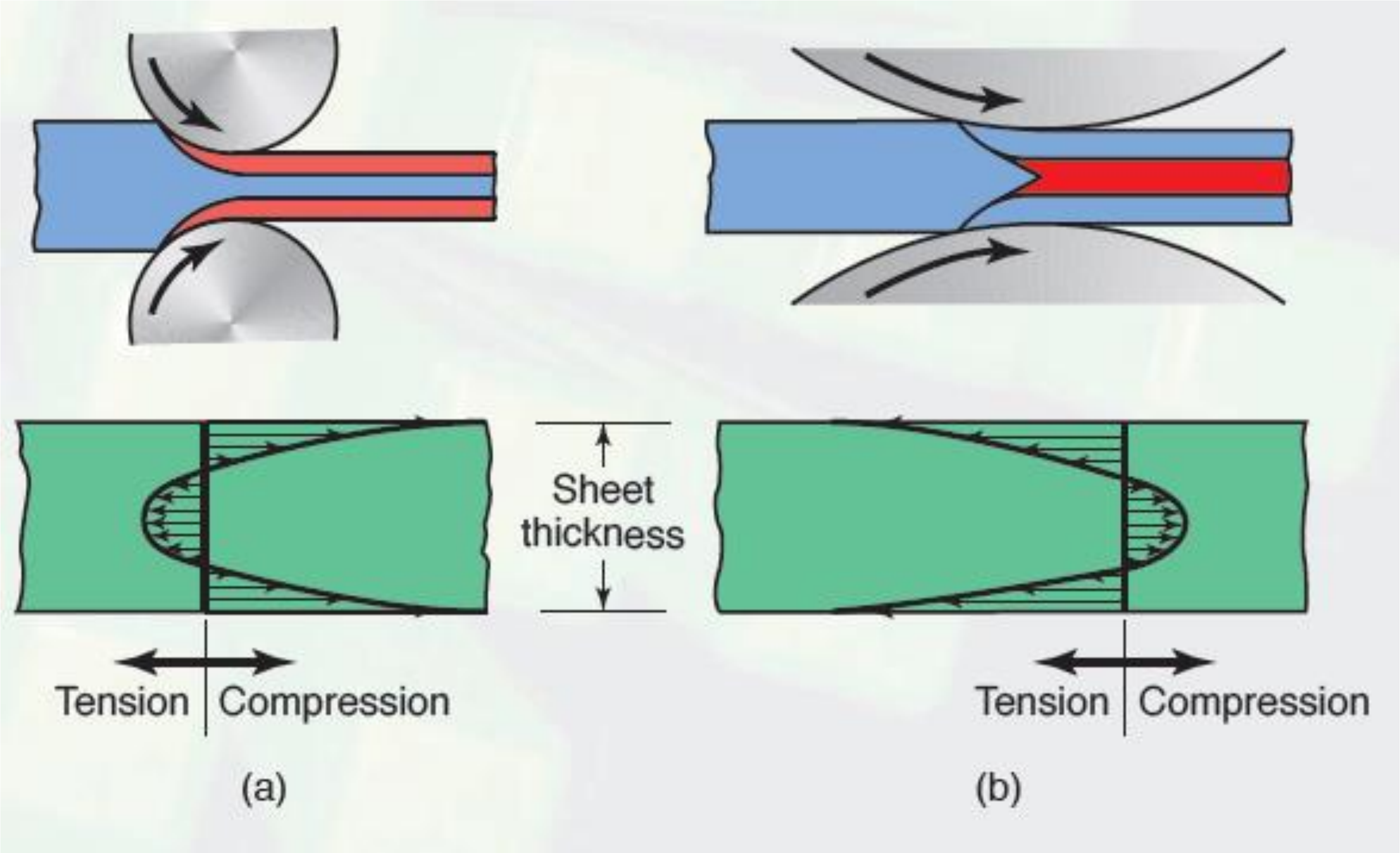
Mo rod rolled at high Δ.

ALLIGATORING



Residual stresses considered as a major factor for defects

- Residual stresses can develop in rolled plates and sheets because of ***inhomogeneous plastic deformation*** in the roll gap.
- ***Small-diameter rolls and/or small reductions in thickness*** tend to deform the metal plastically at its surfaces (similarly to shot peening or roller burnishing)
- This type of deformation generates ***compressive residual stresses*** on the surfaces and tensile stresses in the bulk.
- ***Large- diameter rolls and/or high reductions***, on the other hand, tend to deform the bulk to a greater extent than the surfaces, because of friction at the surfaces along the arc of contact.
- This situation generates ***tensile residual stresses on the surface***, For many applications, these residual stresses can compromise performance.



The effect of roll radius on the type of residual stresses developed in flat rolling:
(a)small rolls and/or small reduction in thickness; and
(b) large rolls and/ or large reduction in thickness.

Vibration and chatter

- Vibration and chatter can have significant effects on product quality and the productivity of metalworking operations.
- ***Chatter*** is defined as ***self-excited vibration***, and can occur in such metal forming and machining processes as rolling, extrusion, drawing, machining, and grinding.
- In rolling, it leads to ***periodic variations in the thickness*** of the rolled sheet and in its surface finish and, consequently, can lead to excessive scrap.
- ***Chatter*** in rolling has been found to occur ***predominantly in tandem mills.***
- Chatter is a very complex phenomenon and results from interactions between the structural dynamics of the mill stand and the dynamics of the rolling operation.
- ***Rolling speed and lubrication are found to be the two most important parameters***. Although not always practical to implement, it also has been suggested that ***chatter can be reduced by increasing the distance between the stands of the rolling mill, increasing the strip width, decreasing the reduction per pass (draft), increasing the roll radius, increasing the strip-roll friction, and incorporating dampers in the roll supports.***

Flat-Rolling Practice

- The initial rolling steps **(breaking down) of the material typically is done by hot rolling** (above the recrystallization temperature of the metal)
- A cast structure typically is dendritic, and it *includes coarse and nonuniform grains*; this structure usually is brittle and may be porous.
- Hot rolling converts the cast structure to a wrought structure with **finer grains and enhanced ductility**, both of which result from the breaking up of brittle grain boundaries and the closing up of internal defects (especially porosity).

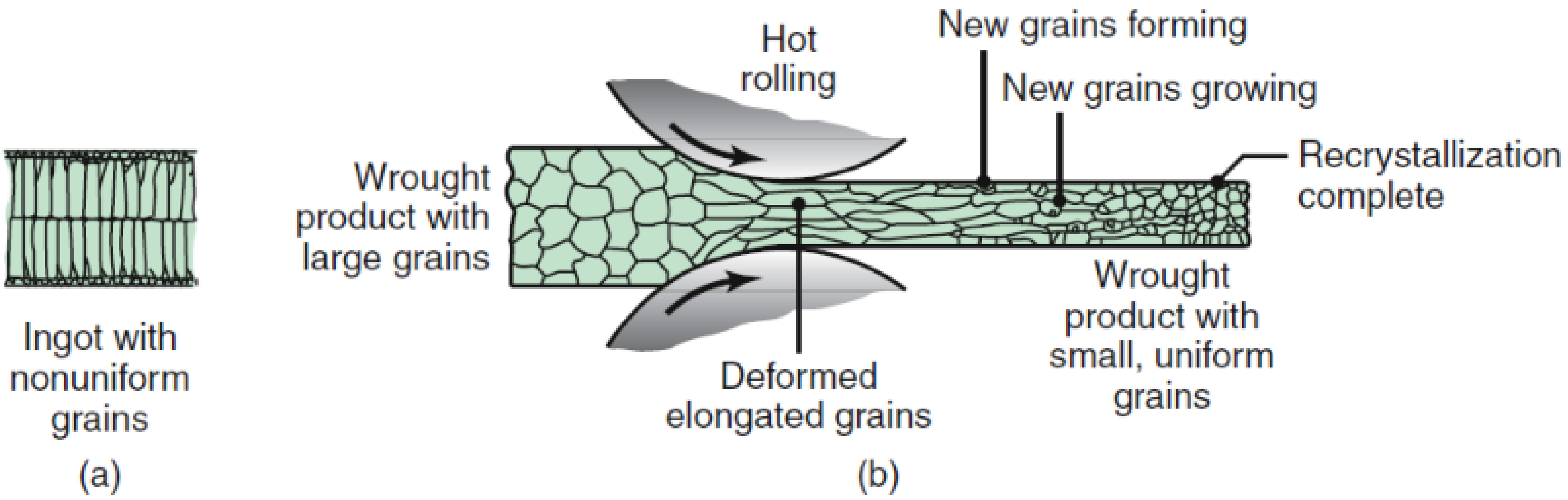
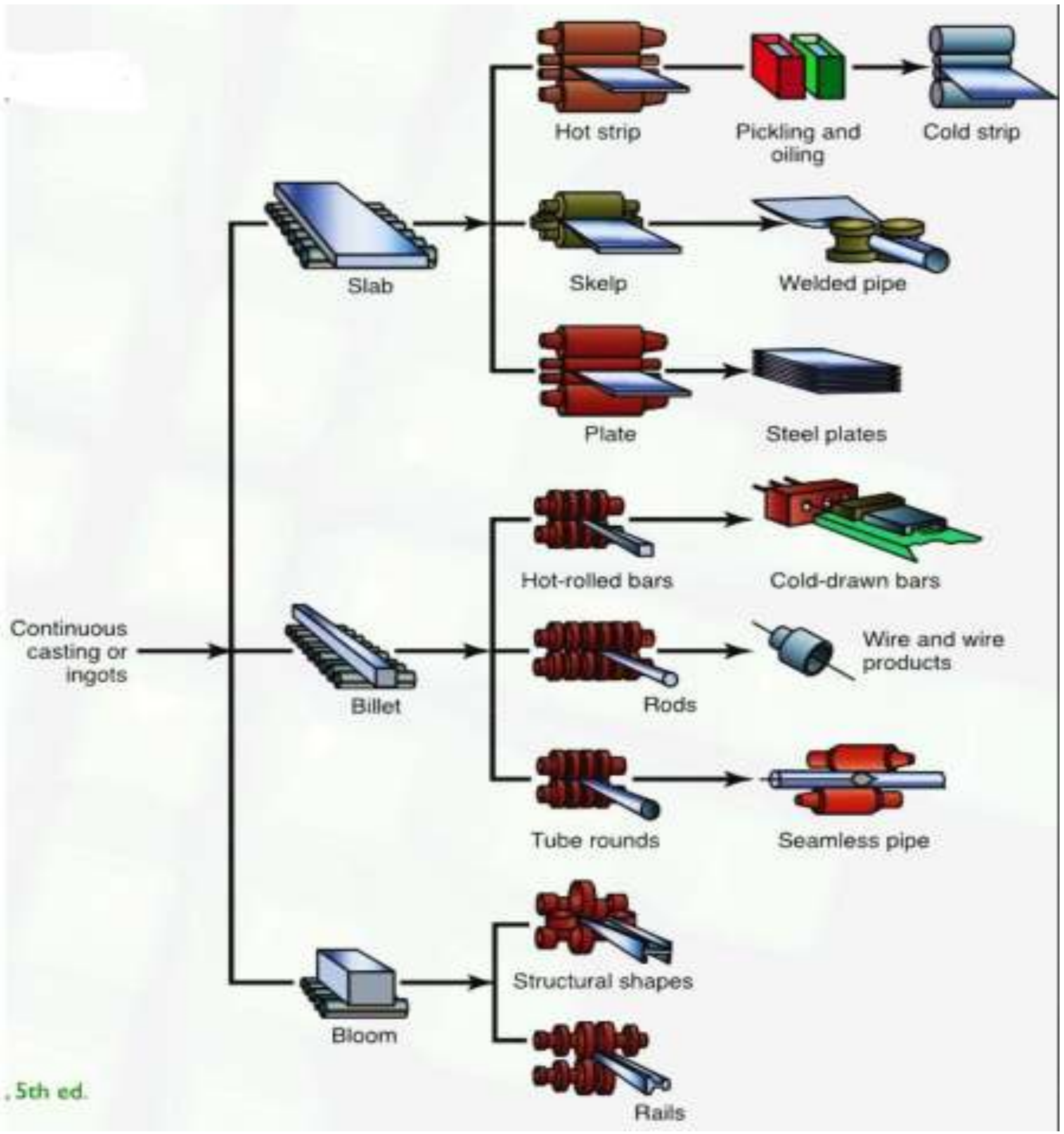


FIGURE 13.6 Changes in the grain structure of cast or of large-grain wrought metals during hot rolling. Hot rolling is an effective way to reduce grain size in metals for improved strength and ductility. Cast structures of ingots or continuous castings are converted to a wrought structure by hot working.



Reference: manufacturing processes for engineering materials by Serope Kalpakjian

- The product of the first hot-rolling operation is called a **bloom**, a **slab**, or a **billet**
- A *bloom* usually has a square cross section, at least 150 mm (6 in.) on the side; a slab usually is rectangular in cross section. Blooms are processed further by ***shape rolling*** into structural shapes such as ***I-beams and railroad rails***.
- ***Slabs are rolled into plates and sheets***. Billets usually are square (with a cross-sectional area smaller than blooms) and later are rolled into various shapes, such as round ***rods and bars, using shaped rolls***. Hot-rolled round rods (**wire rods**) are used as the starting material for rod- and wire-drawing operations.
- In the hot rolling of blooms, billets, and slabs, the surface of the material usually is **conditioned** (prepared for a subsequent operation) prior to rolling them.
- Conditioning is often done by means of ***a torch (scarfing) to remove heavy scale*** or by rough grinding to smoothen surfaces. Prior to cold rolling, the scale developed during hot rolling may be removed by ***pickling with acids*** (acid etching), by such mechanical means as blasting with water, or by grinding to remove other defects as well.

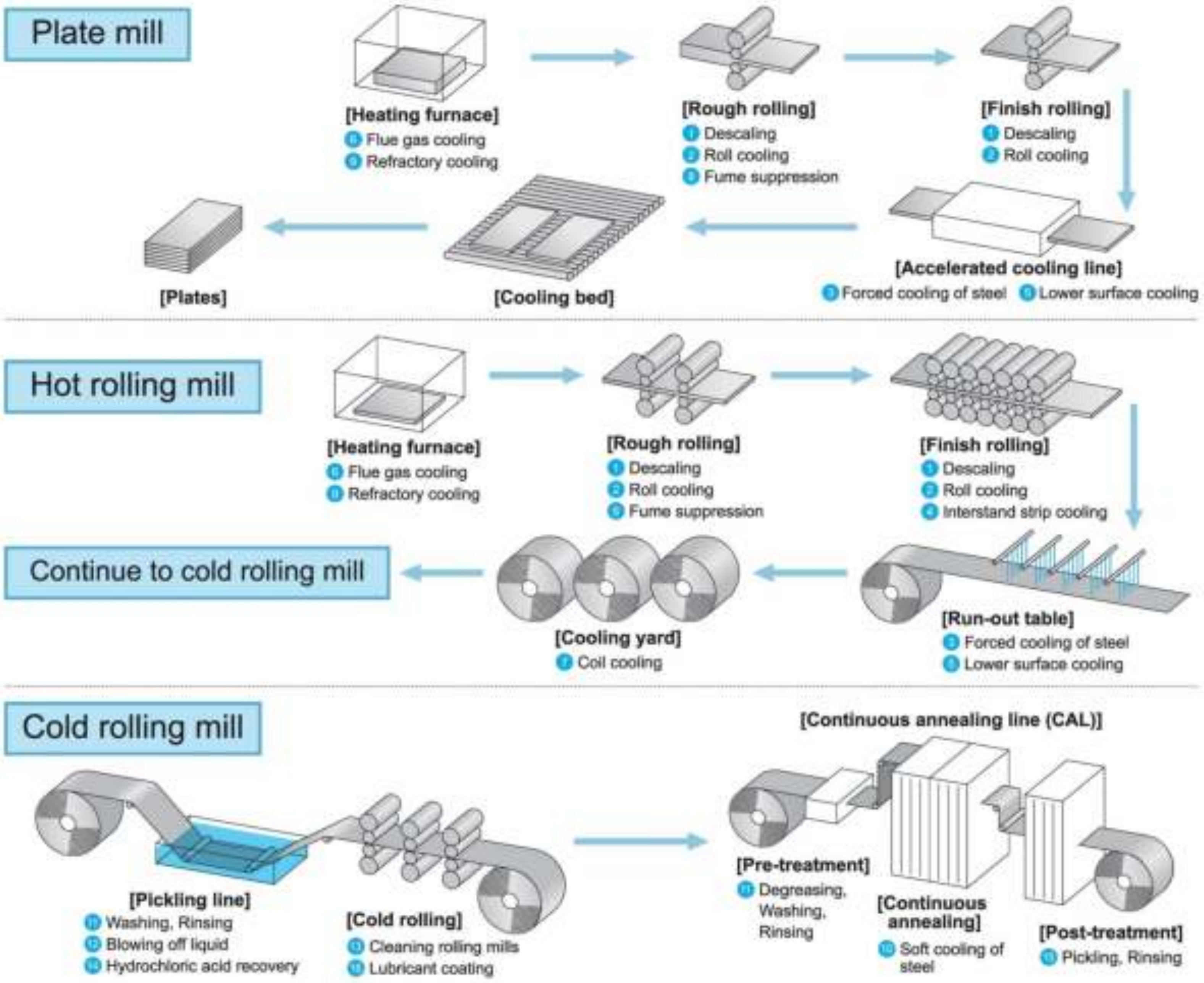


Plate mill
[Heating furnace]
Flue gas cooling
Refractory cooling
[Rough rolling]
Descaling
Roll cooling
Fume suppression
[Finish rolling]
Descaling
Roll cooling
[Accelerated cooling line]
Forced cooling of steel
Lower surface cooling
[Cooling bed]
[Plates]
Hot rolling mill
[Heating furnace]
Flue gas cooling
Refractory cooling
[Rough rolling]
Descaling
Roll cooling
Fume suppression
[Finish rolling]
Descaling
Roll cooling
Interstand strip cooling
[Run-out table]
Forced cooling of steel
Lower surface cooling
[Cooling yard]
Coil cooling
Continue to cold rolling mill
Cold rolling mill
[Pickling line]
Washing, Rinsing
Blowing off liquid
Hydrochloric acid recovery
[Cold rolling]
Cleaning rolling mills
Lubricant coating
[Continuous annealing line (CAL)]
[Pre-treatment]
Degreasing, Washing, Rinsing
[Continuous annealing]
Soft cooling of steel
[Post-treatment]
Pickling, Rinsing

- **Pack rolling** is a *flat-rolling operation in which two or more layers of metal are rolled together, thus improving productivity*.
- Pack rolling is a sheet metal fabrication process used to produce **several thin film sheets at the same time**. The process has several advantages including not requiring the usual small roller sizes due to the increased starting thickness of the "pack" of raw stock.
- This allows the use of conventional rolling equipment and has no negative effect on the finished product. The process typically produces aluminum foil sheets for the lithographic printing, food packaging, and electronics industries

Temper rolling or skin pass

- Rolled mild steel, when subsequently ***stretched during sheet-forming operations***, undergoes ***yield-point elongation*** a phenomenon that causes surface irregularities called stretcher strains or ***Lüder's bands***. To correct this situation, the sheet metal is subjected to a final, light pass of 0.5 to 1.5% reduction known as **temper rolling or skin pass shortly before stretching**.

- A rolled sheet may not be sufficiently flat as it leaves the roll gap, due to factors such as variations in the incoming material or in the processing parameters during rolling.
- To ***improve flatness***, the rolled strip typically goes through a series of ***leveling rolls.*** Several roller arrangements are used.
- The workpiece is flexed in opposite directions as it passes through the sets of rollers. Each roll usually is driven separately by an individual electric motor.

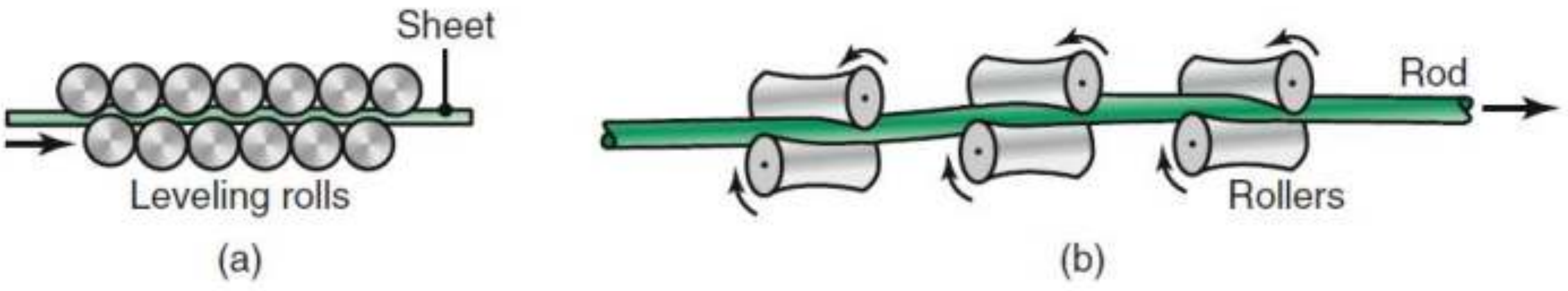


FIGURE 13.7 (a) A method of roller leveling to flatten rolled sheets. (b) Roller leveling to straighten drawn bars.

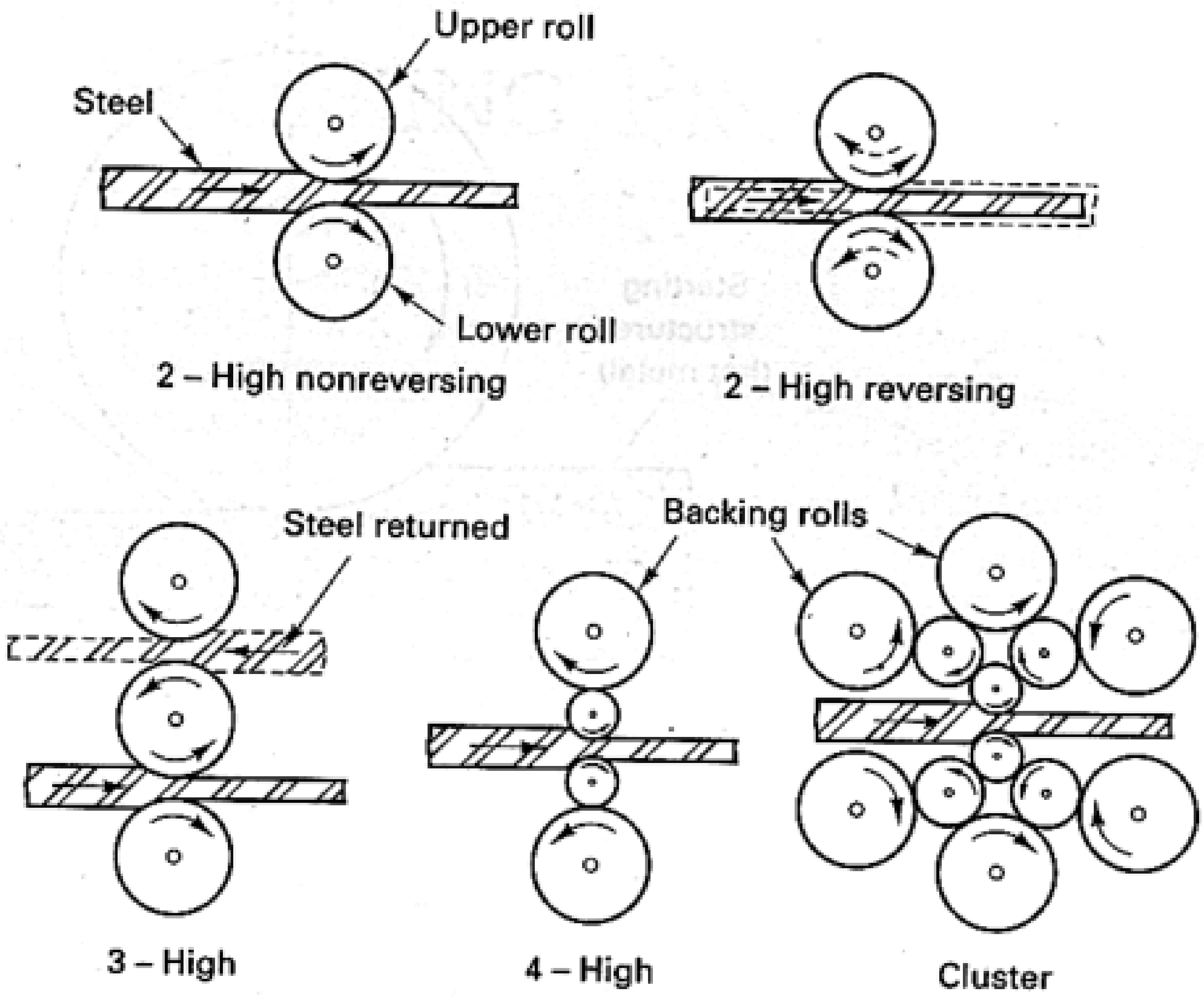


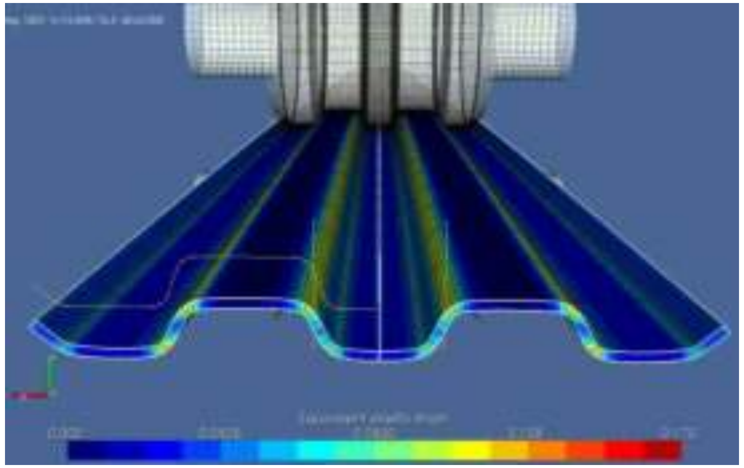
FIGURE 18-3 Various roll configurations used in rolling operations.

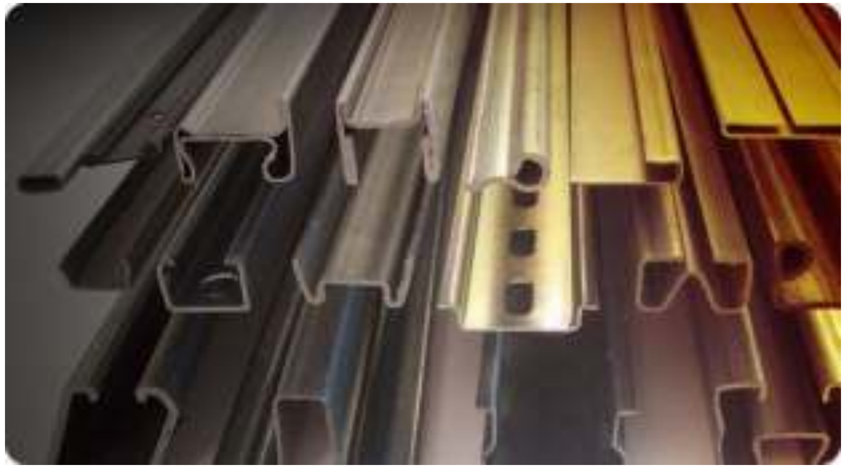

MACHINERY
TECHNOLOGY

MISCELLANEOUS ROLLING OPERATIONS

- Several rolling processes and mills have been developed to produce a specific family of product shapes.

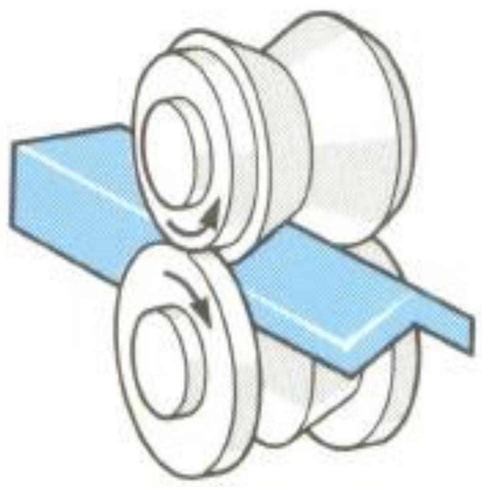
  - Shape Rolling
  - Ring Rolling
  - Thread and Gear
  - Rotary tube piercing
  - Tube rolling
  - Roll forging

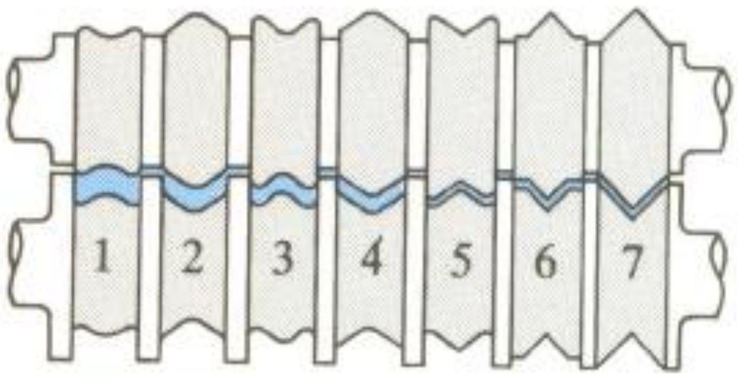




1. Shape-rolling operations

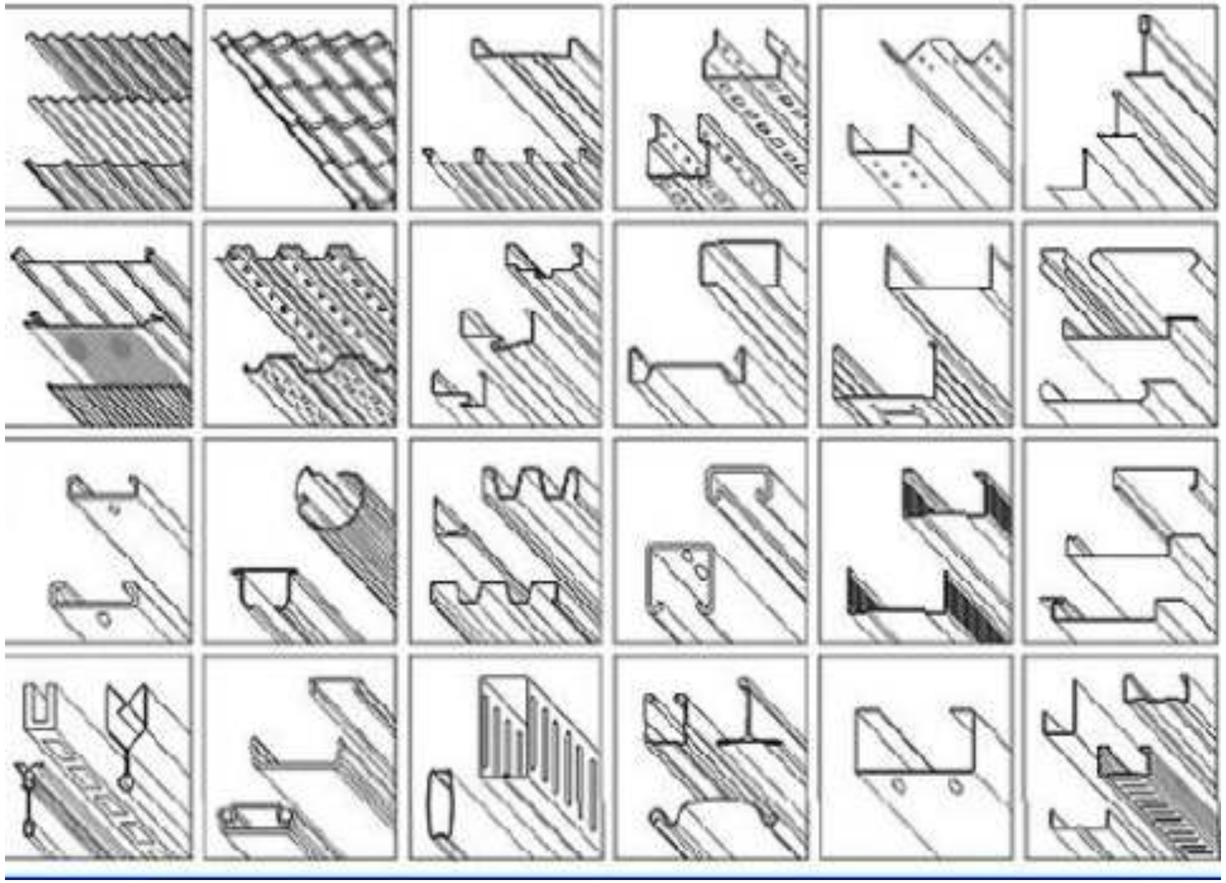
- Straight and long structural shapes, such as solid bars (with various X-section), channels, I-beams and rail road rails, are rolled through a set of ***specially designed rolls.*** The process of producing various shapes are known as SHAPE ROLLING OPERATIONS.
- A special type of cold rolling in which **flat slap** is progressively bent into ***complex shapes*** by passing it through a series of driven rolls.
- ***No appreciable change in the thickness*** of the metal during this process.
- Suitable for producing molded sections such as irregular shaped channels and trim.



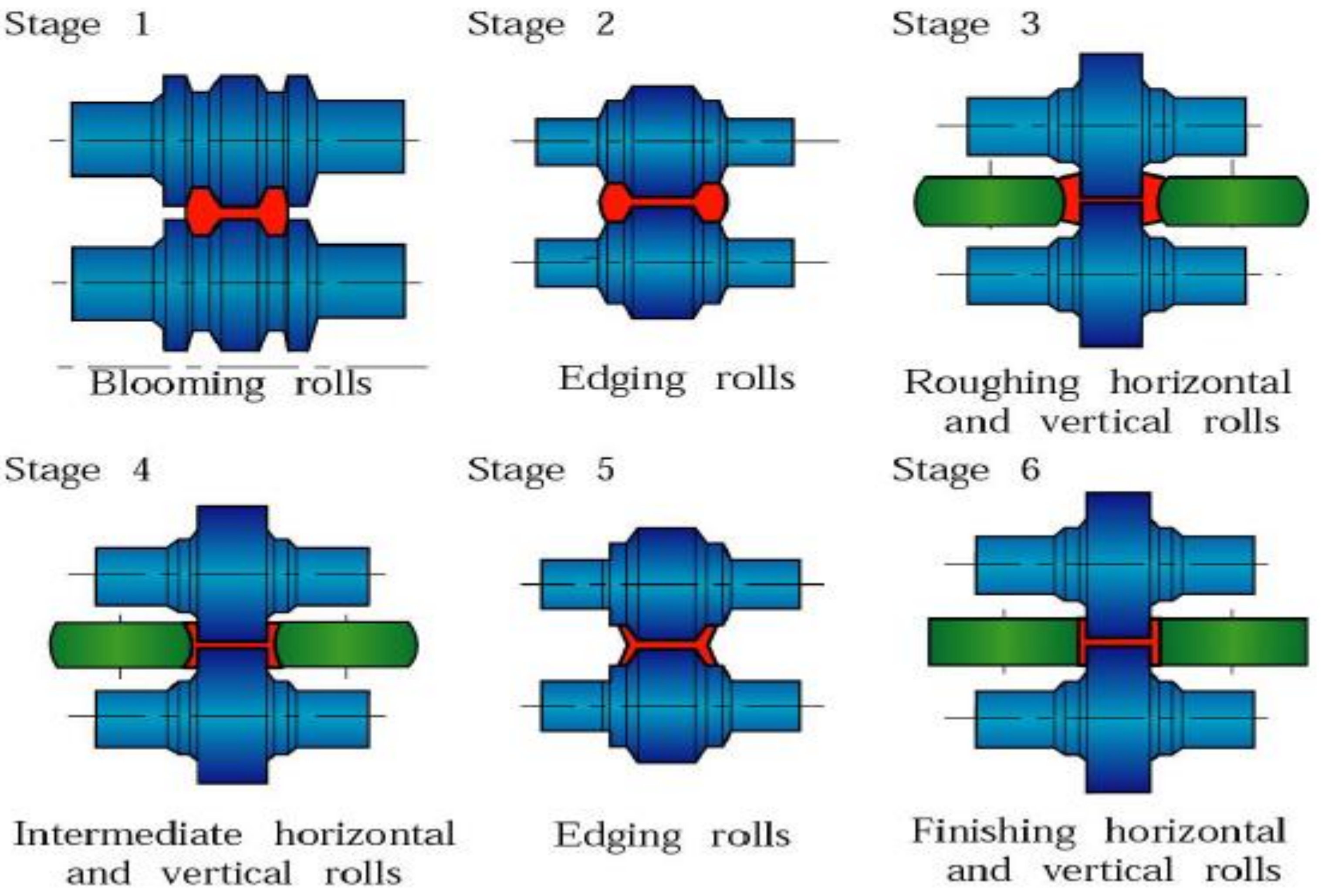


- A variety of sections can be produced by roll forming process using a series of forming rollers in a continuous method to roll the metal sheet to a specific shape.

- Applications:
- Construction Materials,
- Partition Beam
- Ceiling Panel
- Roofing Panels.
- Steel Pipe
- Automotive Parts
- Household Appliances
- Metal Furniture,
- Door And Window Frames
- Other Metal Products.



Shape Rolling



Stages of shape rolling H section


Shape Roll Forming - History
of Innovation
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The Roll Forming Process

2. Ring Rolling

- A ***small-thick diameter for a ring is expanded into a larger one*** (thinner diameter). The ring to be expanded is placed between two rolls, one of which is driven and the other is idler.
- The ***ring thickness is reduced*** by bringing the rolls closer as they rotate (Reduction in thick is compensated by ***increase in diameter*** since volume remains constant during deformations)
- This process can be carried out at room or elevated temperatures depending on the size and strength of the product.

- ***Advantages:*** Short production times, Material Savings, Close dimensional tolerances and favorable grain flow in the product.

- ***Typical Applications***: Large rings for rockets and turbines, gearwheel rims, ball bearing and roller bearing races, flanges and reinforcing rings for pipes and pressure vessel.

Ring Rolling

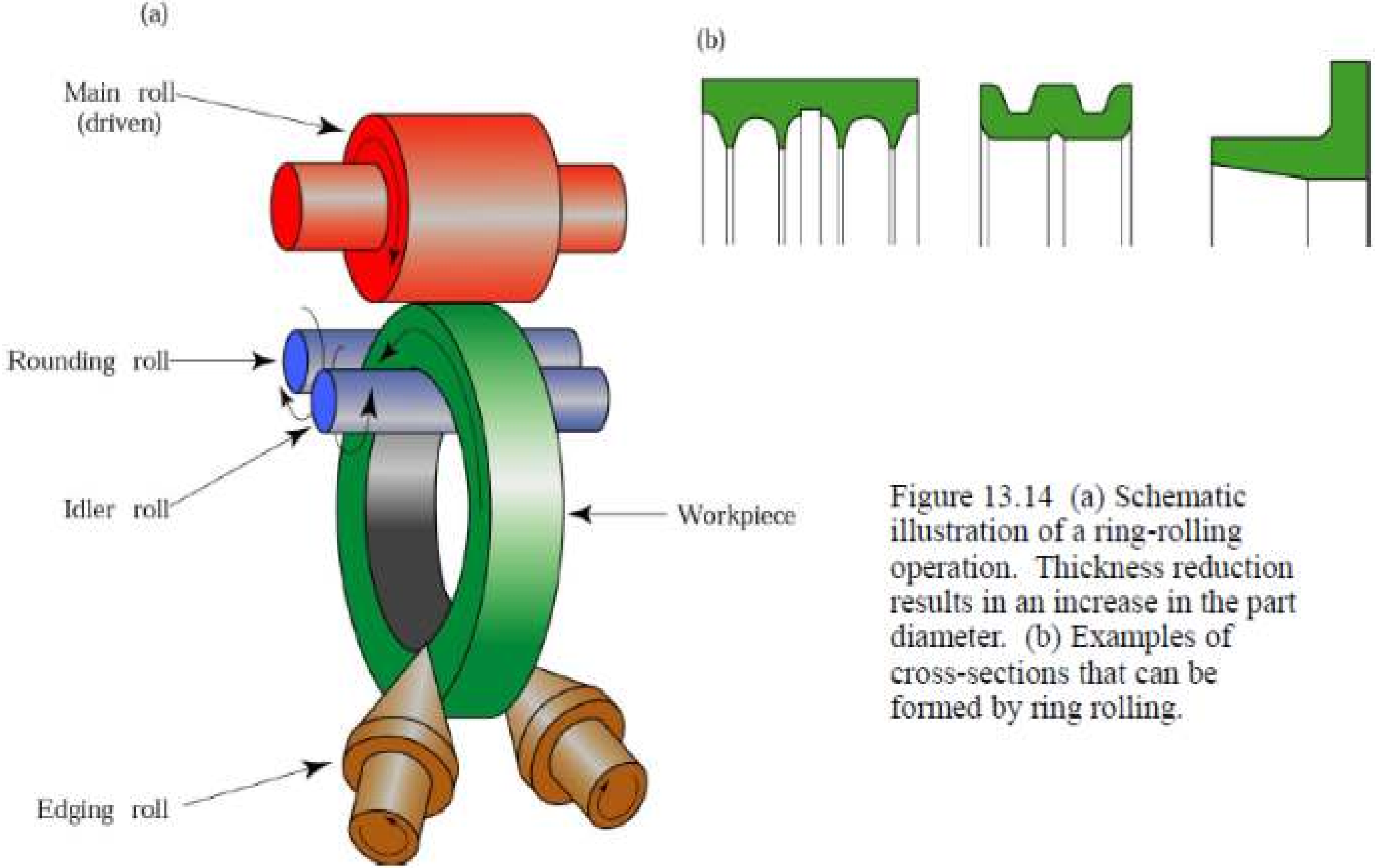
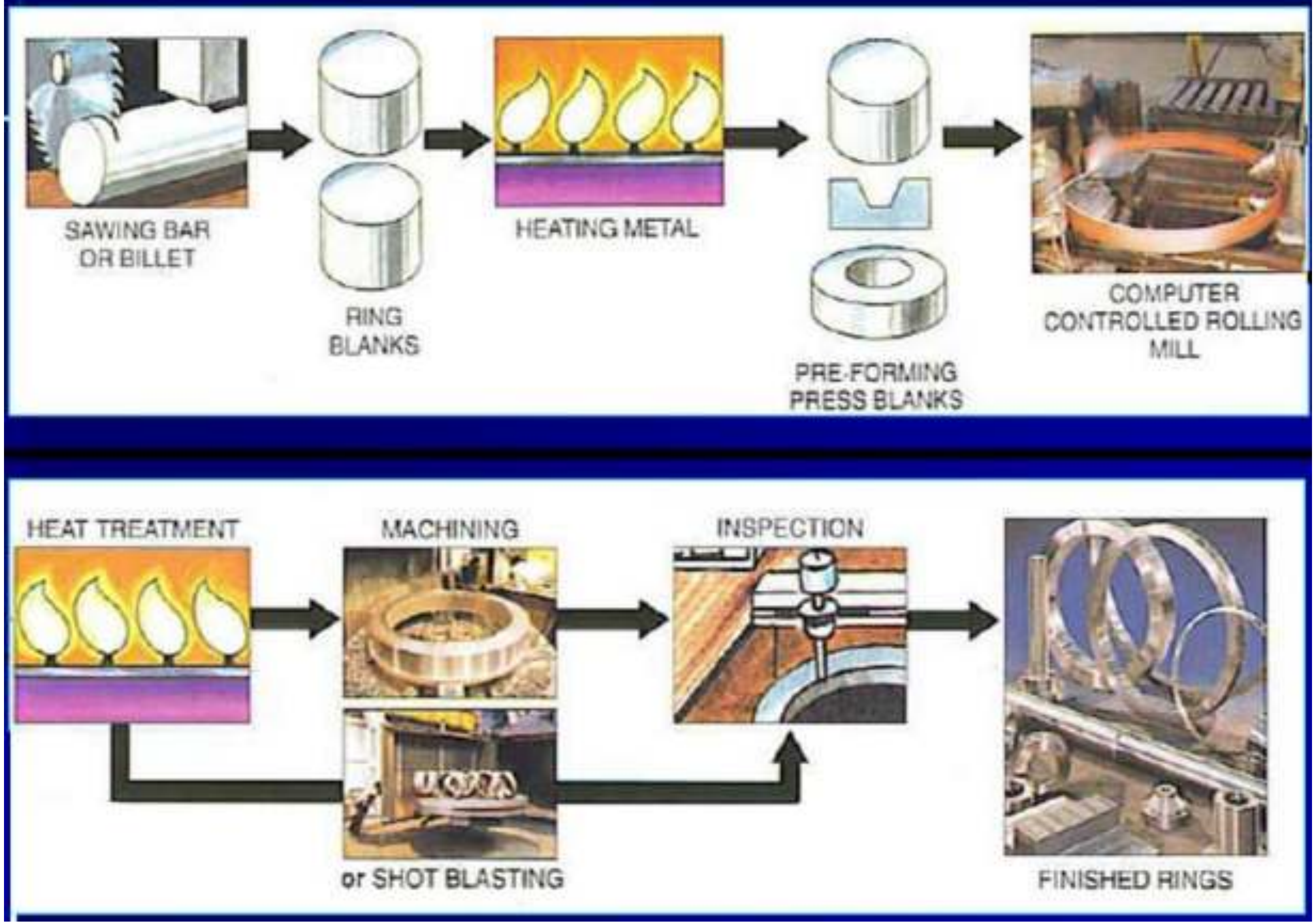


Figure 13.14 (a) Schematic illustration of a ring-rolling operation. Thickness reduction results in an increase in the part diameter. (b) Examples of cross-sections that can be formed by ring rolling.

Seamless ring rolling



3. Thread Rolling And Gear Rolling

- Thread rolling is a metal rolling process used extensively in manufacturing industry to ***produce screws, bolts and other fasteners***.
- This is a cold forming process.
- A common thread rolling process, used in industry to manufacture threaded parts, involves ***forming the threads into the metal of a blank by a pressing and rolling action between two die***.
- The ***die surfaces hold the shape and the force of the action forms the threads into the material***.
- High production rate
- A similar metal forming process has been developed for the ***production of gears***.

- This is a ***cold-forming process*** in which threads are formed on round parts by passing them between ***reciprocating or rotating dies***.
- It is essential that the material have ***sufficient ductility*** and that the rod or wire be of proper size.
- ***Lubrication*** is important for good surface finish and to minimize defects.
- Production rates in thread rolling are as high as ***30 pieces per second***. Thread rolling can also be ***carried out internally*** with a fluteless forming tap, and produces accurate threads with good strength.
- The thread-rolling process produces ***higher-strength threads without any loss of metal because of the cold working involved.*** The surface produced is very smooth, and the process induces ***compressive residual stresses on part surfaces, thus improving fatigue lite.***
- Because of volume constancy in plastic deformation, a rolled thread requires a ***round stock of smaller diameter*** to produce the same major diameter as that of a machined thread.
- Also, machining removes material by cutting through the grain-flow lines of the material, rolled threads have a ***grain-flow pattern that improves the strength of the thread.***

- ***Dies*** are pressed against the surface of cylindrical blank. As the blank rolls against the in-feeding die faces, the material is displaced to form the ***roots*** of the thread, and the displaced material flows radially ***outward*** to form the ***thread's crest***.

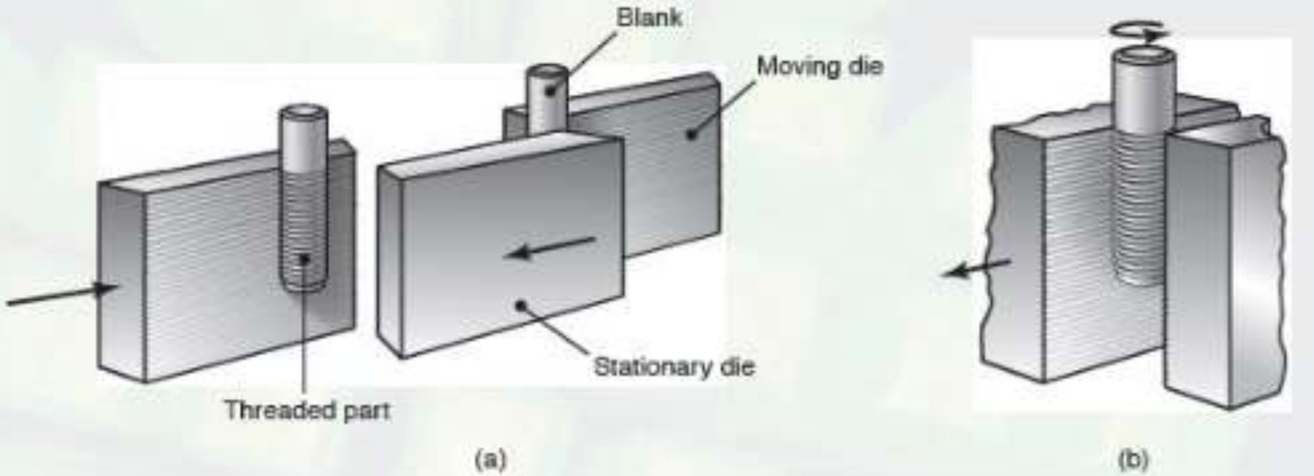
- A blank is fed between ***two grooved die plates*** to form the threads.

- The thread is formed by the ***axial flow*** of material in the work piece. The grain structure of the material is not cut, but is ***distorted*** to follow the thread form.

- Rolled threads are produced in a ***single pass*** at speeds far in excess of those used to cut threads.
- The resultant thread is very much ***stronger*** than a cut thread. It has a greater resistance to mechanical stress and an increase in fatigue strength

- ***Spur and helical gears*** can be produced by processes similar to thread rolling, and may be carried out on solid cylindrical blanks or on precut blanks.
- ***Helical gears*** also can be made by a ***direct extrusion process***, using specially shaped dies. Cold rolling of gears has numerous applications in automatic transmissions and power tools.

Thread Rolling



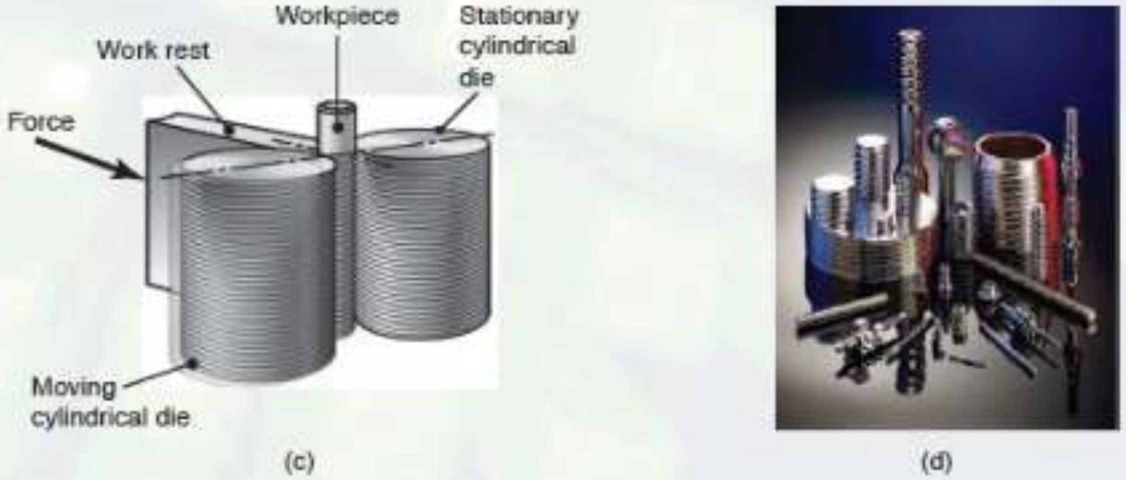


FIGURE 6.44 Thread-rolling processes: (a) and (b) reciprocating flat dies and (c) two-roller dies; (d) thread-rolled parts, made economically and at high production rates. *Source:* (d) Courtesy of Tesker Manufacturing Corp.

Thread Microstructure

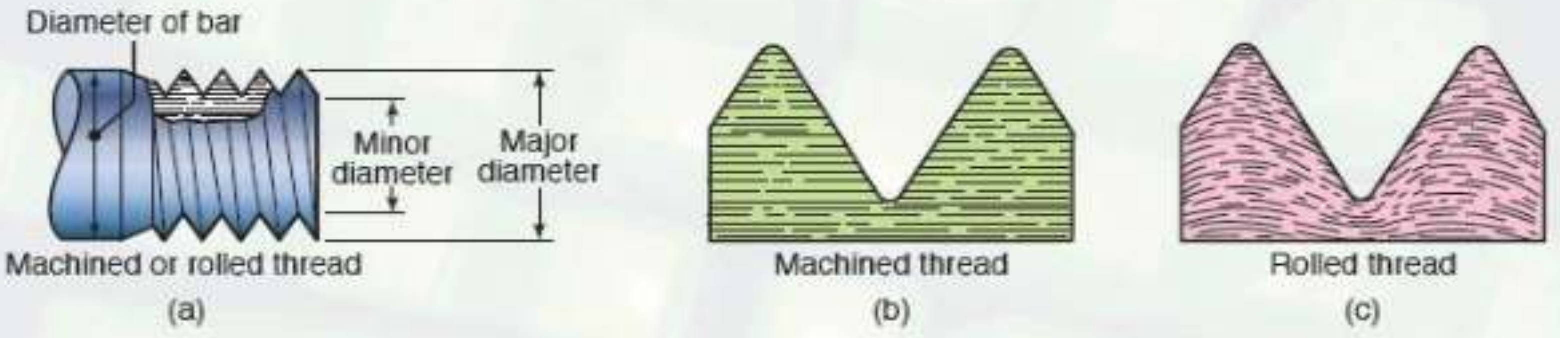
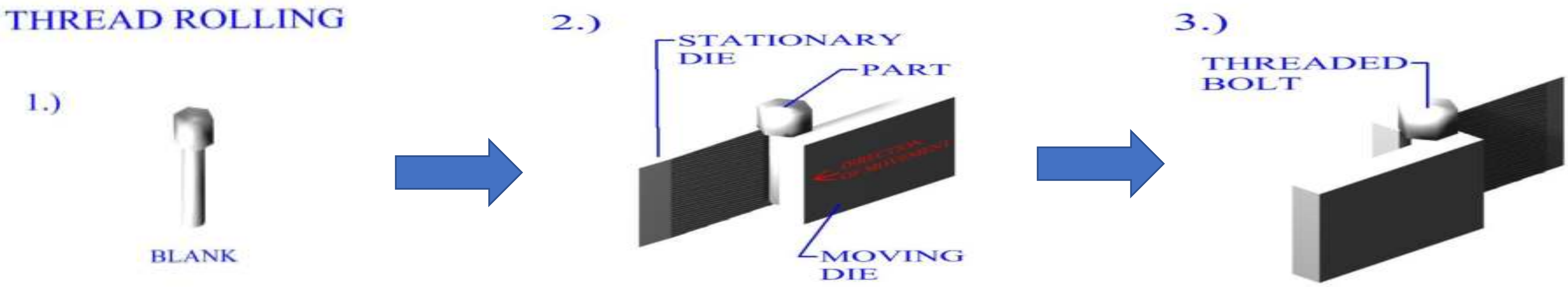


FIGURE 6.45 (a) Schematic illustration of thread features; (b) grain-flow lines in machined and (c) rolled threads. Note that unlike machined threads, which are cut through the grains of the metal, rolled threads follow the grains and because of the cold working involved, they are stronger.



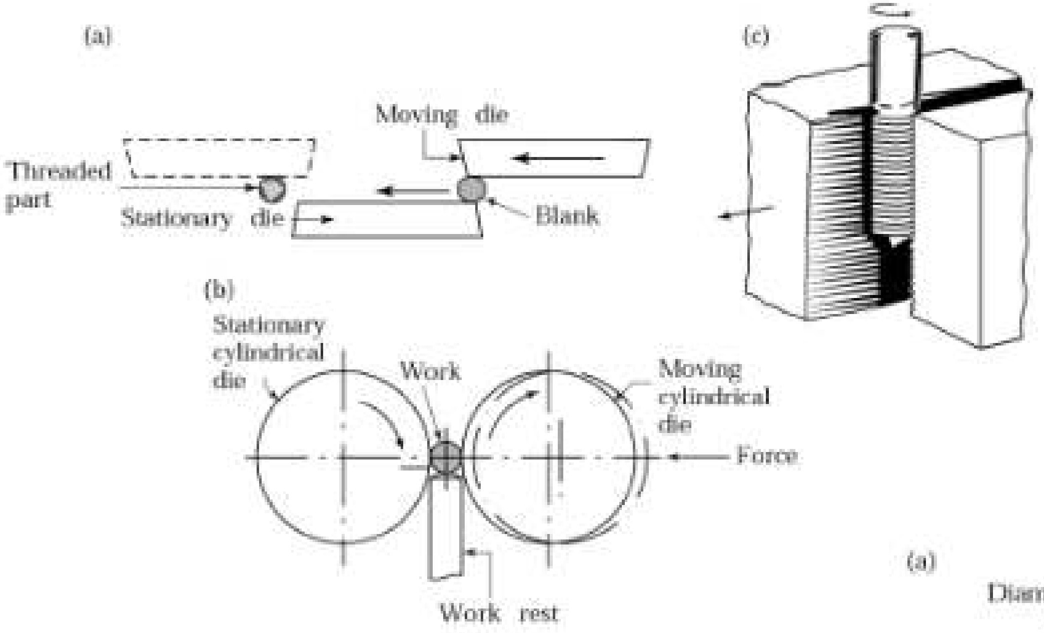


Figure 13.15 Thread-rolling processes: (a) and (c) reciprocating flat dies; (b) two-roller dies. Threaded fasteners, such as bolts, are made economically by these processes, at high rates of production.

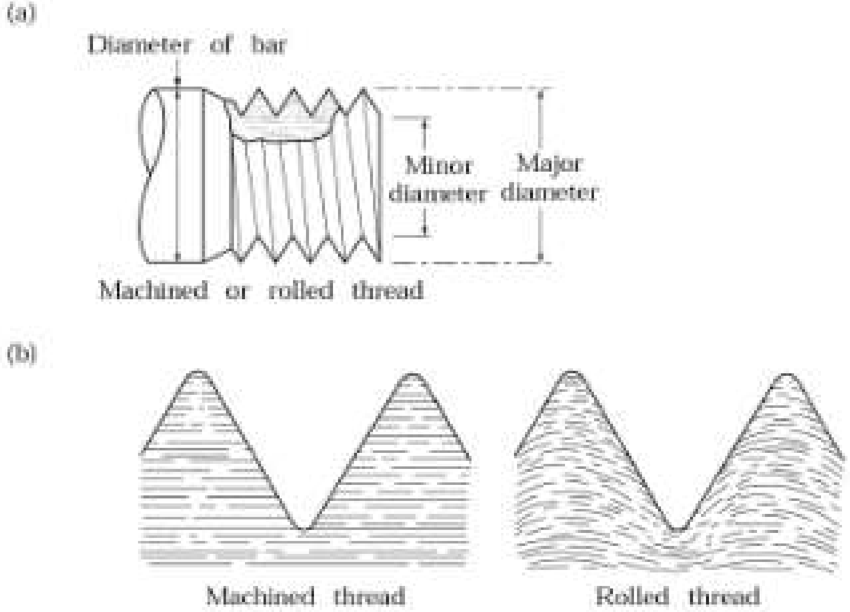


Figure 13.16 (a) Features of a machined or rolled thread. (b) Grain flow in machined and rolled threads. Unlike machining, which cuts through the grains of the metal, the rolling of threads causes improved strength, because of cold working and favorable grain flow.

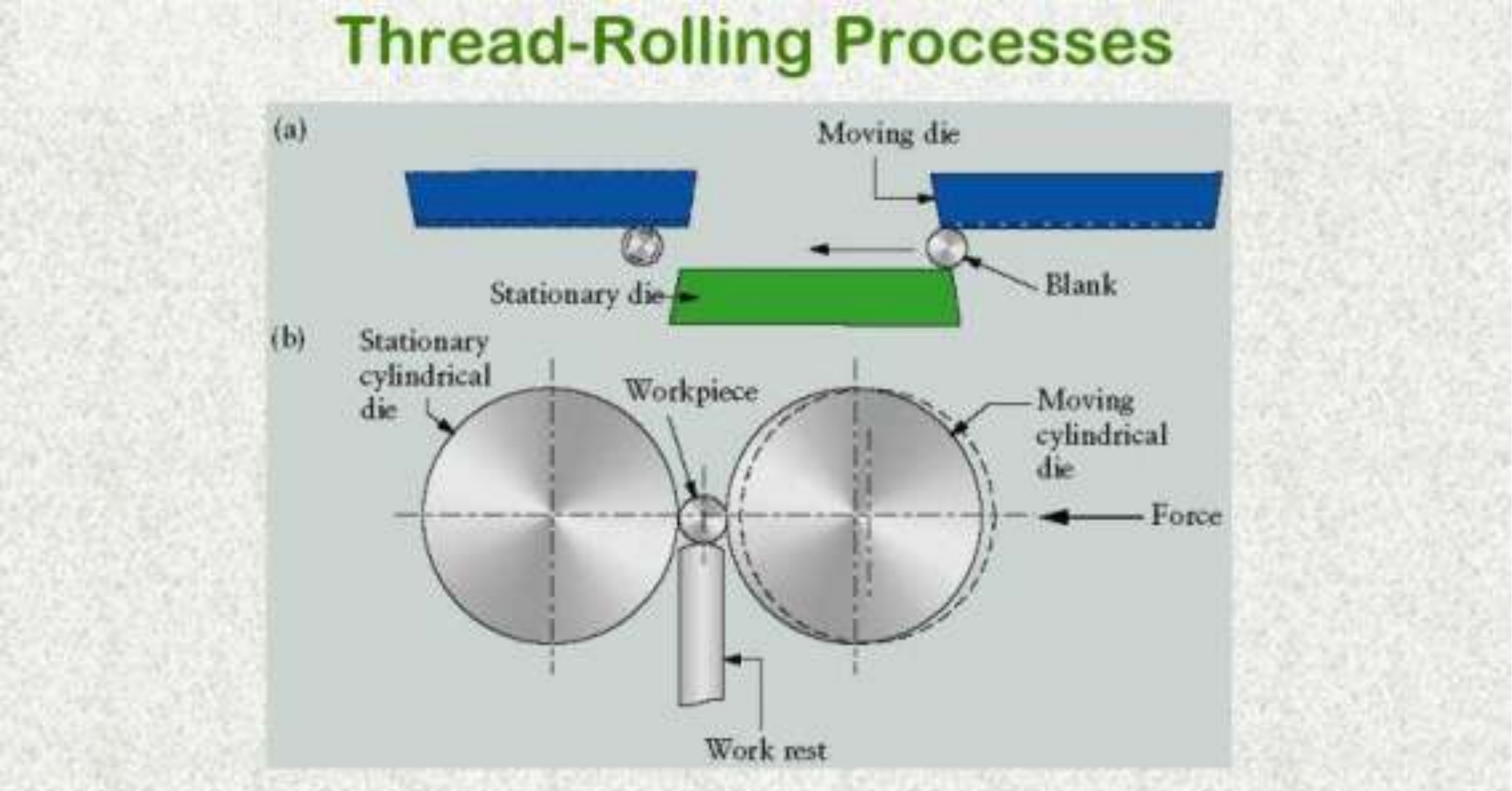


FIGURE 6.46 Thread-rolling processes: (a) flat dies and (b) two-roller dies. These processes are used extensively in making threaded fasteners at high rates of production.

Machined thread or Rolled thread??

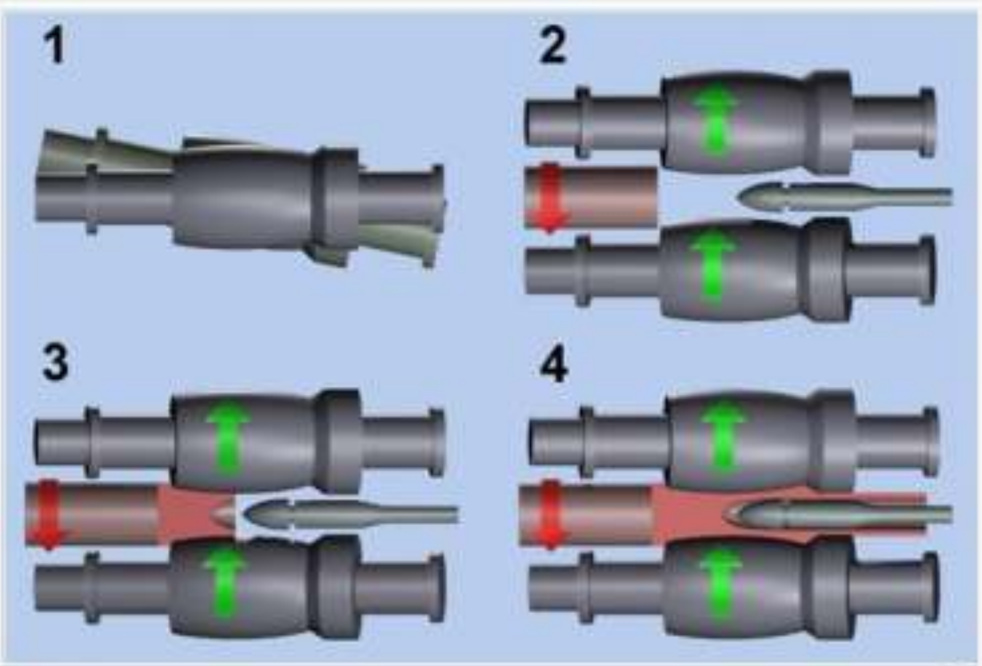
- It should be apparent that the advantages of metal forming are not just in the creation of useful geometric forms but also in the creation of desired material properties as well.

- Cold rolling processes are useful for imparting strength and favorable grain orientation. Since metal rolling affects grain orientation, a part can be rolled in a way as to create grains oriented in a direction such that they give directional strength to a part useful to that part's specific application.

- An example of this can be the difference in grain structure between the threads of a machined bolt and a rolled bolt. The favorable grain orientation of the cold rolled bolt will give it directional strength beneficial to its application.

4. Rotary Tube Piercing (Mannesmann Process)

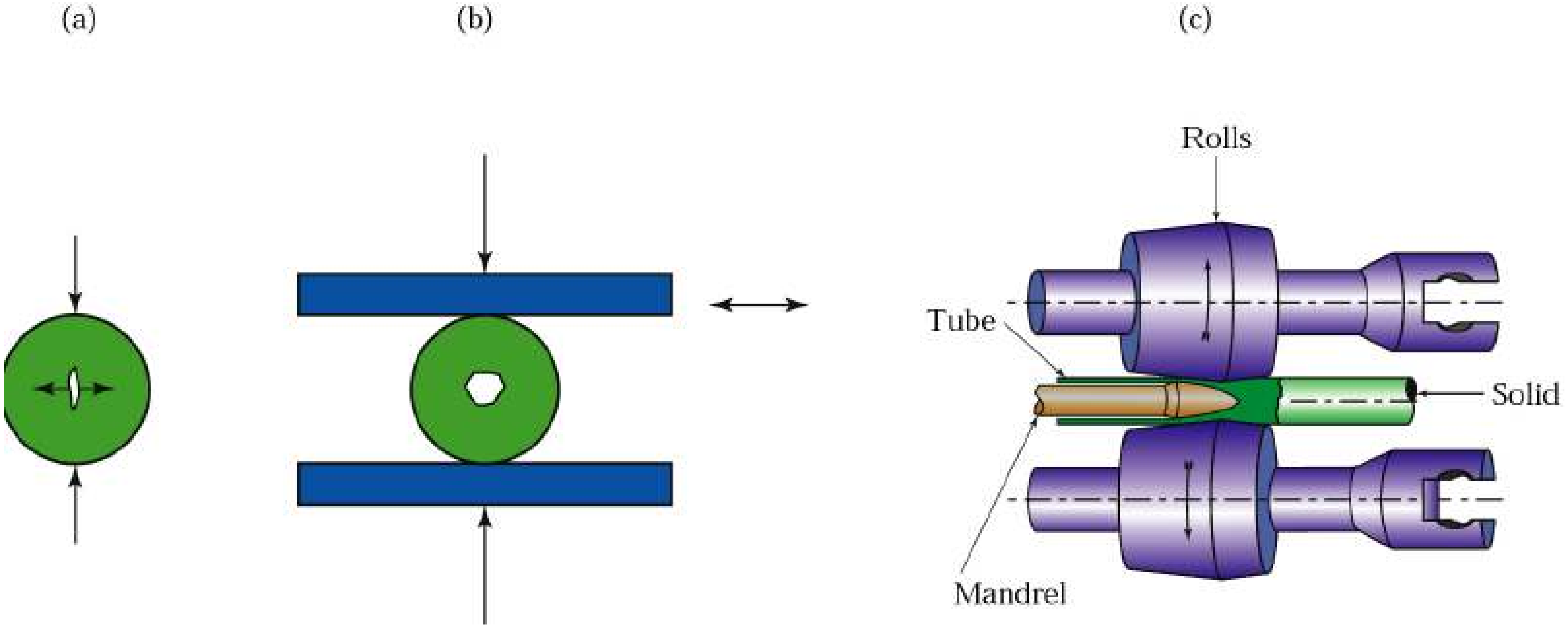
- Rotary tube piercing is used to make long and thick-walled ***continuous seamless pipes and tubing***.
- **Principle**: When a round bar is subjected to radial compressive forces, ***tensile stresses develop at the center*** of the bar.
- When it is subsequently subjected to cyclic compressive stresses, a ***cavity begins to form at the center of the bar***. This phenomenon can be demonstrated with a short piece of ***round eraser***, by rolling it back and forth on a hard flat surface.



A schematic of rotary piercing. Key:

1. Roller configuration
2. The process starts with the blank fed in from the left.
3. The stresses induced by the rolls causes the center of the blank to fracture.
4. Finally, the rolls push the blank over the mandrel to form a uniform inner diameter.

Figure 13.17 Cavity formation in a solid round bar and its utilization in the rotary tube piercing process for making seamless pipe and tubing. (The Mannesmann mill was developed in the 1880s.)



- Rotary tube piercing is carried out using an arrangement of rotating rolls. The axes of the rolls ***are skewed***, in order to pull the round bar through the rolls by the ***axial component of the rotary motion.***

- An ***internal mandrel*** assists the operation, by expanding the hole and ***sizing the inside diameter*** of the tube.

- The mandrel may be held in place by a long rod, or it may be floating mandrel without a support. Because of the severe deformation that the bar undergoes, the material must be high in quality and free from defects.

- The billet entering the piercing mill makes a small angle with each of the piercer (work) rolls.

- The billet when pushed between the rolls gets squeezed and rotated.

- The effect is an alternate squeezing and bulging which produces a hole in the center of the billet.

- The hole is enlarged and made of uniform diameter by a piercing point held on the mandrel.

- Since, there is ***no joint or weld or seam tubes produced*** by Mannesmann mill are smooth, accurate and posses high tensile strength.

5. Tube Rolling

- The ***diameter and thickness of pipes and tubing can be reduced*** by tube rolling, which utilizes shaped rolls.
- Some of these operations can be ***carried out either with or without an internal mandrel***.
- In the ***pilger mill***, the tube and an internal mandrel undergo a reciprocating motion as the tube is advanced and rotated periodically.
- Steel tubing of 265 mm diameter have been produced by this process.

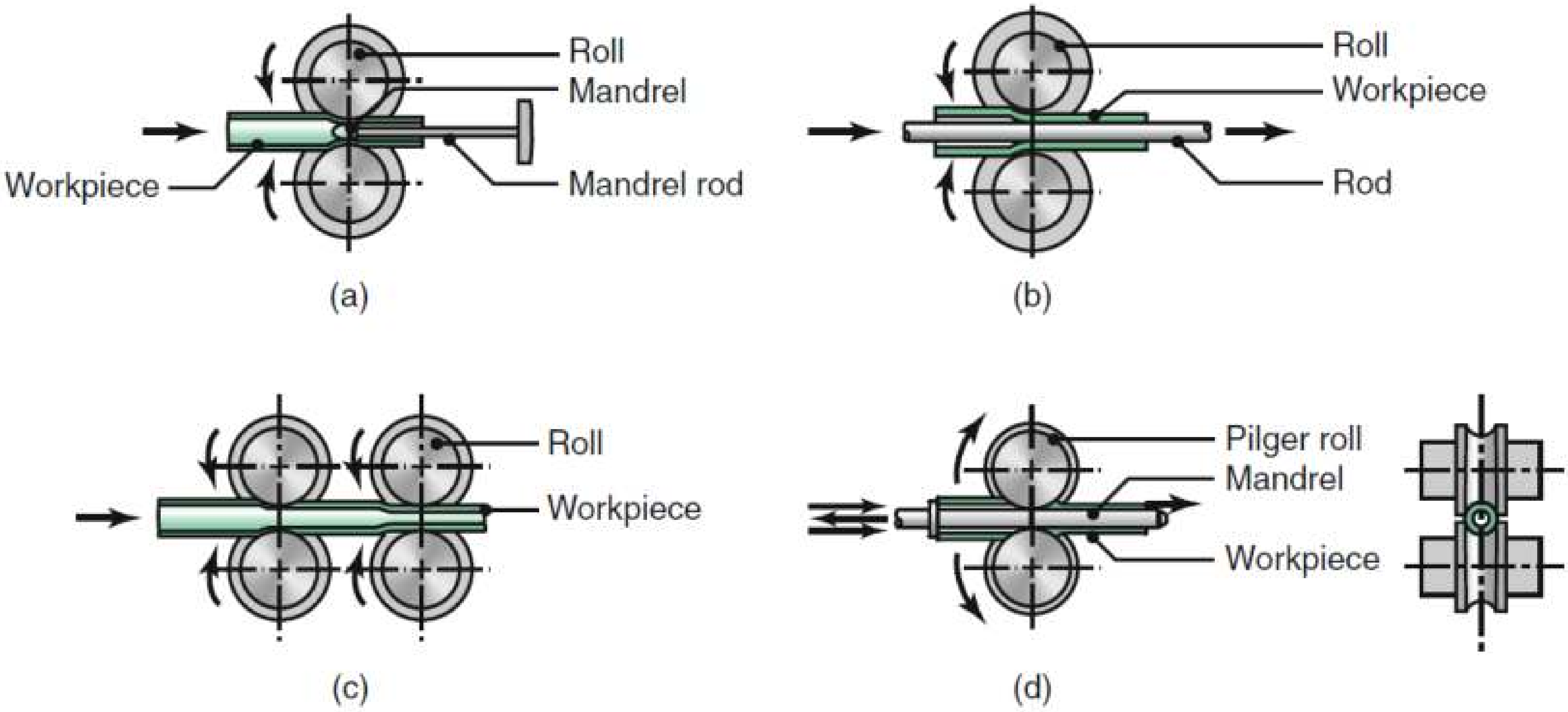


FIGURE 13.19 Schematic illustration of various tube-rolling processes: (a) with a fixed mandrel; (b) with a floating mandrel; (c) without a mandrel; and (d) pilger rolling over a mandrel and a pair of shaped rolls. Tube diameters and thicknesses also can be changed by other processes, such as drawing, extrusion, and spinning.

Tube Manufacturing

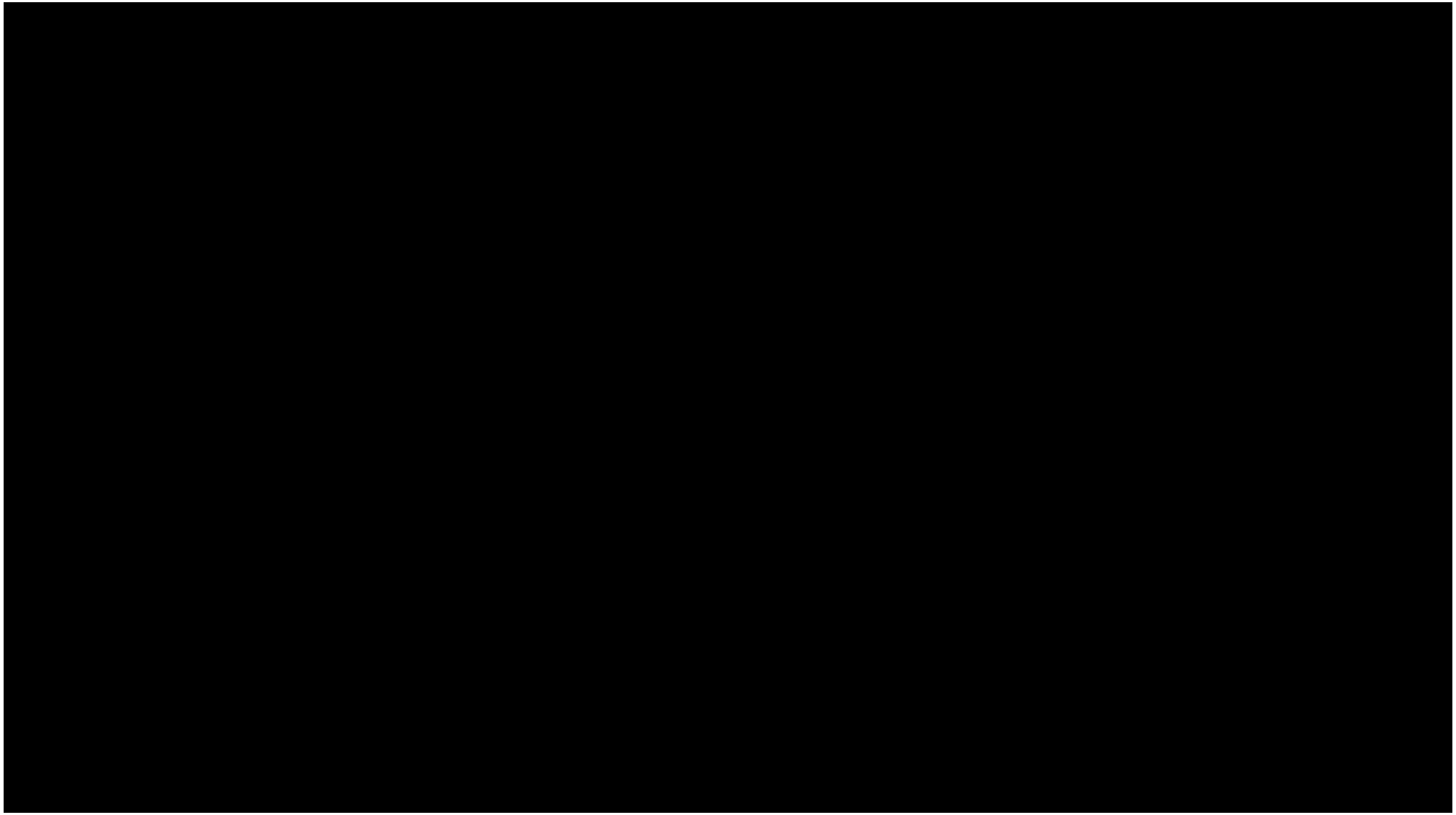
1. Rotary Tube Piercing (Mannesmann Process

2.Surface Treatment process

3.Cold Pilger Cold rolling

4.straigthning process

Seamless Pipe Manufacturing



6.Roll-Forging

- The cross sectional area of a bar is reduced and altered in shape by passing it through a **pair of rolls with grooves of various shapes**
- This operation may also be used to produce a part that is basically the final product, such as tapered leaf spring, table knives, and numerous tools.
- Roll forging is also used as a preliminary forming operation followed by other forging processes
- Products made by this method include
  - **Crankshaft**
  - **Other automotive components**

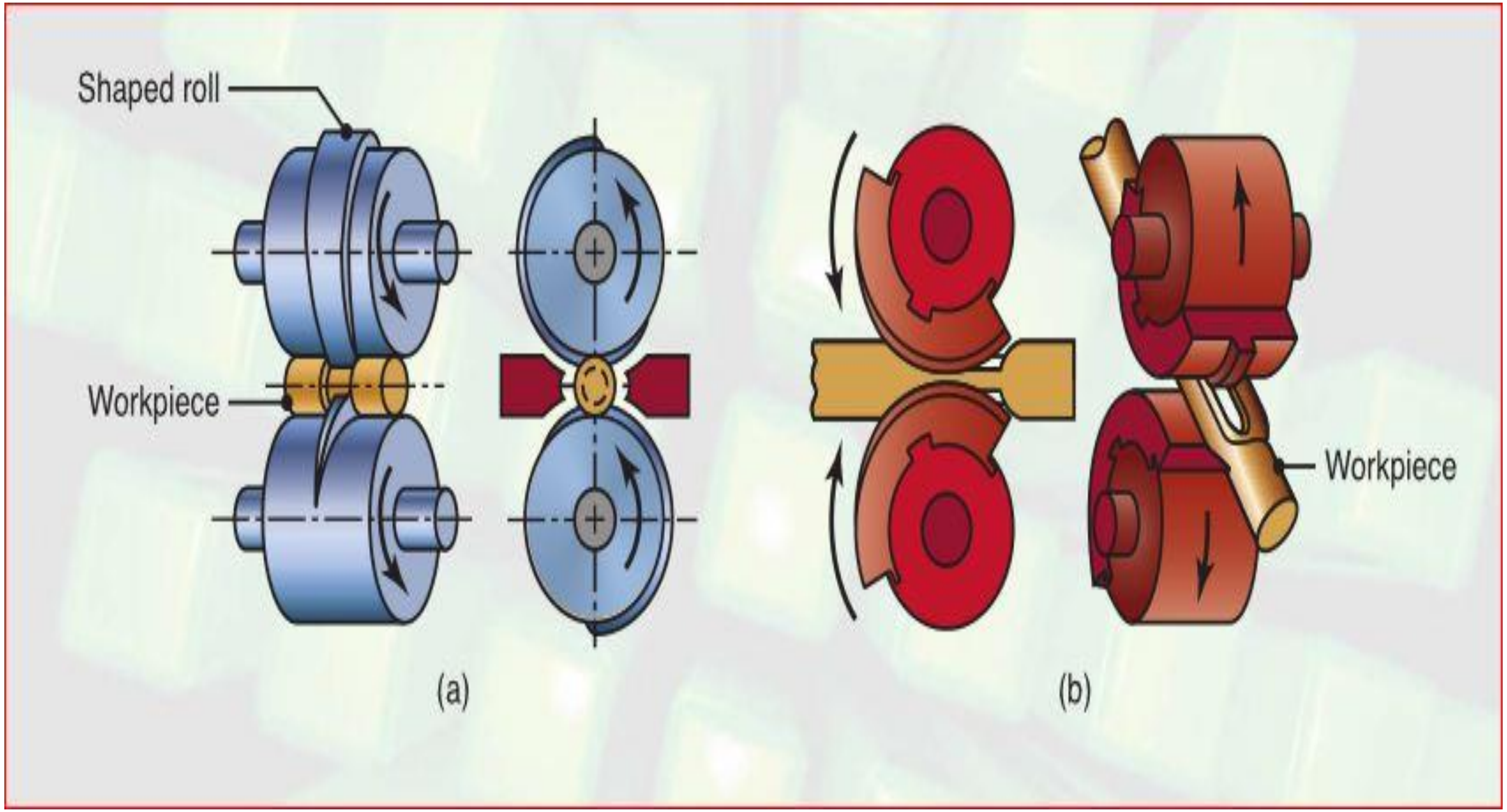


Figure 06.20 Two examples of the roll-forging operation, also known as *cross-rolling.* Tapered leaf springs and knives can be made by this process.

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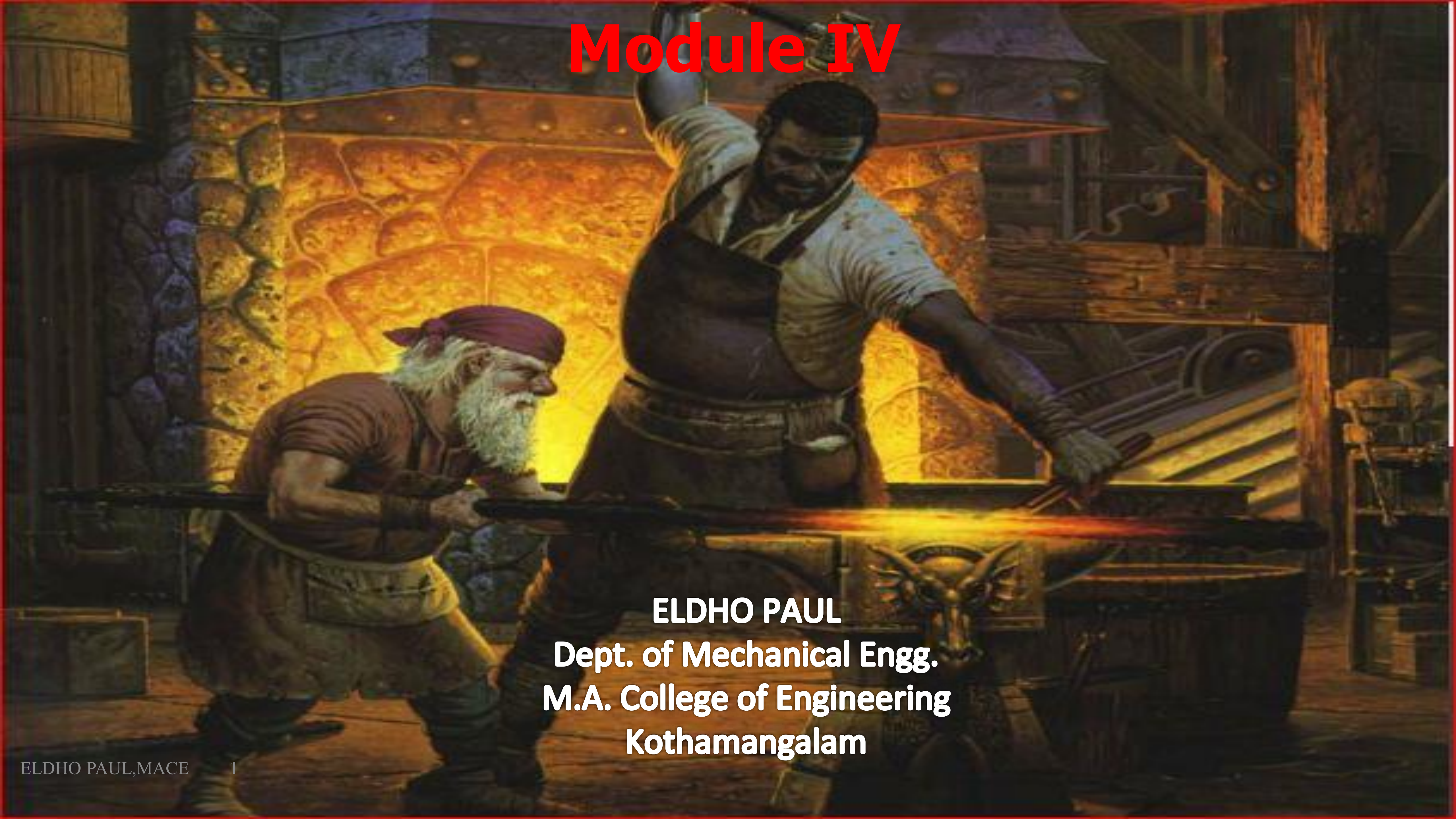
- Thank you…

Module IV



ELDHO PAUL
Dept. of Mechanical Engg.
M.A. College of Engineering
Kothamangalam

INTRODUCTION

- Forging denotes a family of process by which plastic deformation of the work piece is carried out by compressive forces.
- Parts made by forging –
  - Crank shaft
  - Connecting roads for engine
  - Gears
  - Bolt head
  - Hand tool and other structural components

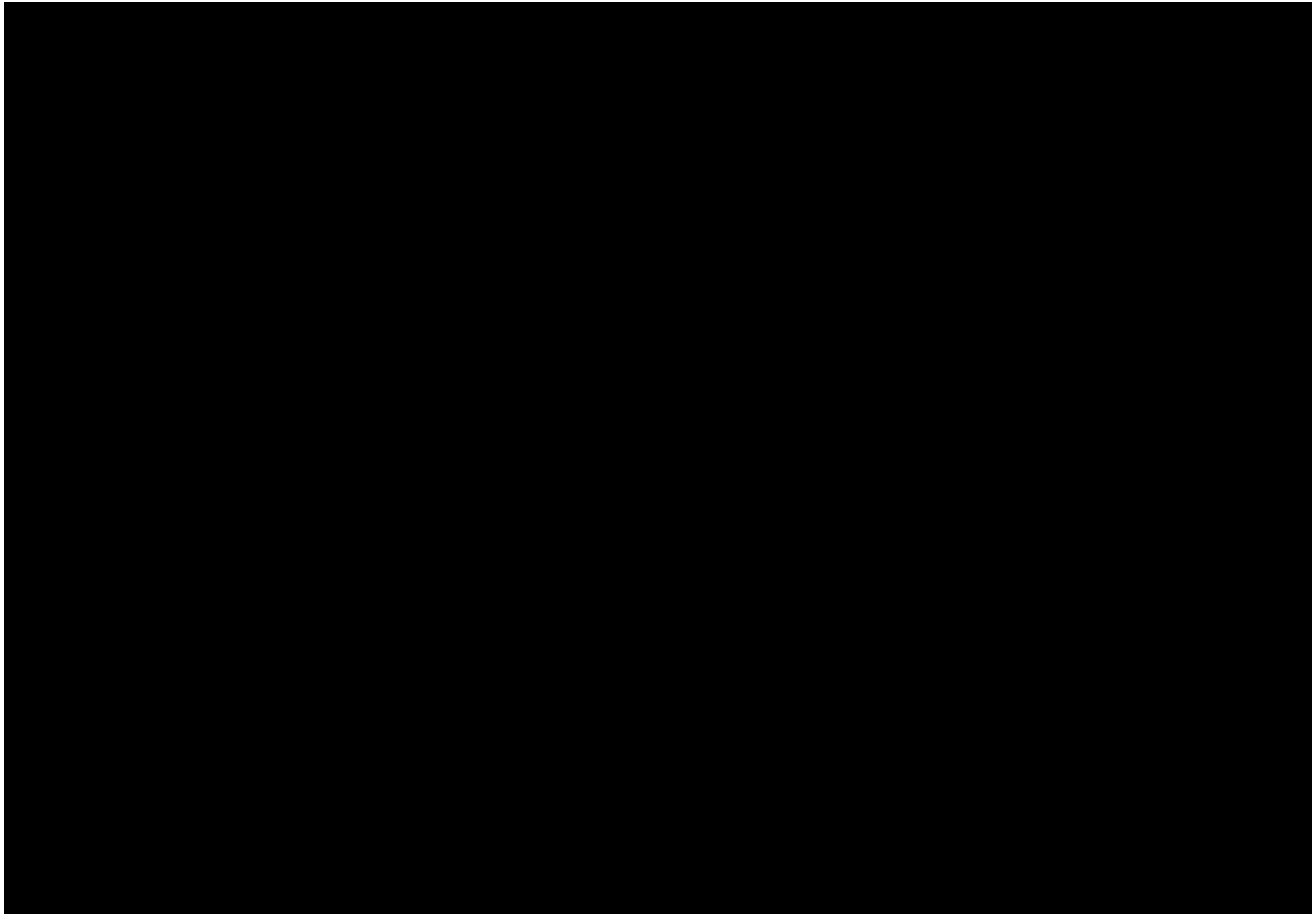
- Forging can be carried out at room temperature called cold working
- Or at elevated temperature called *warm and hot forging*

Forming

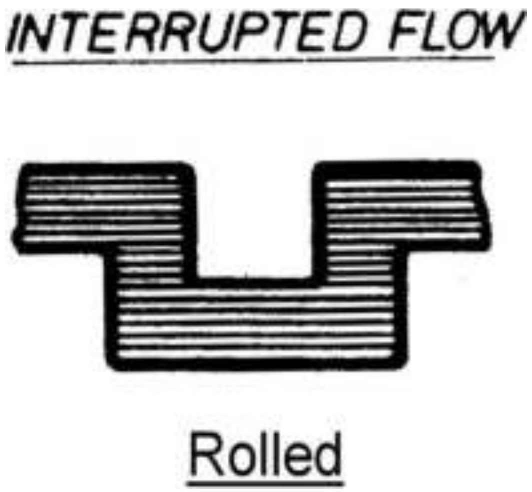
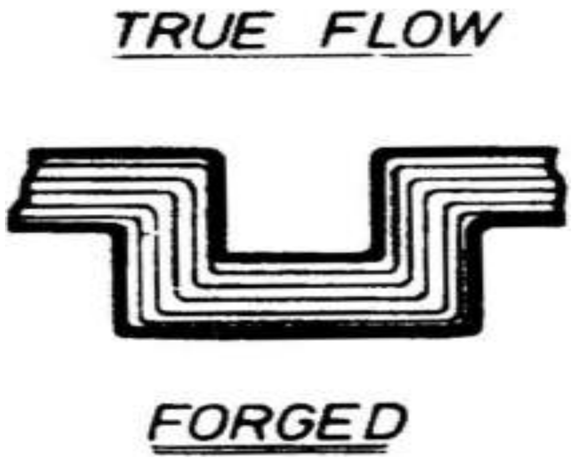
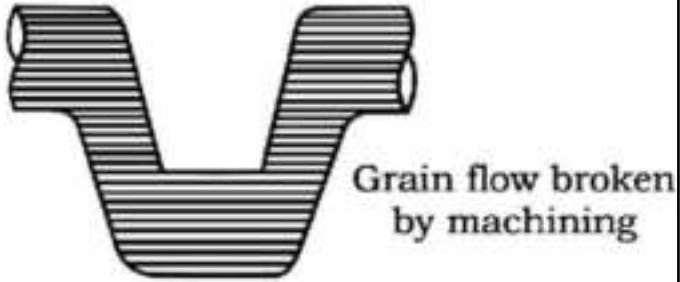
- High production rate
- Improved mechanical properties
- Reduced internal defects
- Compressive residual stress
- Easy automation
- Close control over the properties
- High strength to weight ratio

- Anisotropic structure and properties
- Limited to simple shapes
- Needs machining to achieve required finish and tolerance
- Difficult control of process parameters
- Mechanical properties namely yield strength and ductility affects success of process

- Simple forging can be made with a heavy hammer and an anvil by techniques used by blacksmiths.
- In **Impact** or **Hammer Forging** the forging rapid blows are given to the surface of the metal.
- In this intensity of the metal is maximum only at the surfaces and reduces below as the energy is absorbed by the deforming metal.
- In **Press Forging** the metal is subjected to slow speed compressive forces. Here the pressure increases as the metal is being deformed and its maximum value is obtained just before the pressure is released.



Grain Flow in Cast, Rolled part Machined and Forged Part

Cast Part		Forged Part	Machined part
			
No Grain Flow. Grains arranged randomly.	Interrupted Grain Flow	Uniform Grain Flow	

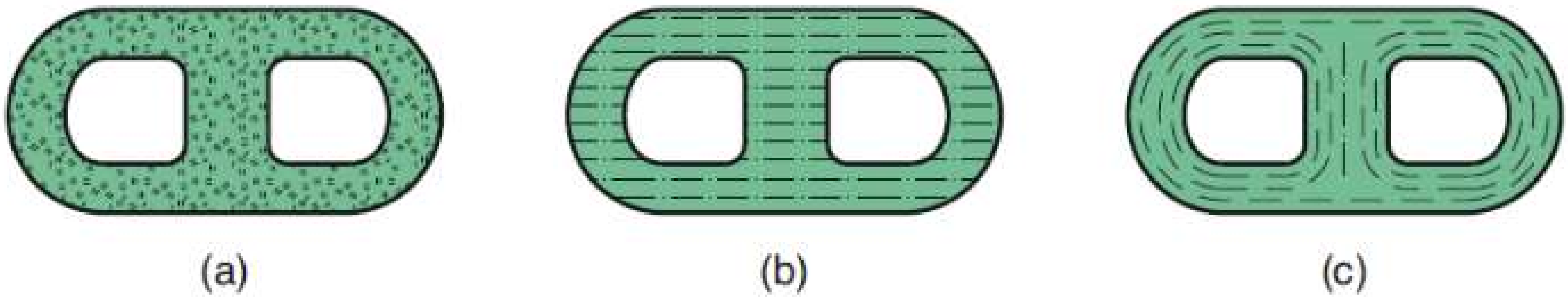


FIGURE 14.2 Schematic illustration of a part made by three different processes and showing grain flow. (a) Casting by the processes described in Chapter 11. (b) Machining from a blank, described in Part IV of this book, and (c) forging. Each process has its own advantages and limitations regarding external and internal characteristics, material properties, dimensional accuracy, surface finish, and the economics of production. *Source*: Courtesy of the Forging Industry Association.

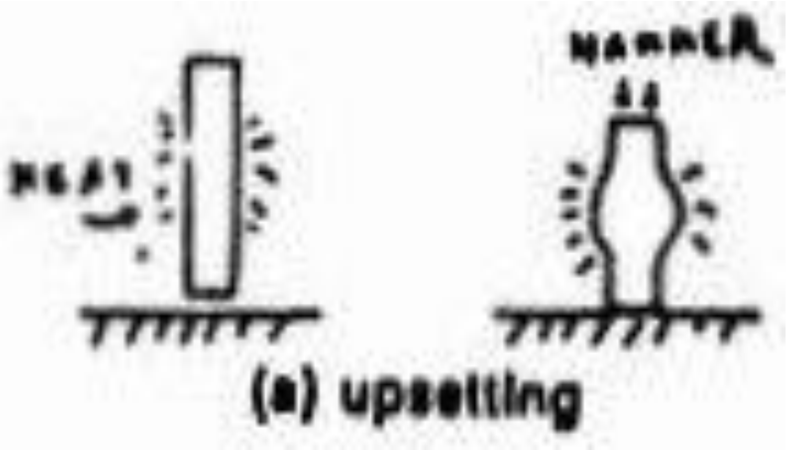
- The metal flow during forging **provides fibrous microstructure** (revealed by etching). This structure gives better mechanical properties in the plane of maximum strain but (perhaps) lower across the thickness.
- The workpiece often undergo recrystallisation, therefore, provide ***finer grains*** compared to the cast dendritic structure resulting in improved mechanical properties.

- Grain flow is a directional orientation of metal grains that have been deformed by forging. Individual grains are ***elongated*** in the direction of the metal flow or plastic deformation.
- Some ***mechanical properties*** do vary with respect to the orientation.
- The forged component will be ***anisotropic*** with respect to a number of mechanical properties.
- The grain flow has significant effect on **crack propagation** in a material.
- The billet or bar used for forging already will have a grain flow direction. This may be altered by the forging process. As the billet is compressed in the longitudinal direction, the ***grain flow undergoes reorientation***.
- By properly controlling metal flow and grain structure, forged parts having ***good strength and toughness*** can be obtained, which can be used for highly stressed and critical applications.

Forging Operations

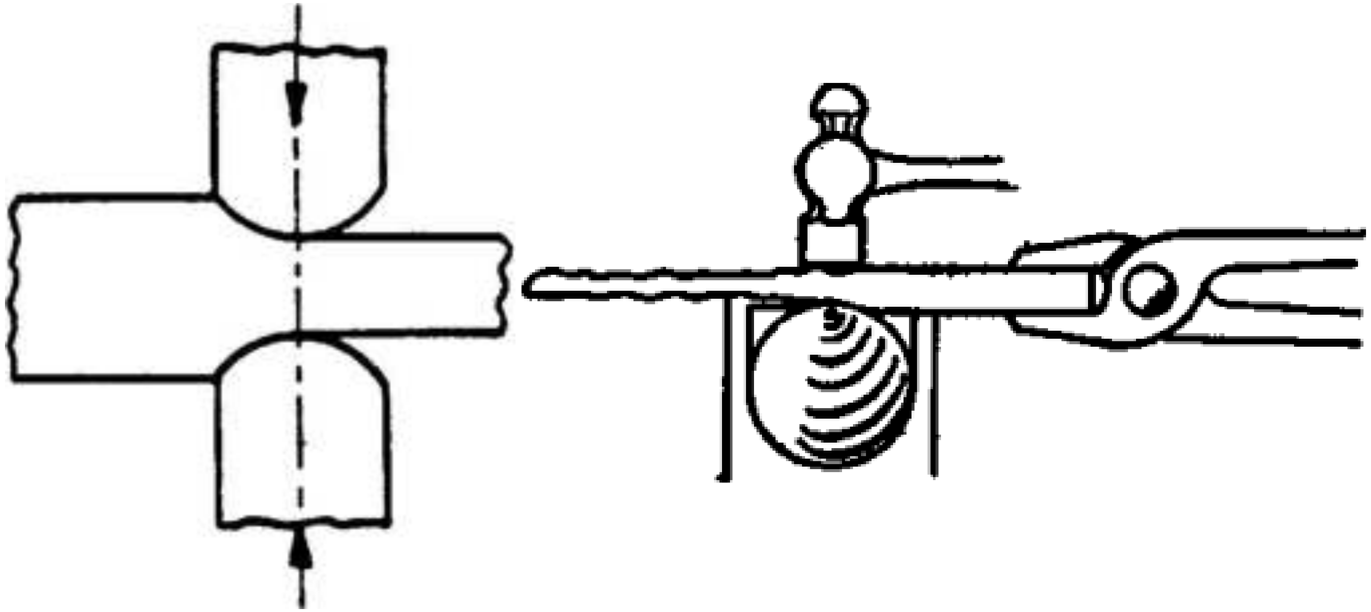
1. Upsetting

- Upsetting is carried-out to ***increase the thickness or diameter of a material and to reduce its length.***
- This is done generally to obtain localized increase in thickness.
- For example, ***forming of a bolt head***. The heated metal is held by tong at one end and supported by anvil at other end.
- Then pressure is applied on the job by means of a hammer or dropping weight from a convenient height.

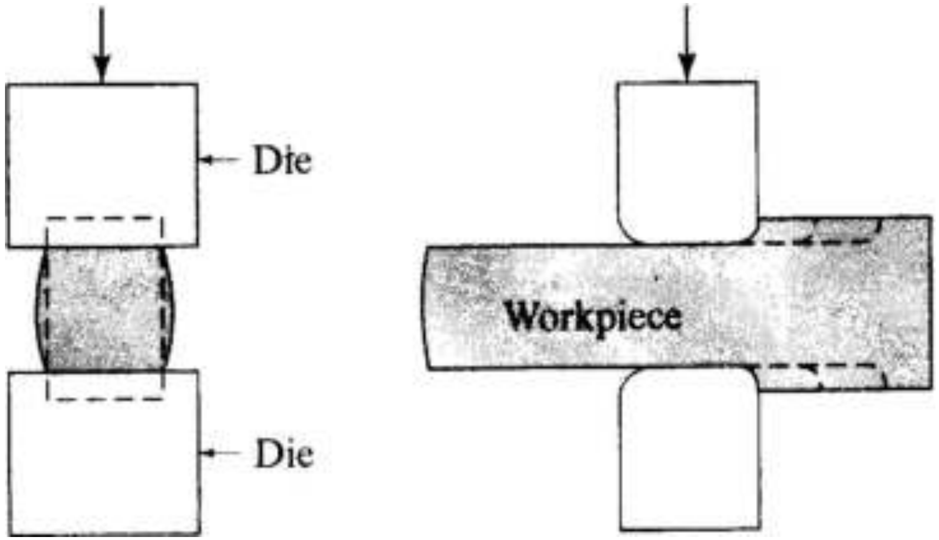


2. Drawing Down (Cogging)

- It is used to reduce the ***thickness of a bar and to increase the length***
- Method used for distributing the material from center to outward uniformly and in this process the **length of the component is increasing and diameter is reducing uniformly**.
- This operation is carried out by hammering the hot work piece keeping it on the anvil and holding it by a suitable tong.



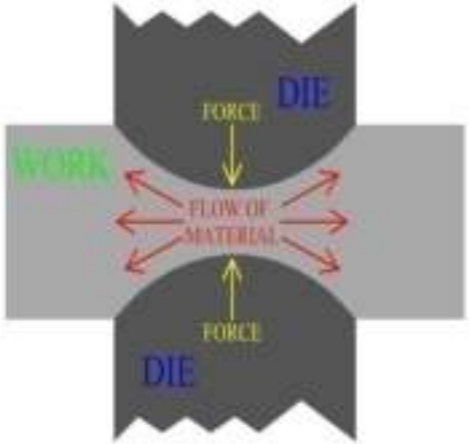
- An open die forging process.
- During operation the ***thickness of bar*** is reduced by successive forging.

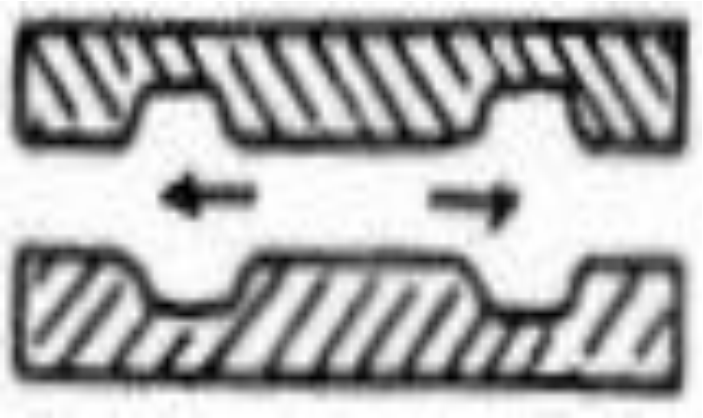



FZ making knives
The material for rolling bearing ball
bearing balls varies widely...

3.Fullering

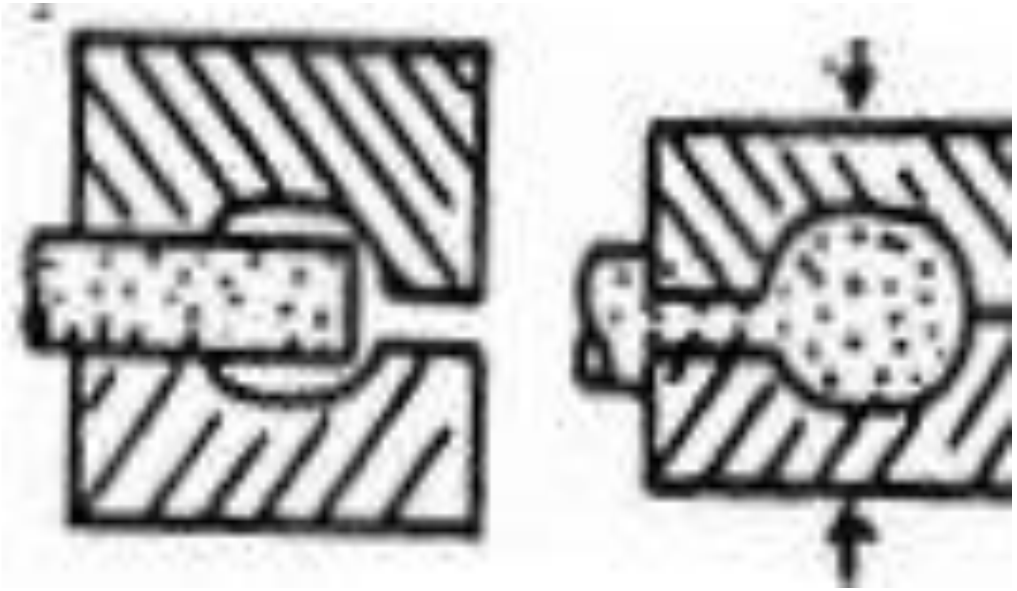
- It is used to ***reduce the cross-sectional area*** of a portion of a stock.
- It is a process used to ***distribute the material from center to the outwards non uniformly*** so that in this process the length of the component is increasing and diameter is reducing **Non uniformly**
- The metal flow is outwards and away from the center of the fullering tool.



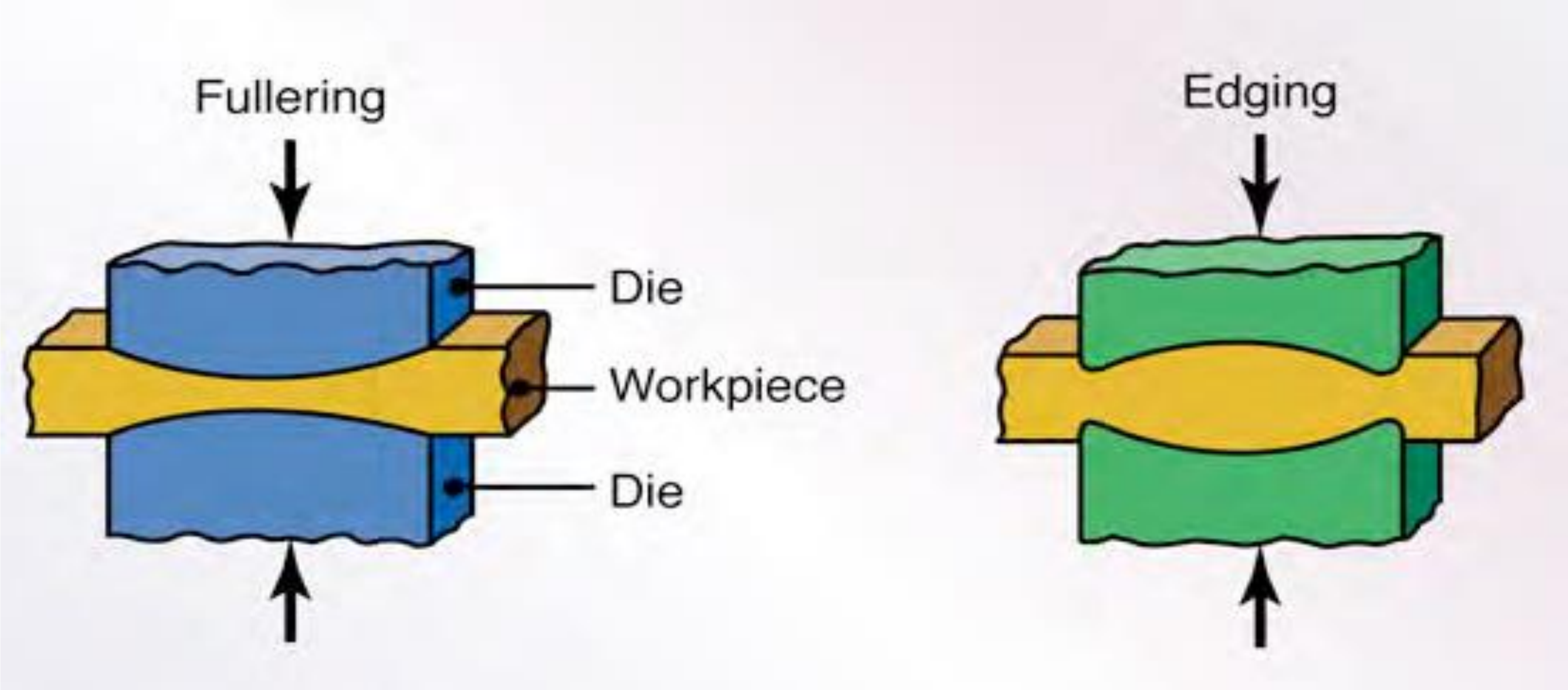


4.Edging

- Method used for collecting the ***material locally.***



FULLERING AND EDGING

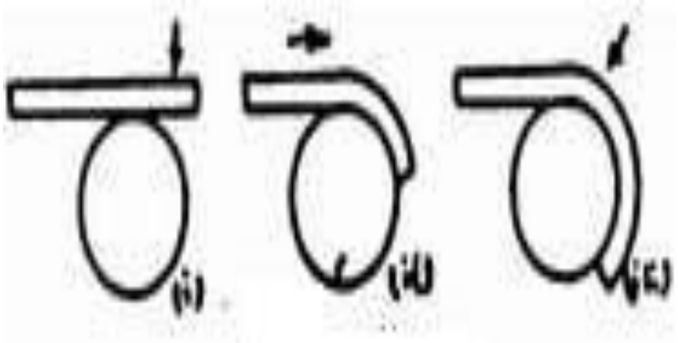


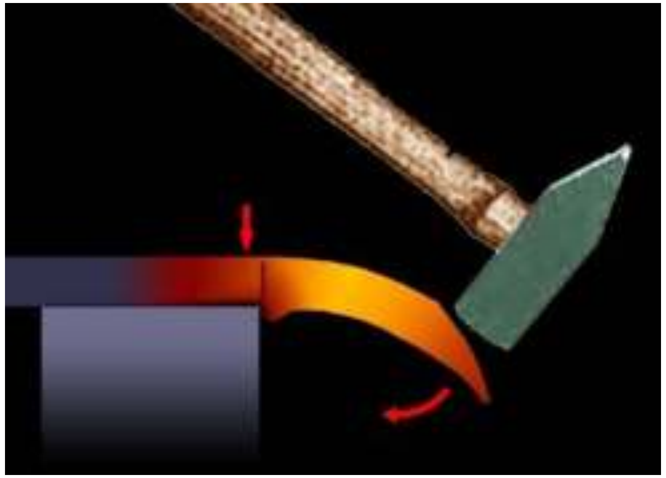
5. Swaging/blocking

- Swaging is done to reduce and finish work to the desired size and shape.
- ***Approximate shape*** can produce by this method.
- After this need a finishing operation.

6.Bending

- This is a common operation done in forging.
- The part to be bent is heated to plastic form and then hammered by placing it on the anvil side.
- Variety of bend shapes such as ***circles, ovals and angles*** can be done by bending operation.



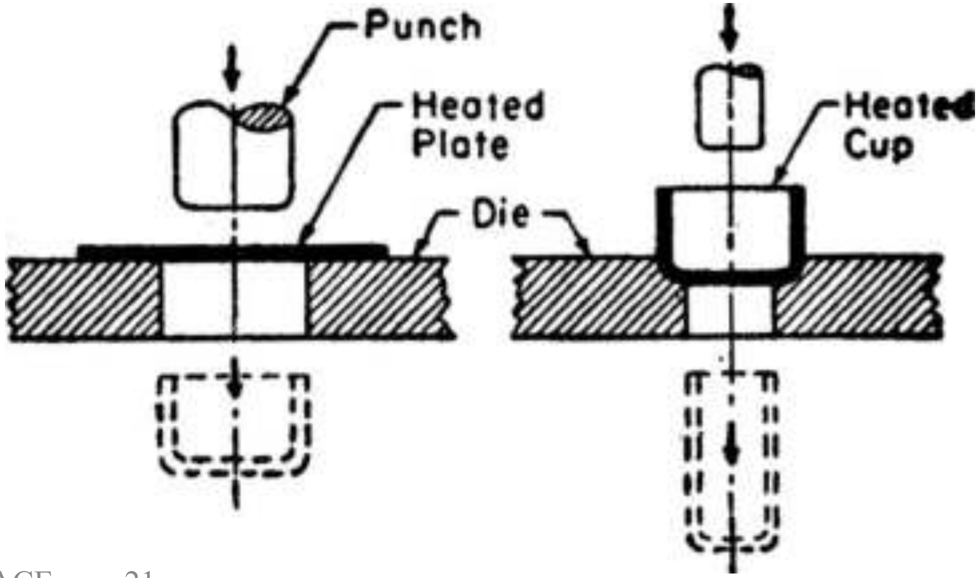


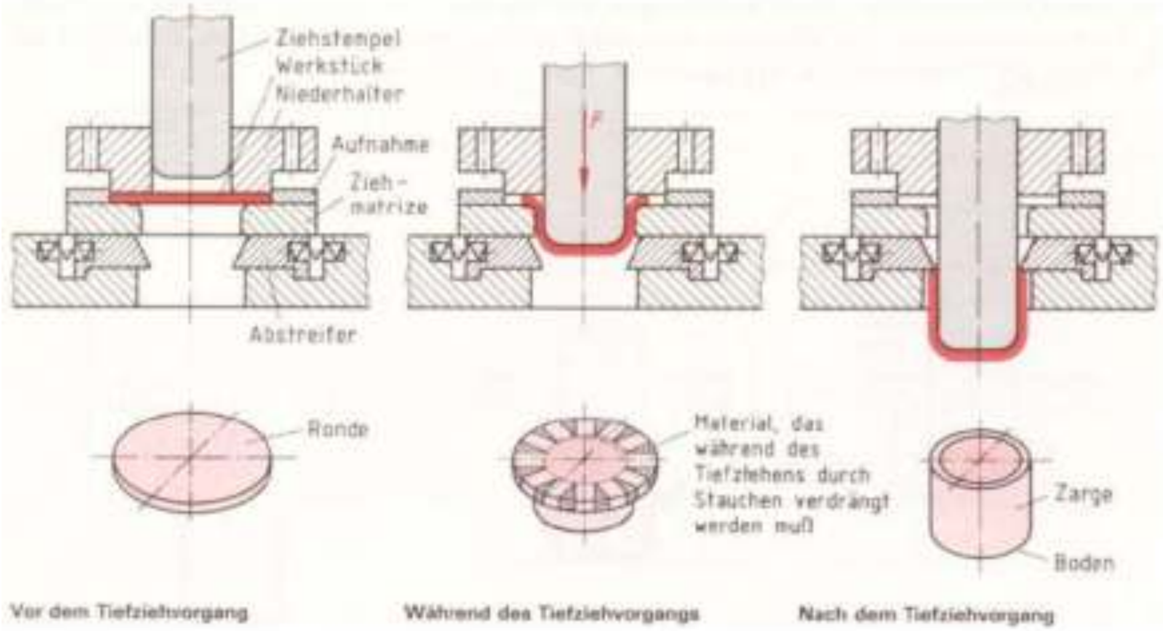
7. Cutting or Trimming

- Cutting operation is the ***removal of extra metal from the job***.
- Cutting operation is classified into Cold State Cutting and Hot State Cutting.
- In Hot State cutting, steel is heated up to 900^0C to 1000^0C and hot-set(a chisel) is used for cutting.

8.Deep Drawing

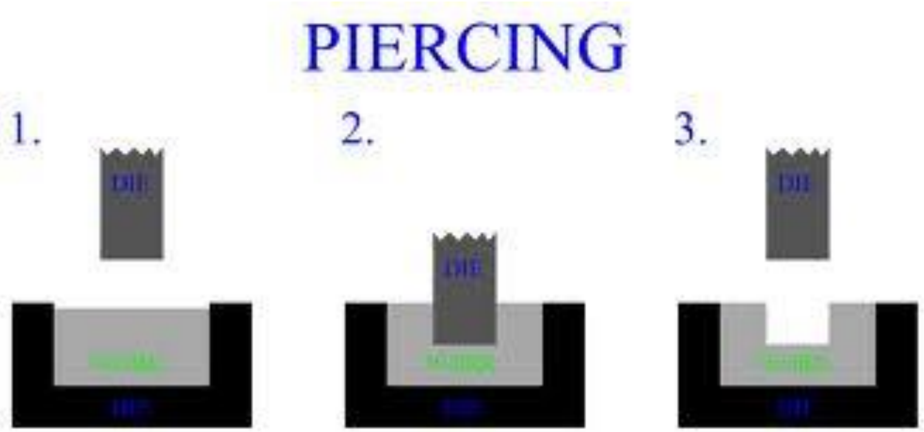
- Deep Drawing is the process of ***forming a flat metal piece into a hollow shape (or cup shape)*** by means of a punch which causes the blank(metal piece) to flow into the die cavity.
- During operation the flat metal piece is placed over a circular die opening.
- The ***punch*** moves down and forces the blank into the die cavity.





9.Piercing

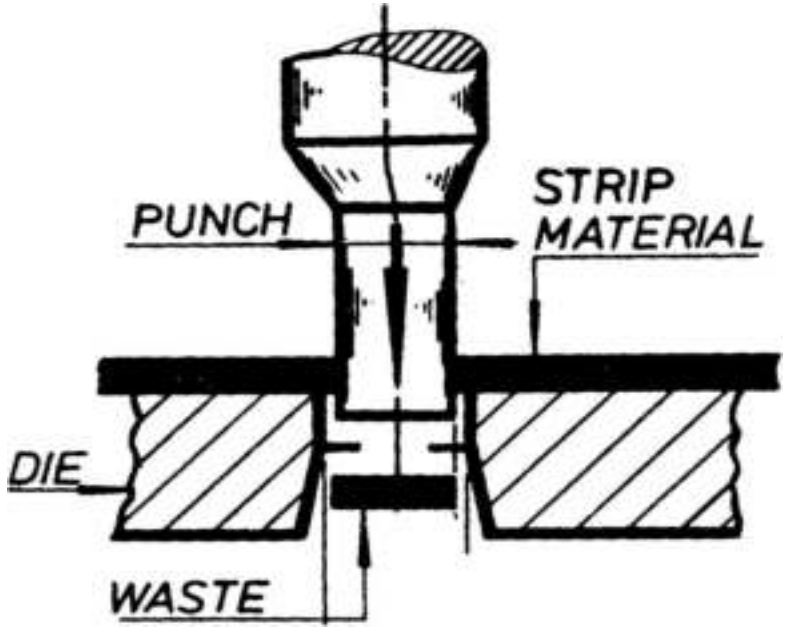
- Piercing is a punching operation.
- In Piercing operation there won’t be any scrap metal (waste metal) produced.

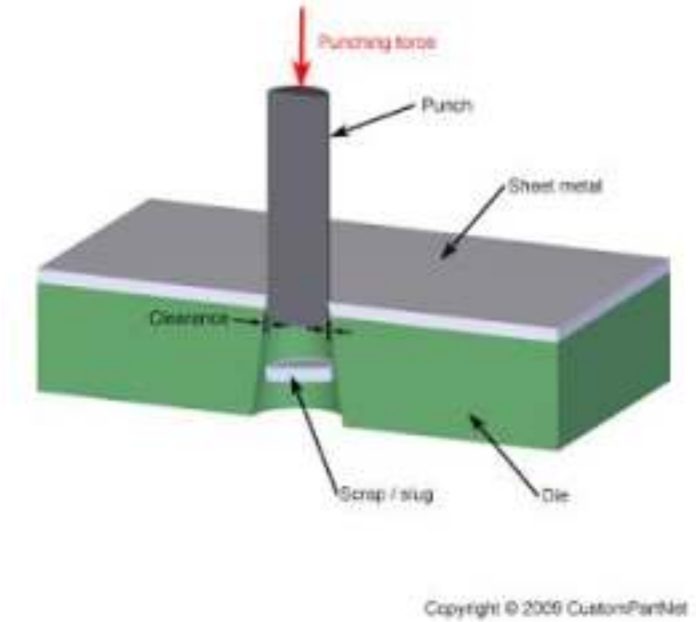


10.Punching

- It is a process of producing a hole in a metal piece using a punch and a die.

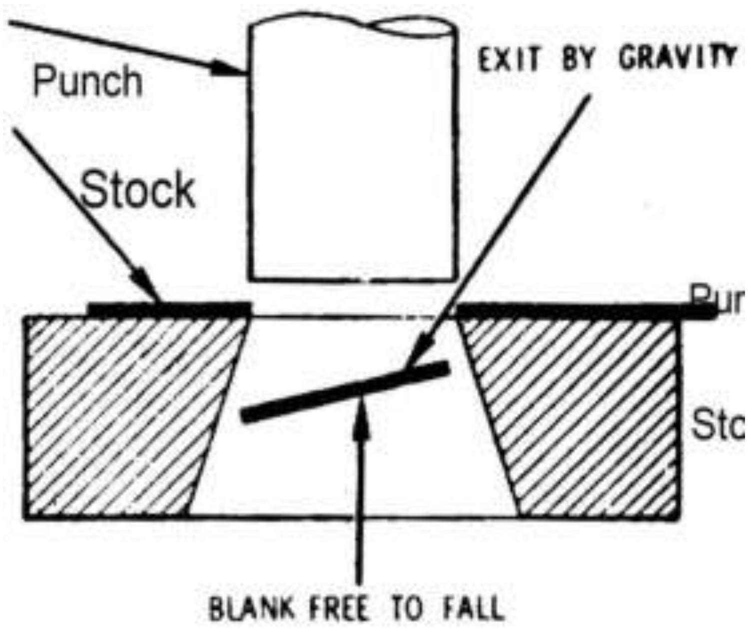
- Metal with the hole is the required product and part removed is the scrap.





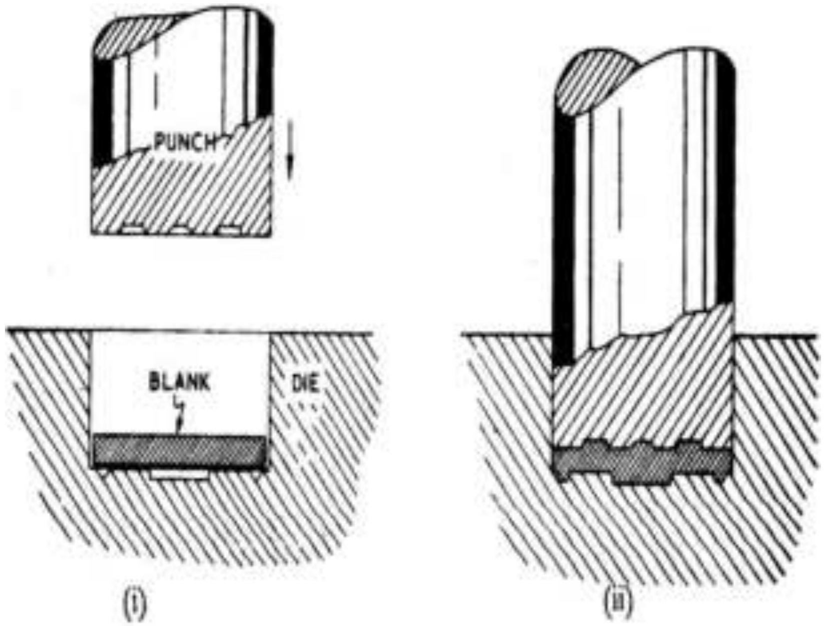
11.Blanking

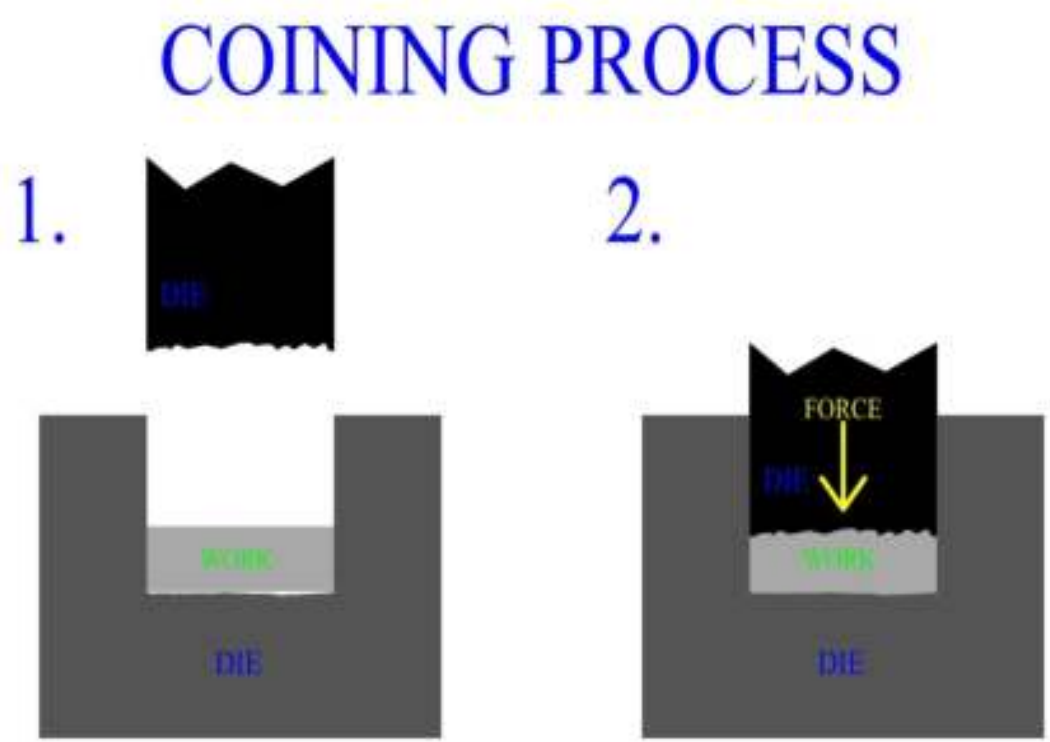
- Blanking is the operation of cutting a shape from a metal strip.
- The ***piece detached from the strip is called Blank***.
- The remaining metal strip is called scrap.
- Consists of a punch and a blanking die.
- Blanking die must have a clearance, otherwise blank would not fall freely.



12.Coining

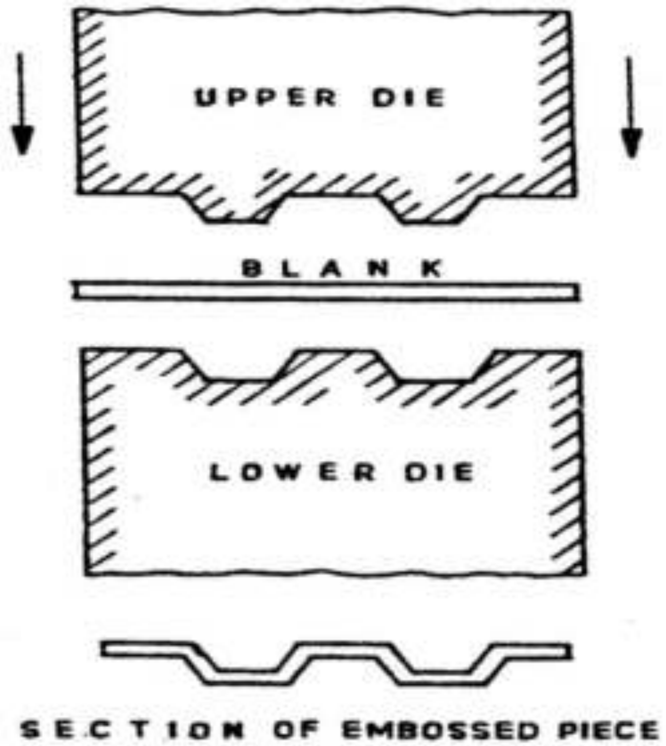
- Coining operation is to force the ***impressions on the die to the surface of the metal***
- Make use of blank sheet metal.
- Make use of Closed Dies.





13.Embossing

- Embossing is like Coining operation, carried out to force the impressions on the die to the surface of the metal.
- ***Thickness remain the same in embossing***, where as in coining, thickness changes.



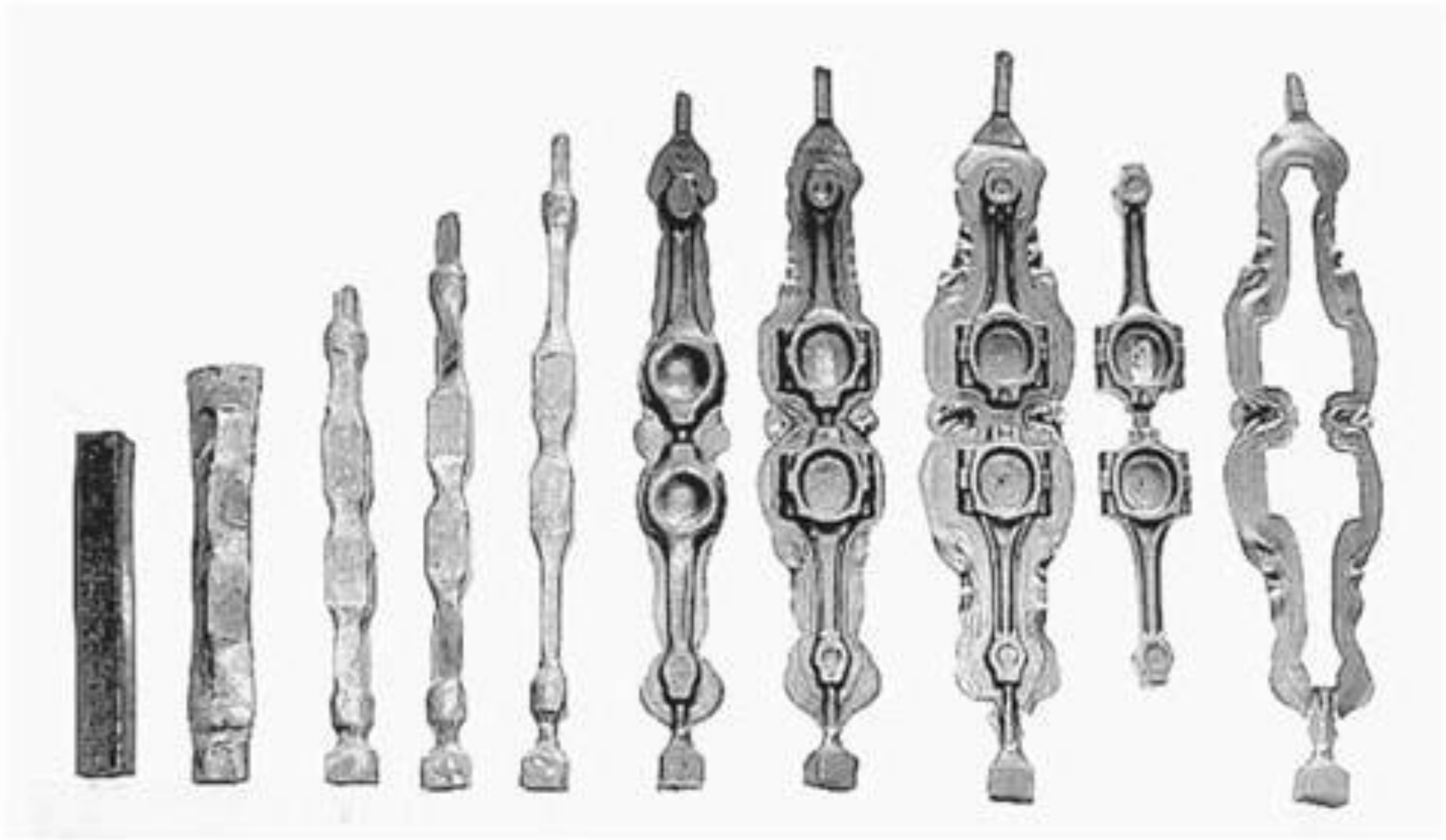
14. Hubbing

- A hardened punch is pressed into the surface of a block of a metal to produce a cavity.(which is shallower than piercing)
- Pressure required to generate a cavity is three times the UTS (UTS is the maximum stress that a material can withstand while being stretched or pulled before failing or breaking) of the material of the block.
- Hubbing force= 3(UTS)(A)
  - Where, A is the projected area of the impression.

- 15. flattening
  - Operation used for producing flat surfaces
- 16. chamfering
  - Operation used for converting sharp edges in to rounded corners
- Method of producing connecting rod?
- Method of producing bolt head?

Upsetting
Flattening
Swaging
chamfering

Fullering
Edging
Swaging
Finishing
trimming



Forging sequence in closed-die forging of connecting rods

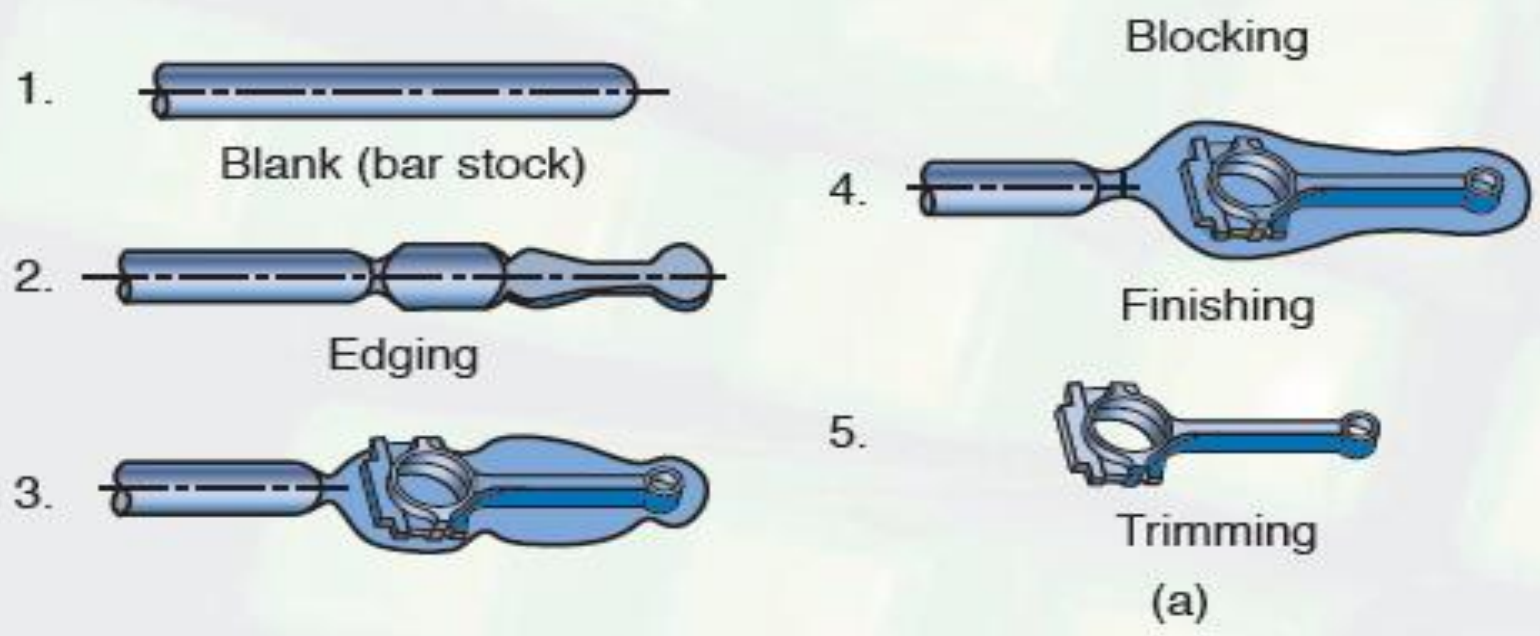


FIGURE 6.25 Stages in forging a connecting rod for an internal combustion engine. Note the amount of flash developed, which is important in properly filling die cavities.

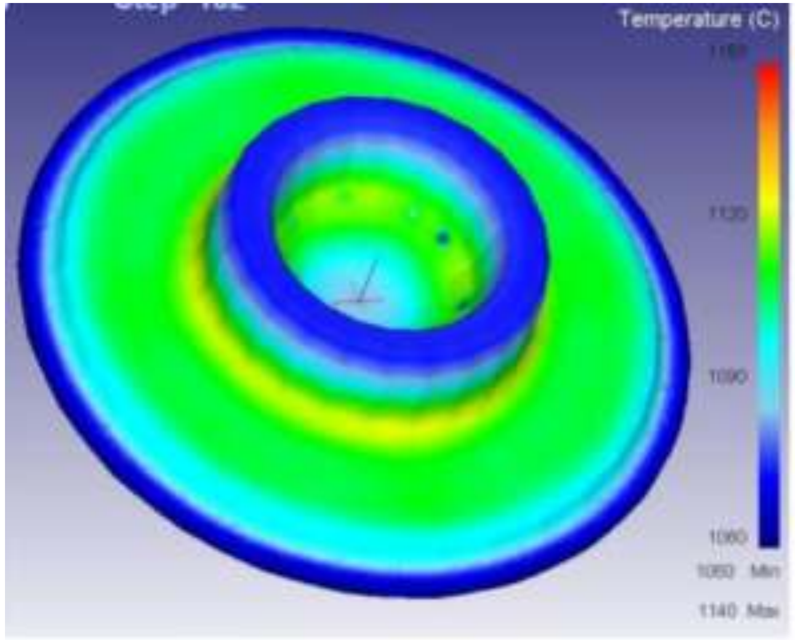
Material Characterization

- Most important ***material variables*** in the analysis of a metal forging process are,
  - Material composition
  - Deformation/heat treatment history and corresponding microstructure of material.
  - The flow stress and the workability (or forgeability) of material in various directions (anisotropy).
- For a given microstructure, the flow stress σ_f , is expressed as a function of strain, ε, strain rate $\dot{\varepsilon}$, and temperature T.

ie,
$$\sigma_f = f(\bar{\varepsilon}, \dot{\bar{\varepsilon}}, T)$$

- From different test results the ***constitutive equation*** can formulate.
- Temperature variation should considered in evaluating and using the test results.

- ***Workability, forgeability, or formability*** is the capability of the material to ***deform without failure***; it depends on
    - Conditions existing during deformation processing (such as temperature, rate of deformation, stresses, and strain history)
    - Material variables (such as composition, voids, inclusions, and initial microstructure).
- In hot forging processes, ***temperature gradients*** in the deforming material (for example, due to local die chilling) also influence metal flow and failure phenomena.



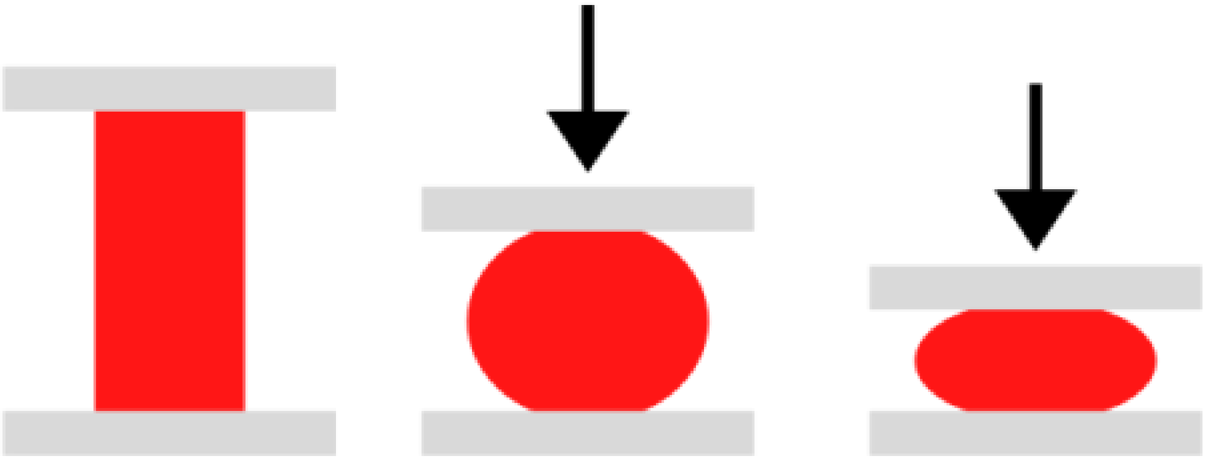
Classification of forging

- Based on the force applied
  - Hand forging
    - Always use drop hammer type because continuous force by human hand is not sufficient to produce deformation to work piece.
  - Machine forging
    - It is possible to use either continuous load application or intermittent impact load application known as drop hammer type.
- By equipment
    - 1) Forging hammer or drop hammer
    - 2) Press forging
- Based on method of shape obtained
  - Open die forging
  - Impression die forging or closed die forging
  - Semi closed die forging

Open die forging

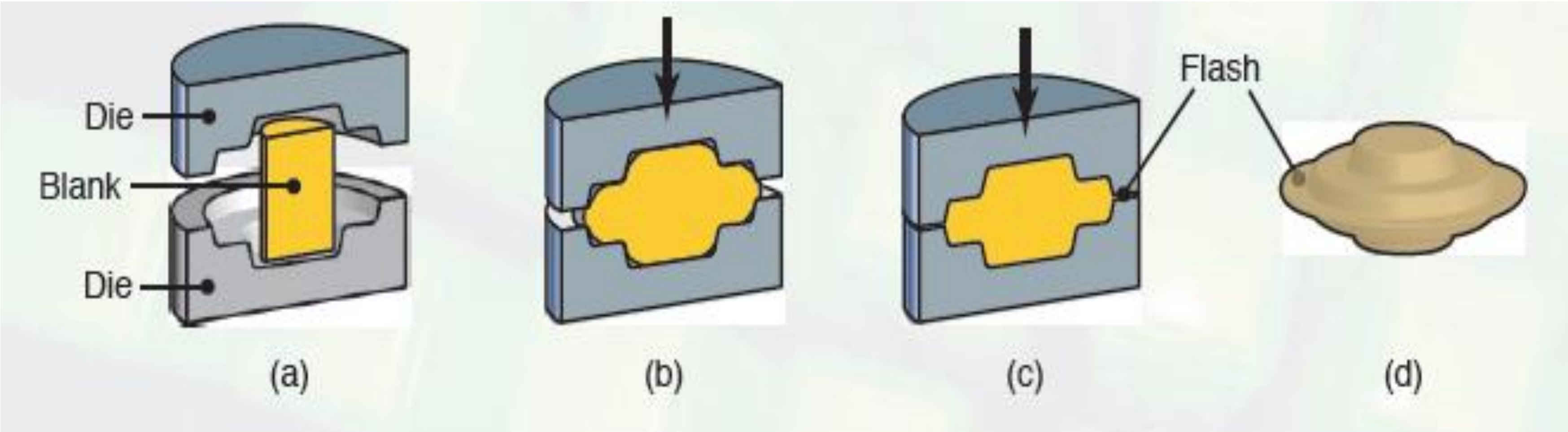
- If the required shape and size of the components is obtained by ***changing the position of the component*** in b/w the blows it is called as Open die forging.
- Press forging not used always since there is no time for changing the position of the component.
- Open-die forging is also known as ***smith forging***.
- In open-die forging, a hammer strikes and deforms the work piece, which is placed on a stationary anvil.
- Open-die forging gets its name from the fact that the dies (the surfaces that are in contact with the work piece) ***do not enclose the work piece***, allowing it to flow except where contacted by the dies.
- Therefore the operator, or a robot, needs to orient and position the work piece to get the desired shape.
- The dies are usually flat in shape, but some have a specially shaped surface for specialized operations.

OPEN-DIE
FORGING

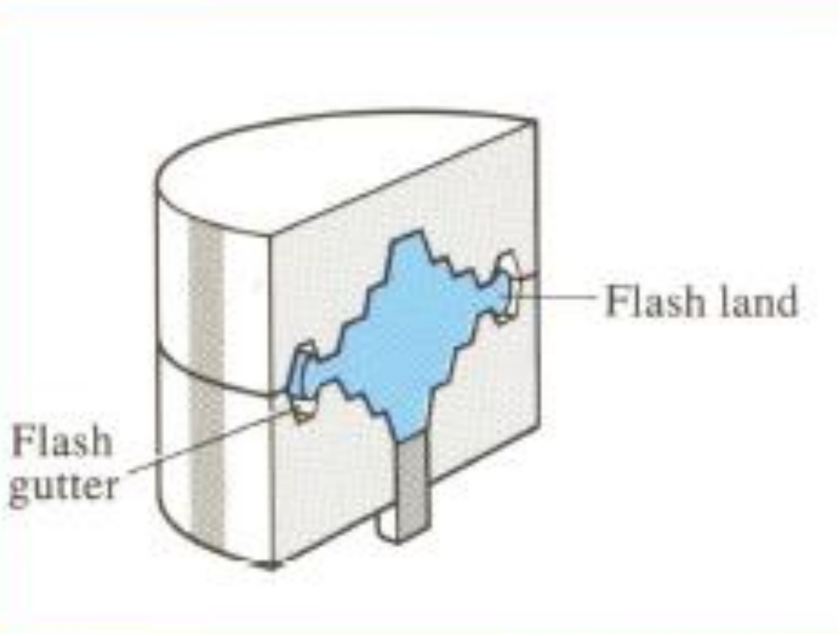


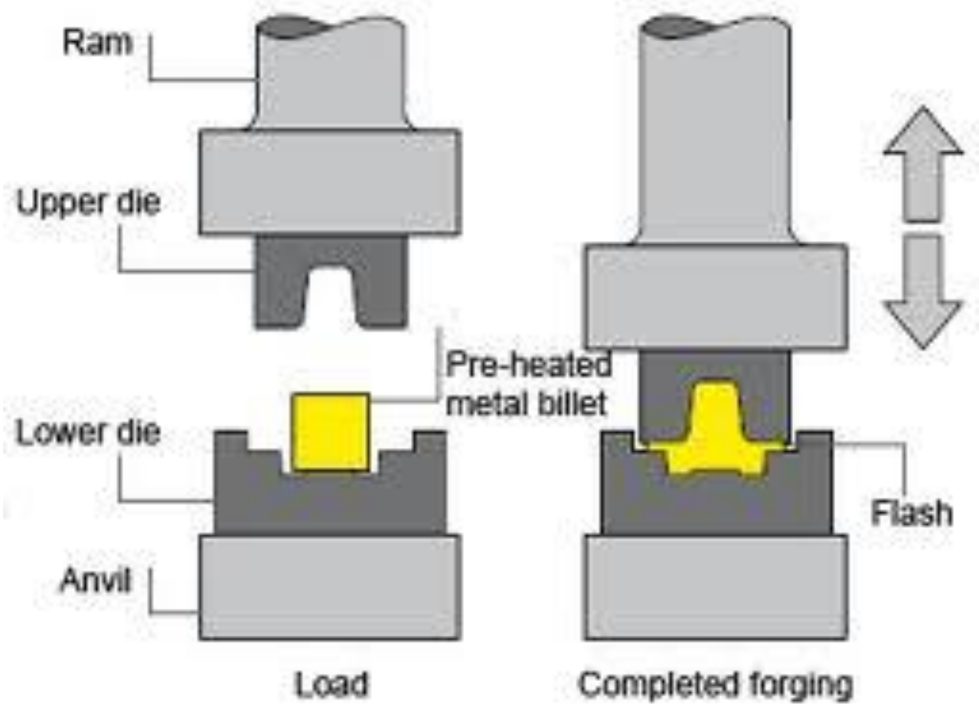
▪ Impression die forging and closed die forging.

- In this forging the work piece acquires the shape of the die cavities while being forged between two shaped dies.
- i.e., ***shape of the die is impressed on the component*** hence it is also called impression die forging.
- The type of force application may be either press forging or drop hammer type.
- In true close die forging no flash is formed.

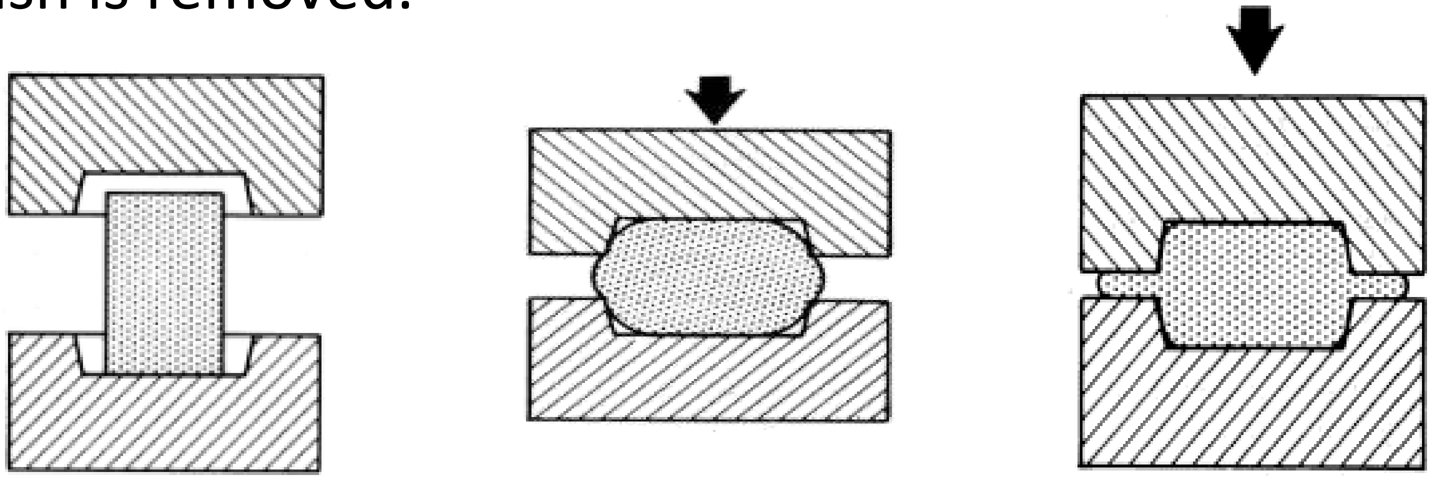


- In impression-die forging, the metal is placed in a die resembling a mold, which is attached to the anvil.
- Usually, the hammer die is shaped as well.
- The hammer is then dropped or pressed on the work piece, causing the ***metal to flow and fill the die cavities***

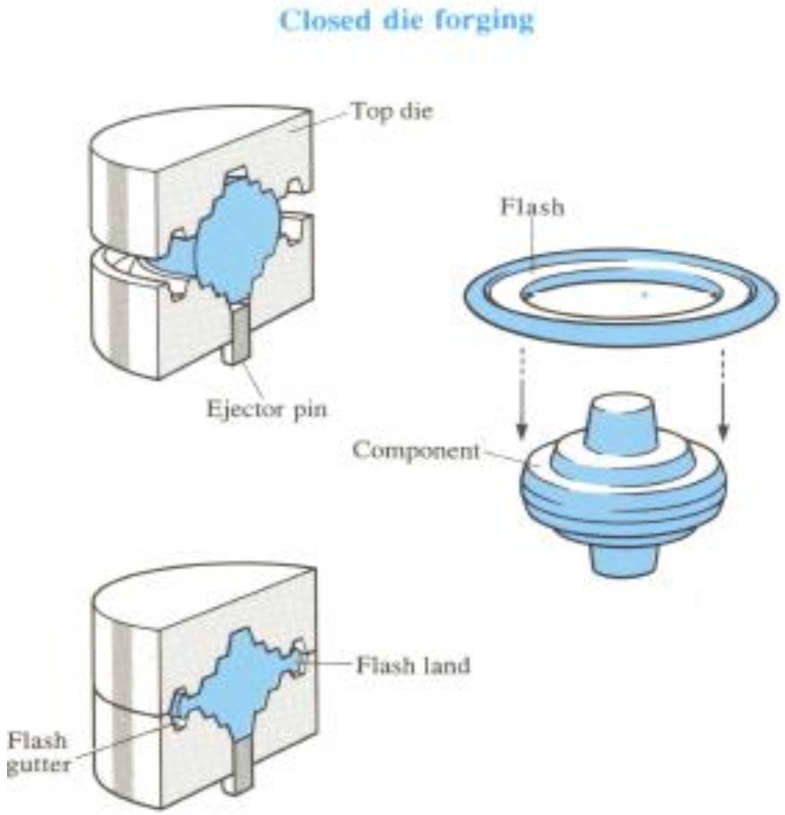


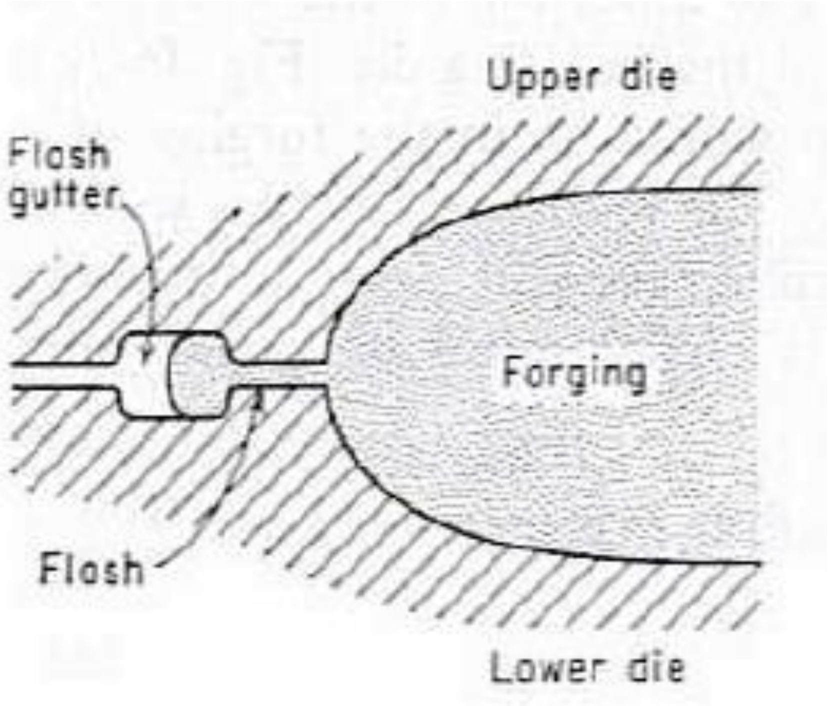


- Depending on the size and complexity of the part, the hammer may be dropped multiple times in quick succession.
- Excess metal is squeezed out of the die cavities, forming what is referred to as ***flash***.
- The ***flash cools more rapidly than the rest of the material***; this cool metal is ***stronger than the metal in the die***, so it helps prevent more flash from forming.
- This also forces the metal to completely fill the die cavity.
- After forging, the flash is removed.



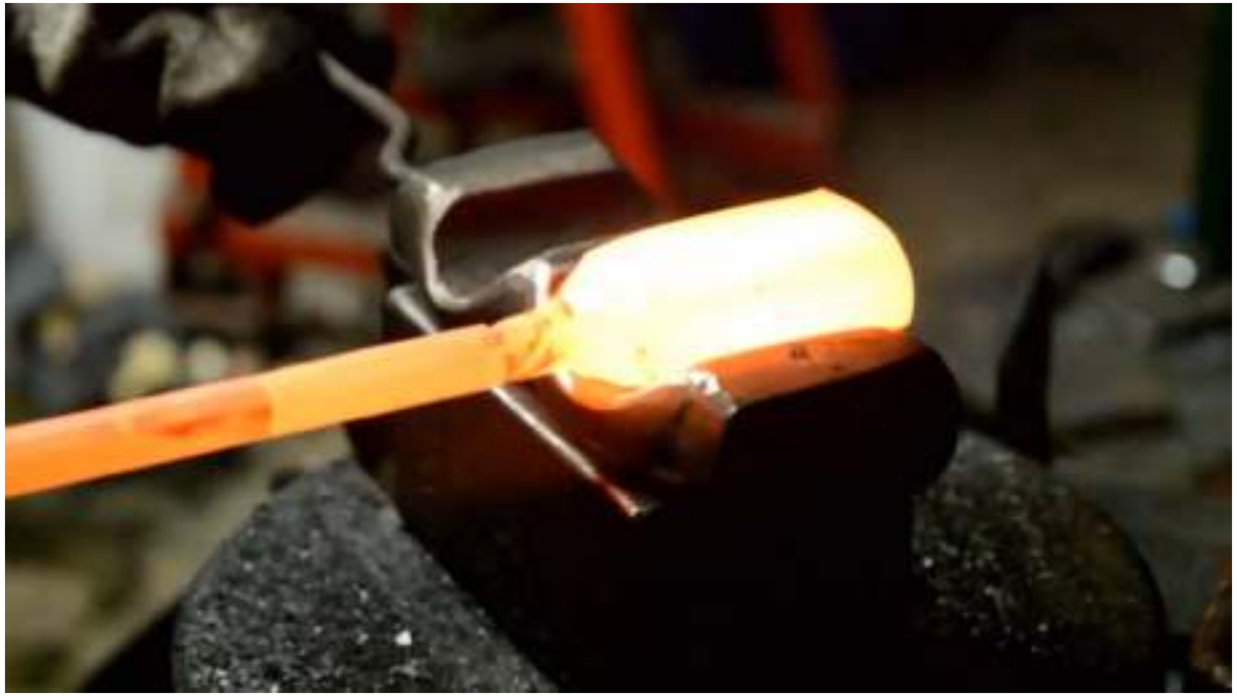
- The flash serves two purposes: [Slide 71]
    - Acts as a '***safety value***' for excess metal.
    - Builds up ***high pressure*** to ensure that the metal fills all recesses of the die cavity.





Semi closed die forging

- Shape and size of component obtained is remaining same as that of shape and size of half die used.
- But the required shape and size of the component can be obtained by changing the position of component in between blows.
- Only drop hammer type of force application is possible here.

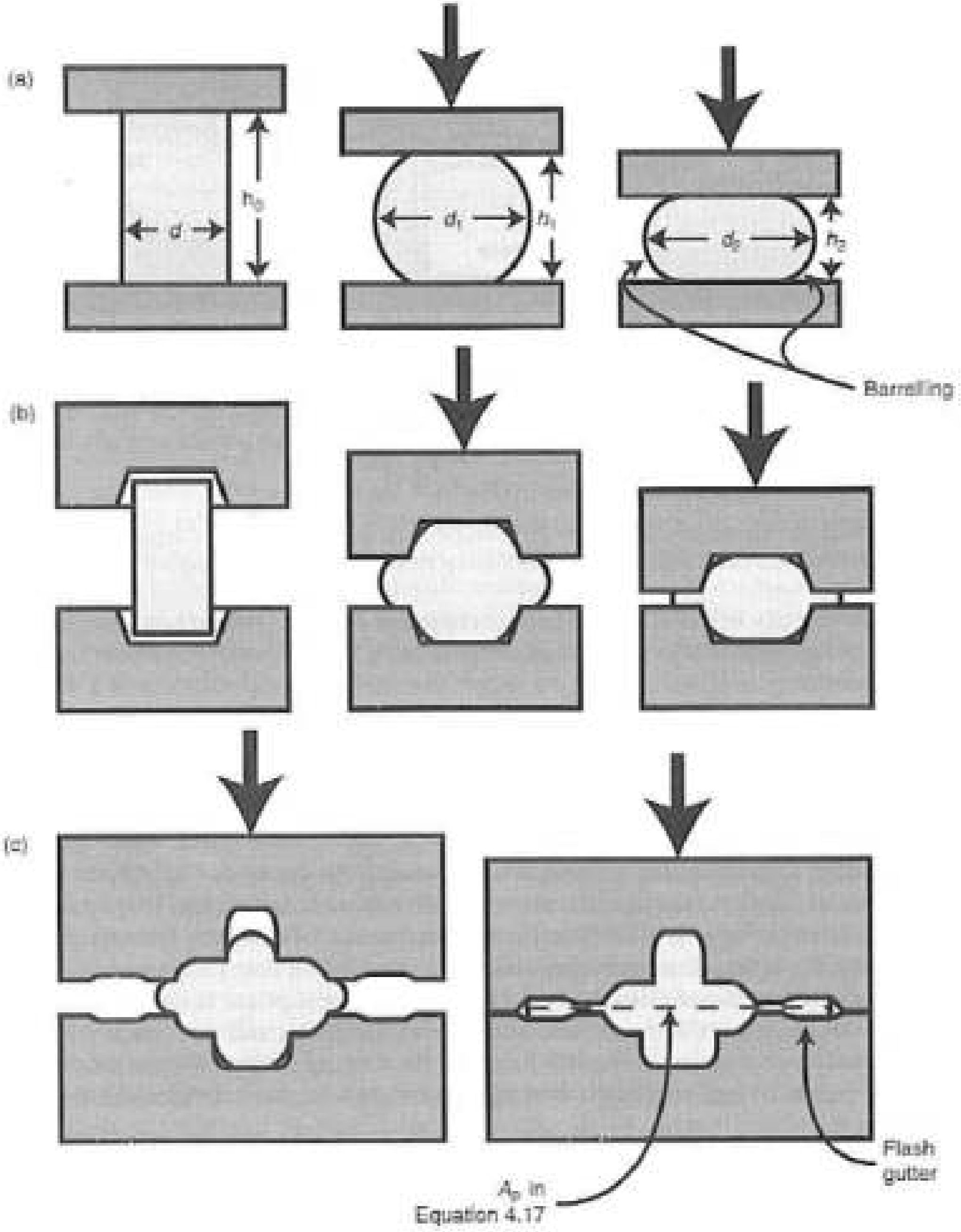


Characteristics of Forging

TABLE 14.1

General Characteristics of Forging Processes

Process	Advantages	Limitations
Open die	Simple and inexpensive dies; wide range of part sizes; good strength characteristics; generally for small quantities	Limited to simple shapes; difficult to hold close tolerances; machining to final shape necessary; low production rate; relatively poor utilization of material; high degree of skill required
Closed die	Relatively good utilization of material; generally better properties than open-die forgings; good dimensional accuracy; high production rates; good reproducibility	High die cost, not economical for small quantities; machining often necessary
Blocker	Low die costs; high production rates	Machining to final shape necessary; parts with thich webs and large fillets
Conventional	Requires much less machining than blocker type; high production rates; good utilization of material	Higher die cost than blocker type
Precision	Close dimensional tolerances; very thin webs and flanges possible; machining generally not necessary; very good material utilization	High forging forces, intricate dies, and provision for removing forging from dies

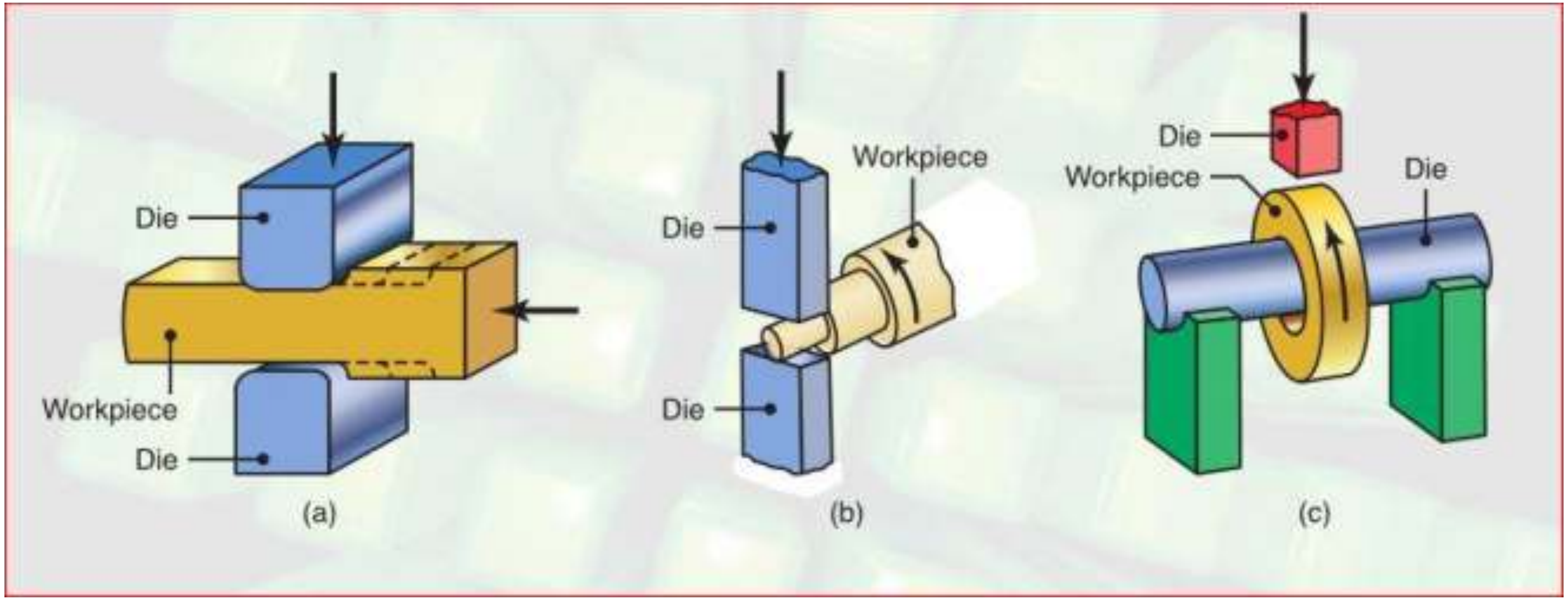


Open-die forging

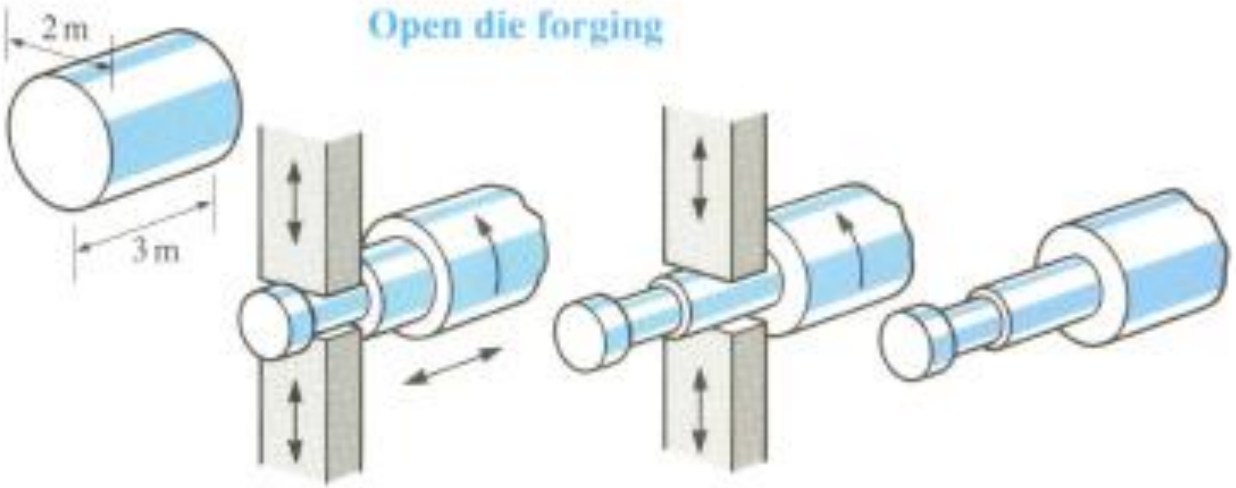
Closed-die forging

Impression-die forging

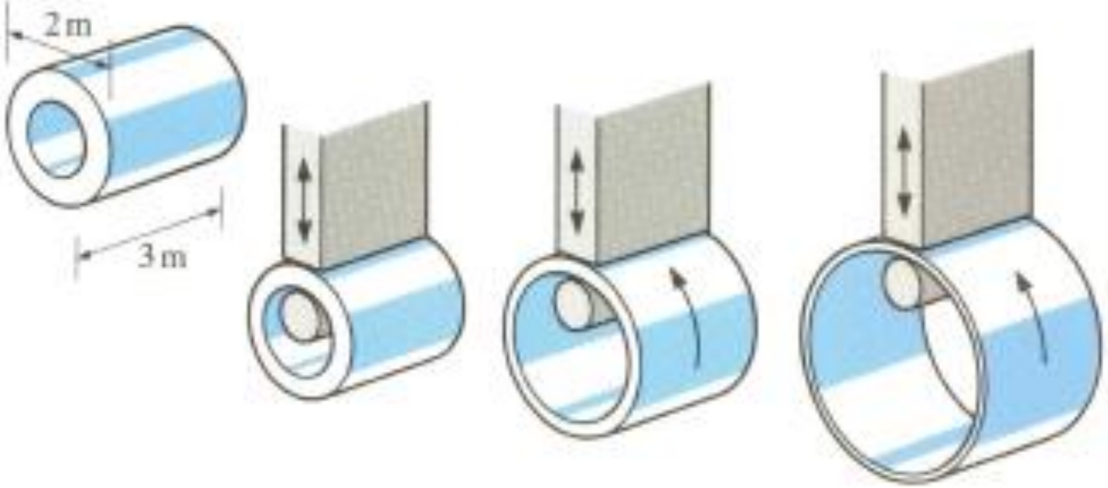
Open die forging



(a) Schematic illustration of a cogging operation on a rectangular bar. Blacksmiths use a similar procedure to reduce the thickness of parts in small increments by heating the work piece and hammering it numerous times along the length of the part. (b) Reducing the diameter of a bar by open-die forging; note the movements of the die and the work piece. (c) The thickness of a ring being reduced by open-die forging.

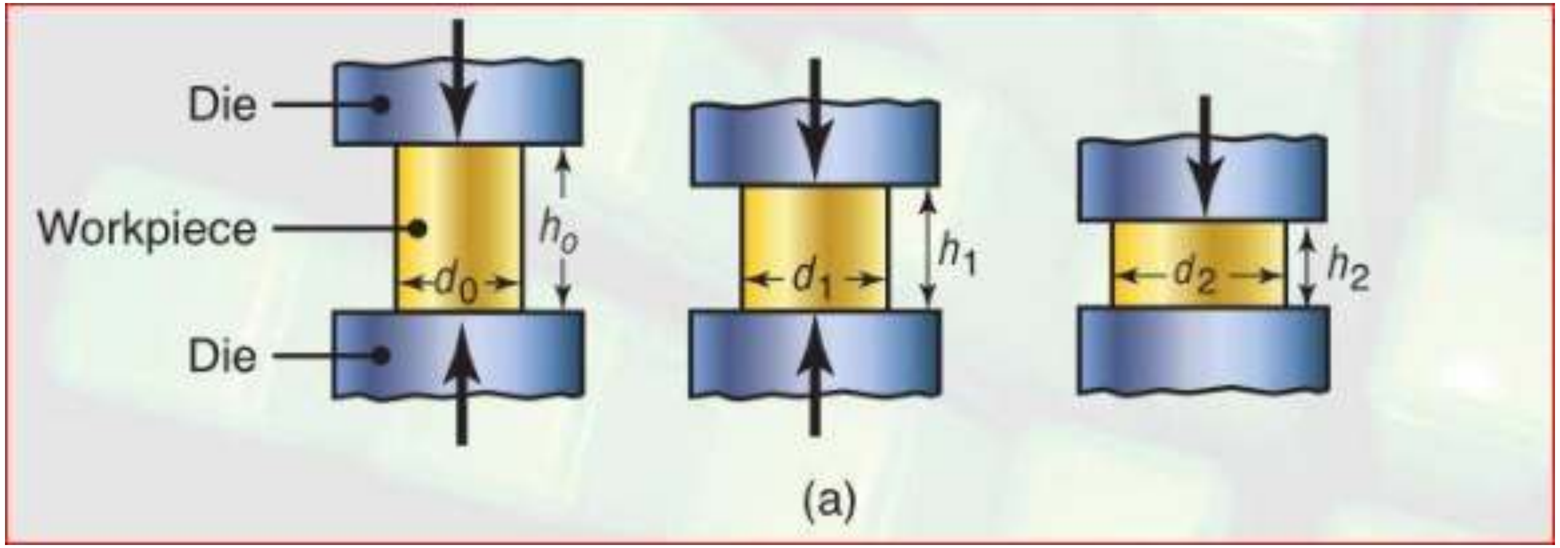


Forging large turbine shaft



Forging pressure vessel cylinder

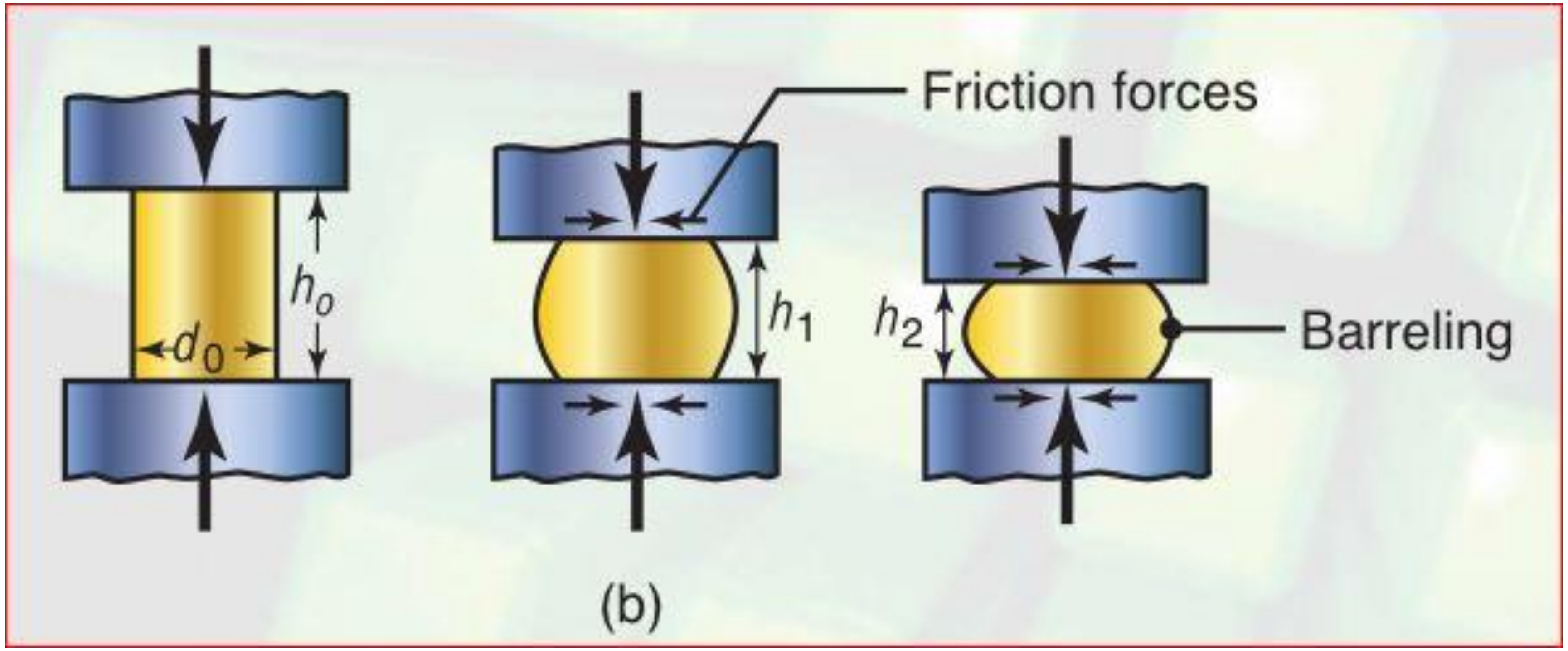
- Open die forging process can be depicted by a solid work piece placed between two flat dies and reduced in height by ***compressing it***.
- This process also known as ***upsetting.***
- ***Under ideal condition*** homogeneous deformation take place shown in figure
- The volume of the cylinder remain constant, any reduction in its height increase its diameter.
- Work piece deform uniformly.



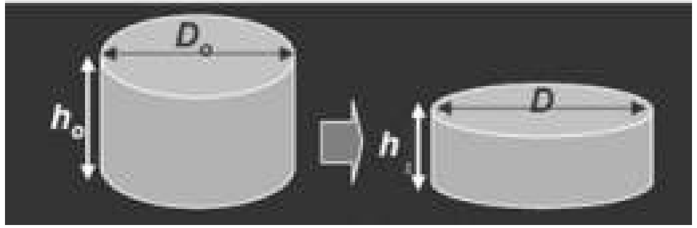
(a) *Ideal deformation of a solid cylindrical specimen compressed between flat frictionless dies (platens), an operation known as upsetting.*

Barreling is caused by ***frictional force*** at the die-work piece interfaces that oppose the outward flow of the material at the interface.

- Barreling also occur in upsetting hot work piece between cool dies.
- In barreling the material flow within the specimen become non uniform or inhomogeneous.



(b) Deformation in upsetting with friction at the die-work piece interfaces. Note barrelling of the billet caused by friction.



Reduction in height $= \frac{h_o - h_1}{h_o} \times 100\%.$ eq.1

the engineering strain is $e_1 = \frac{h_o - h_1}{h_o}$ eq.2

and the true strain is

$$\epsilon_1 = \ln\left(\frac{h_o}{h_1}\right)$$ eq.3

$$\varepsilon = \ln(e+1)$$

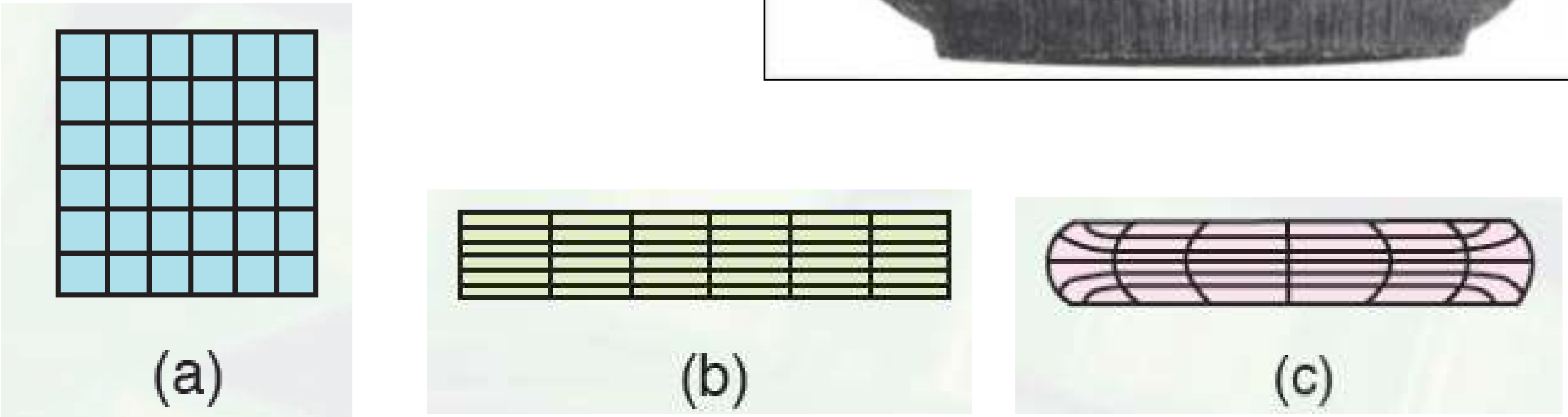
- With a relative velocity v between the platens, the strain rate encountered by the specimen as,

$$\dot{e}_1 = -\frac{v}{h_o}$$ eq.4

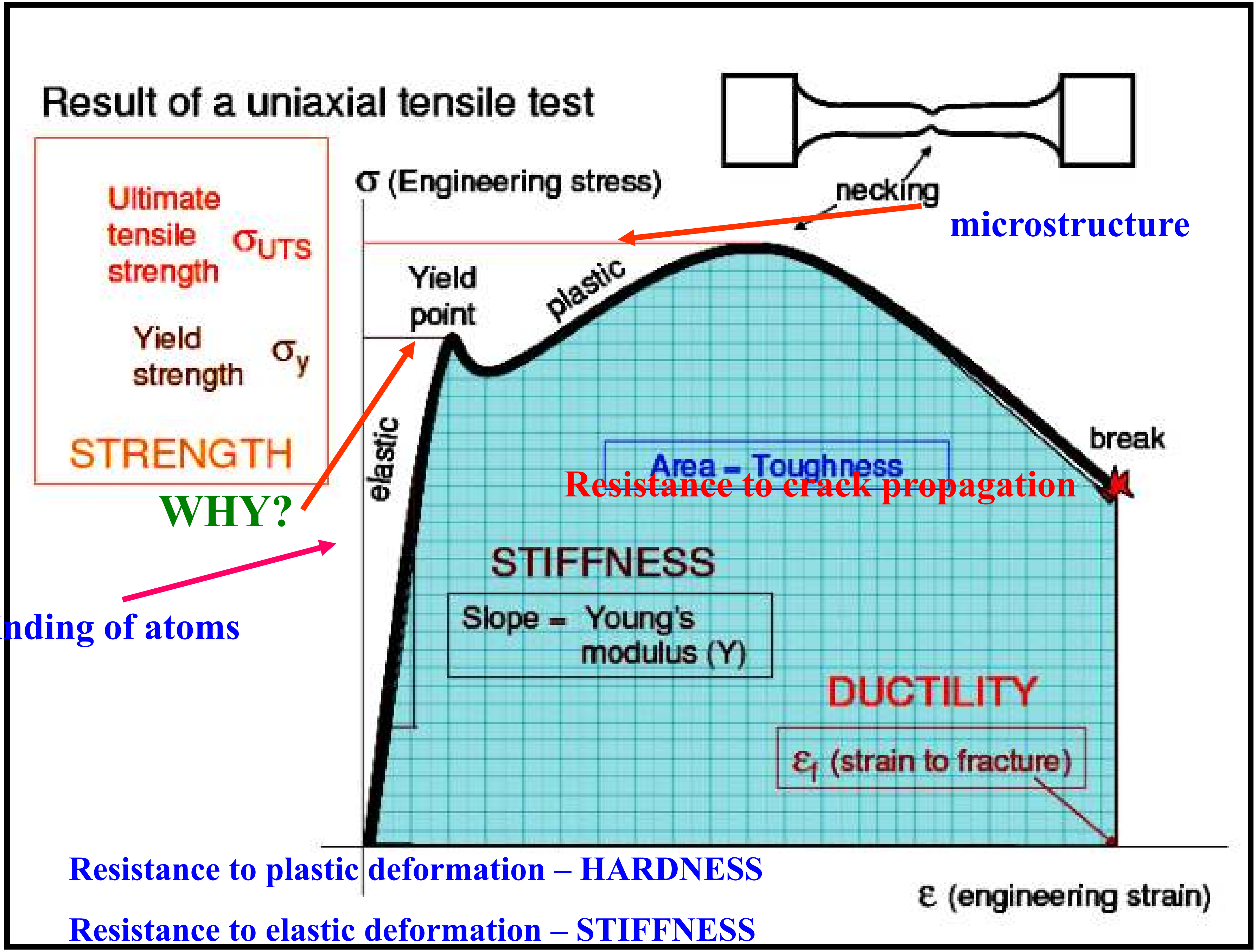
$$\dot{\epsilon}_1 = -\frac{v}{h_1}.$$ eq.5

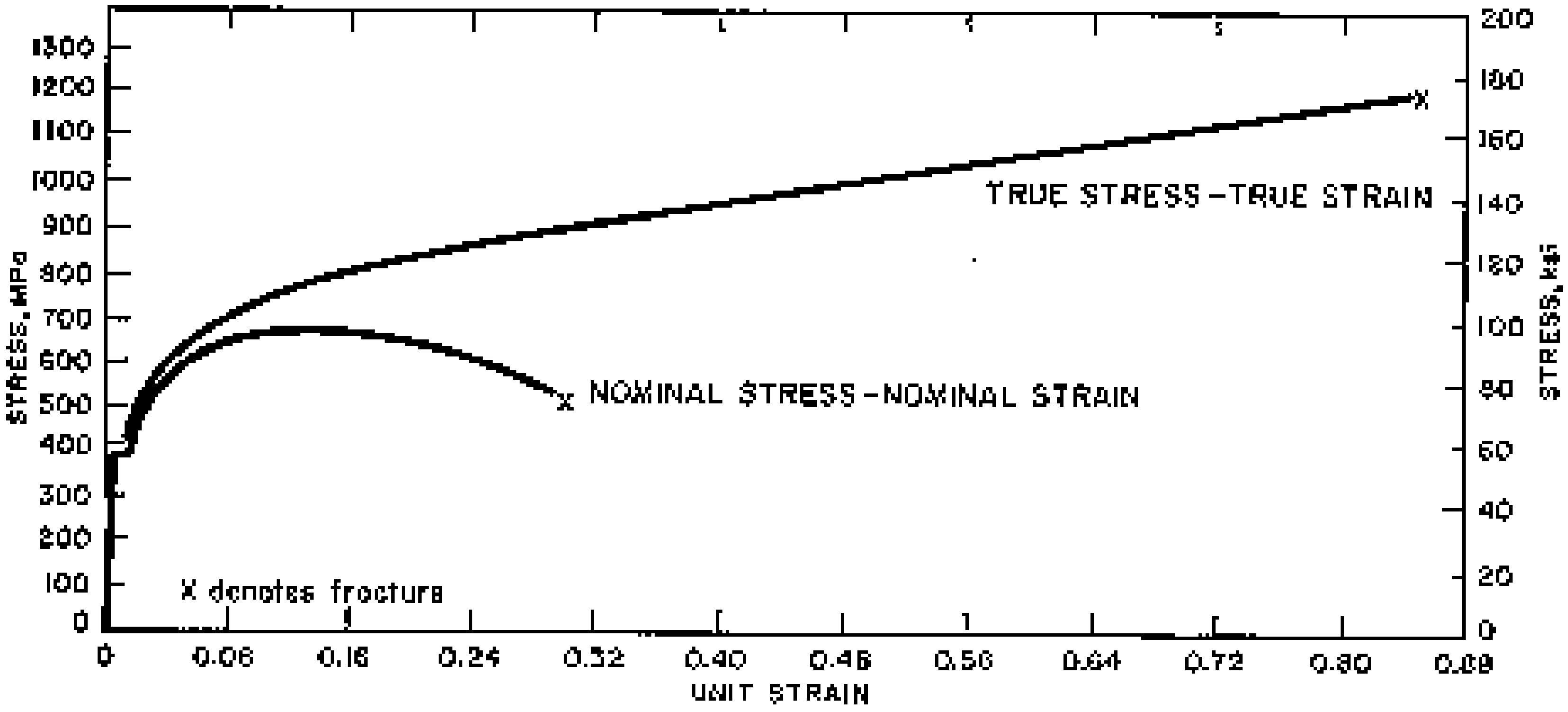
- True strain rate, ε̇, increases rapidly as the height of the specimen approaches zero.

Grain flow lines in upsetting a solid, steel cylindrical specimen at elevated temperatures between two flat cool dies. Note the ***highly inhomogeneous deformation and barrelling***, and the difference in shape of the bottom and top sections of the specimen.



Schematic illustration of grid deformation in upsetting: (a) original grid pattern; (b) after deformation, without friction; (c) after deformation, with friction. Such deformation patterns can be used to calculate the strains within a deforming body.


Result of a uniaxial tensile test
Ultimate tensile strength σ_{UTS}
Yield strength σ_y
STRENGTH
WHY?
Binding of atoms
σ (Engineering stress)
necking
microstructure
Yield point
plastic
elastic
break
Area = Toughness
Resistance to crack propagation
STIFFNESS
Slope = Young's modulus (Y)
DUCTILITY
ε_f (strain to fracture)
ε (engineering strain)
Resistance to plastic deformation – HARDNESS
Resistance to elastic deformation – STIFFNESS



ENGINEERING STRESS $$\sigma_E = \frac{P}{A_0}$$

TRUE STRESS $$\sigma_T = \frac{P}{A_i}$$

Forging analysis

- The calculation for forging load can be ***divided into three cases*** according to friction:
  1. **In the absence of friction**
  2. **Low friction condition (slab method)**
  3. **High friction condition (sticky friction condition)**

- Forging methods analysis is used to theoretically determine ***stresses, strains, strain rates, forces, and local temperature rise in deformation processing.***
- Commonly used analysis methods for forging are,
  - Slab analysis
  - FEM

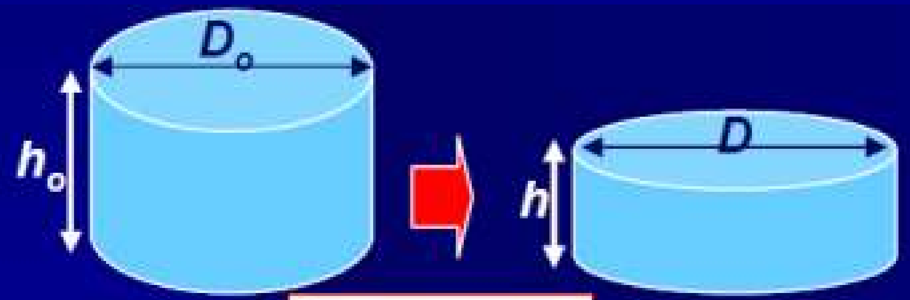
1.Forces and work of deformation under ideal condition

- Forces and work of deformation under ***ideal conditions***.
- If friction at the workpiece-die interfaces is ***zero*** and the material is ***perfectly plastic*** with a yield strength of $\boldsymbol{\sigma_y}$,
- The normal compressive stress on the cylindrical specimen is uniform and at the level of $\boldsymbol{\sigma_y}$.
- The compressive force at any height h_1 is,

$$F = \sigma_y \times A_1 \qquad \text{eq.6}$$

where A is the cross-sectional area and is obtained from volume constancy:

$$A_1 = \frac{A_o h_o}{h_1} \qquad \text{eq.7}$$



$$D_o^2 h_o = D^2 h$$

Note: from volume constant

Where h is the instantaneous height of the metal bar during forging

h_o is the original height of the metal bar

D_o is the original diameter of the metal bar.

- The ideal work of deformation is the product of the specimen ***volume and the specific energy.***

$$\text{Work} = (u) \times (\text{volume}) \qquad \text{eq.8}$$

$$\text{Work} = \left(\int_0^{\varepsilon_1} \sigma \, d\varepsilon_1\right) \times (\text{volume}) \qquad \text{eq.9}$$

If the material is ***strain hardening***, with a true stress-strain curve follow the equation, $\sigma = K\varepsilon^n$

$$F = \sigma_f \times A_1$$

And

$$\text{work} = (\bar{\sigma} \times \varepsilon_1) \times (\text{volume}) \qquad \text{eq.10}$$

Where, $\bar{\sigma}$ is the average flow stress of the material.

$$\bar{\sigma} = \frac{K{\varepsilon_1}^n}{n+1} \qquad \text{eq.11}$$

The total energy required for deformation process;

$$U_{total} = U_{ideal} + U_{friction} + U_{redundant}$$

Note: redundant work = work that does not contribute to shape change of the workpiece

2. Slab method (sliding or Low friction condition)

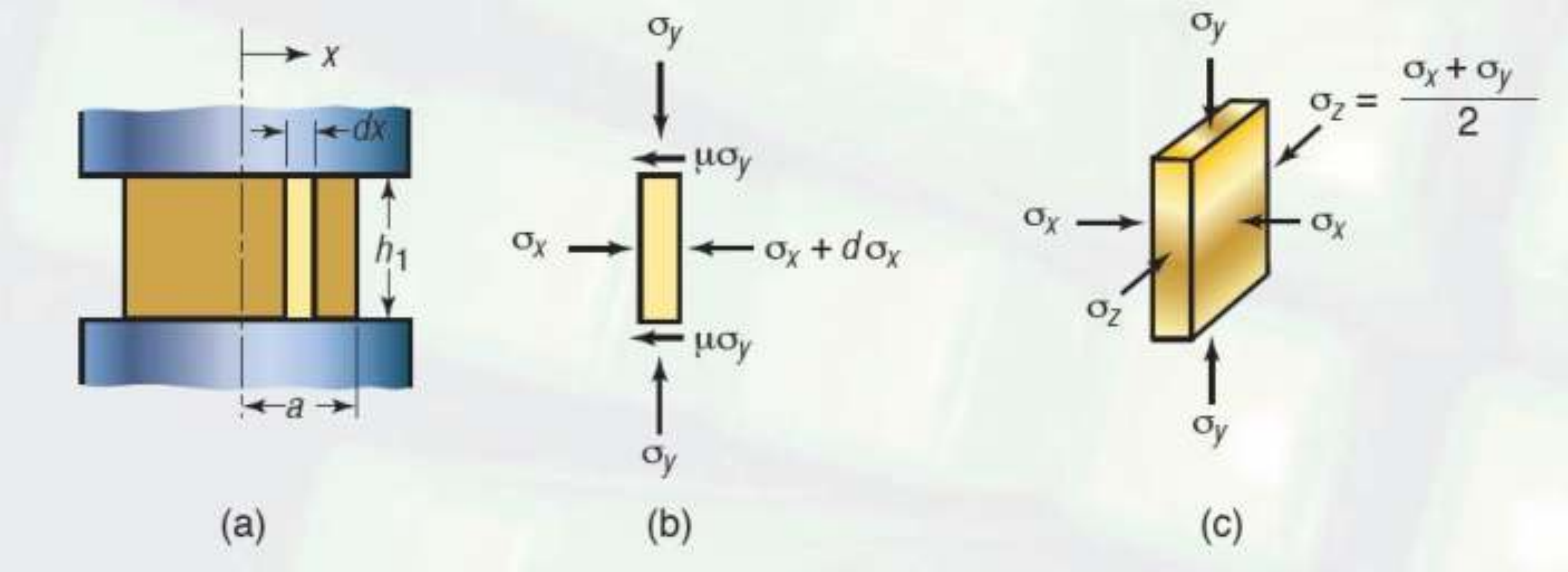
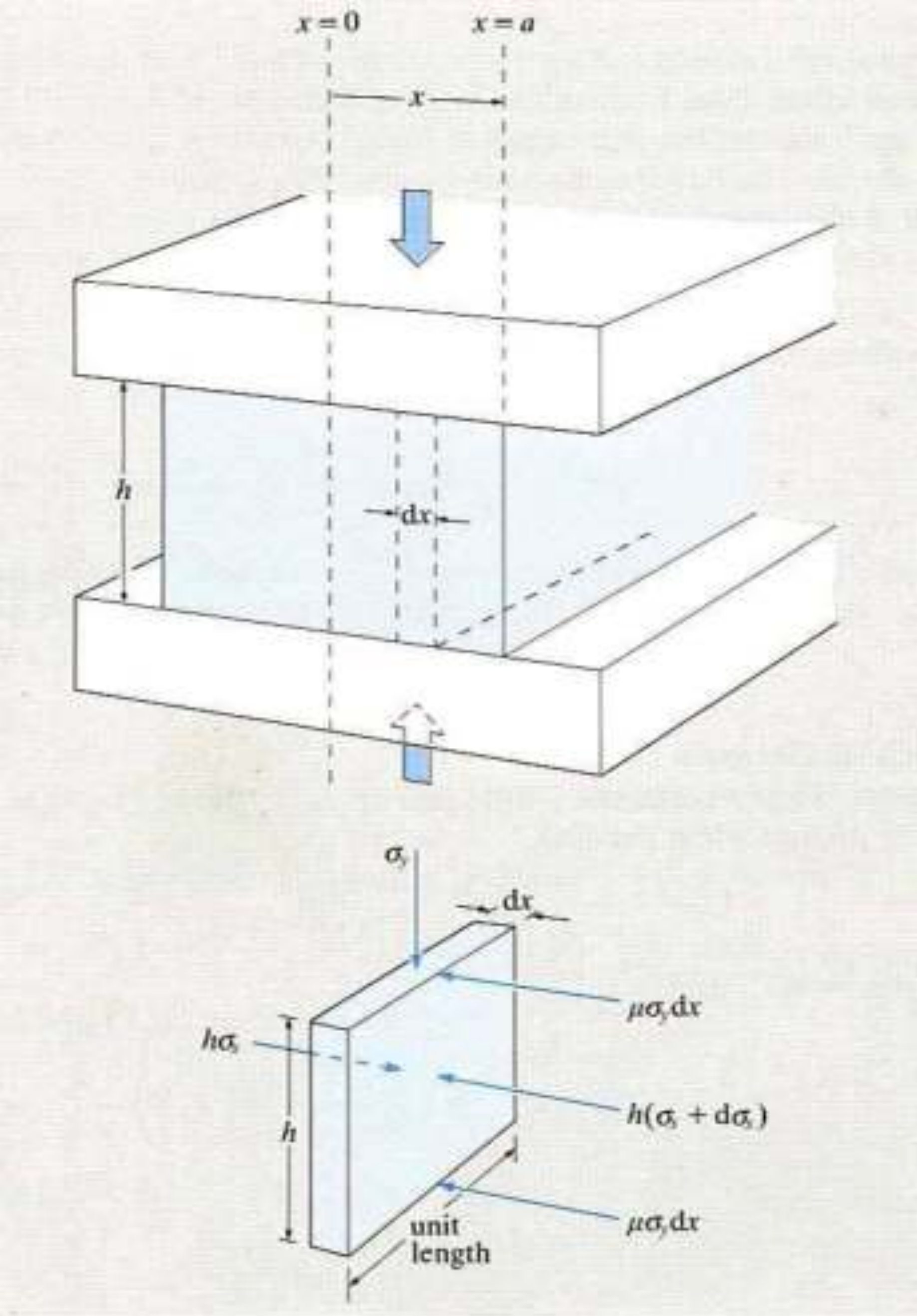
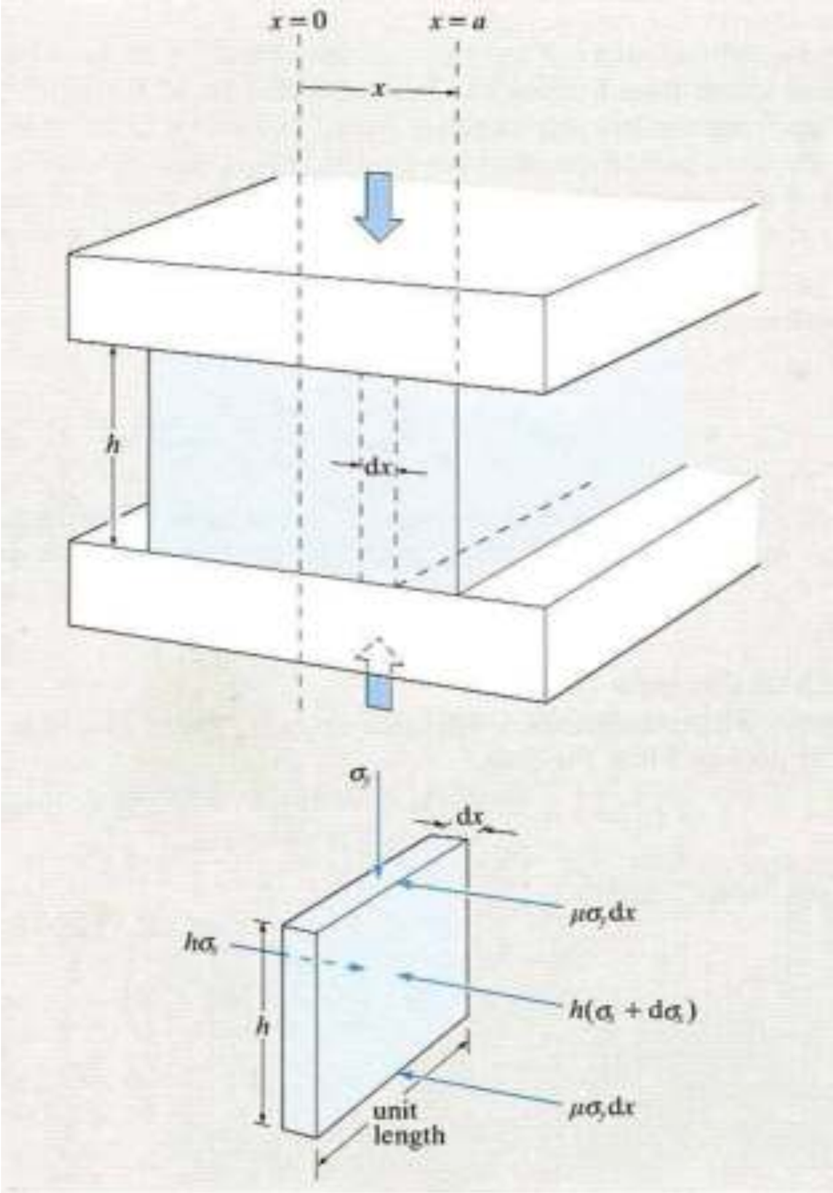


FIGURE 6.1 Stresses on an element in plane-strain compression (forging) between flat dies with friction. The horizontal stress σ_x is assumed to be uniformly distributed along the height *h* of the element. Identifying the stresses on an element (slab) is the first step in the slab method of analysis of metalworking processes.

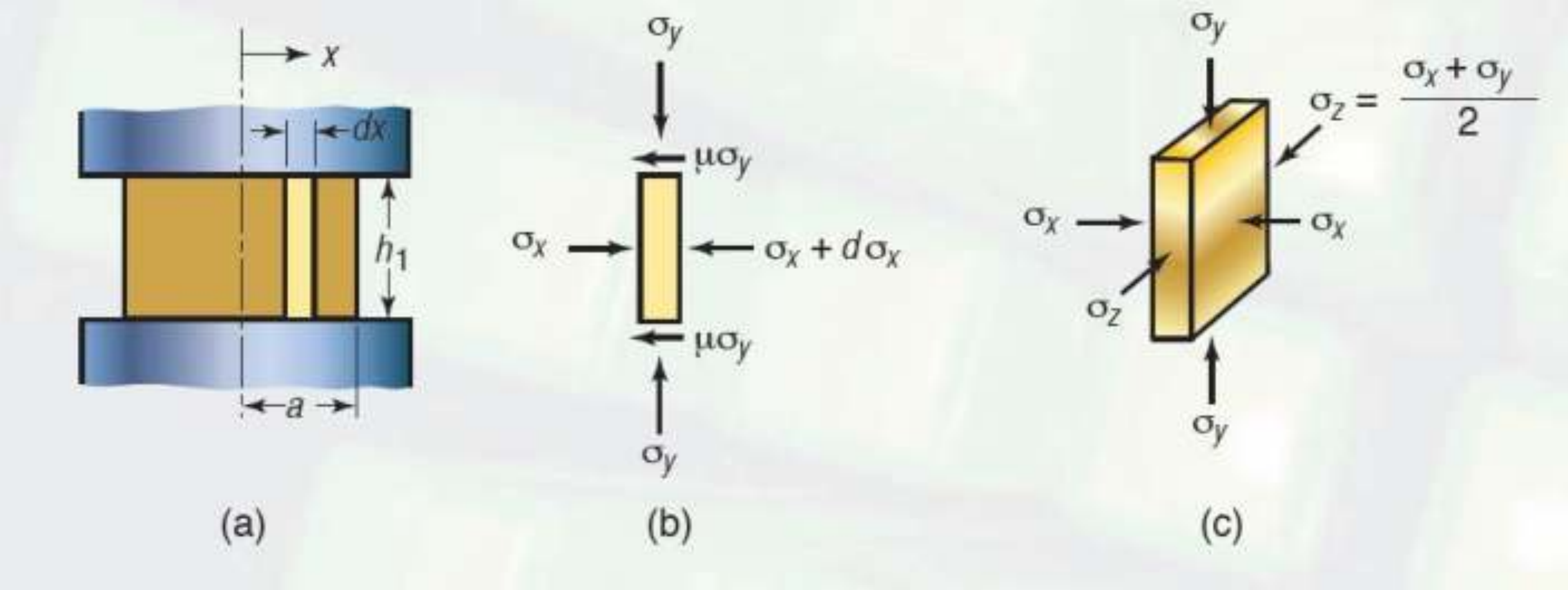


x = 0
x = a
x
h
dx
σy
dx
μσy dx
hσx
h(σx + dσx)
h
μσy dx
unit
length

- Consider the case of simple ***compression with friction***.
- As the flat dies reduce the part thickness, it expands laterally, causing frictional forces to act in the opposite direction to the motion.
- The frictional forces are indicated by the horizontal arrows.
- ***Assume*** that the deformation is in ***plane strain***; that is, the workpiece is not free to flow in the z-direction.
- Also, consider a ***perfectly plastic material***, so that the **flow stress is the yield stress** of the material.
- An element showing all the applied stresses is shown in Fig.



- Note the difference between the horizontal stresses acting on the side faces, which is due to the ***frictional stresses on the element***.
- ***Assume*** also that the lateral stress distribution, σ_x is uniform along the height, h, of the element.
- ***Assume*** unit width for the element.



- Consider the force acting on a vertical element of unit length and width dx. The element is at some distance x from the central point, in this case to the right.
- The ***vertical force acting*** on the element is,

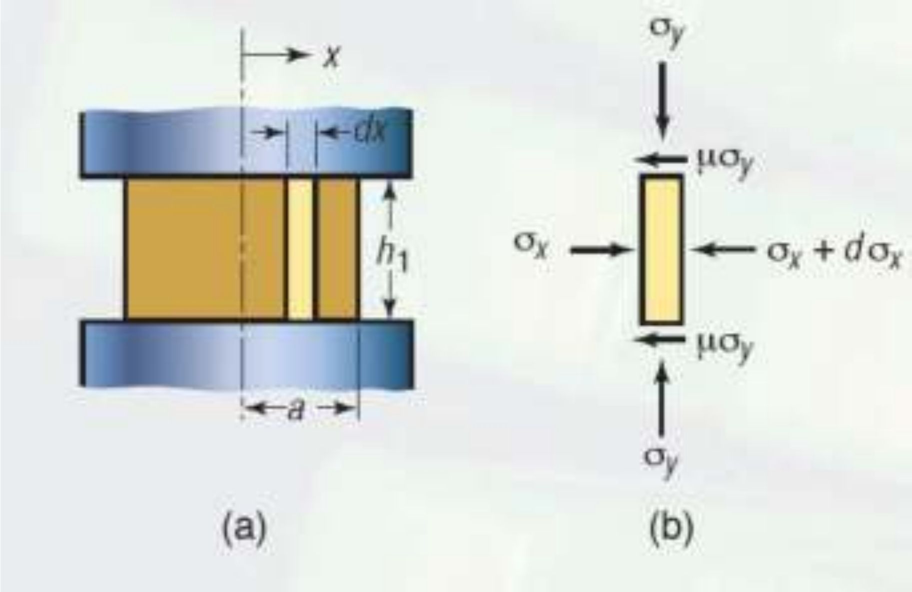
$$\text{stress x area} = \boldsymbol{\sigma_y} \times dx \times 1$$

- If the coefficient of friction for the die-workpiece interface is μ, the magnitude of the friction force will be,

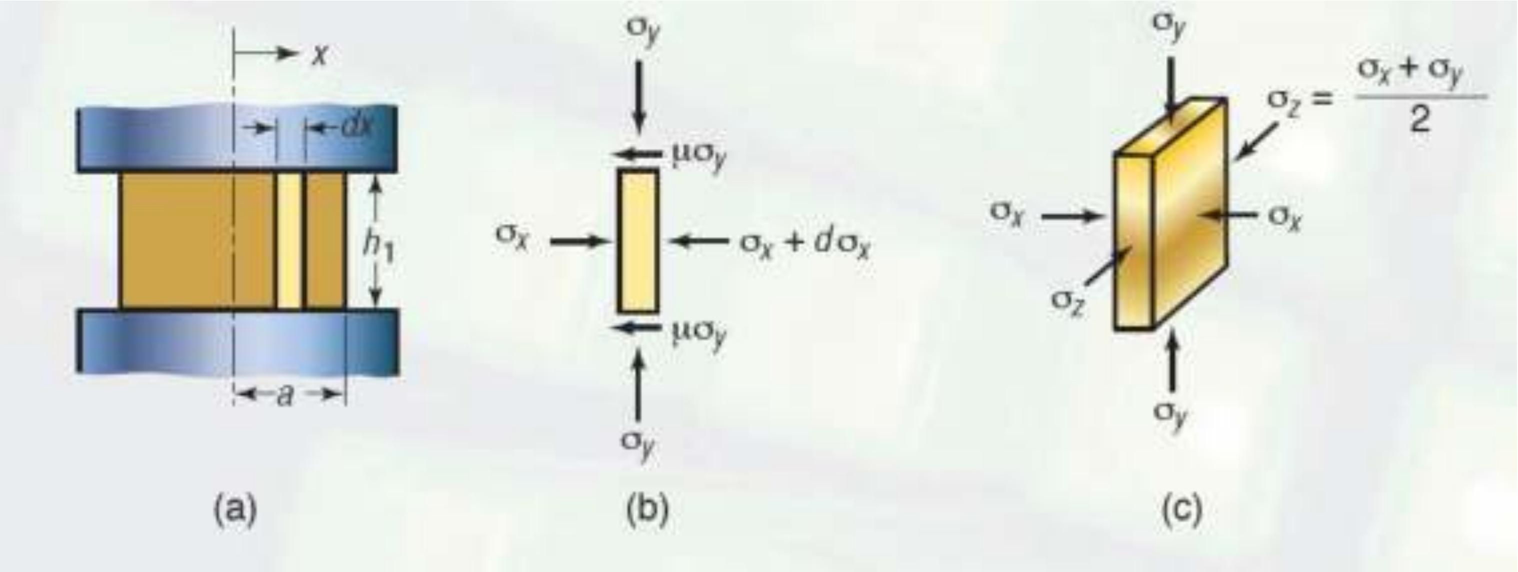
$$\boldsymbol{\mu \times \sigma_y \times dx \times 1}$$

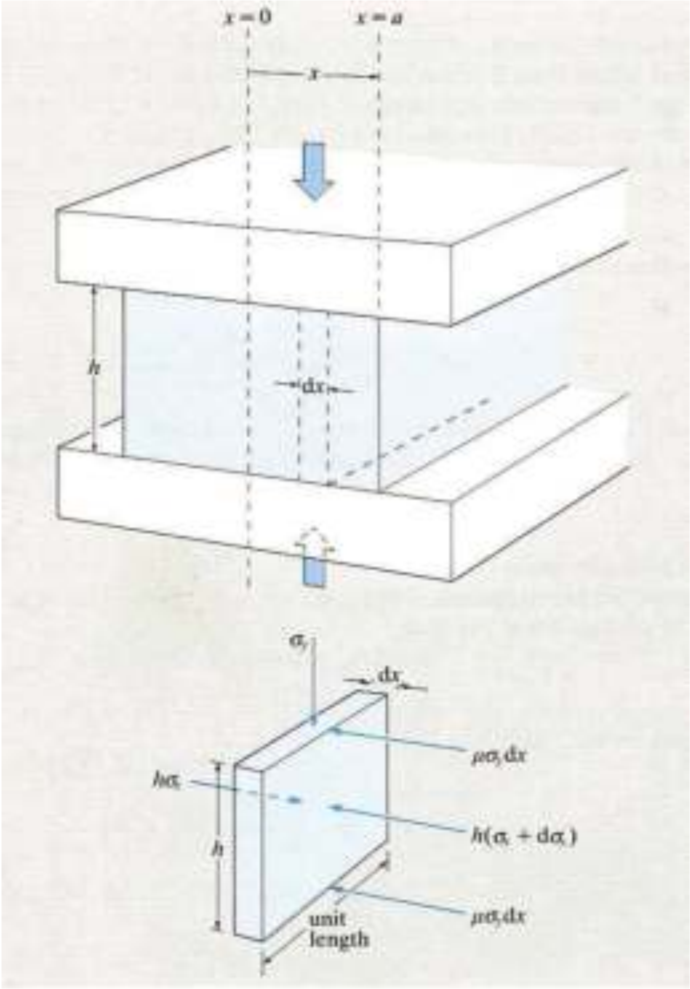
- The frictional force acts at both ends of the element so the total horizontal force from the right is,

$$\boldsymbol{2 \times \mu \times \sigma_y \times dx \times 1}$$



- Acting on the left will be the force $\boldsymbol{\sigma_X h}$ and from the right the force $(\boldsymbol{\sigma_X + d\,\sigma_X})\boldsymbol{h}$.
- The horizontal compressive stress $\boldsymbol{\sigma_X}$ varies from a ***maximum at the centre*** of the workpiece to ***zero at the edge*** and changes by $d\boldsymbol{\sigma_X}$ across the element width dx.





- Element must be in static equilibrium condition.
- So balance the horizontal forces, we get,

$$(\sigma_x + d\sigma_x)\,h + 2\mu\sigma_y dx - \sigma_x h = 0$$

$$d\sigma_x + \frac{2\mu\sigma_y}{h} dx = 0.$$

$$\frac{d\sigma_x}{\sigma_y} = -\frac{2\mu}{h} dx \qquad \text{eq.12}$$

- Here we have only one equation but two unknowns, ***σ_x and σ_y.***
- The required second equation is obtained from a ***yield criterion***
- This element is subjected to triaxial compression.

Plastic deformation in plane strain

Here, one principal strain is zero. Let this be ε_3. Then $\delta\varepsilon_3 = 0$.

From the Levy-Mises equation,

$$\frac{\delta\varepsilon_1}{\sigma_1 - \frac{1}{2}(\sigma_2+\sigma_3)} = \frac{\delta\varepsilon_2}{\sigma_2 - \frac{1}{2}(\sigma_3+\sigma_1)} = \frac{\delta\varepsilon_3}{\sigma_3 - \frac{1}{2}(\sigma_1+\sigma_2)} \neq 0$$

It follows that $\sigma_3 = \frac{1}{2}(\sigma_1+\sigma_2)$ in order to avoid $\frac{\delta\varepsilon_1}{\sigma_1 - \frac{1}{2}(\sigma_2+\sigma_3)} = 0$

Hence σ_3 is the mean of σ_1 and σ_2. By convention we define $\sigma_1 > \sigma_2$ $\sigma_1 > \sigma_3 > \sigma_2$. Therefore the maximum shear stress in the σ_1- σ_2 plane is at 45° to the axes and has magnitude $\frac{\sigma_1-\sigma_2}{2}$.

If we now examine the Tresca and von Mises yield criteria, we find:

- Tresca $\frac{\sigma_1-\sigma_2}{2} = k = \frac{Y}{2}$ (k = shear yield stress and Y = uniaxial yield stress)
- von Mises $(\sigma_1-\sigma_2)^2 + (\sigma_2-\sigma_3)^2 + (\sigma_3-\sigma_1)^2 = 6k^2 = 2Y^2$

$$\text{If } \sigma_3 = \frac{1}{2}(\sigma_1+\sigma_2), \frac{3}{2}(\sigma_1-\sigma_2)^2 = 6k^2 = 2Y^2$$

$$\Rightarrow (\sigma_1-\sigma_2) = 2k = \frac{2Y}{\sqrt{3}}$$

Flow stress = Y= σ_f

Reference : Von Mises yield criterion in **plain strain condition**. Here Y is the flow stress

Therefore, if we have plane strain, the Tresca yield criterion and the von Mises yield criterion have the same result expressed in terms of k. It is unnecessary to specify which criterion we are using, provided we use k.

- According to the ***distortion-energy criterion*** for ***plane strain condition.***
- As the frictional force is usually much smaller then both σ_x and σ_y which are principal stresses. Thus we can use them in the yield criterion when the slab will yield,

$$\sigma_x - \sigma_y = \frac{2}{\sqrt{3}}\sigma_f = \sigma'_f \qquad \text{eq.13}$$

Where

σ'_f is the ***flow stress in plane strain and*** σ_f ***is the uniaxial flow stress,***

- Differentiation of the yield condition gives $d\sigma_x = d\sigma_y$ eq.14

Substituting for $d\sigma_x$ in Eq. 12 gives,

$$\frac{d\sigma_y}{\sigma_y} = -\frac{2\mu}{h}dx, \qquad \text{eq.15}$$

- Integrating both sides of this differential equation gives,

$$\ln \sigma_y = -\frac{2\mu x}{h} + C$$

$$\sigma_y = C \exp\left(-\frac{2\mu x}{h}\right) \quad \text{or} \quad \sigma_y = Ce^{-2\mu x/h} \qquad \text{eq.16}$$

where C is a constant of integration.

We can evaluate C by looking at the boundary conditions. At the edge of the workpiece where **$x = a$, $\sigma_x = 0$** and from the yield criterion(eq.13)

$$\boldsymbol{\sigma_y - \sigma_x = \sigma'_f}$$

So $\boldsymbol{\sigma_y = \sigma'_f}$

Constant C is $C = \sigma'_f e^{2\mu a/h}$ eq.17

- Eq. 16 after substituting C value,

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3.Forging under sticking condition

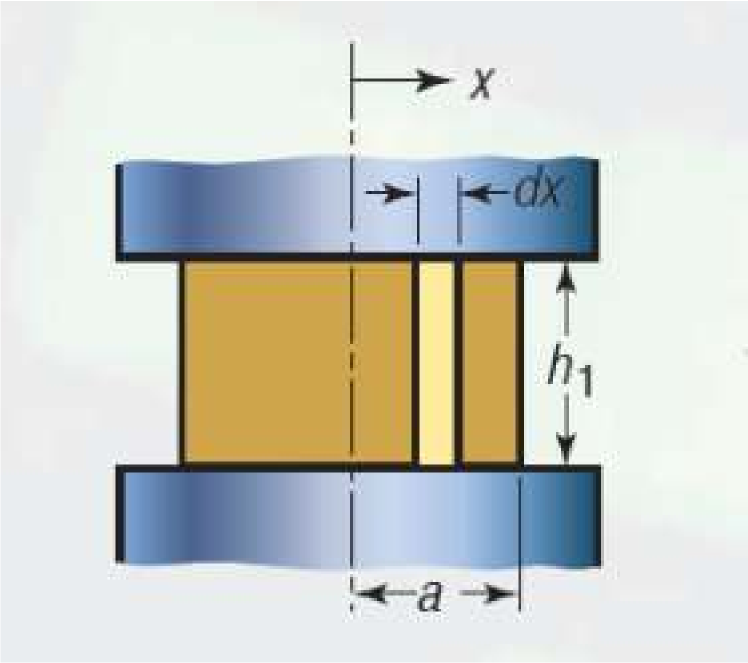
$$p = \sigma_y = \sigma'_f e^{2\mu(a-x)/h}$$

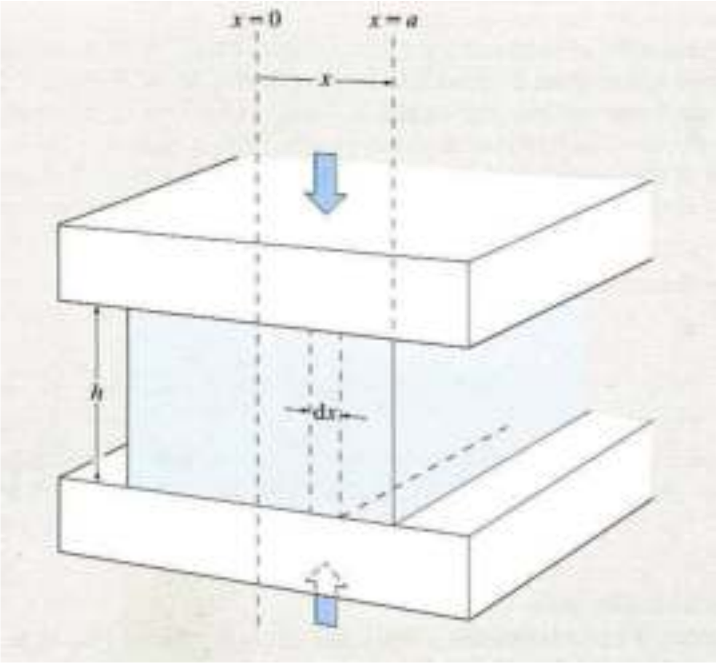
or

$$\sigma_y = \sigma'_f \exp\left[\frac{2\mu}{h}(a-x)\right] \qquad \text{eq.19}$$

and

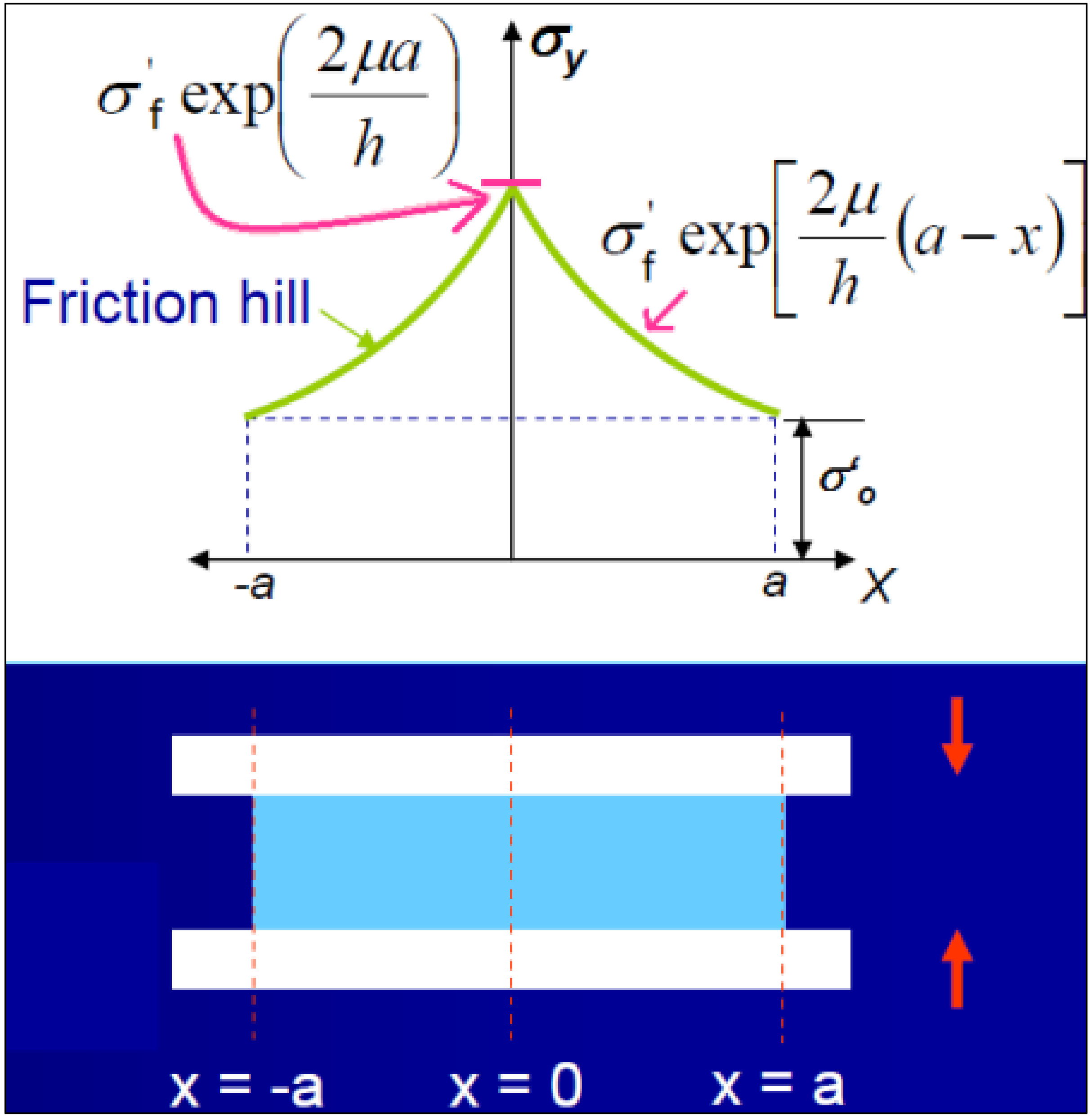
$$\sigma_x = \sigma_y - \sigma'_f = \sigma'_f\left[e^{2\mu(a-x)/h} - 1\right] \qquad \text{eq.18}$$

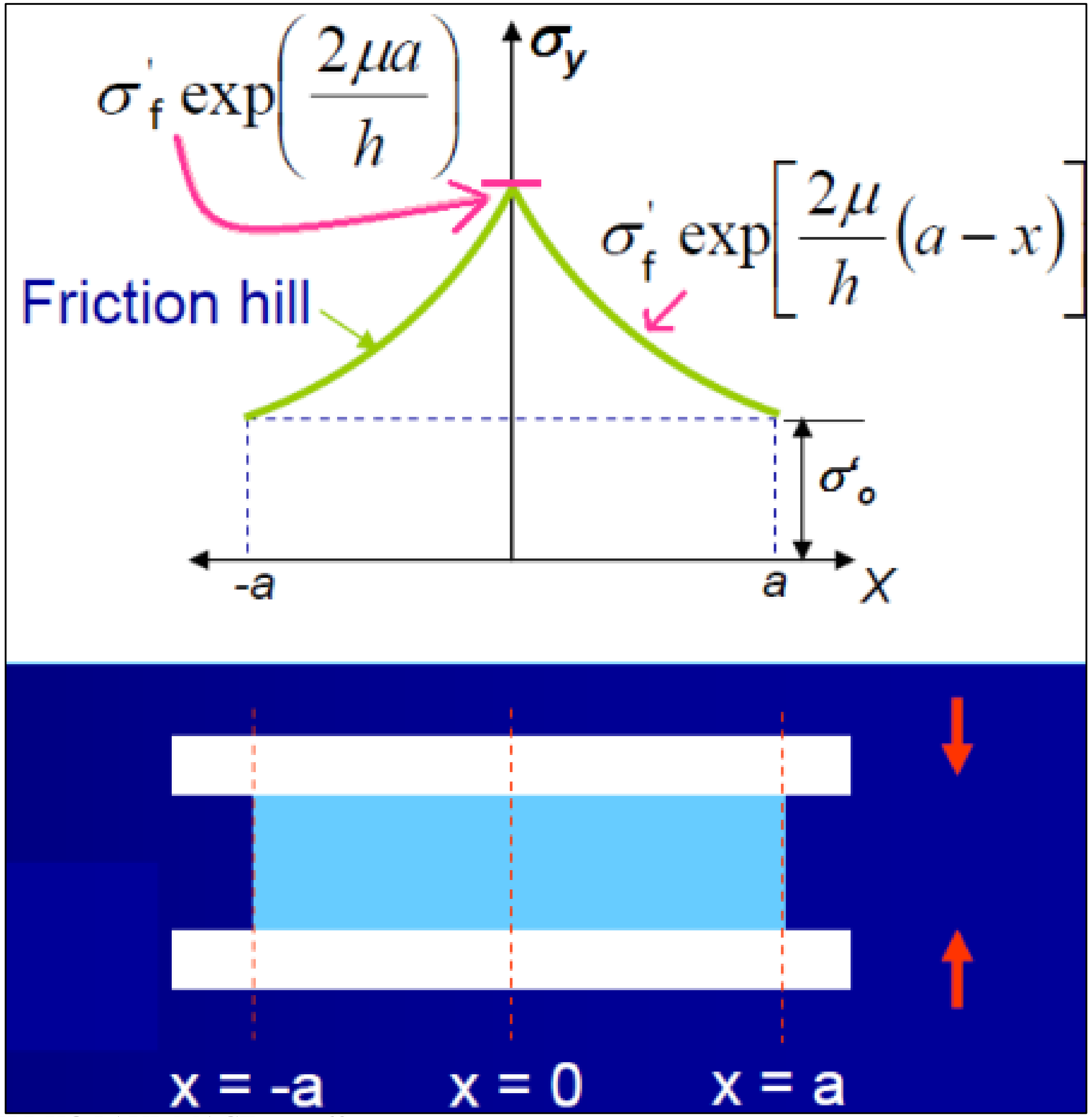




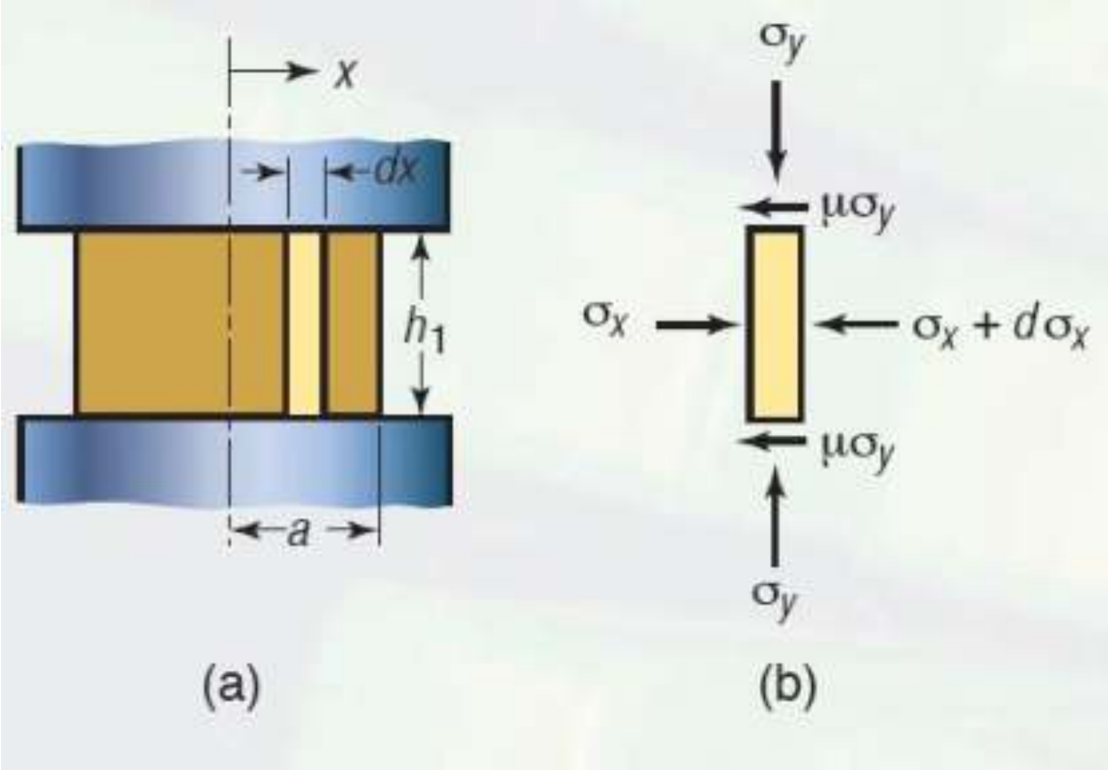
Die Pressure Distribution

- Equation (17) 1s plotted qualitatively.
- Note that the ***pressure increases exponentially toward the center*** of the part, and that it ***increases with the a/h ratio and increasing friction***.
- Because of its shape, the pressure-distribution curve in Fig. is referred to as the ***friction hill.***





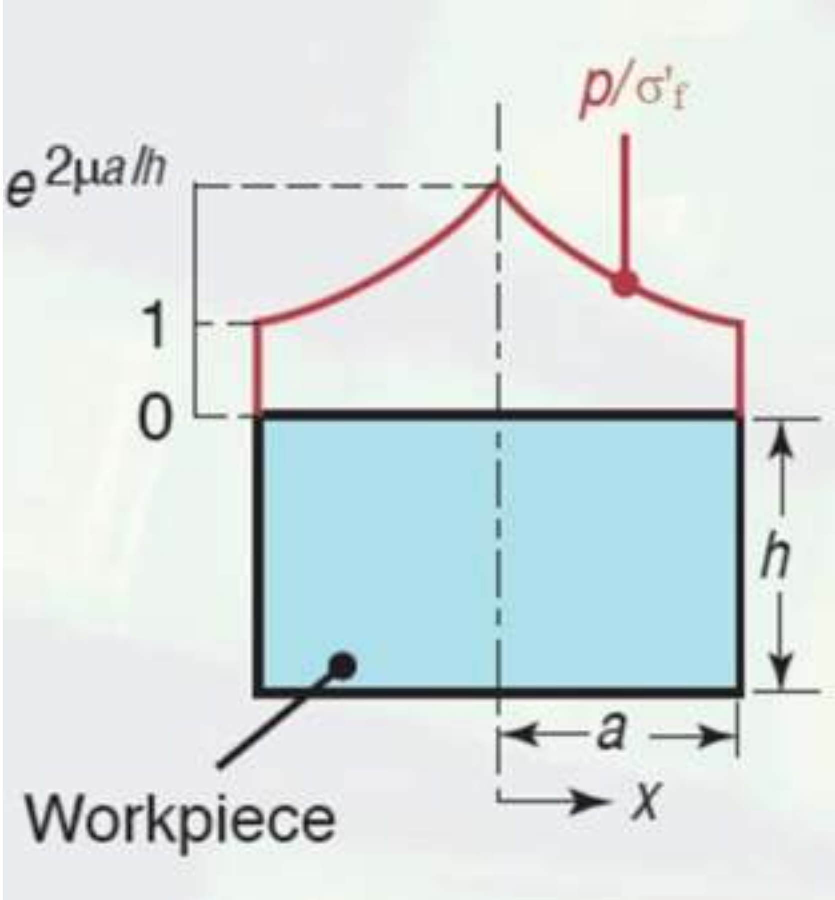
σ_y
$\sigma'_f \exp\left(\frac{2\mu a}{h}\right)$
$\sigma'_f \exp\left[\frac{2\mu}{h}(a-x)\right]$
Friction hill
σ'_o
-a
a
X
x = -a
x = 0
x = a



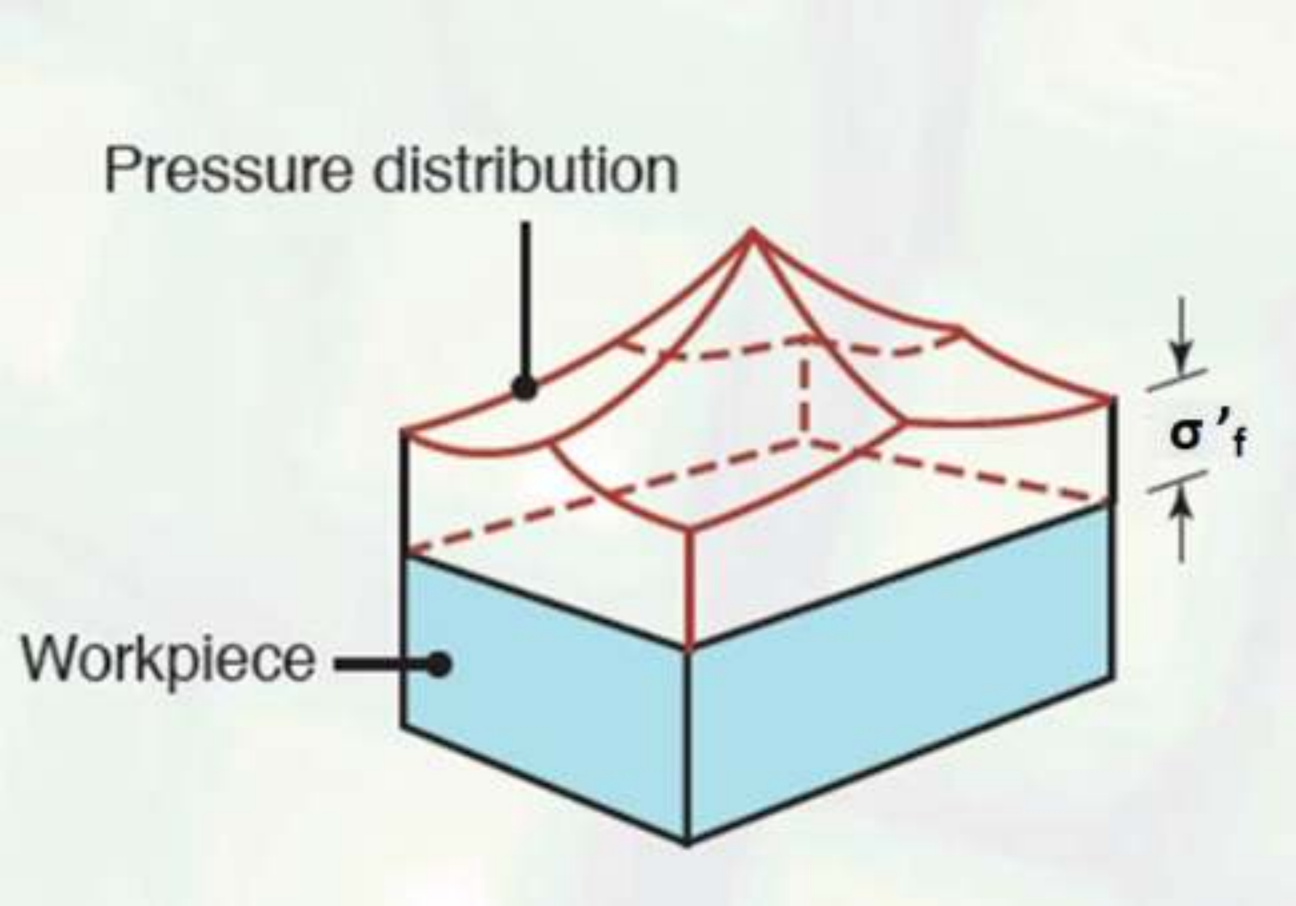
x
dx
h_1
a
(a)
σ_y
$\mu\sigma_y$
σ_x
$\sigma_x + d\sigma_x$
$\mu\sigma_y$
σ_y
(b)

Die Pressure Distribution

- The ***pressure with friction is higher than it is without friction***, and, with ***thin workpieces***, significantly so. Since the work required to overcome friction must be supplied by the upsetting force, ***friction is increasingly important with high aspect ratios***.



Distribution of die pressure, in dimensionless form of p/σ_f', in plane-strain compression with ***sliding friction***. Note that the pressure at the left and right boundaries is equal to the yield stress of the material in plane strain, σ_f'. Sliding friction means that the frictional stress is directly proportional to the normal stress.



Die pressure distribution in compressing a rectangular workpiece with sliding friction and under conditions of plane stress, using the distortion-energy criterion.

Why plane stress? A rectangular specimen can be upset without being constrained on its sides

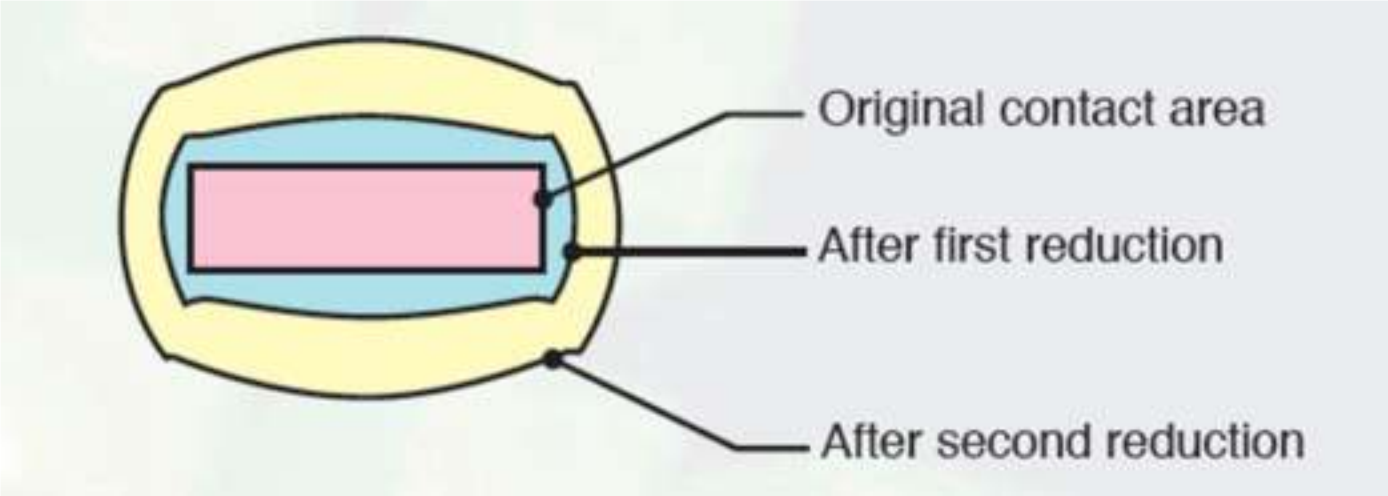


FIGURE 6.7 Increase in die workpiece contact area of an originally rectangular specimen (viewed from the top) compressed between flat dies and ***with friction***. Note that the length of the specimen (horizontal dimension) has increased proportionately less than its width (vertical dimension). Likewise, a specimen originally in the shape of a cube acquires the shape of a pancake after deformation with friction.

The reason for the significantly larger increase in width is because the ***material flows the most in the direction of least resistance*** (thus minimizing the energy dissipated). Because of its smaller magnitude, the ***width has less cumulative frictional resistance than does the length***.

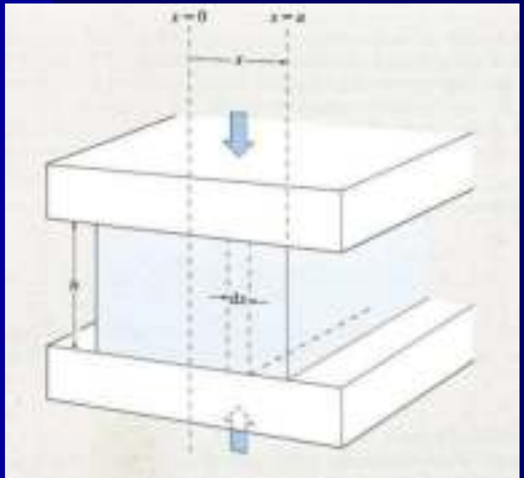
Forging Force

The total forging load, F, is given by $F = 2\bar{p}aw$ ....*Eq. 20*

Where $\bar{p}$ is the average forming pressure across the workpiece
w is the width of the workpiece (in the plane of the paper).

This equals σ_y and can be estimated by integrating *Eq.19*:

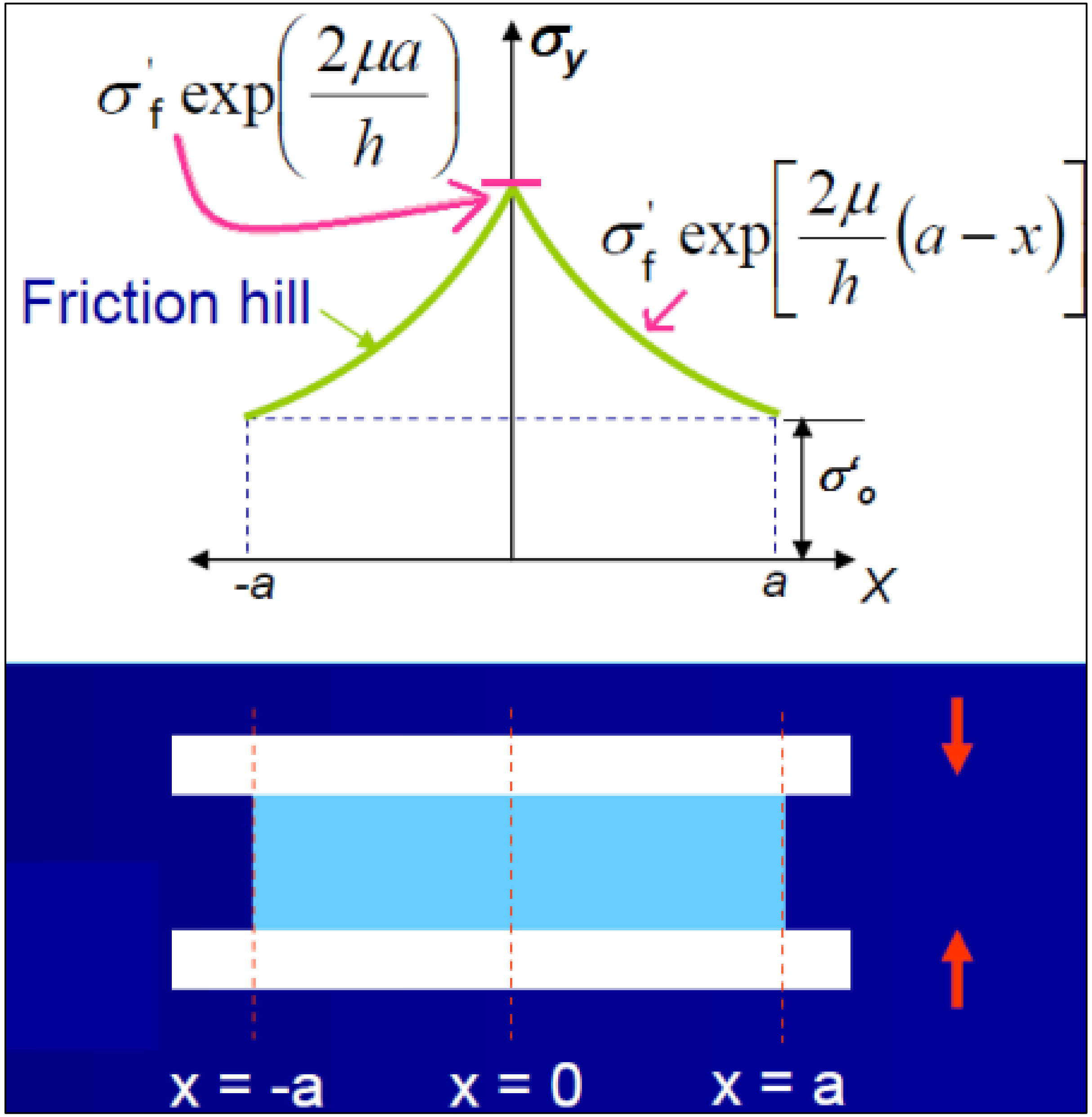
$$\bar{p} = \int_0^a \frac{\sigma_y}{a}\,dx = \int_0^a \frac{\sigma_f}{a}\exp\left[\frac{2\mu}{h}(a-x)\right]dx$$ ....*Eq. 21*



The general series expansion for ***exp x*** is

$$\exp x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \ldots$$ ....*Eq. 22*

Since μ is usually small (<1) we can approximate ***exp x*** as ***(1+x)*** for small ***x***.


σ_y
$\sigma'_f \exp\left(\frac{2\mu a}{h}\right)$
$\sigma'_f \exp\left[\frac{2\mu}{h}(a-x)\right]$
Friction hill
σ'_o
-a
a
X
x = -a
x = 0
x = a

Thus we can approximate *Eq.19* as

$$\sigma_y = \sigma_f'\left[1+\frac{2\mu(a-x)}{h}\right] \quad \text{....Eq. 23}$$

and *Eq.21* becomes

$$\bar{p} = \int_0^a \frac{\sigma_f'}{a}\left[1+\frac{2\mu(a-x)}{h}\right]dx \quad \text{....Eq. 24}$$

Integrating this gives:

$$\bar{p} = \frac{\sigma_f'}{a}\left[x+\frac{2\mu a x}{h}-\frac{\mu x^2}{h}\right]_0^a \quad \text{....Eq. 25}$$

So that the average axial tooling pressure, $\bar{p}$, is

$$\bar{p} = \sigma_f'\left(1+\frac{\mu a}{h}\right) \quad \text{....Eq. 26}$$

We can see that as the ratio ***a/h*** increases, the forming pressure $\bar{p}$ and hence the forming load rises rapidly.

- For a rectangular work piece under plain strain

Forging average pressure (P_{av}) required is

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$$\bar{p} = \sigma_f' \left(1 + \frac{\mu a}{h}\right) \qquad \text{eq.26}$$

imp

Where $\sigma'_f = \sigma_x - \sigma_y = \frac{2}{\sqrt{3}} \sigma_f$

σ'_f is the *flow stress in plane strain and*

σ_f *is the uniaxial flow stress,*

μ frictional coefficient

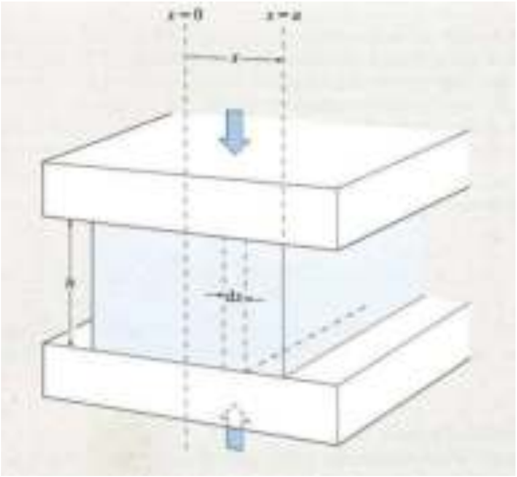
h instantaneous height of work piece

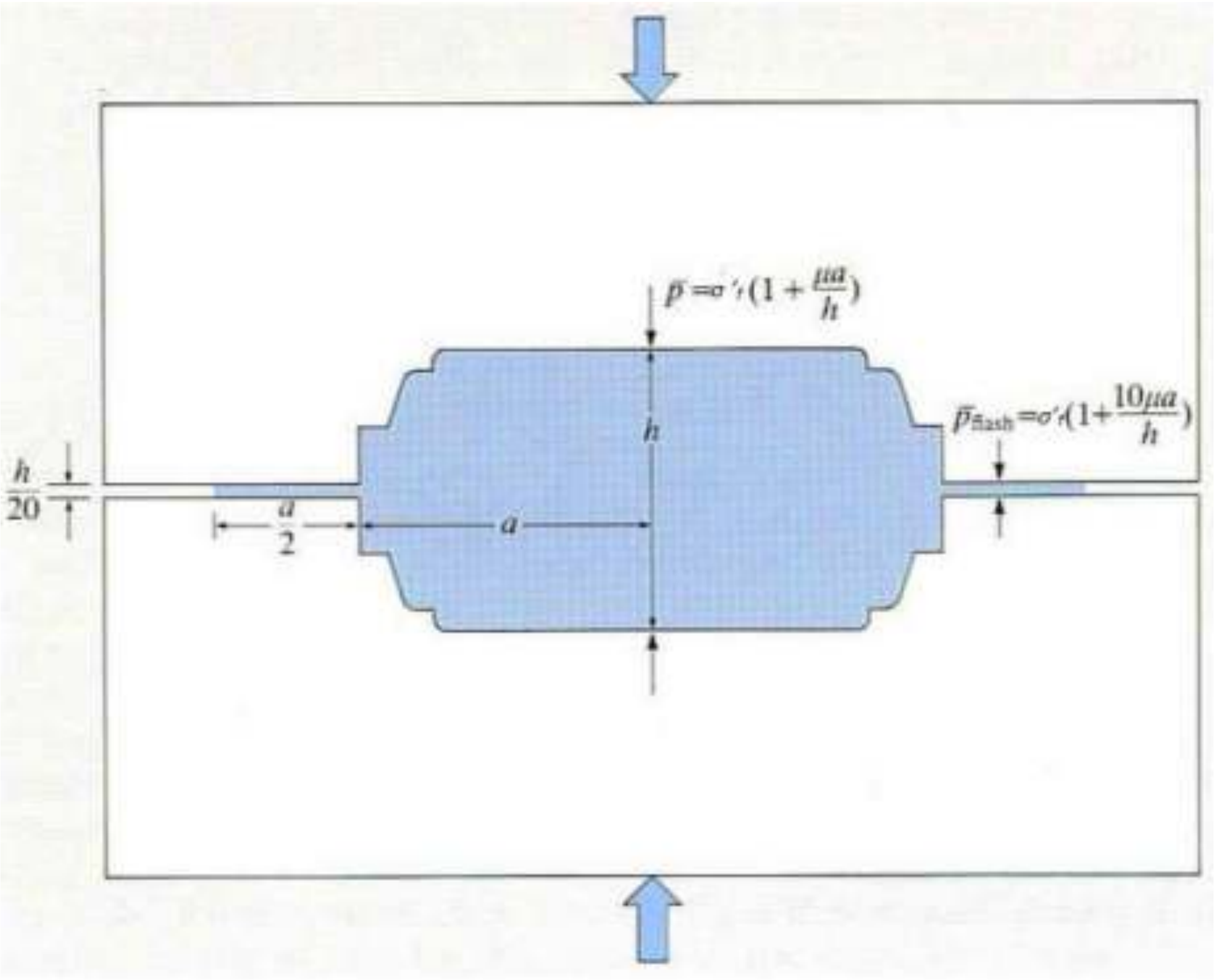
2a width

So forging force is,

$$F = P_{av} \times 2a \times \text{width} \qquad \text{eq.20}$$

$$F = \sigma_f' \left(1 + \frac{\mu a}{h}\right) \times 2a \times \text{width}$$





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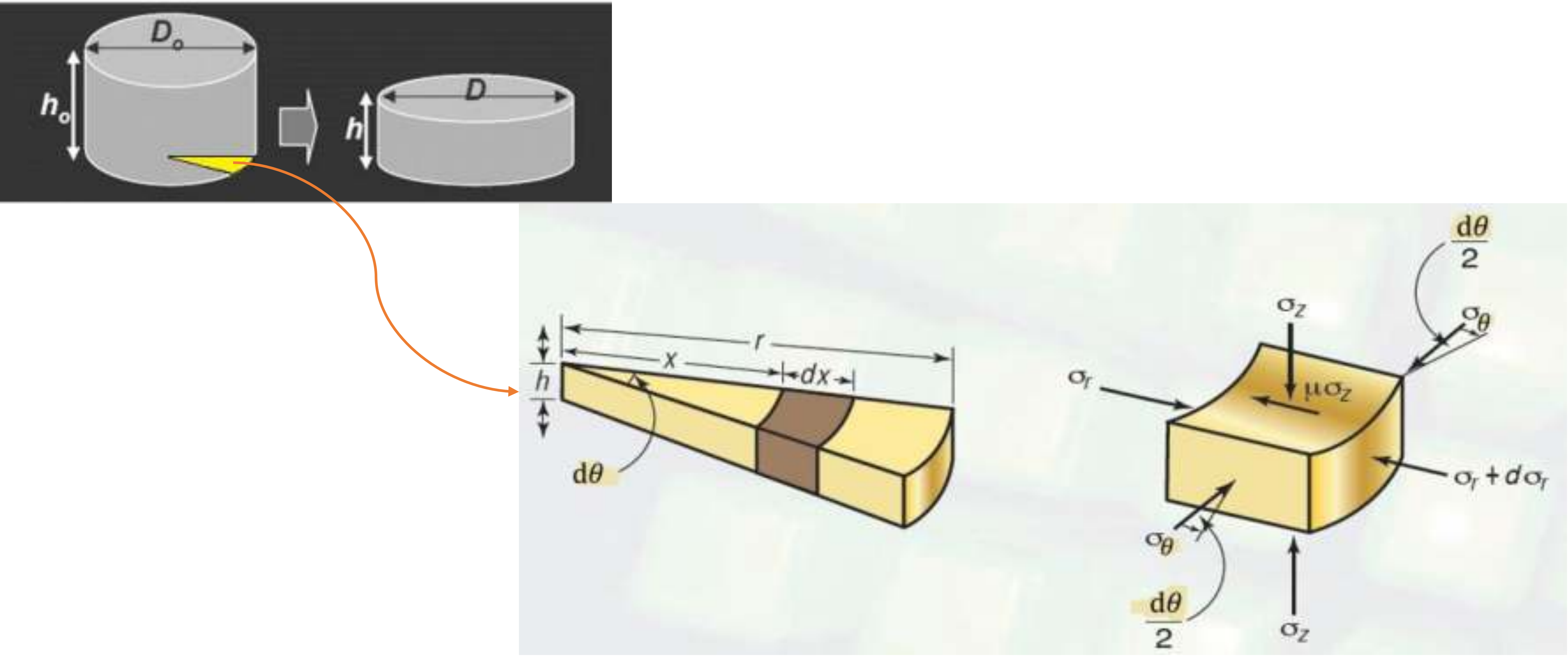
- The flash has high deformation resistance than in the die (due to much ***higher a/h ratio***), therefore the material ***completely fills*** the cavity rather than being extruded sideward out of the die.

Slab method for Solid cylindrical work piece



Stresses on an element in forging of a solid cylindrical workpiece between flat dies and with friction.

- Here determine the pressure distribution in forging of a solid cylindrical specimen.
- First isolate a segment of angle dθ in a cylinder of radius r and height h.
- Take a small element of radial length dx, and place on this element .
- All normal and frictional stresses acting on it.
- Follow the similar approach of plane strain case in slab method.
- We obtain the expression for the pressure p, at any radius x as.

The pressure P at any section is,

$$\sigma_y = p = \sigma_f \, e^{2\mu(r-x)/h} \qquad \text{eq.27}$$

The average pressure P_{av} is,

$$p_{av} \simeq \sigma_f \left(1 + \frac{2\mu r}{3h}\right) \qquad \text{eq.28}$$

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The forging force F is,

$$F = (p_{av})(\pi r^2) \qquad \text{eq.29}$$

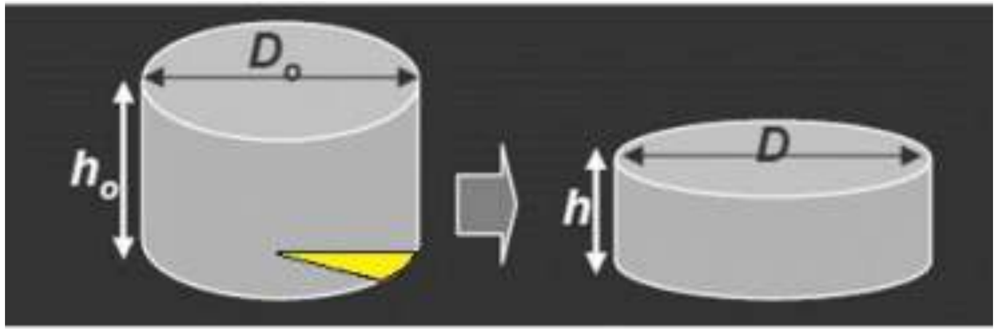
Where

σ_f *Is the uniaxial flow stress (For perfectly plastic material σ_f is replace with Yield stress (σ_y)*

μ Frictional coefficient

h Instantaneous height of work piece

r Radius



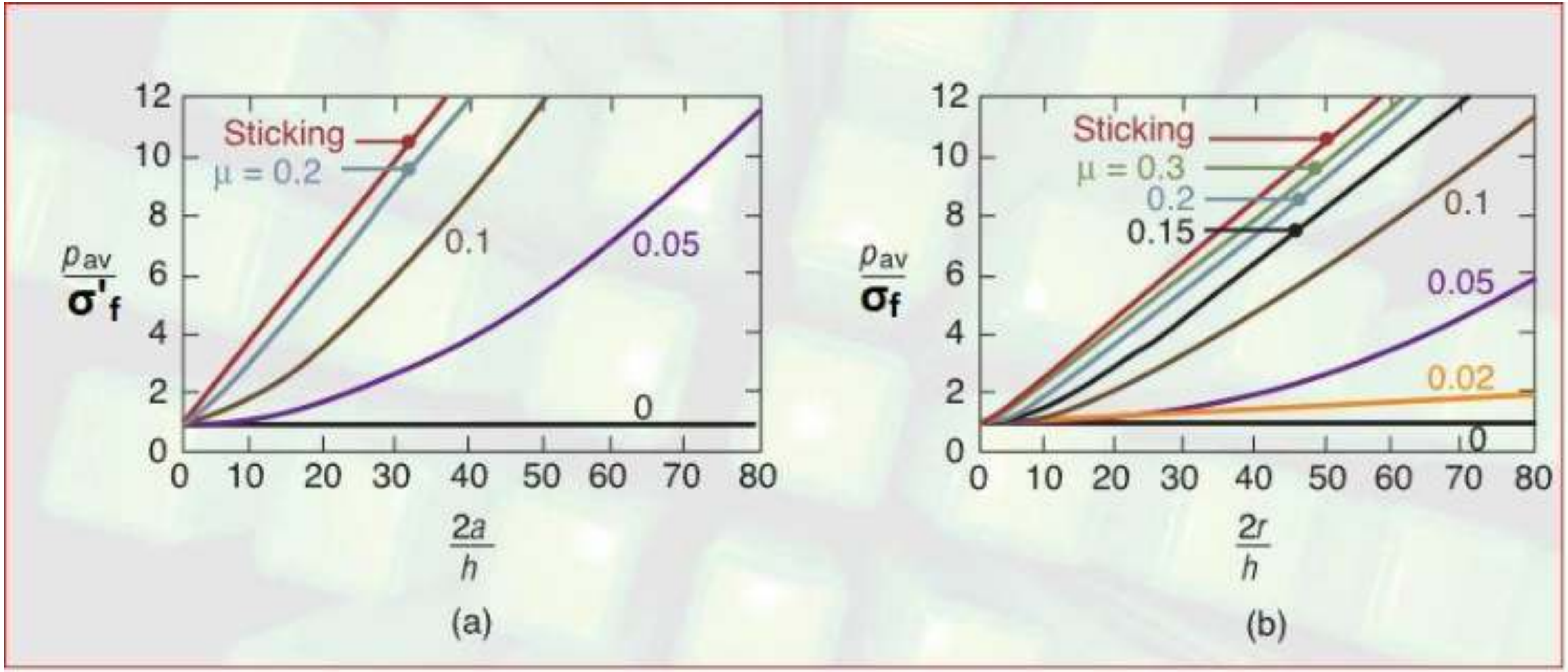


FIGURE 6.9 Ratio of average die pressure to yield stress as a function of friction and aspect ratio of the specimen: (a) plane- strain compression; and (b) compression of a solid cylindrical specimen. **Note that the yield stress in (b) is σ_f, and not σ_f' as it is in the plane-strain compression shown in** (a).

μ value between 0.05 and 0.1 for cold forging

0.1 to 0.2 in hot forging

- **3 factors** which affect the forging force in upsetting of rectangular or solid cylindrical workpiece are,

- **Friction (or coefficient of friction μ).**
- **Aspect ration or (a/h or r/h) ratio of the specimen.**
- **Flow stress of the material (σ_f)**

- These curves show the significance of friction and the aspect ratio of the specimen on upsetting pressure.

3.Forging under sticking condition

- The product of μ and σ_y is the frictional stress (surface shear stress) at the interface at an location x from the centre of the specimen.
- As the σ_y increase towards the center, $\mu\sigma_y$ also increase. However the value of $\mu\sigma_y$ cannot be grater than the shear yield stress (k) of the material.

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- When $\mu\sigma_y$ =k sticking take place.

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- In plane strain case value of k is **(σ_f' /2)**
- Sticking does not necessary mean adhesion at the interface.
- It reflect the fact that, relative to the platen surface, the material does not move.

Normal stress (pressure) distribution under sticking condition

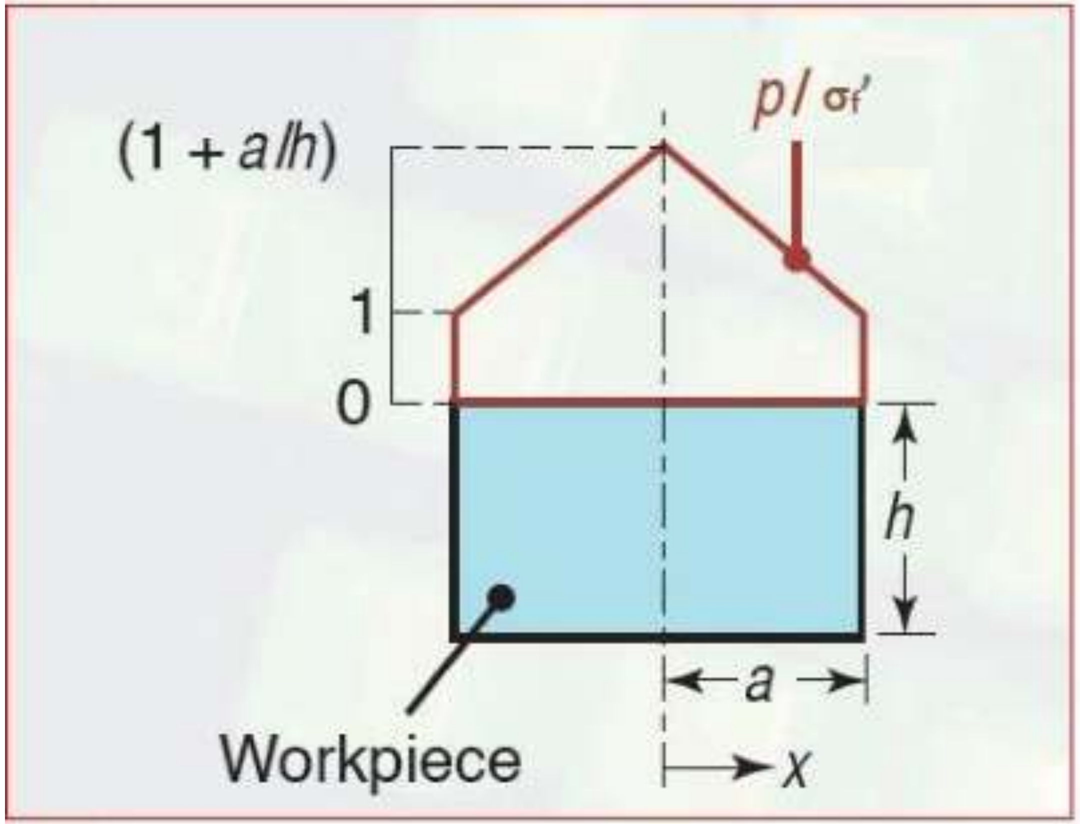
Results for sticking friction in plane strain:

$$p = \sigma'_f \left(1 + \frac{a - x}{h}\right)$$

Results for sticking friction with cylinder:

$$p = \sigma_f \left(1 + \frac{r - x}{h}\right)$$

Rectangular work piece in plane strain & under sticking condition

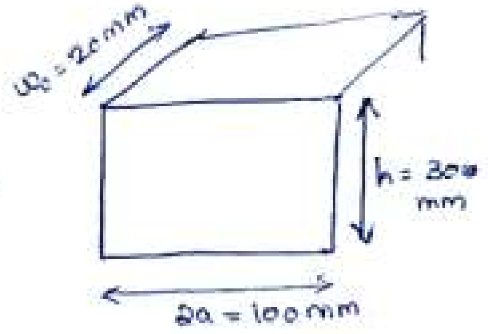


Distribution of dimensionless die pressure, **p / σ_f'**, in compressing a rectangular specimen in plane strain and under sticking conditions. Sticking means that the frictional (shear) stress at the interface has reached the shear yield stress of the material. Note that the pressure at the edges is the uniaxial yield stress of the material in plane strain, **σ_f'**.

Problems

- Average pressure require for rectangular work piece?
- Forging force require for rectangular work piece?
- Average pressure require for cylindrical work piece?
- Forging force require for cylindrical work piece?
- Normal stress or pressure acting on rectangular work piece under sticking condition?
- Normal stress or pressure acting on cylindrical work piece under sticking condition?

- A rectangular workpiece has the following original dimensions: 2a = 100 mm, h = 30 mm and width = 20 mm. The metal has a strength coefficient of 400 MPa and a strain hardening exponent of 0.3. It is being forged in plane strain with μ = 0.2. Calculate the force required at a reduction of 20%.



- K = 400 mpa
- n = 0.3
- Plain strain Problem → (width will not vary)

  So $\sigma_F' = \frac{2}{\sqrt{3}} \sigma_F$ —— eq. 13
- μ = 0.2
- % of Reduction = 20%
- Reduction in highd = $30 \times \frac{20}{100} = 6$

  Final height = 30 − 6 = 24
- True strain $\varepsilon = \ln\left(\frac{30}{24}\right) = 0.223$ —— eq. 8
- Material is a strain hardened material so, —eq. 10
- Flow stress $\sigma_F = K\varepsilon^n = 400 \times 0.223^{0.3} = 255$ mpa
- Flow stress in Plain strain

  $\sigma_F' = \frac{2}{\sqrt{3}} \times \sigma_F = 294$ mPa

- New final dimension a_1 calculated from volume constancy

Volume before forging = Volume after forging

$$100 \times 30 \times 20 = 2a_1 \times 24 \times 20$$

$$a_1 \doteq 62.5 \text{ mm.}$$

$$\text{Force Required} = P_{average} \times 2a_1 \times \text{width} \quad \text{— eq. 20}$$

where

$$P_{average} = \sigma_f' \left(1 + \frac{\mu a}{h}\right) \quad \text{— eq. 26}$$

$$= 294\left(1 + \frac{0.2 \times 0.0625}{0.024}\right)$$

$$\doteq 447 \text{ MPa}$$

$$\text{Force} = 447 \times 2 \times 0.0625 \times 0.02$$

$$= \underline{1.11 \text{ MN}}$$

Given: A cylindrical specimen made of annealed 4135 steel has a diameter of 150 mm and is 100 mm high. It is upset, at room temperature, by open-die forging with flat dies to a height of 50 mm.

Find: Assuming that the coefficient of friction is 0.2, calculate the upsetting force required at the end of the stroke. Use the average-pressure formula.

Solution: The average-pressure formula, from Eq. (6.18), is given by

$$p_{av} \simeq \sigma_f \left(1 + \frac{2\mu r}{3h}\right),$$

where S_y is replaced by σ_f because the workpiece material is strain hardening. From Table 2.2, $K = 1015$ MPa and $n = 0.17$. The absolute value of the true strain is

$$\epsilon_1 = \ln\left(\frac{100}{50}\right) = 0.693,$$

and therefore,

$$\sigma_f = K\epsilon_1^n = (1015)(0.693)^{0.17} = 953.6 \text{ MPa}.$$

The final height of the specimen, h_1, is 50 mm. The radius r at the end of the stroke is found from volume constancy:

$$\left(\frac{\pi 150^2}{4}\right) 100 = \left(\pi r_1^2\right)(50) \quad \text{and} \quad r_1 = 106.1 \text{ mm}.$$

Thus,

$$p_{av} \simeq 953.6\left[1 + \frac{(2)(0.2)(106.1)}{(3)(50)}\right] = 1223 \text{ MPa}.$$

The upsetting force is

$$F = \pi(1223)(0.1061)^2 = 43.25 \text{ MN}.$$

Note that Fig. 6.9b can also be used to solve this problem.

- Estimate the force required to upset a 5mm diameter C74500 brass rivet in order to form 10 mm diameter head. Assume that the coefficient of friction between the brass and the tool-steel die is 0.25 and that the rivet head is 5mm in thickness. Use σ_f = 175 MPa.

$$p_{av} \simeq \sigma_f \left(1 + \frac{2\mu r}{3h}\right)$$

$$F = (p_{av})\left(\pi r^2\right)$$

Deformation zone geometry

- In a simple frictionless compression test with flat die, the top and bottom surfaces of the specimen are always in contact with the dies, and the specimen deform uniformly.
- $\frac{h}{L}$ **is the importent parameter in** determining the inhomogeneity of deformation or deformation zone geometry.
- Here we use **frictionless nature** that is important.
- Because if there is friction it will affects the forces particularly at low value of $\frac{h}{L}$
- Deformation zone geometry depends on the particular process and such parameters as die geometry and percent reduction of the material.

- Deformation zone and pressure required shown in the figure.
- Die pressure required in **frictionless plane strain** conditions for a variety of metalworking operations. The geometric relationship between contact area of the dies and workpiece dimensions is an important factor in predicting forces in plastic deformation of materials
- The larger the $\frac{h}{L}$ ratio the higher the die pressure becomes.

▪ But in actual case If smaller this ratio the greater is the ***effect of friction at the die-workpiece interface.***

▪ The reason is that contact area, and hence friction increase with a decreasing $\frac{h}{L}$ ratio.

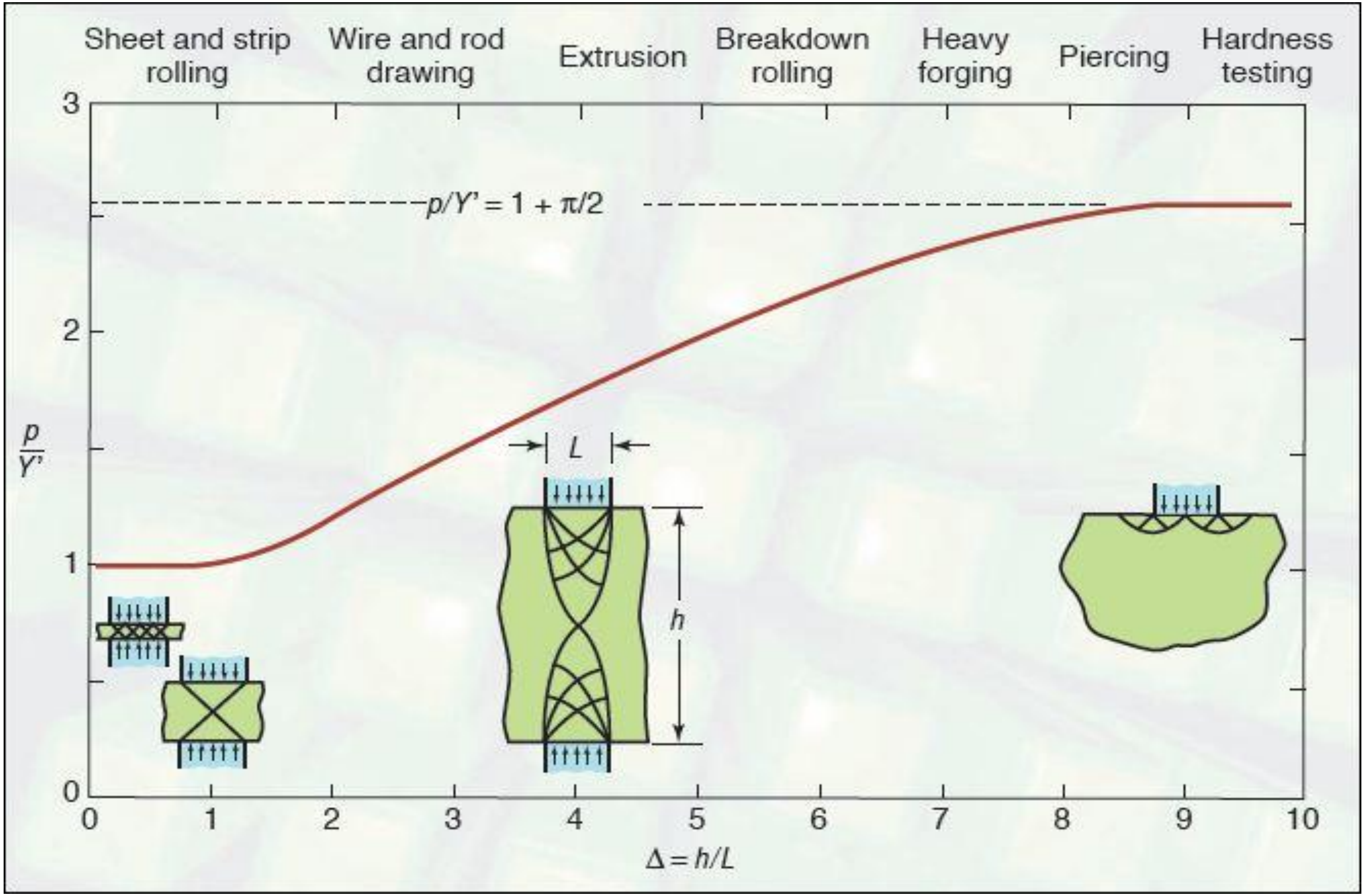

Sheet and strip rolling
Wire and rod drawing
Extrusion
Breakdown rolling
Heavy forging
Piercing
Hardness testing
p/Y' = 1 + π/2
p/Y'
L
h
Δ = h/L
0
1
2
3
4
5
6
7
8
9
10

FIGURE 2.27 Bulk deformation in mild steel under a spherical indenter. Note that the depth of the deformed zone is about one order of magnitude larger than the depth of indentation. For a hardness test to be valid, the material should be allowed to fully develop this zone. This is why thinner specimens require smaller indentations. *Source:* Courtesy of M.C. Shaw and C.T. Yang.

If we assume that the volume under the indenter is a column of material, it would exhibit a uniaxial compressive yield stress, Y. However, the volume being deformed under the indenter is, in reality, surrounded by a rigid mass. The surrounding mass prevents this volume of material from deforming freely. In fact, this volume is under triaxial compression. This material requires a normal compressive yield stress that is higher than the uniaxial yield stress of the material.

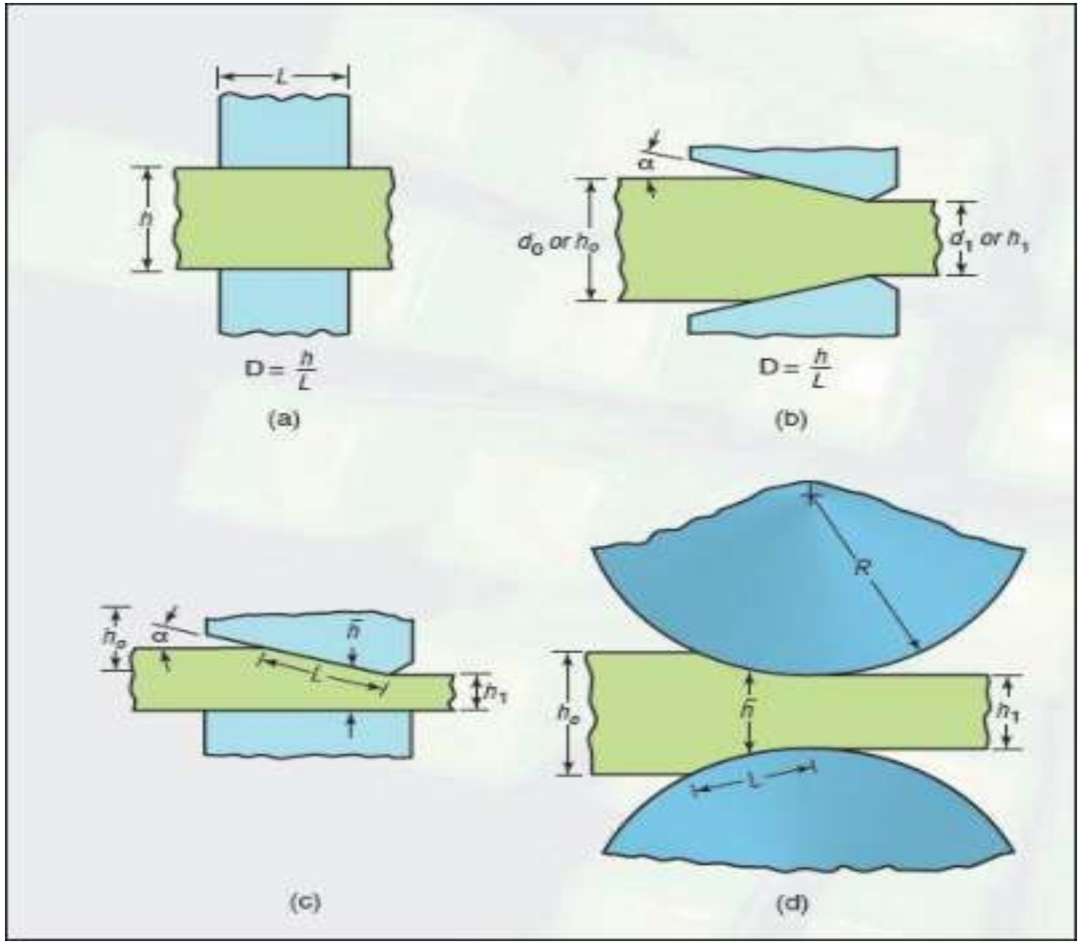
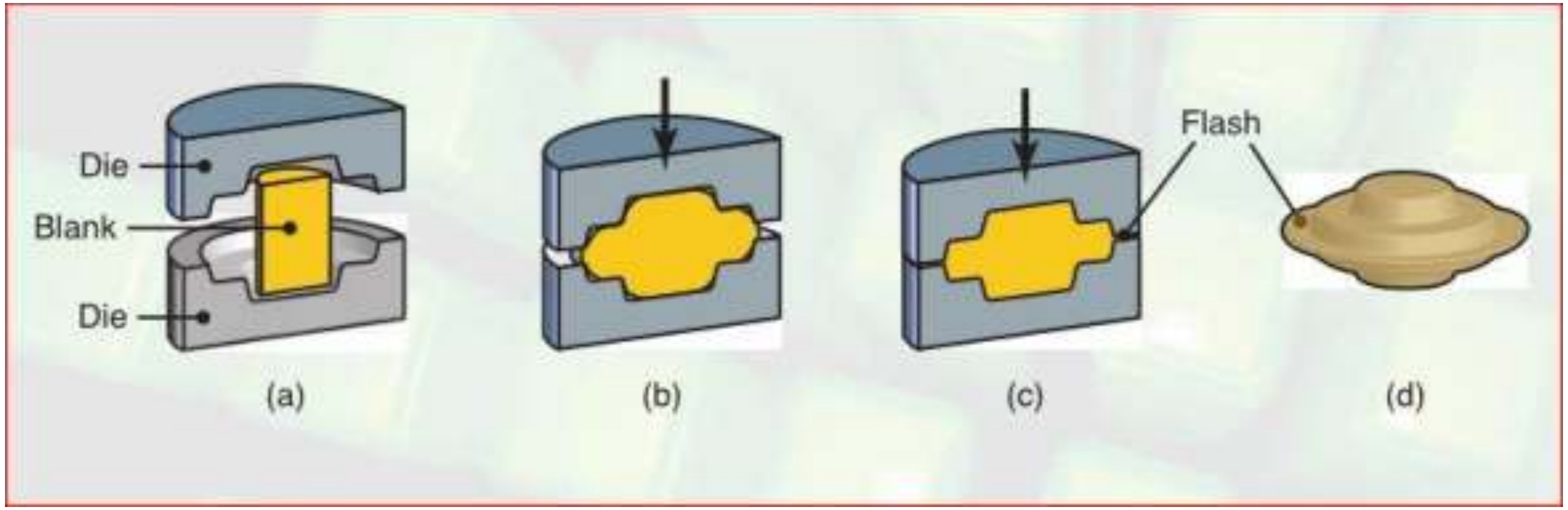


FIGURE 6.13 Examples of plastic deformation processes in plane strain, showing the *h*/*L* ratio. (a) Indenting with flat dies, an operation similar to the cogging process, as shown in Fig. 6.19. (b) Drawing or extrusion of a strip with a wedge-shaped die, as described in Sections 6.4 and 6.5. (c) Ironing; see also 7.53. (d) Rolling, described in Section 6.3.

Impression die forging



Schematic illustrations of stages in impression-die forging. Note the formation of a flash, or excess material that subsequently has to be trimmed off.

- In impression die forging, the workpiece acquires the shape of the die cavities (impression) while it is being upset between the closing dies.
- Some of the material flows radially outward and forms a ***FLASH.***
- Because of its high length to thickness ratio ($\frac{a}{h}$ ratio) the flashes subjected to high pressure, which in turn signifies high frictional resistance to material flow in the radial direction in the flash gap.
- Since high friction encourages the filling of the die cavities.
- In case of forging at elevated temperature flashes will cool or strengthen than the bulk of the workpiece.
- So ***flashes resist deformation more than the bulk*** does and helps fill the die cavities.

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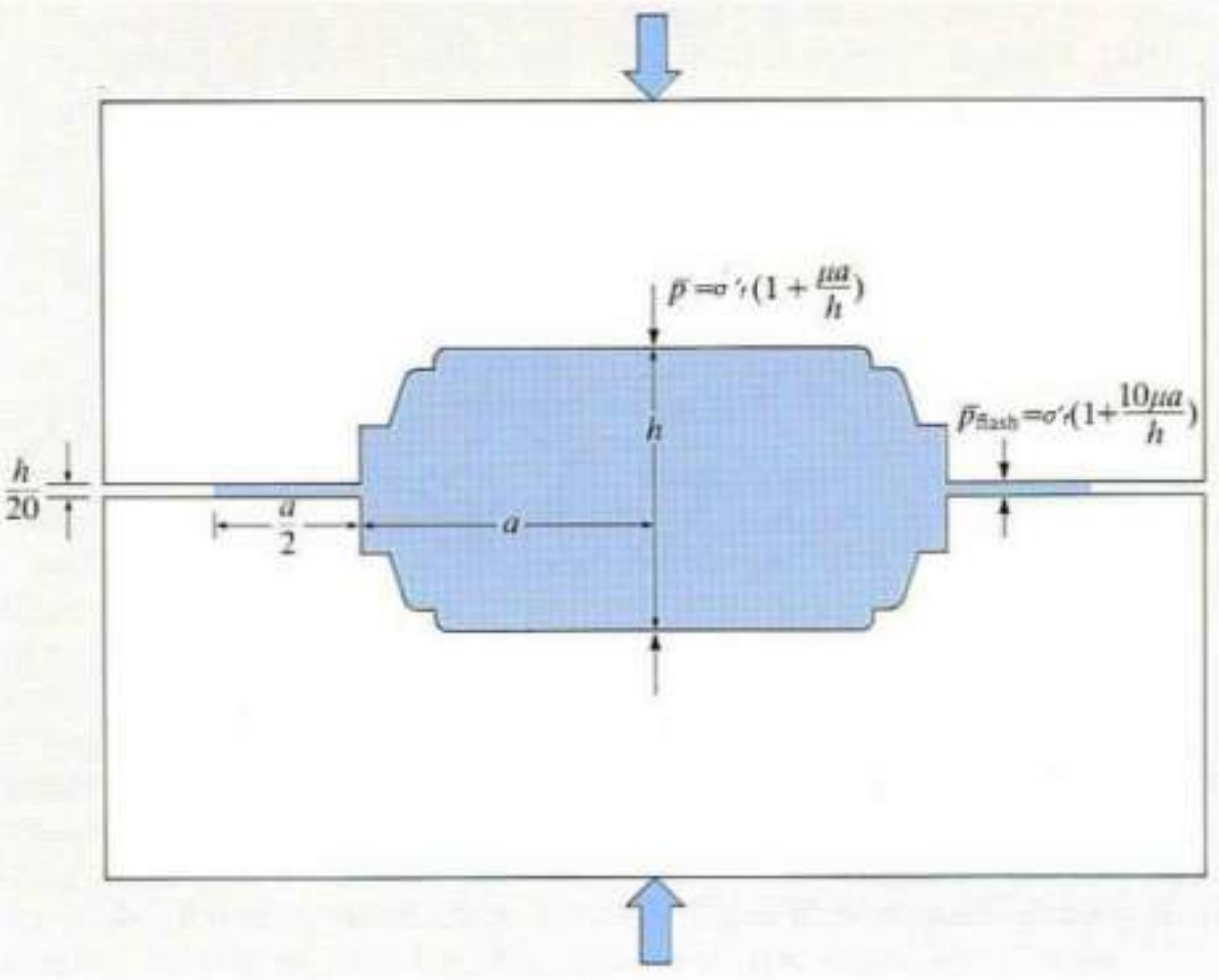


- The flash has high deformation resistance than in the die (due to much ***higher a/h ratio***), therefore the material ***completely fills*** the cavity rather than being extruded sideward out of the die.

Impression-Die Forging

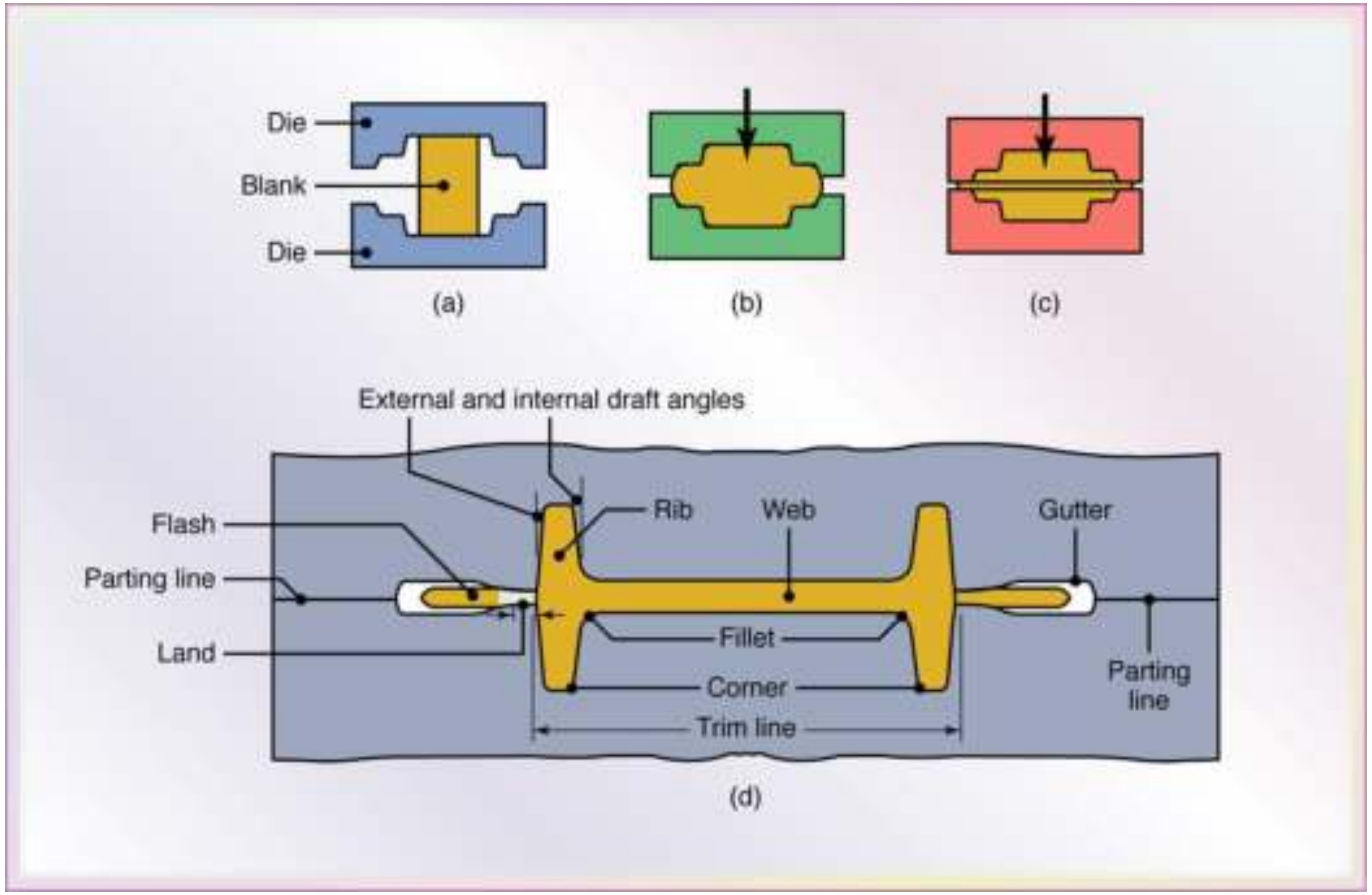


Figure (a) through (c) Stages in impression-die forging of a solid round billet. Note the formation of flash, which is excess metal that is subsequently trimmed off (d) Standard terminology for various features of a forging die.

- Because of complex shape involved, accurate calculation of forces in impression die forging is difficult.
- So we use a pressure multiplying factors K_P have been recommended. Shown in table.

Forging force:

$$F = K_p \sigma_f A$$

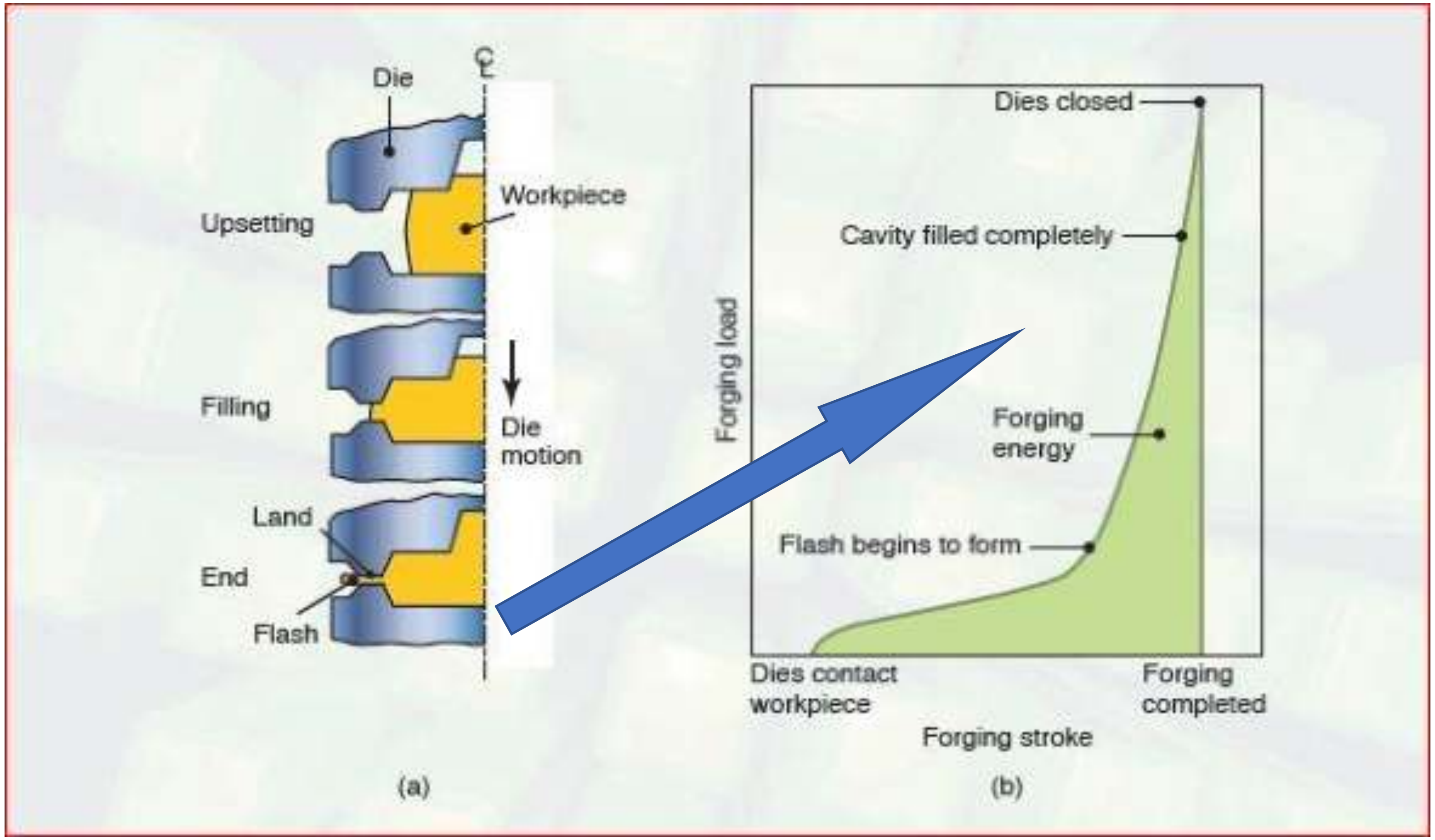
TABLE 6.2 Range of K_p values in Eq. (6.22) for impression-die forging.

Simple shapes, without flash	3-5
Simple shapes, with flash	5-8
Complex shapes, with flash	8-12

- F → Forging force.
- A → Projected area of forging including flashes.
- σ_f → Flow stress of the material at the strain material, strain rate and temperature to which the material is subjected.

Load-Stroke Curve in impression die forging

- Force increases gradually as the cavity is filled.
- The force then increases rapidly as flash forms.
- When die close further steeper rise in the forging load.



Close die forging

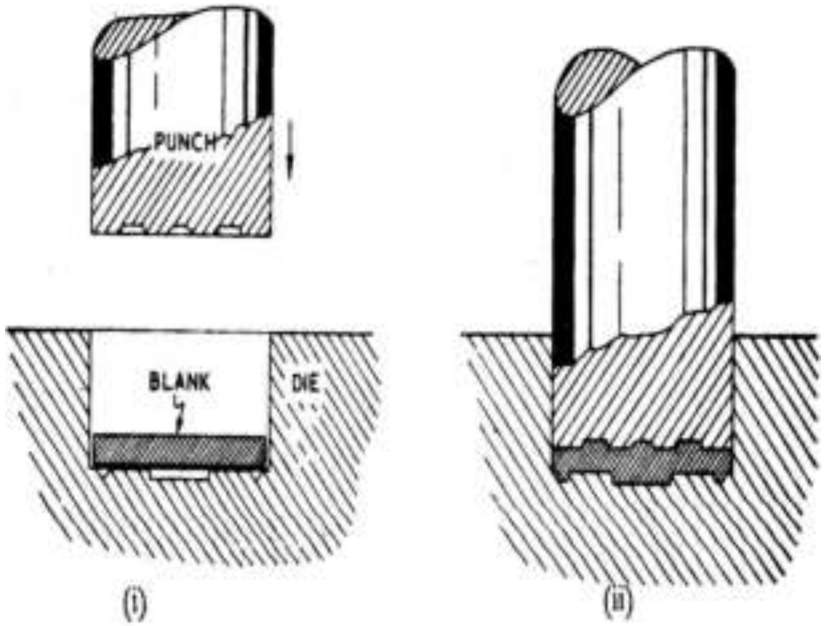
- In true closed die forging, no flash is formed and work piece is completely surrounded by the dies,
- While in impression die forging any excess metal in the die cavity is formed into the **flash**.
- Proper control of the volume of material is essential to obtain a forging of desired dimensions.
- Undersized blanks will ***prevent the complete filling*** of the die cavity, and oversized blanks may cause ***premature die failure or jamming.***

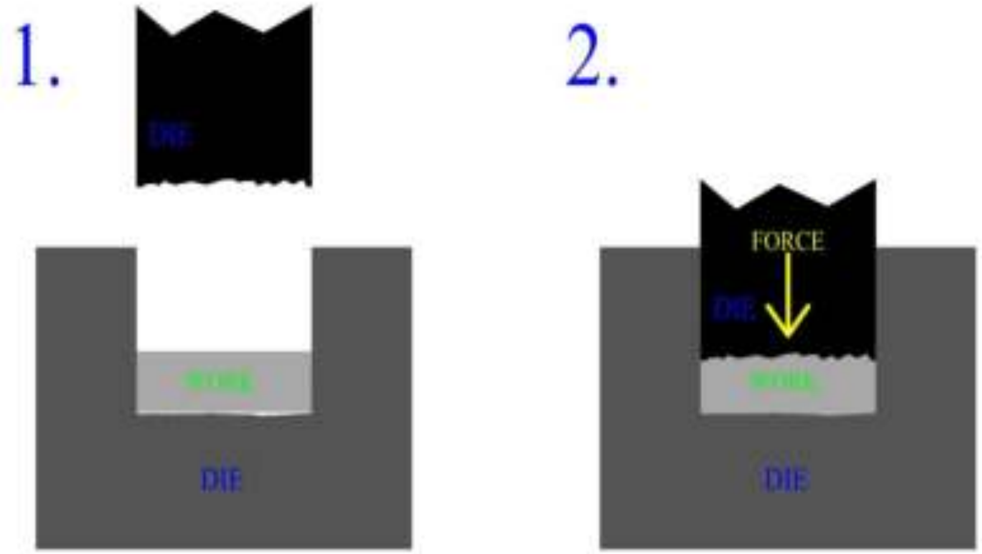
Miscellaneous forging operations

1. Coining
2. Roll forging
3. Skew rolling

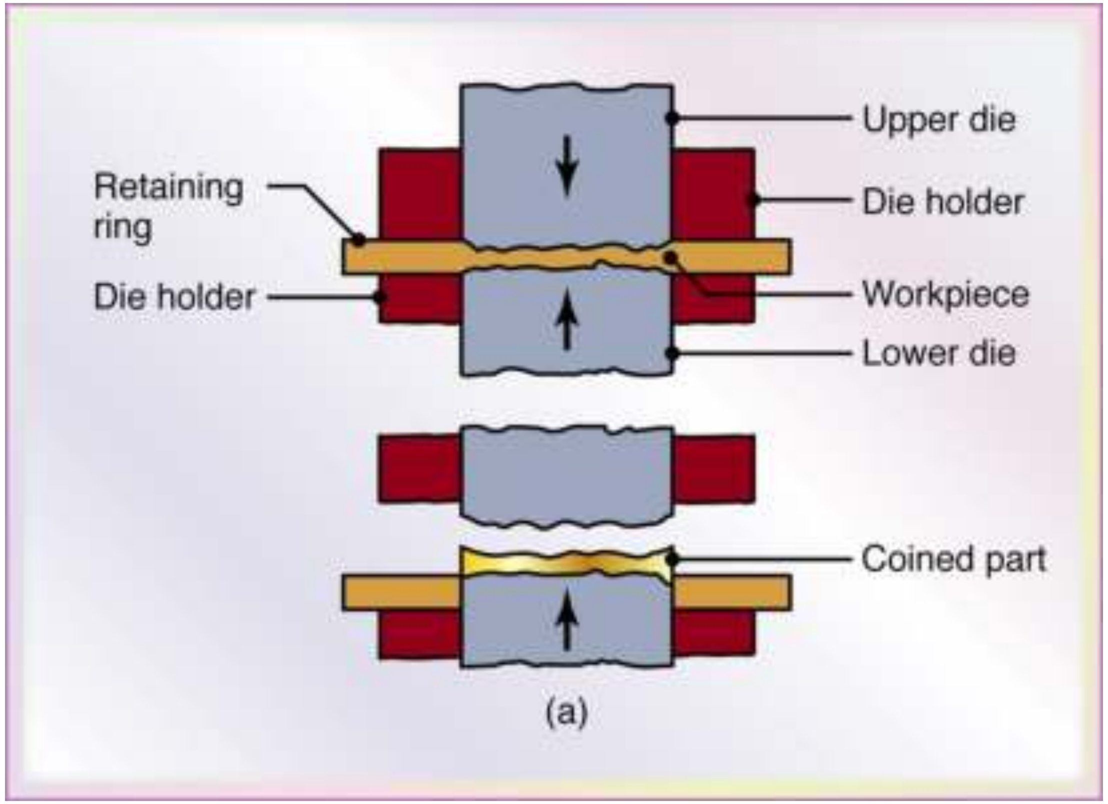
1.Coining

- Example of ***closed die forging***.
- Minting of coins.
- The pressure required can be as great as ***five to six times the flow stress*** of the material in order to produce the ***fine details*** of a coin.
- The pressure large and usually very little change in shape take place.
- ***Several coining operations*** may be necessary in order to obtain full details on some parts.
- ***Lubricants cannot be tolerated in coining***, because they can be trapped in die cavities and ***prevent reproduction of fine die surface details.***





- Coining operation is to force the impressions on the die to the surface of the metal
- Make use of blank sheet metal
- Make use of Closed Dies



(b)

Figure 14.10 (a) Schematic illustration of the coining process. The earliest coins were made by open-die forging and lacked precision and sharp details. (b) An example of a modern coining operation, showing the workpiece and tooling. Note the detail and superior finish that can be achieve in this process. *Source*: Courtesy of C & W Steel Stamp Co., Inc.

2.Roll-Forging

- The cross sectional area of a bar is reduced and altered in shape by passing it through a **pair of rolls with grooves of various shapes.**
- This operation may also be used to produce a part that is basically the final product, such as tapered leaf spring, table knives, and numerous tools.
- Roll forging is also used as a preliminary forming operation followed by other forging processes.
- Products made by this method include
  - **Crankshaft**
  - **Other automotive components**

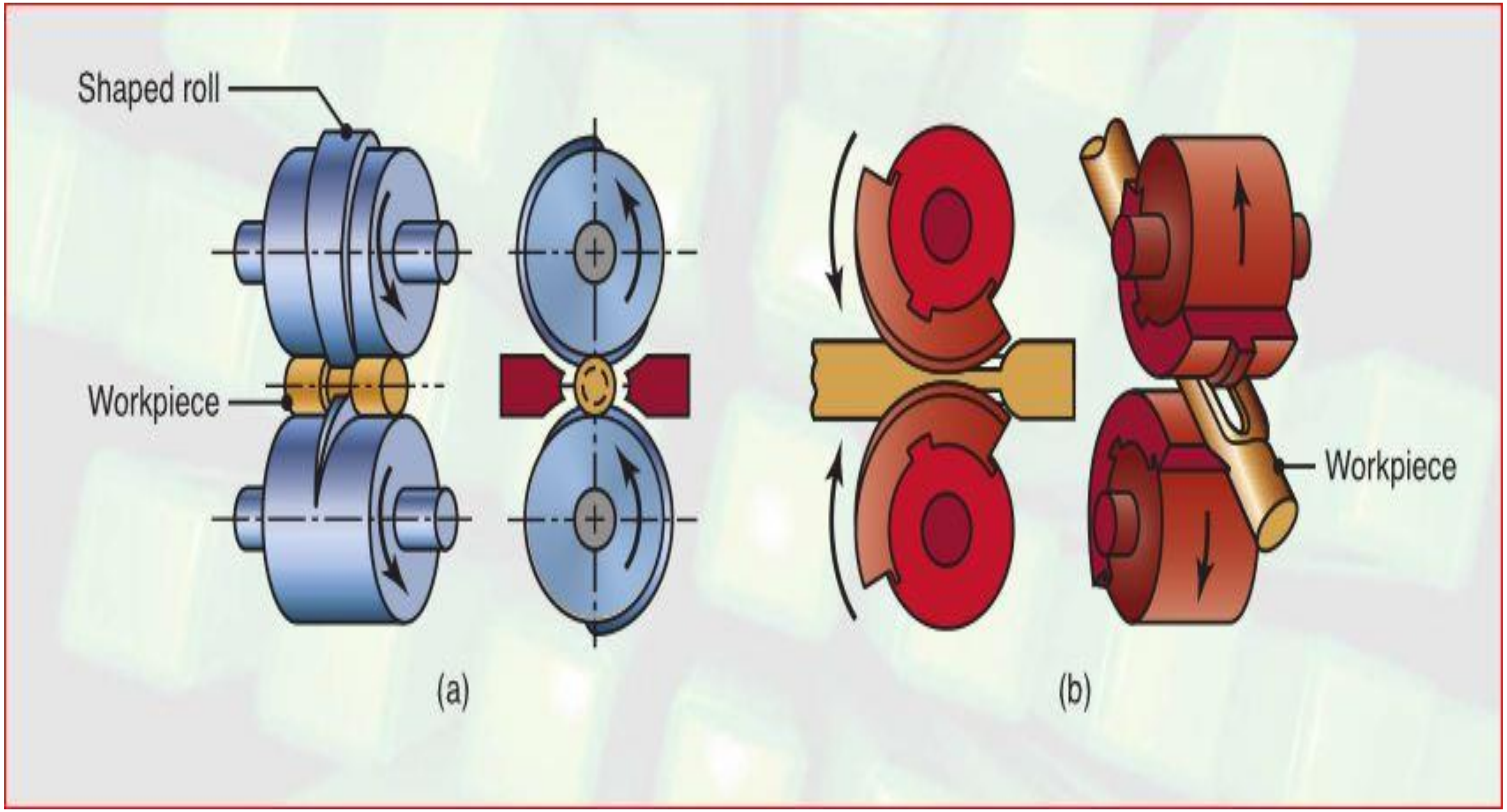


Figure 06.20 Two examples of the roll-forging operation, also known as *cross-rolling.* Tapered leaf springs and knives can be made by this process.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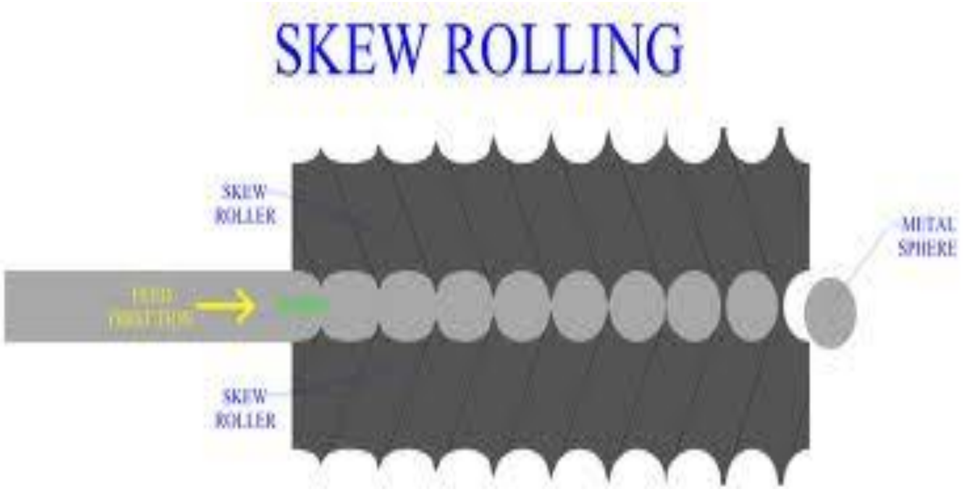
3.Skew rolling

- A process similar to roll forging is skew rolling.
- Which is used for making **ball bearing.**
- Round wire or rod stock is fed into the roll gap, and spherical blanks are formed continuously by the ***rotating rolls.***
- Another method of forming blanks for ball bearings is by cutting pieces from a round bar and upsetting them.
- The balls are then ground and polished in spherical machinery.



Production of Steel Balls by skew rolling

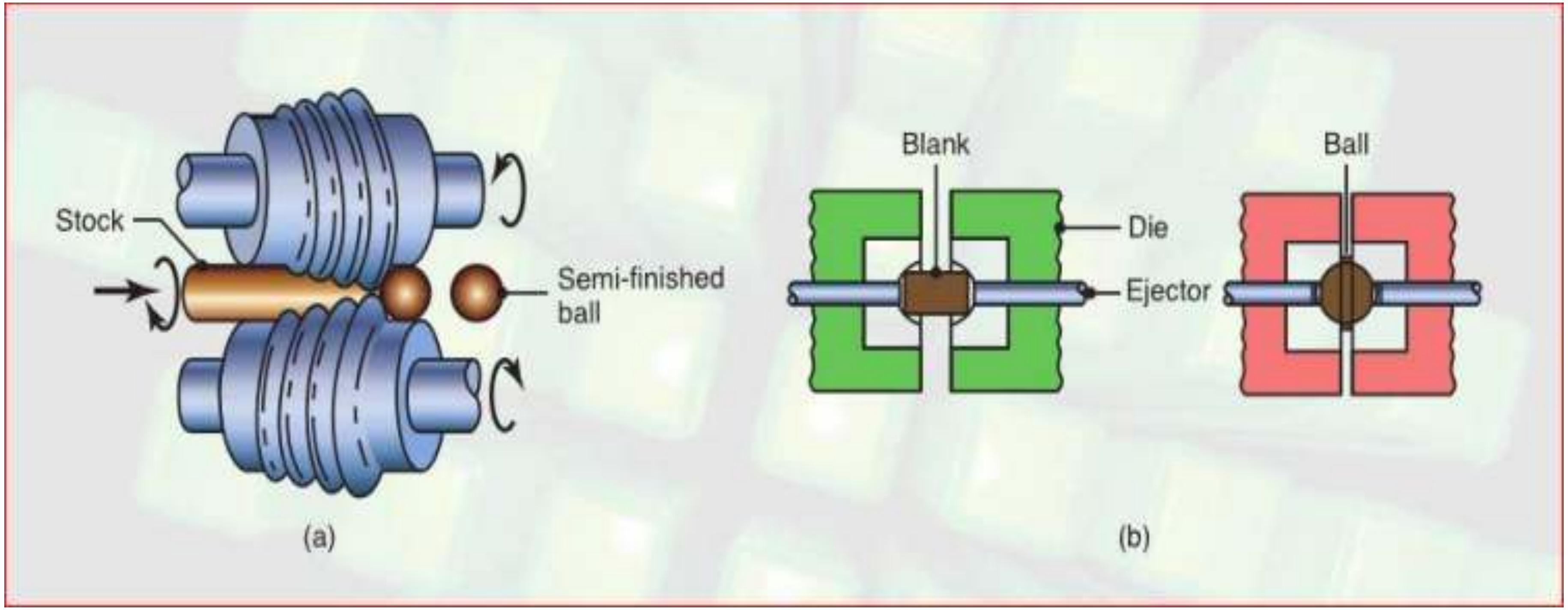
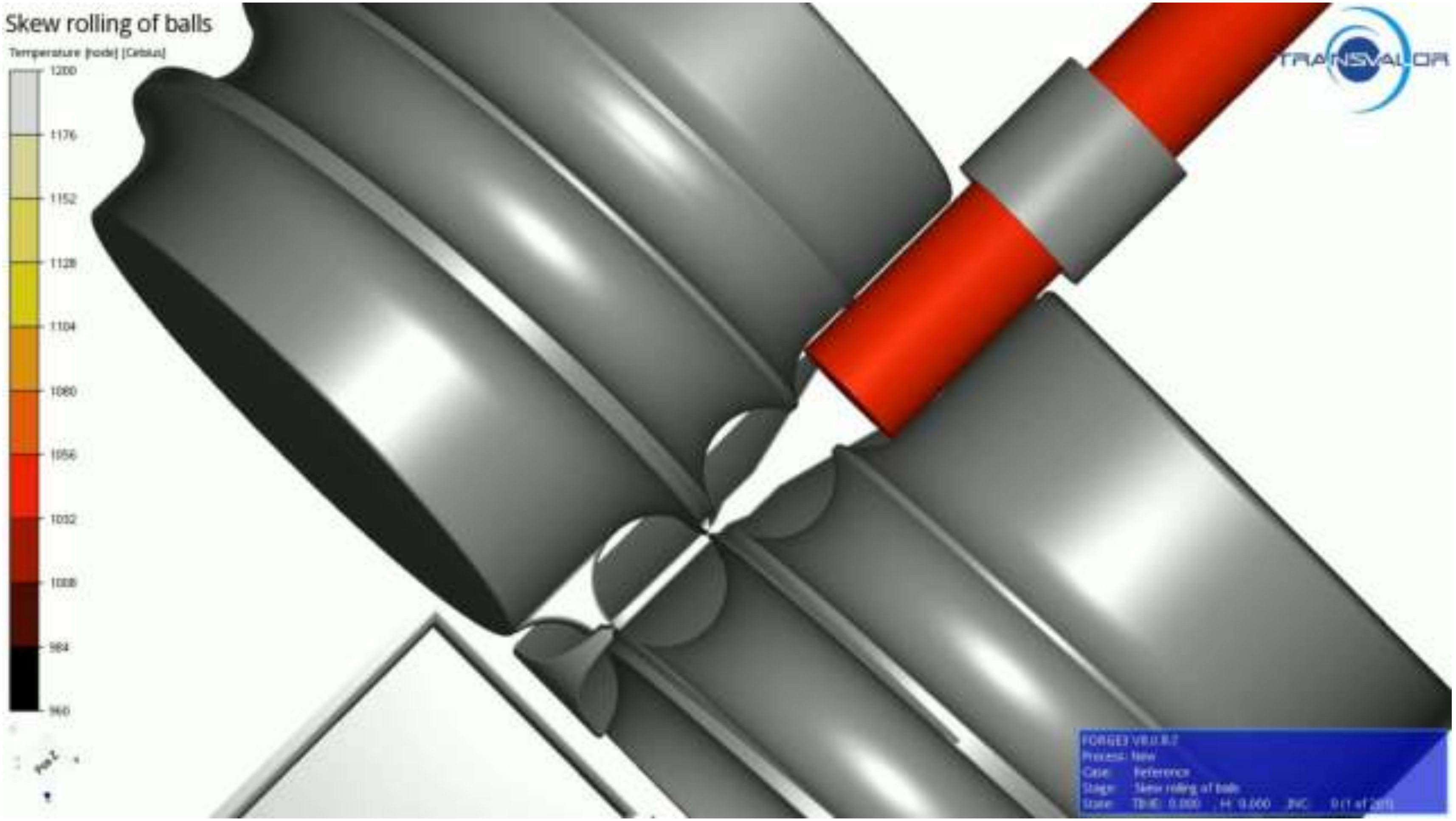


Fig.6.21 (a) Production of steel balls for bearings by skew rolling.

(b) Production of steel balls by upsetting of a short cylindrical blank; note the formation of flash. The balls are subsequently ground and polished to be used as ball bearings and similar components.



Skew rolling of balls
Temperature [node] [Celsius]
1200
1176
1152
1128
1104
1080
1056
1032
1008
984
960
TRANSVALOR

Defects in forging

1.Surface cracking

- Due to sticking and barrelling, leading to tensile forces on the surface.

Other defects are caused by material flow patterns in the die cavity.

2. Laps

- Laps form when metal folds over itself while forging. Excess material in the web of a forging can ***buckle*** during forging and develops ***laps***.

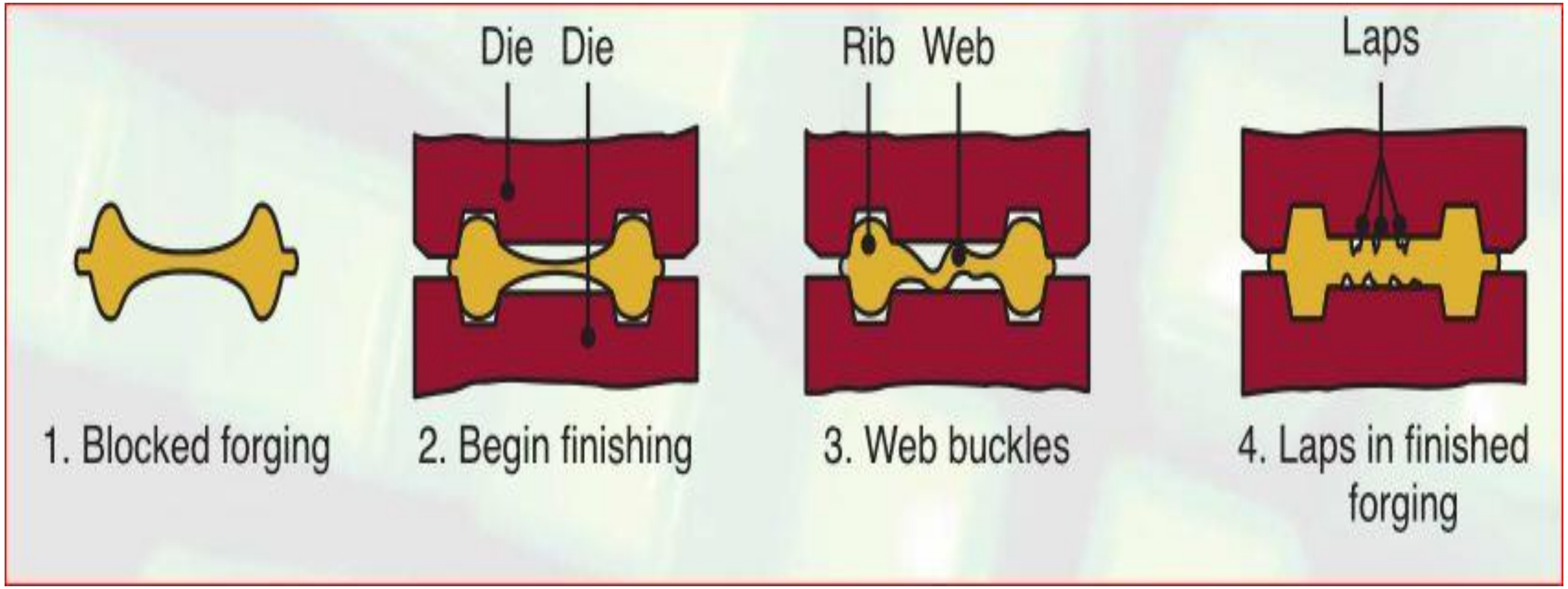


FIGURE : Stages in **lap formation** in a part during forging, due to **buckling of the web**. Web thickness should be increased to avoid this problem.

3.Internal crack :

- If the web is thick, the excess material flows past the already forged portion and develops ***internal cracks***.
- Laps and internal crack indicate the importance of properly distributing material and controlling the flow in the die cavity.

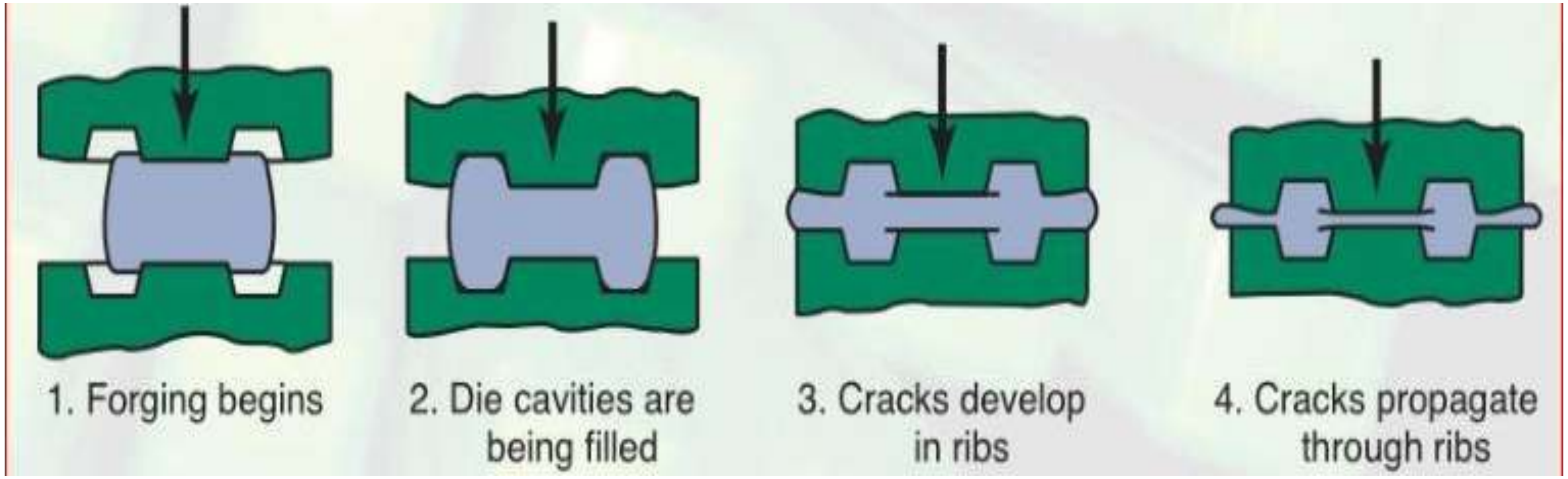
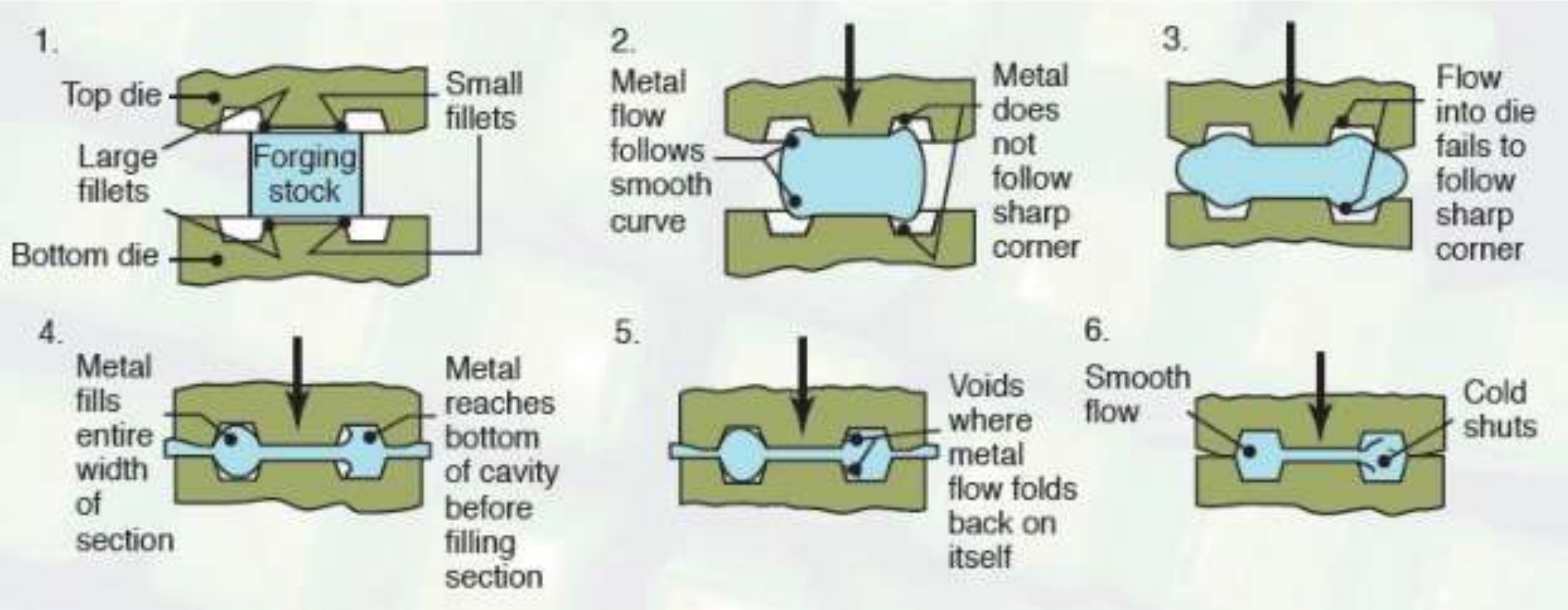
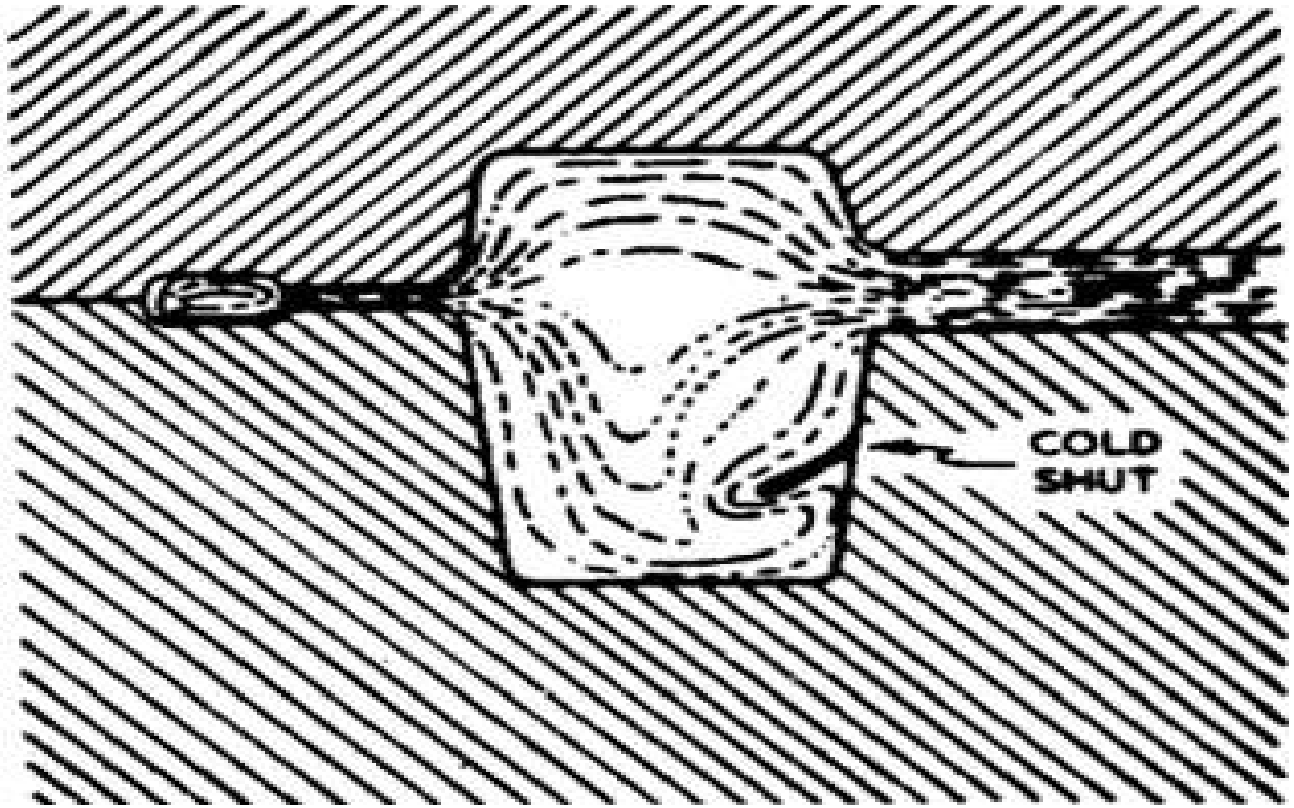


FIGURE : Stages in internal defect formation in a forging because of an oversized billet. The die cavities are filled prematurely, and the ***material at the centre of the part flows radially outward and past the filled regions*** as deformation continues.

4.COLD SHUTS

- The various radii in the die cavity can significantly affect formation of defects.
- The material flows better around a larger corner radius than it does around a small radius.
- With smaller radii, the material can thus fold over itself, producing a lap called cold shut.
- During service life it may lead to fatigue failure, corrosion, and wear.




COLD
SHUT

5.Grain flow pattern

- Another factor affect quality of forging is grain flow pattern.
- The grain flow lines may ***reach a surface perpendicularly***, exposing the grain boundaries directly to the environment(end grains)
- During it may attack by environment (salt water, acid, other chemicals), also act as a ***stress raisers***
- End grains can avoid by proper selection of blank orientation in the die cavity and by control of material flow during forging.
- Metal flow in various direction and temperature variation in forging. So the properties of forging are generally Anisotropic.
- Anisotropic can be defined as a difference, when measured along different axes, in a material's physical or mechanical properties (absorbance, refractive index, conductivity, tensile strength, etc.)

6.Pitting :

- Are small depressions on the surface of forge.
- Caused when scales(oxides) are not removed from the surface.

7.Mismatching :

- Due to the improper alignment of upper and lower die.

8.Blowholes : Blowholes may remain in the forgings if they are present in the ingot.

9.**Dirt, slag and Sand** :Dirt, slag or sand may be present in the ingot used for forging.

Costs of a Rod Made by Forging and Casting

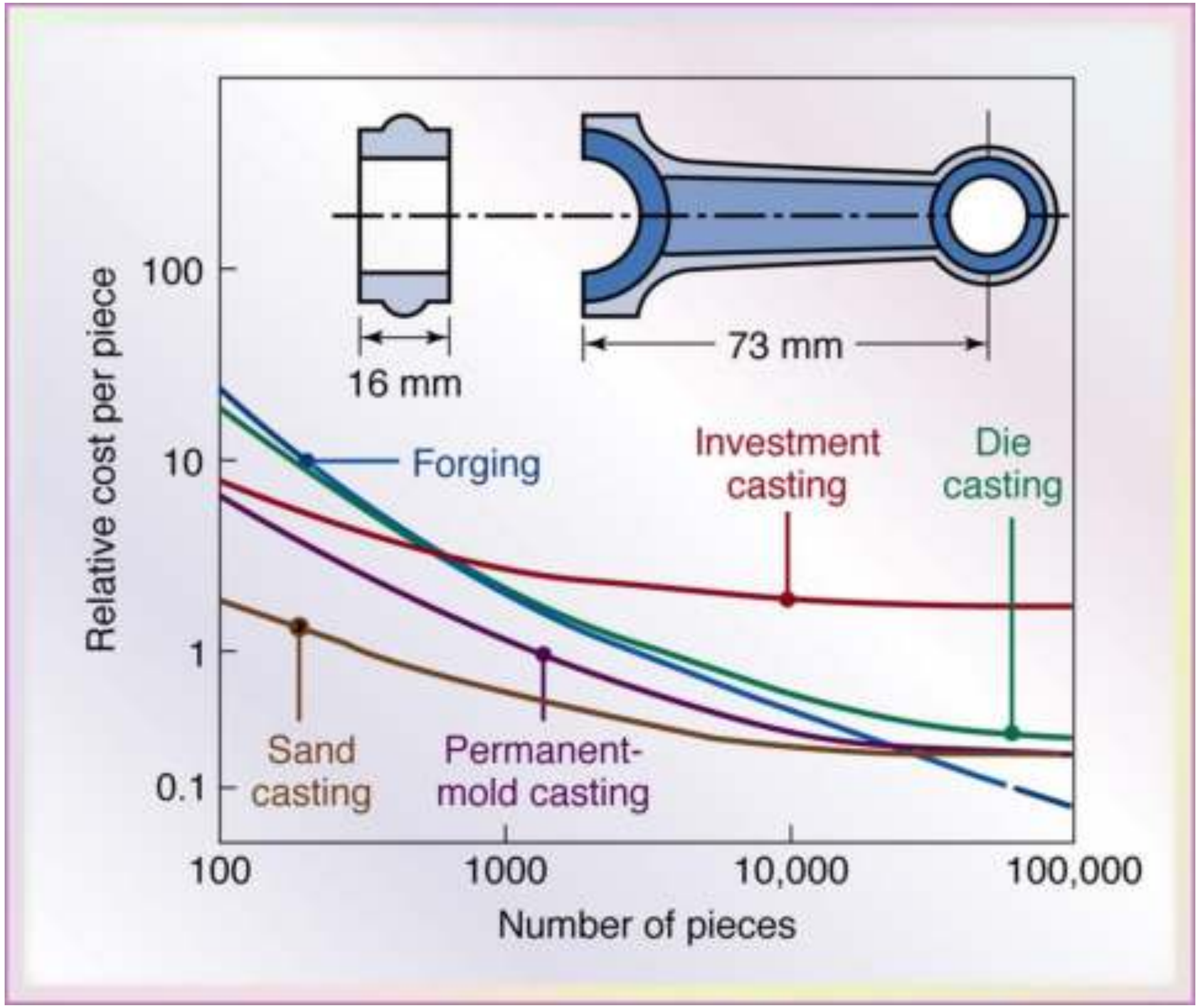


Figure 14.19 Relative unit costs of a small connecting rod made by various forging and casting processes. Note that, for large quantities, forging is more economical. Sand casting is the most economical process for fewer then about 20,000 pieces.

Thank you...

Module IV

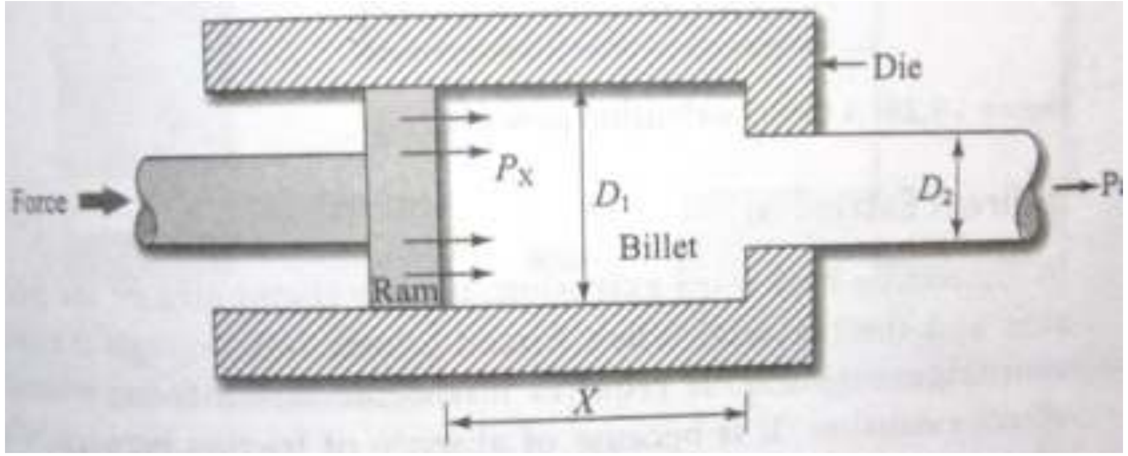
Metal Extrusion

ELDHO PAUL
Dept. of Mechanical Engg.
M.A. College of Engineering
Kothamangalam

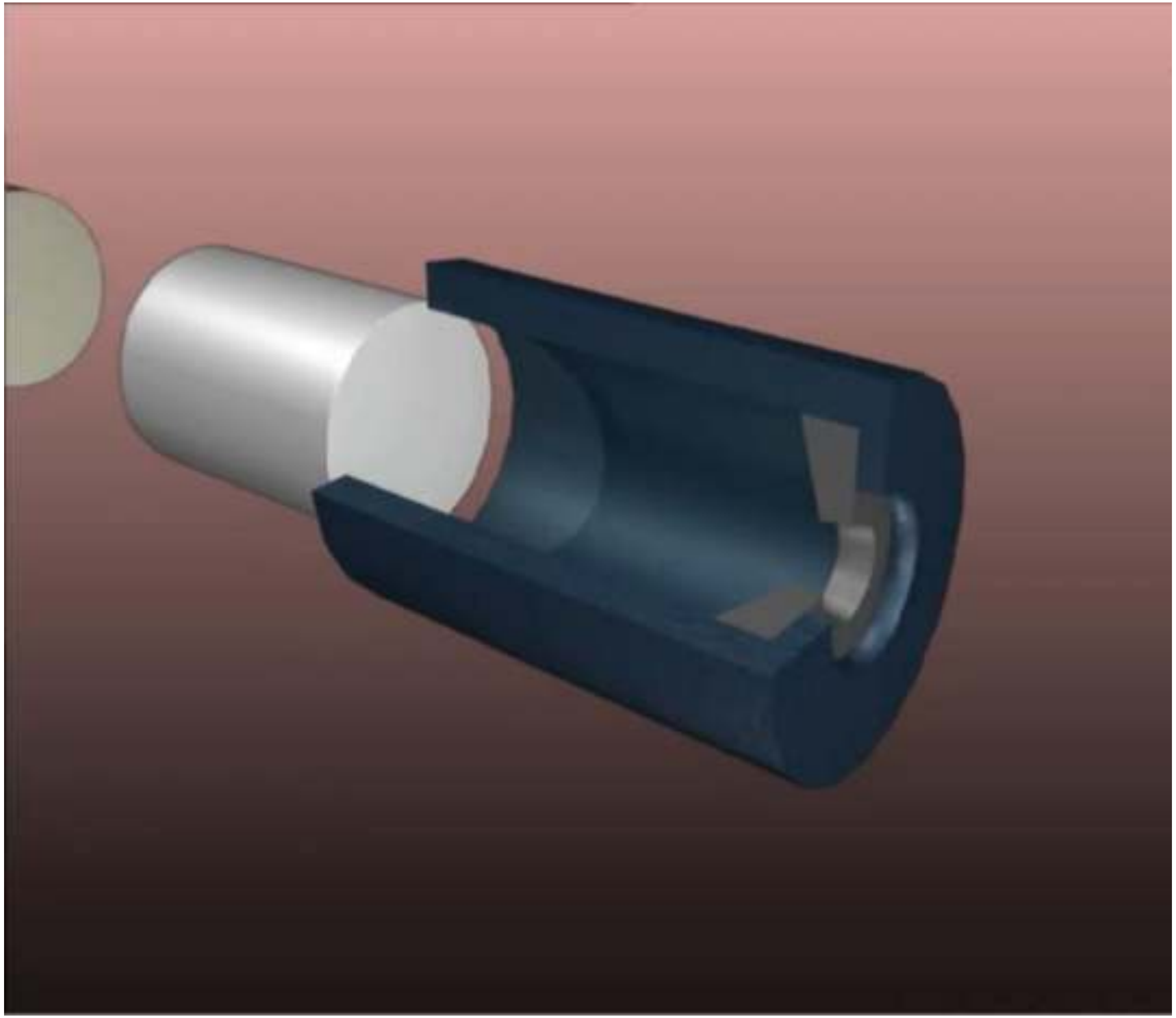
Extrusion

- A process of forcing a metal enclosed in a container to flow through the opening of a ***die***.
- Depending on the ductility of the material, extrusion is carried out at ***room or elevated temperatures***.
- An extrusion press has three major components.

   1. Container
   2. Die
   3. Ram



- Used to manufacture roads, tubes, variety of circular, rectangular hexagonal and other shapes both in solid and hollow form, channel, I, Z, T and other sections.



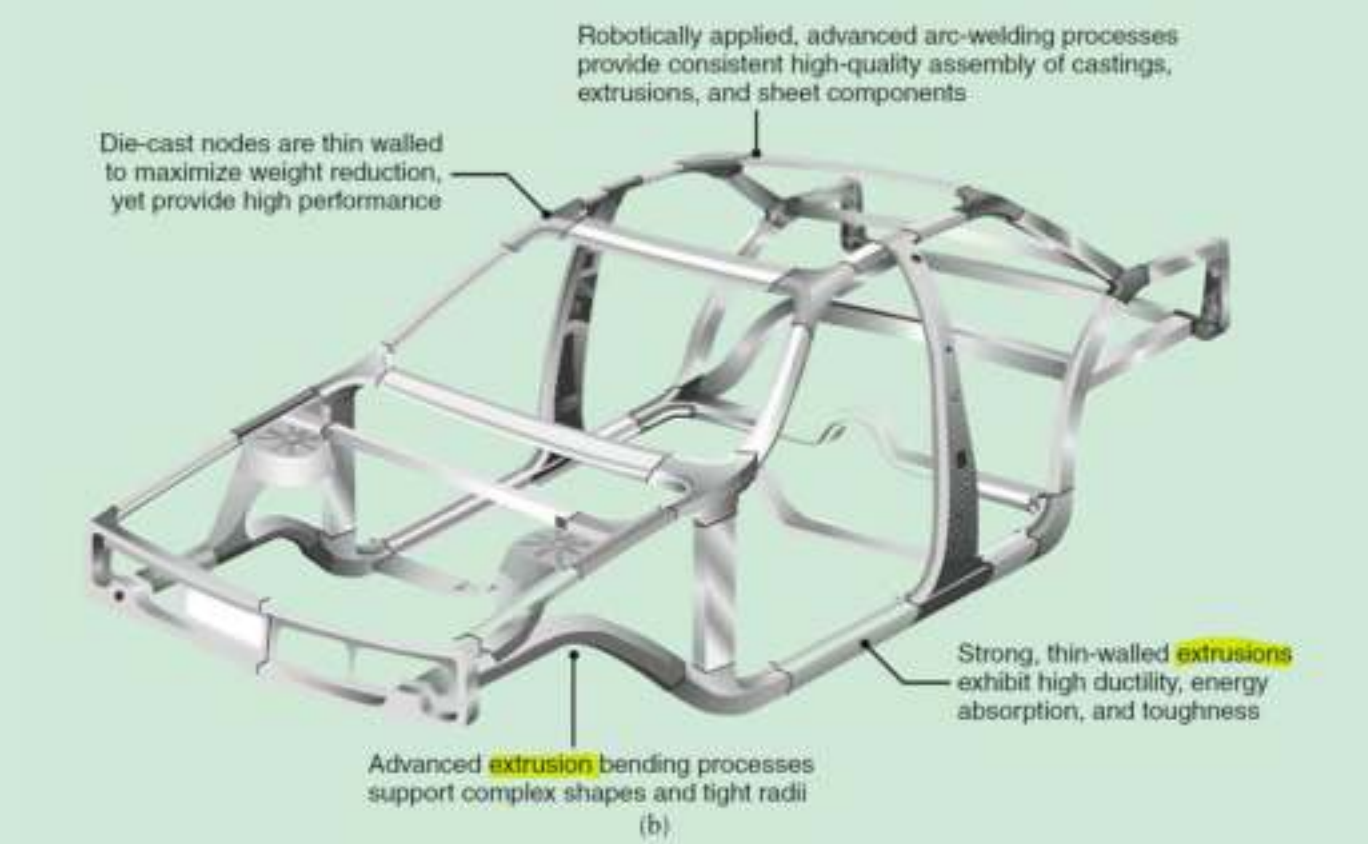


FIGURE 6.2 (a) The Audi A8 automobile, which has an all-aluminum body structure. (b) The aluminum body structure, showing various components made by extrusion, sheet forming, and casting processes. *Source*: Courtesy of ALCOA, Inc.

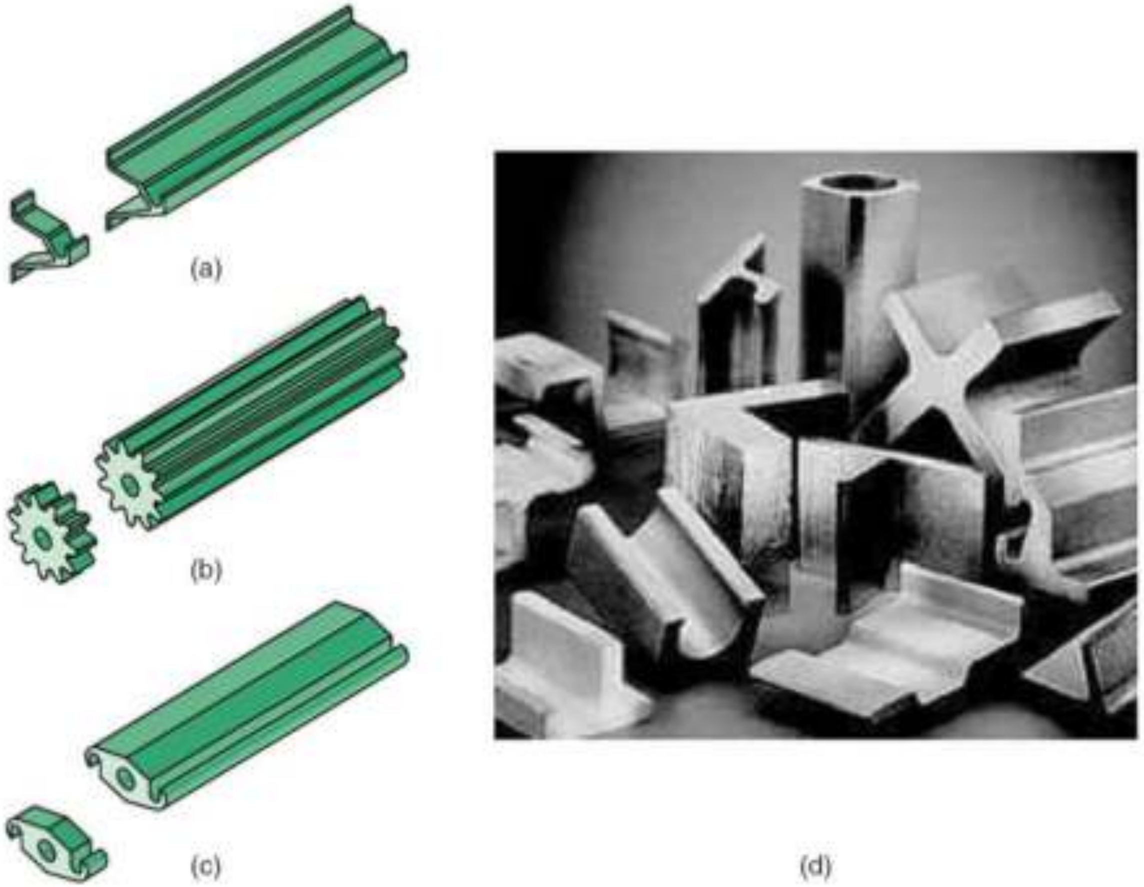


FIGURE 15.2 Extrusions and examples of products made by sectioning off extrusions. *Source*: Courtesy of Plymouth Extruded Shapes.

- Production of long lengths of solid or hollow shapes with ***constant cross section***; product is then cut into desired lengths;
- Usually performed at ***elevated temperatures; cold extrusion*** has similarities to forging and is used to make discrete products;
- Moderate-to-high die and equipment cost;
- Low-to-moderate labor cost;
- Requires low-to-moderate operator skill.

- A wide variety of ***solid or hollow*** cross sections may be produced by extrusion, which essentially are semifinished parts.
- A characteristic of extrusion (from the Latin extrudere, meaning "to force out") is that large deformations can take place ***without fracture*** because the material is under high ***triaxial compression.***

Different methods of extrusion

1. Direct extrusion

- Flow of metal through the die in the ***same direction as the movement of the ram***.
- Billet is placed with in the container that has die at one end.
- A Ram forces the billet through the die opening, ***producing the extruded product***.

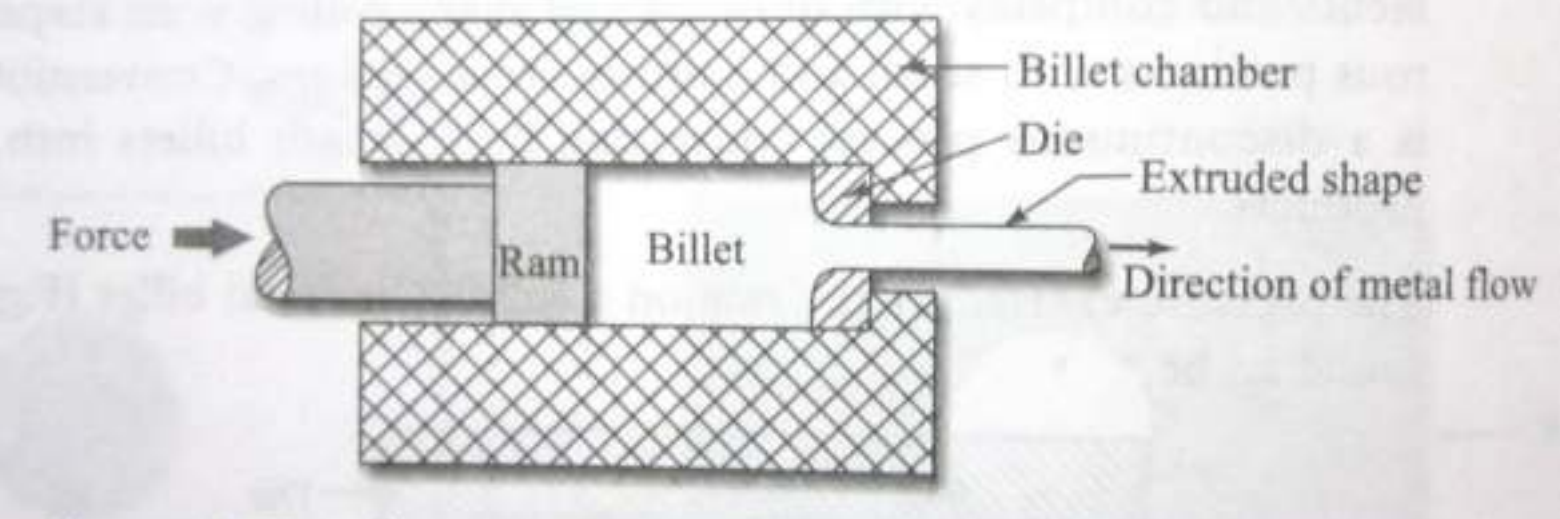
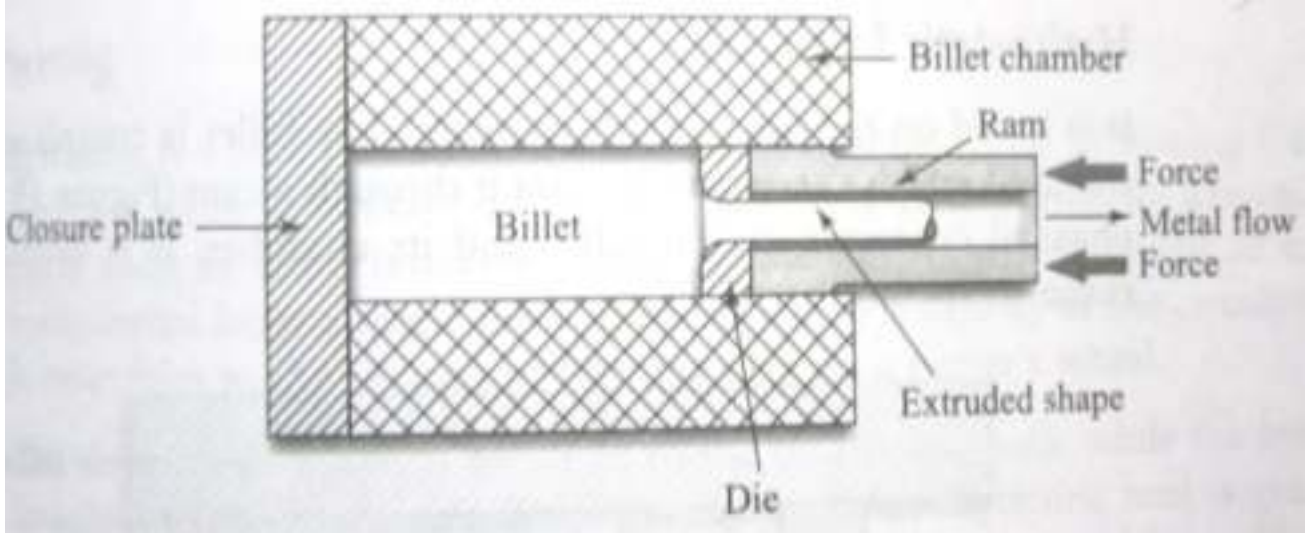


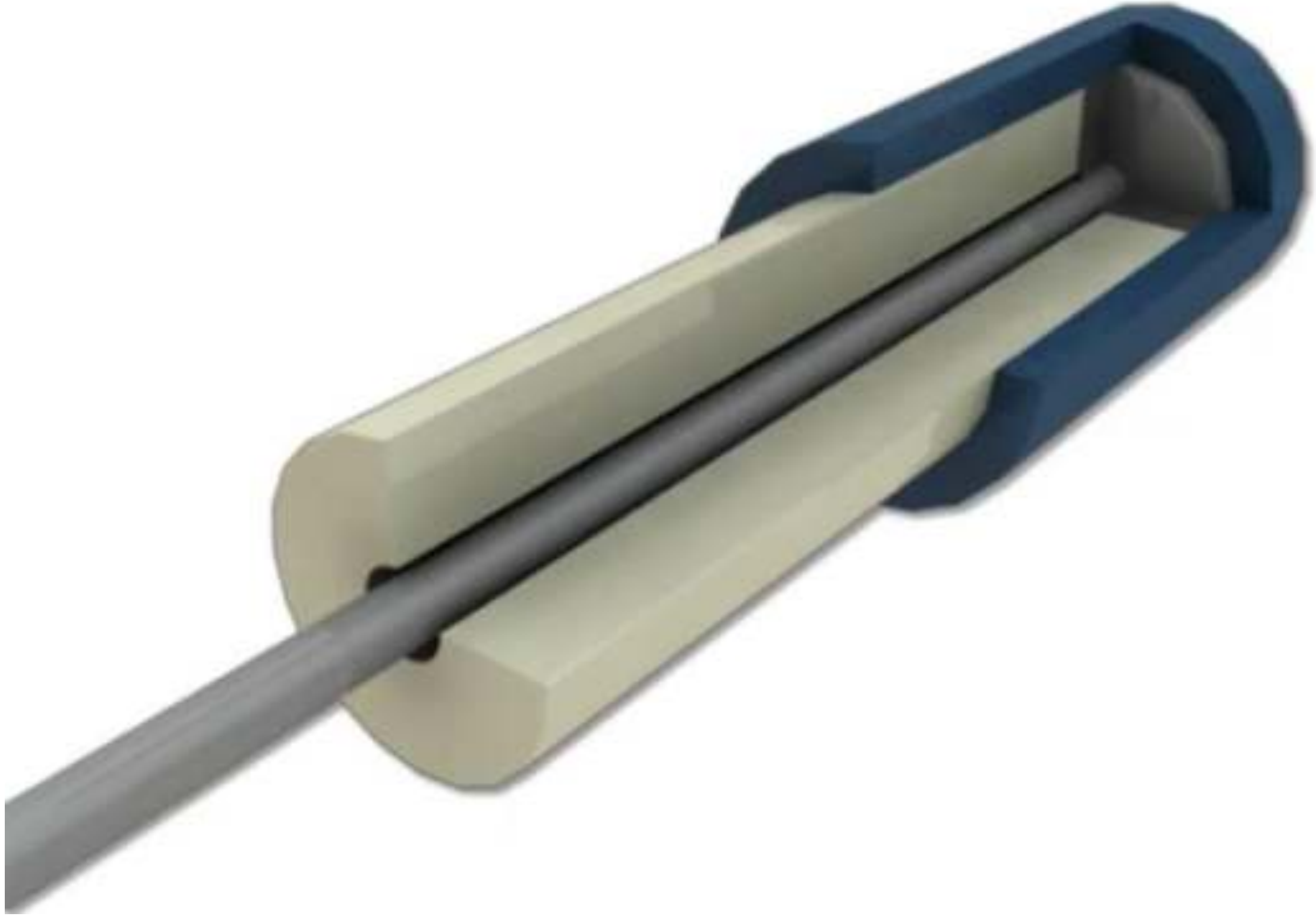
Figure 19.28: A direct extrusion process

2. Indirect extrusion

- The die is mounted on the face of the hollow ram and the material when forced comes out through the ***opening in the ram.***
- Indirect extrusion ***does not require much force*** as compared direct extrusion.
- Indirect extrusion has the advantage of having no billet–container friction, since ***there is no relative motion.***
- Thus, indirect extrusion is used on materials with ***very high friction, such as high strength steels.***

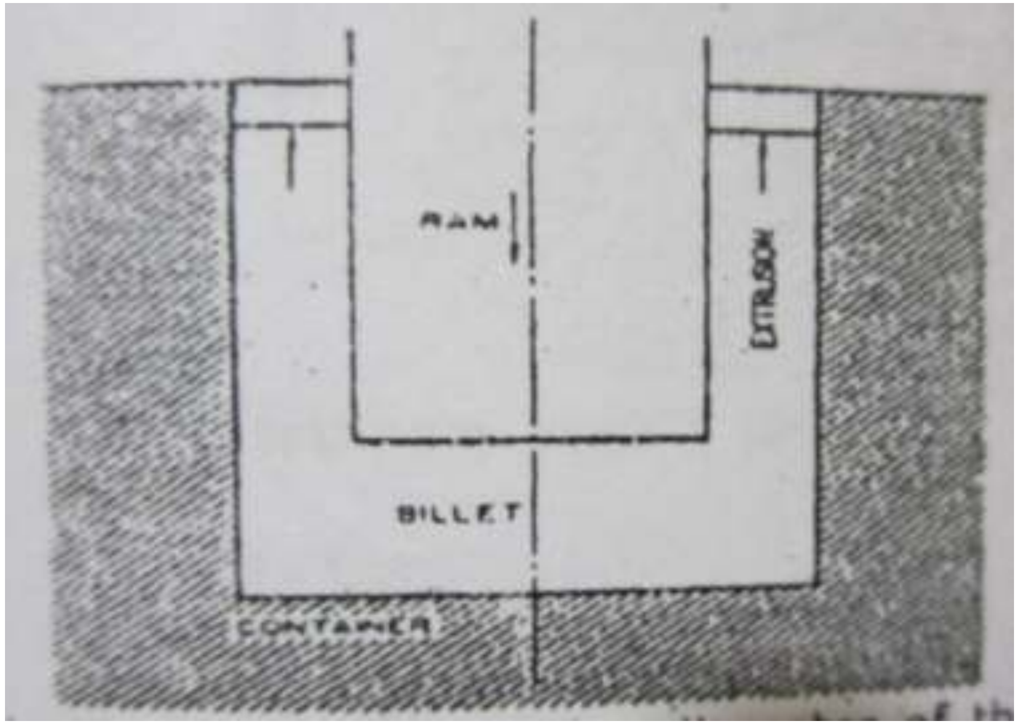


BACKWARD EXTRUSION



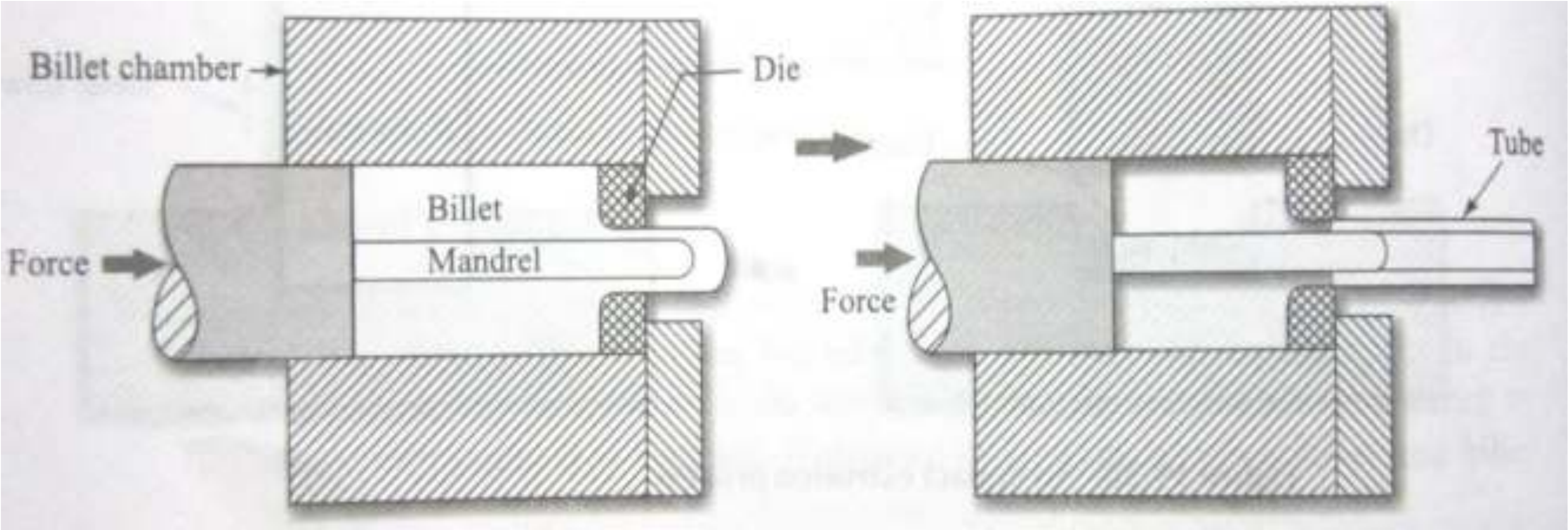
3. Backward extrusion

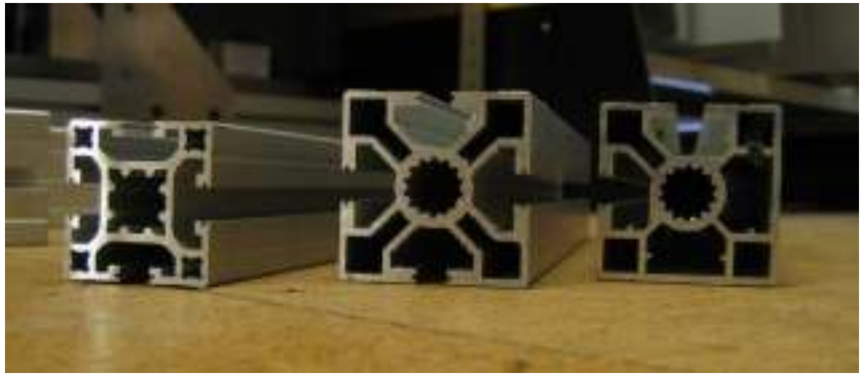
- Diameter of the ram is less than that of the diameter of bore of the container.
- Normally use heated billets for the operation.
- So those process are called ***hot extrusion.***



4. Tube extrusion

- Produce ***tubular products*** with help of mandrel.
- Heated billets is placed in billet chamber and is pushed through a ram.
- The pressure exerted by ram helps to flow the metal ***around the mandrel and come through die opening.***



Metal flow in extrusion

- Metal flow patterns have influence on the quality and mechanical properties of the final product.
- The material flow longitudinally, much like ***incompressible fluid flow*** in a channel.
- Thus the extruded products have an elongated grain structure.
- Fig shows a flow pattern obtained by this technique in direct extrusion with square die (90^o die angle).
- The flow pattern is a function of several variables including friction.
- The metal at the corners is essentially stationary which is called Dead metal zone.

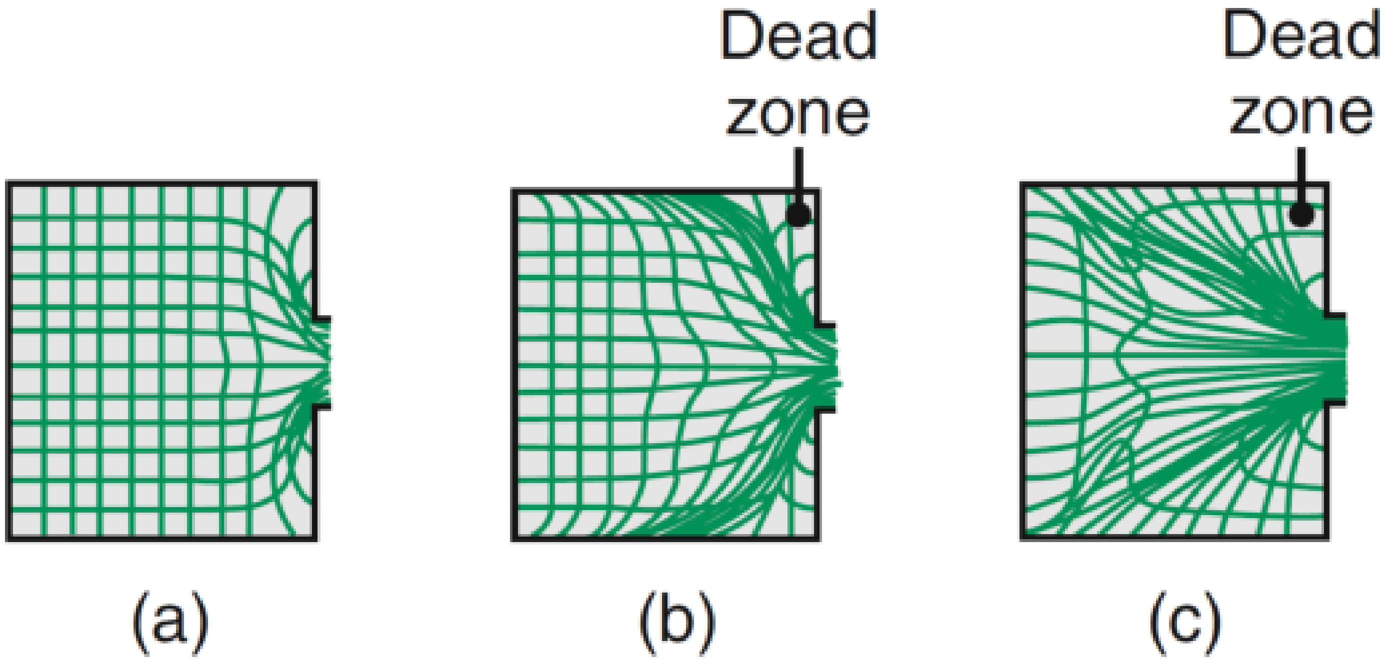


FIGURE 15.6 Types of metal flow in extruding with square dies. (a) Flow pattern obtained at low friction or in indirect extrusion. (b) Pattern obtained with high friction at the billet–chamber interfaces. (c) Pattern obtained at high friction or with cooling of the outer regions of the billet in the chamber. This type of pattern, observed in metals whose strength increases rapidly with decreasing temperature, leads to a defect known as pipe (or extrusion) defect.

- The most homogeneous (uniform) flow pattern occurs when there is no friction at the interfaces. This type of flow also occurs in indirect extrusion, where there is ***no friction*** at the billet container interfaces because ***there is no movement***.
- When friction along all interfaces is high, a ***dead-metal zone*** develops, Note the high-shear area as the material flows into the die exit. This configuration may cause the billet surfaces (with their oxide layer and entrained lubricant) to enter this high-shear zone and be extruded, resulting in product defects.
- In the third configuration, note that the ***high-shear zone extends farther back into the billet***. This situation can be due to ***high container-wall friction*** (which retards the or in flow of the billet) extruding materials with a flow stress that drops rapidly with increasing temperature (such as titanium). In hot extrusion, the ***material near the container walls cools rapidly***, thus becoming stronger; as a the material in the central regions of the billet flows more easily than that at the outer regions. A large dead-metal zone then forms, and the ***flow becomes inhomogeneous***, leading to a defect known as a ***Pipe or extrusion defect***.

Mechanics of Extrusion

- Extrusion process is analyzed in order to estimate the extrusion force under ***different conditions of temperature and friction***, and ***how this force can be minimized***.
- The ram or stem force in direct extrusion for the following different conditions are analyzed.
  1. Ideal force, no friction.
  2. Ideal force, with friction.
  3. Actual forces.
     - Optimum die angle calculation.
  4. Force in hot extrusion.

- The geometric variables in extrusion are,
  - Die angle.
  - Ratio of the cross-sectional area of the billet (A_0) to that of the extruded product (A_f) , called the extrusion ratio, R.
  - Temperature of the billet.
  - The speed at which the ram travels.
  - and the type of lubricant used.

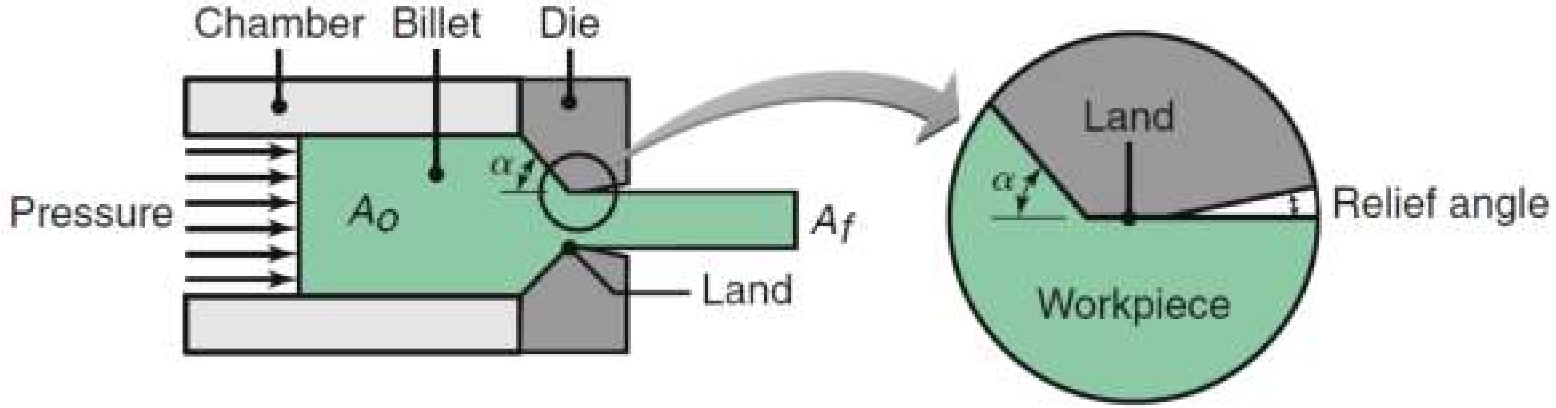


FIGURE 15.4 Process variables in direct extrusion. The die angle, reduction in cross section, extrusion speed, billet temperature, and lubrication all affect the extrusion pressure.

Ideal force (no friction)

- The absolute value of the ***true strain*** that the material,

$$\epsilon_1 = \ln\left(\frac{A_o}{A_f}\right) = \ln\left(\frac{L_f}{L_o}\right) = \ln R_e, \qquad \text{......Eq 1}$$

Where,

A and A_s and L_o and L_f are the areas and the lengths of the billet and the extruded product, respectively.

- For a ***perfectly plastic material*** with a yield strength of σ_y, the energy dissipated in plastic deformation per unit volume, u, is

$$u = \sigma_y \varepsilon_1 \qquad \text{......Eq 2}$$

- Work done on the billet is,

$$W = Volume \times Stress \times Strain$$
$$= Volume \times u$$
$$= A_0 \times L_0 \times u \qquad \text{......Eq 3}$$

- The ***work is supplied by the ram force***, F, which travels a distance L_o. Therefore,

$$\text{Work} = FL_o = pA_oL_o$$ ……Eq 4

where, p is the extrusion pressure.

From Eq.1,2,3 and 4.

……Eq 5

Extrusion pressure = $\boldsymbol{p} = \boldsymbol{u} = \sigma_y In\left(\frac{A_0}{A_f}\right) = \sigma_y \text{In Re}$

Ideal force is,

……Eq 6

$$F = p\,A_0$$

Note that for strain-hardening materials, σ_y, must be replaced by the average flow stress $\bar{\sigma}$, of. Also note that Eg. 6 is equal to area under the true stress-true strain curve for the material.

Ideal force (with friction)

- Based on the slab method of analysis, and for ***small die angles***, it can be shown that ***with friction*** at the die-billet interface and ignoring the container wall friction, the ***extrusion pressure, p***, is given by the expression,

$$p = \sigma_y \left(1 + \frac{\tan\alpha}{\mu}\right)\left[R_e^{\mu \cot\alpha} - 1\right]$$

- If it is assumed that the ***frictional stress is equal to the shear yield strength k***, and that because of the dead zone formed, the material flows along ***a 45° "die angle***," the ***pressure*** can be estimated as,

$$p = \sigma_y \left(1.7 \ln R_e + \frac{2L}{D_o}\right)$$

- Note that as the ram travels further toward the die, ***L decreases***, and thus the pressure and force decrease.

Actual forces

- In extrusion practice, as well as in all metalworking processes, there are difficulties in estimating,
  - The ***coefficient of friction*** and its variation throughout a process;
  - The ***flow stress of the material*** under the actual conditions of temperature and strain rate;
  - The work involved in ***inhomogeneous deformation***.
- A simple empirical formula has been developed in the form of,

$$p = \sigma_y(a + b \ln R_e)$$

- where a and b are experimentally determined constants. It has been determined that an approximate value for a is ***0.8***, and that ***b ranges from 1.2 to 1.5***

Optimum die angle

- The ***die angle has an important effect on forces in extrusion***, which can be summarized as follows,
  - The ***ideal force*** is a function of the strain that the material undergoes, and thus is a function of the extrusion ratio R. Consequently, it is independent of the die angle
  - The force due to friction increases with ***decreasing die angle***. This is because, the length of contact along the billet-die interface increases as the die angle decreases.
  - An additional force is required for redundant work due to inhomogeneous deformation of the material during extrusion. This work ***increases with the die angle***.
- The total extrusion force is the sum of these three components. There is a specific angle at which this force is a minimum, referred to as the optimum angle.

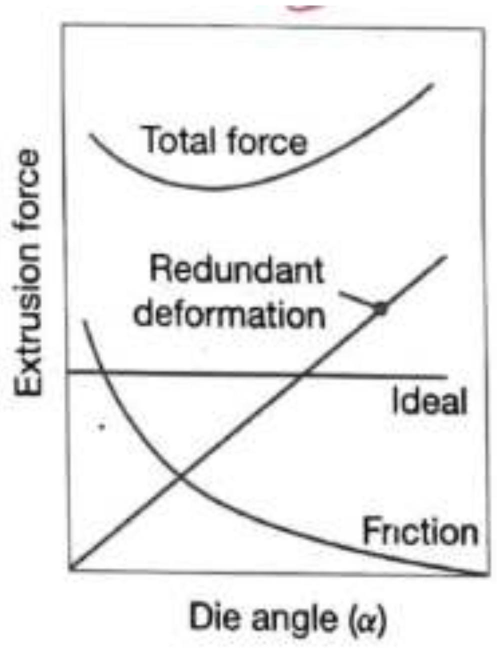
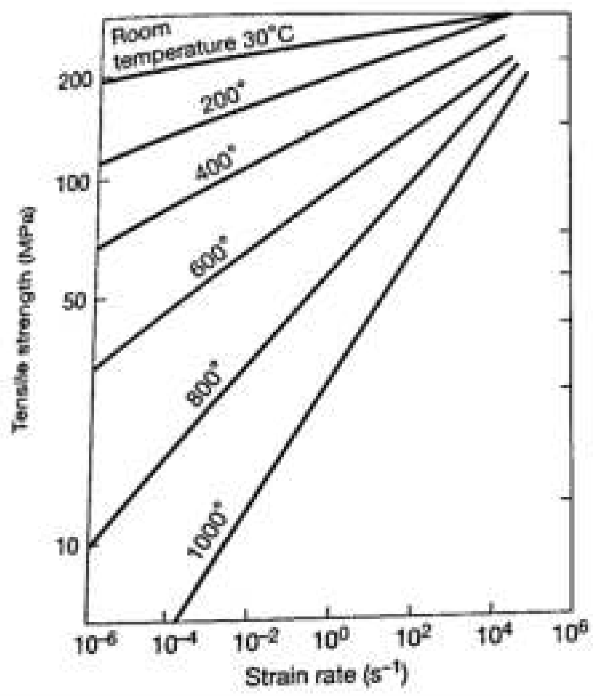


FIGURE 6.49 Schematic illustration of extrusion force as a function of die angle. Note that there is a die angle where the total extrusion force is a minimum (optimum die angle).

Force in hot extrusion

- Because of the ***strain-rate sensitivity of metals at elevated temperatures***, the force in hot extrusion can be difficult to calculate accurately.



Increasing the strain rate increase the strength. Sensitivity of this variation increase with increase in temp. High temp has high influence on the strain rate

FIGURE 2.10 The effect of strain rate on the ultimate tensile strength of aluminum. Note that as temperature increases, the slope increases. Thus, tensile strength becomes more and more sensitive to strain rate as temperature increases. *Source:* After J.H. Hollomon.

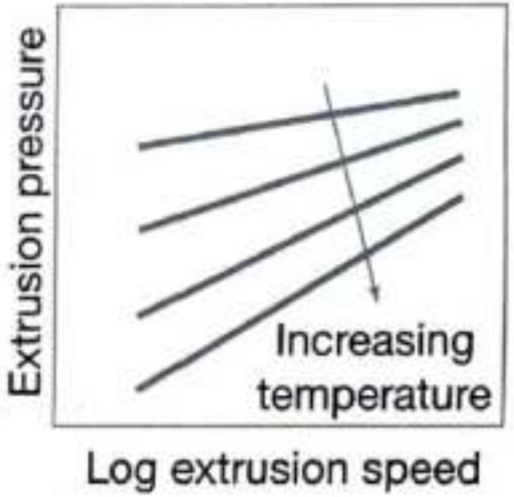


FIGURE 6.50 Schematic illustration of the effect of temperature and ram speed on extrusion pressure. Note the similarity of this figure with Fig. 2.10.

- The pressure increases rapidly with ***ram speed***, especially at elevated temperatures due to ***increased strain-rate sensitivity***.
- As speed increases, the rate of work done per unit time also increases. Also, the ***heat generated at higher speeds*** will not be removed fast enough, thus raising the temperature. The higher temperature can then lead to incipient melting of the workpiece material and possibly cause defects.
- ***Circumferential surface cracks*** caused by hot shortness also may develop , a phenomenon known as speed cracking (because of the high ram speed involved).

Force in hot extrusion

- It can be shown that the ***average true strain rate*** $\bar{\dot{\varepsilon}}$***,*** that the material undergoes is given by the expression,

$$\dot{\epsilon} = \frac{6V_o D_o^2 \tan\alpha}{D_o^3 - D_f^3} \ln R_e$$

where V_o is the ram speed.

- For high ***extrusion ratios***, that is $D_0 > D_f$; and (b) a ***die angle of α = 45°***, as is the case with a square die and ***under poor lubrication*** (thus developing a dead zone), the ***true strain rate reduces to***

$$\dot{\epsilon} = \frac{6V_o}{D_o} \ln R_e$$

- A parameter used to estimate the force in ***hot extrusion*** is an experimentally determined extrusion constant, K_e, that includes various factors involved in the operation.

$$p = K_e \ln R_e$$

Some values of K_e for a variety of materials are

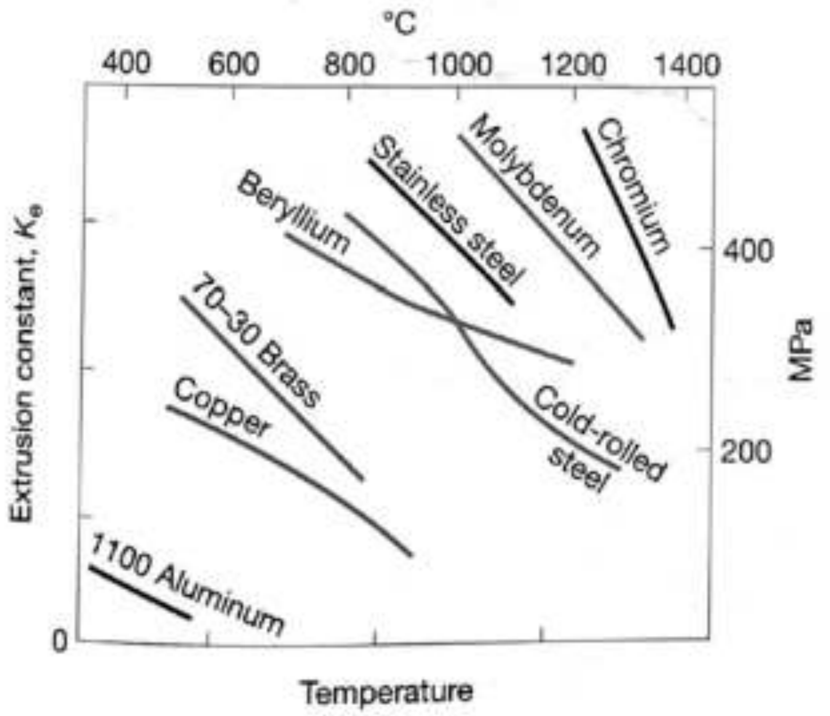


FIGURE 6.51 Extrusion constant, K_e, for various materials as a function of temperature. *Source:* After P. Loewenstein.

Miscellaneous Extrusion Processes

1. Cold extrusion

- Cold extrusion is a general term that often is used to describe a combination of processes, particularly extrusion combined with forging.
- Many ***ductile metals can be cold extruded into various configurations***, with the billet mostly at ***room temperature*** or at a few hundred degrees.
- Typical parts made are *automotive components* and gear blanks.

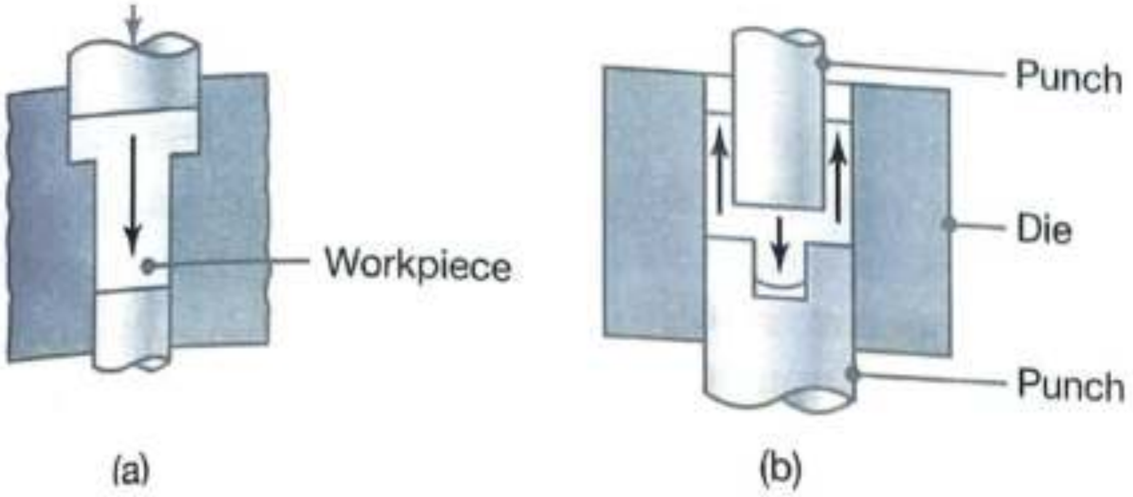
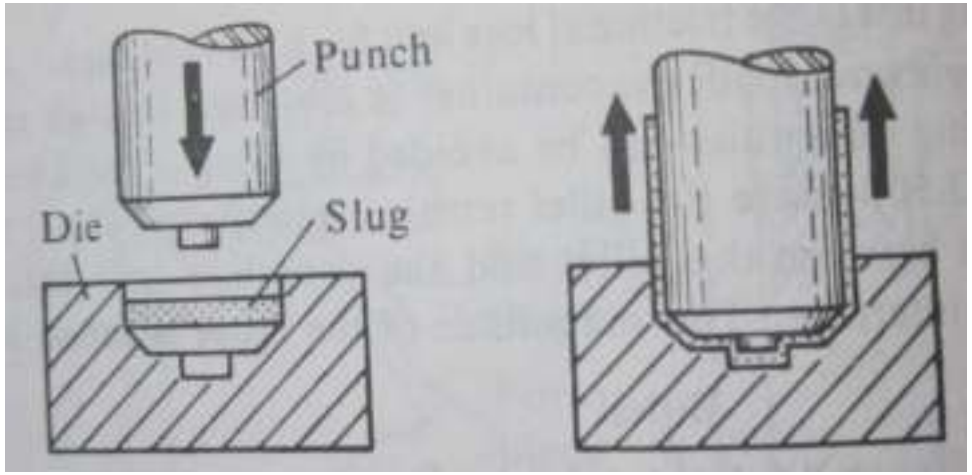


FIGURE 6.52 Two examples of cold extrusion. Arrows indicate the direction of material flow. These parts may also be considered as forgings.

- Advantages
  - Improved mechanical properties as a result of ***strain hardening***
  - ***Good dimensional tolerances***, thus requiring a minimum finishing operations;
  - ***Improved surface finish***, partly due to the absence of oxide film provided that lubrication is effective; and
  - ***High production rates*** and relatively low cost.
- ***Stresses on tooling*** and dies in cold extrusion are very high.
- So tooling must have sufficient strength, toughness, and resistance to wear and fatigue.

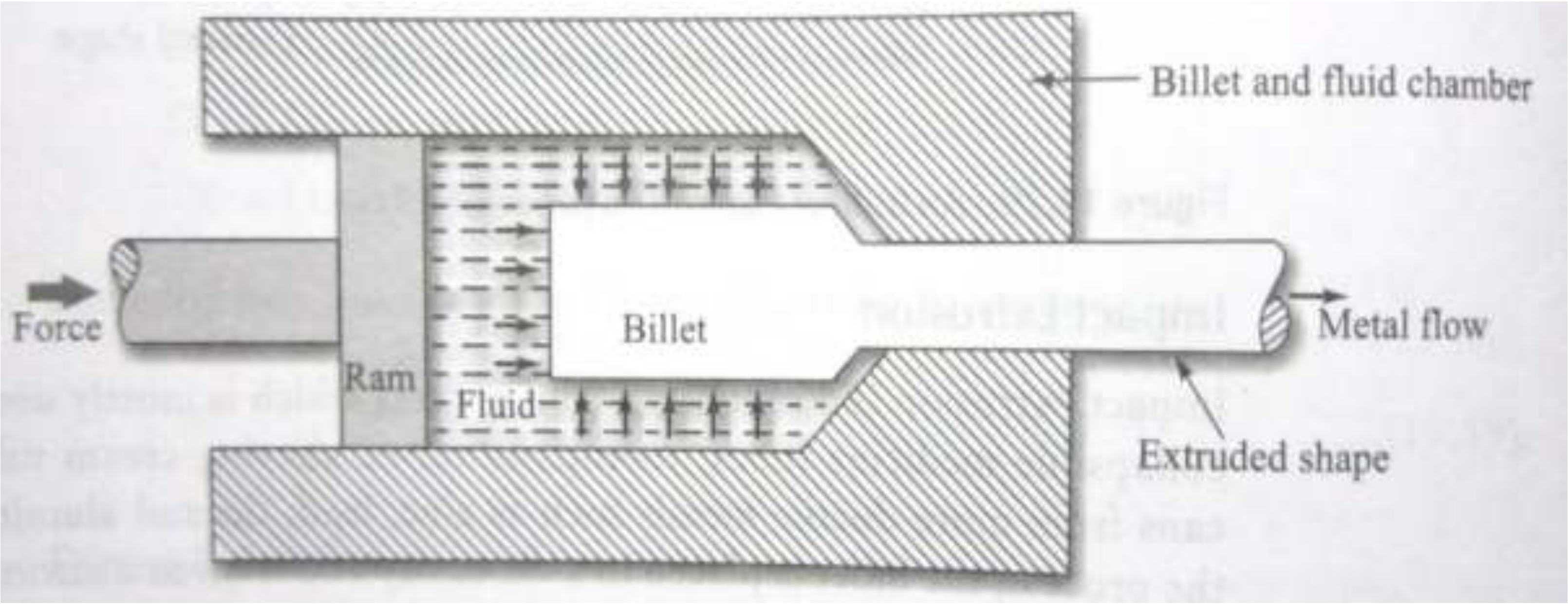
2. Impact Extrusion or hooker process

- A cold process, Small unheated metal(billets) is placed in the die cavity.
- Punch is forced into the die cavity causing the metal to flow upward through the gap between punch and die.
- Causes the ***metal to flow plastically around the punch***.
- Used for making ***collapsible medicine tubes, toothpaste tube, food cans with wall thicknesses*** that are small in relation to their diameter.
- Low cost, excellent surface finish.
- Thickness of tube is controlled by the ***clearance between*** the die and punch.



3. Hydrostatic extrusion

- Billets is surrounded by a working fluid which is pressurized by ram to provide the extrusion process.
- There is no friction along the container wall.
- Pressure on the order of 1400 MPa.
- This operation reduces the detects in extruded products.



4. Coaxial extrusion.

In this process, coaxial billets are extruded an joined together. Cladding is another application of this process; an example is copper clad with silver.

Defects in extrusion

- There are three principal extrusion defects
  - Surface cracking (Bamboo defect)
  - Pipe and
  - Internal cracking

Surface cracking

- High extrusion temperature, friction and speed can cause surface cracking and tearing.
- Cracks are formed along the grain boundaries and is caused by **hot shortness**.
- This defect mainly occur in Al, Mg and Zn alloys.
- Can be avoided by lowering the billet temperature and the extrusion speed.
- Surface cracking also occurs at lower temperatures, in which the extruded product sticks along the die.
- When the extruded product sticks on to the die, the extrusion pressure increases rapidly.
- Thus, the product moves forward again and pressure is released.
- This cycle is repeated continuously producing periodic circumferential cracks on the surface known as **bamboo defect**.

Pipe

- This type of metal flow pattern tends to draw surface oxides and impurities towards the center of the billet, much like a funnel. This defect is known as pipe defect or tailpipe, or fishtailing.

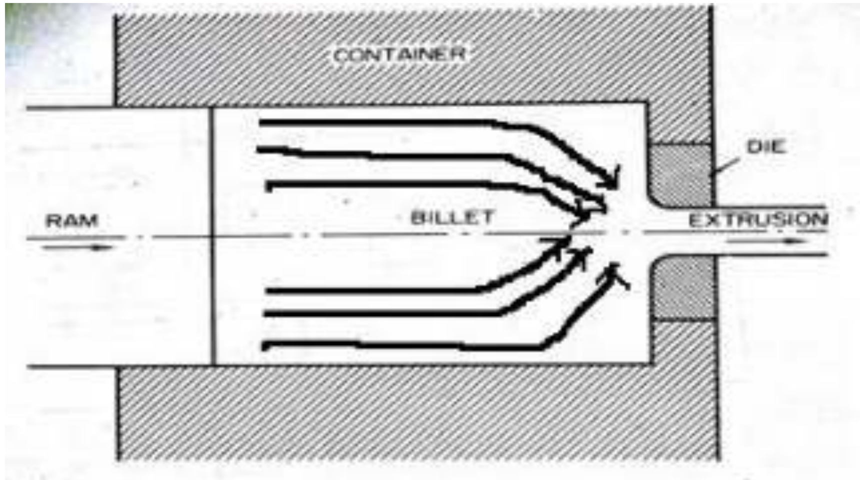
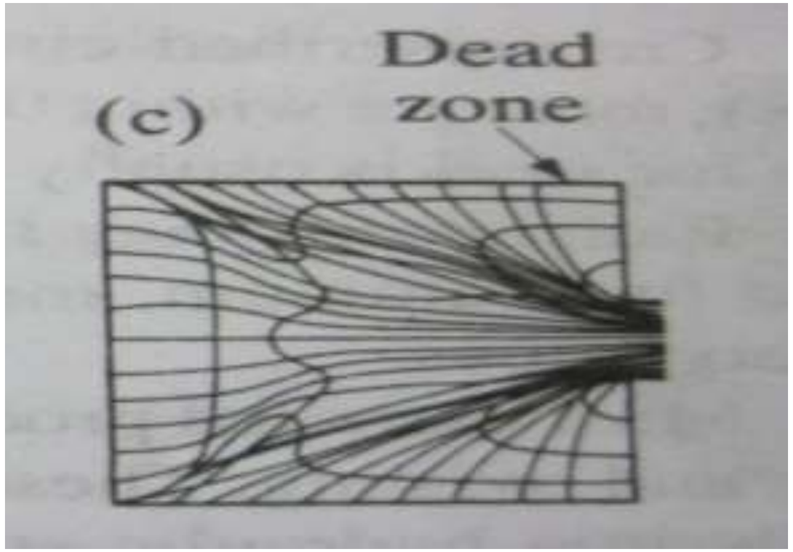


Fig. 22.2. Direct extrusion

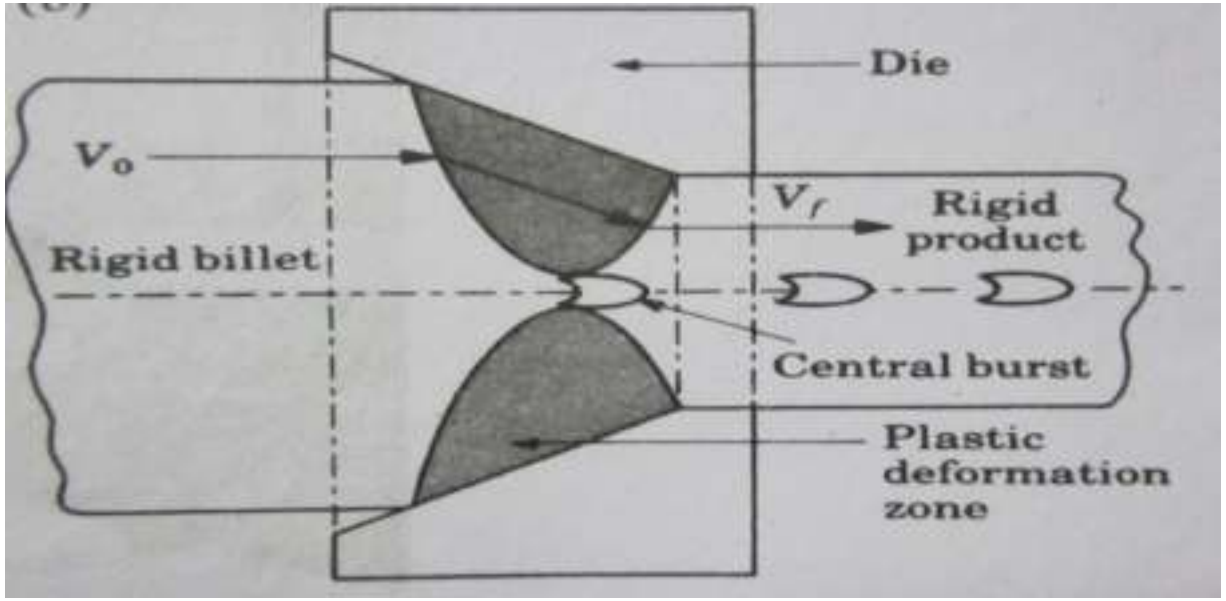


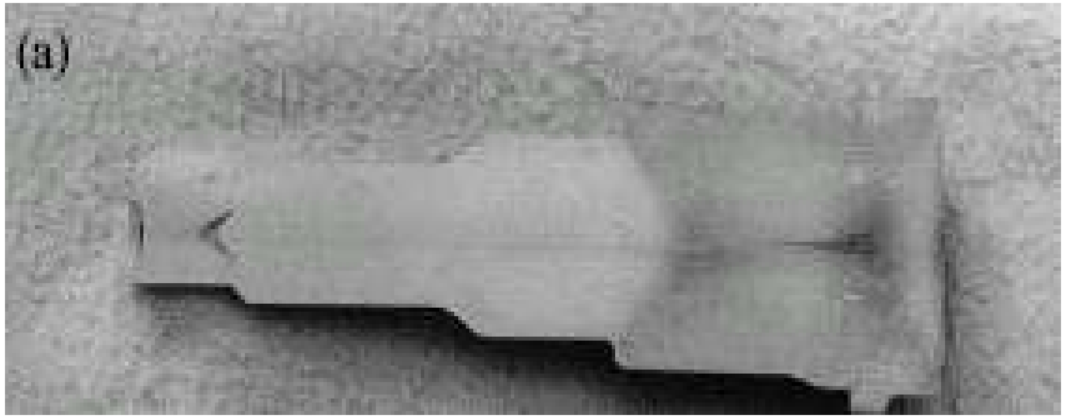
- As much as one third of the length of the extruded product may contain this type of defect and have to be cut off as scrap.
- Piping can be minimized by modifying the flow pattern to a more uniform one.

Internal cracking

The center of the extruded product can develop cracks variously called center cracking, center burst, arrowhead fracture, or chevron cracking

- These cracks are attributed to a state of hydrostatic ***tensile stress*** at the centerline in the deformation zone in the die.





- The major variables affecting hydrostatic tension are the
  - (a) Die angle;
  - (b) Extrusion ratio (or reduction in cross-sectional area);
  - (c) And friction.

- The role these factors based on the extent of inhomogeneous deformation during extrusion.

Module 5

Locating and Clamping

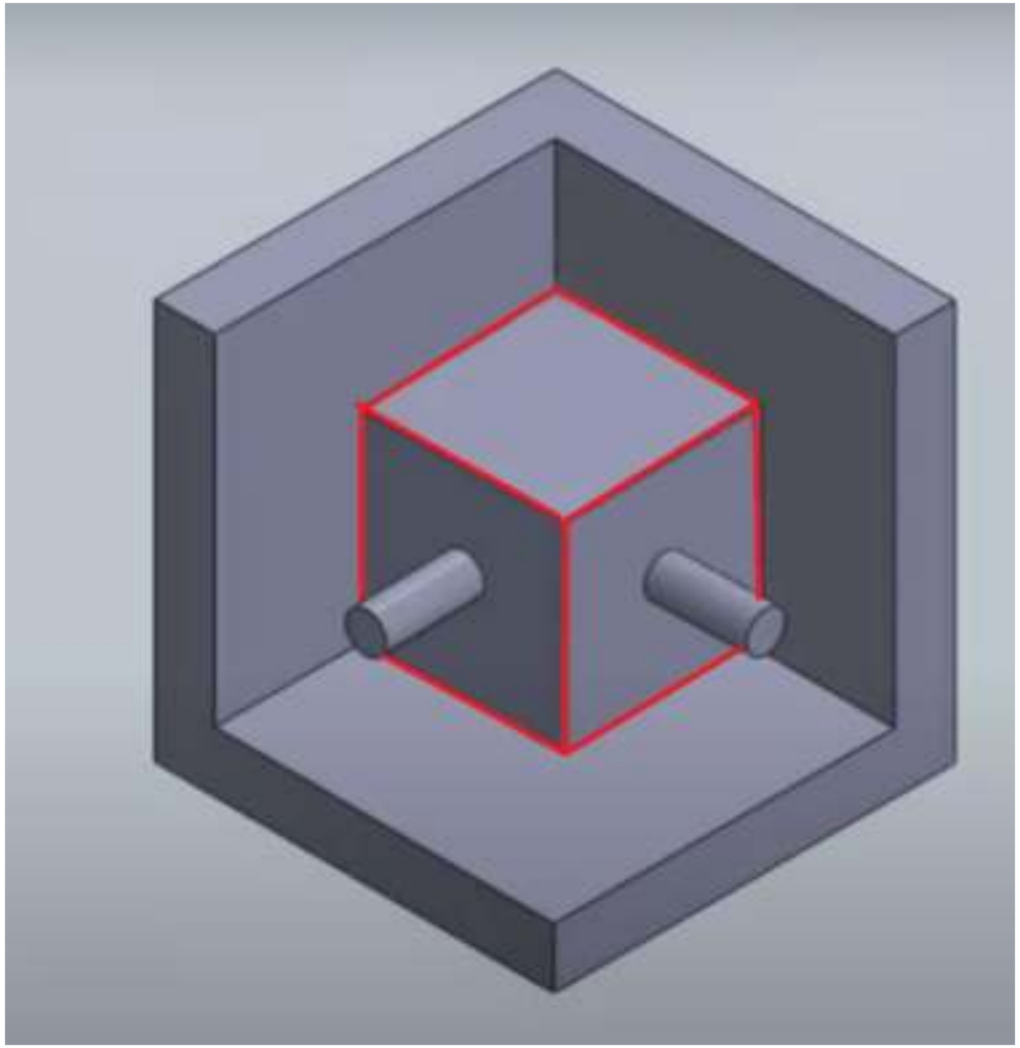
ELDHO PAUL
Dept. of Mechanical Engg.
M.A. College of Engineering
Kothamangalam

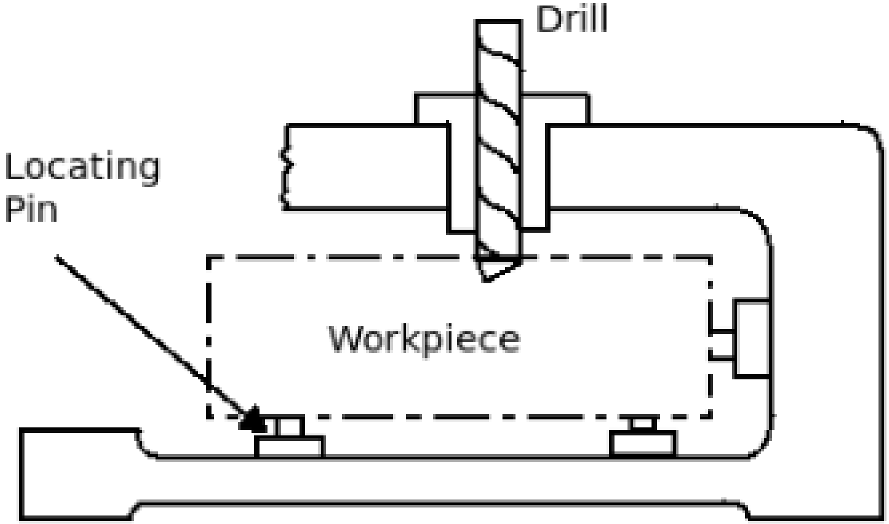
Syllabus

5.1	Locating and clamping methods: - basic principle of location; locating methods; degrees of freedom; locating from plane, circular, irregular surface –simple problems.	2	CO4
	Locating methods and devices: - pin and button locators, rest pads and plates, nest or cavity location.	1	
5.2	Basic principles of clamping:-strap, cam, screw, latch, wedge, hydraulic and pneumatic clamping –simple problems. (Donaldson, Wilson F.W.).	2	CO4
5.3	Sheet metal operations: Press tool operations: shearing action, shearing operations: blanking, piercing, simple problems, trimming, shaving, nibbing, notching – simple problems - applications.	2	CO4 CO5
5.4	Tension operations: stretch forming - Compression operations: - coining, sizing, ironing, hobbing - tension and compression operations: drawing, spinning, bending, forming, embossing – simple problems- applications. (Donaldson, Wilson F.W., Rao P.N).	2	CO4
	Fundamentals of die cutting operations - inverted, progressive and compound die - simple problems. (Donaldson)	1	

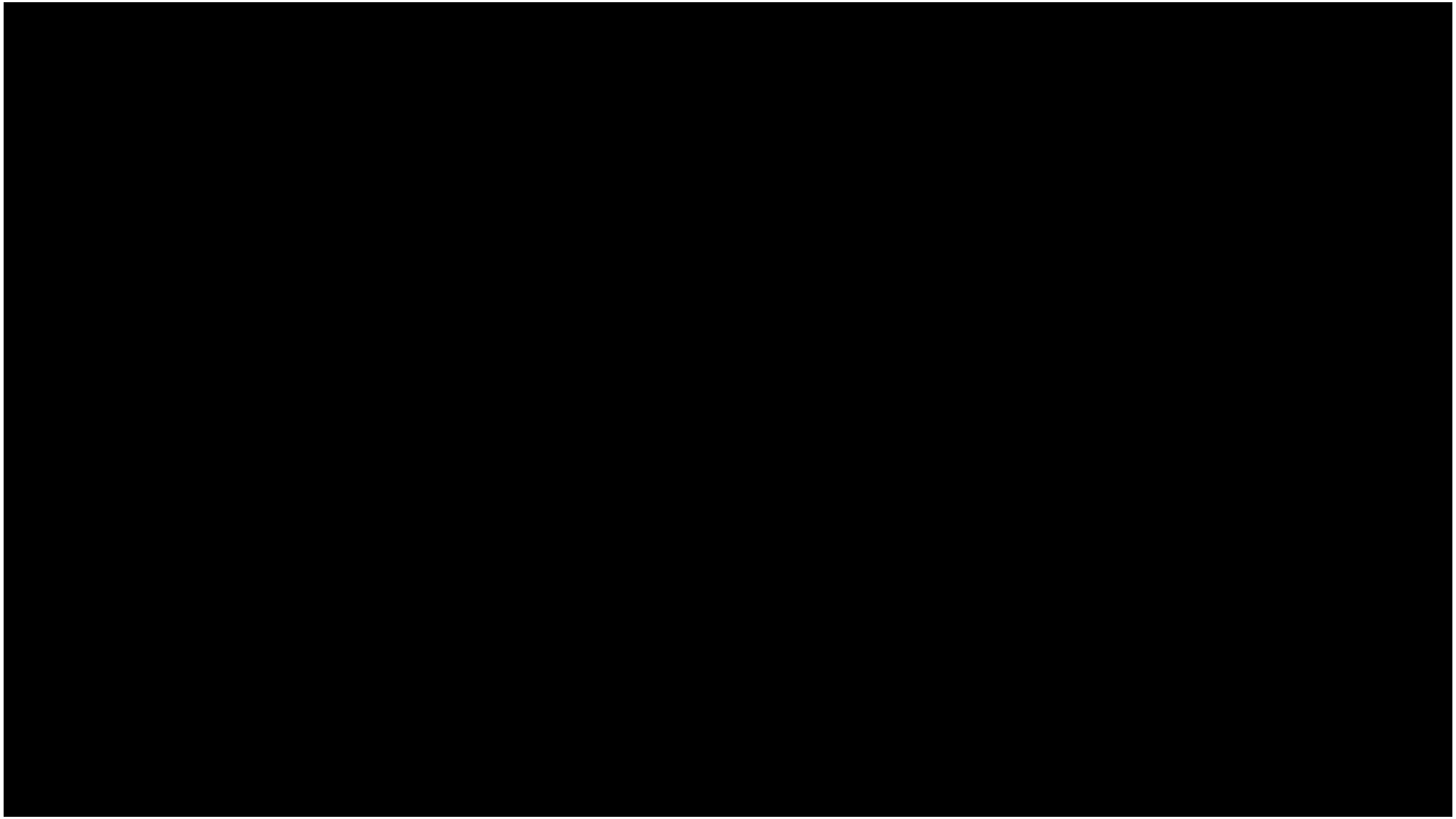
THE BASIC PRINCIPLES OF LOCATION

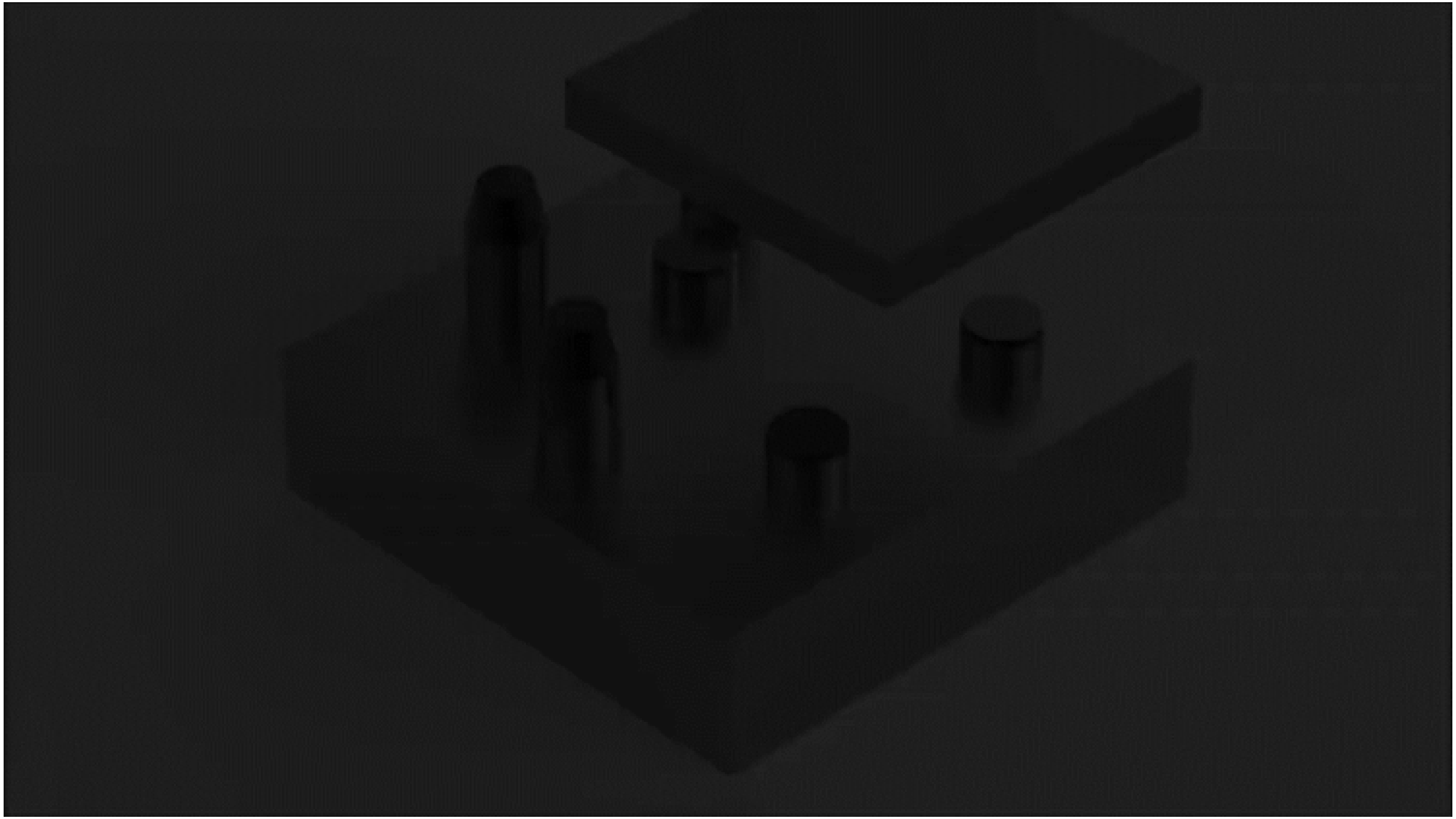
- The term, ***'location'*** refers to the method of establishing correct relative position of the workpiece with respect to the cutting tool.
- In order to decide upon the location method, one has to consider the workpiece shape, surfaces and features that are likely to obstruct the tool movement or access direction.
- The correct positioning of the workpiece essentially requires ***restricting all the degrees of freedom*** of the workpiece
- This is done with the help of ***locators***, which must be strong enough to resist the cutting forces while maintaining the position of the workpiece.
- The proper location of a workpiece requires use of ***minimum number of locating points.***
- Redundant location is not desired in a jig or a fixture design. For external plain surface ***3-2-1 principle of location*** is generally employed.

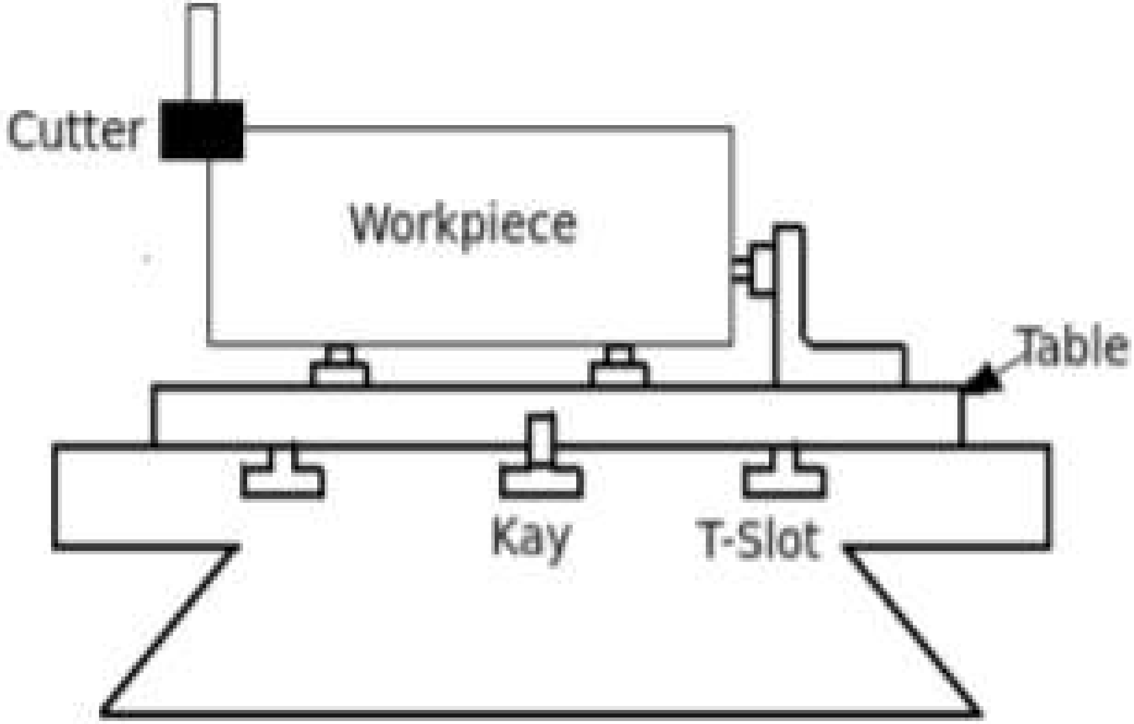


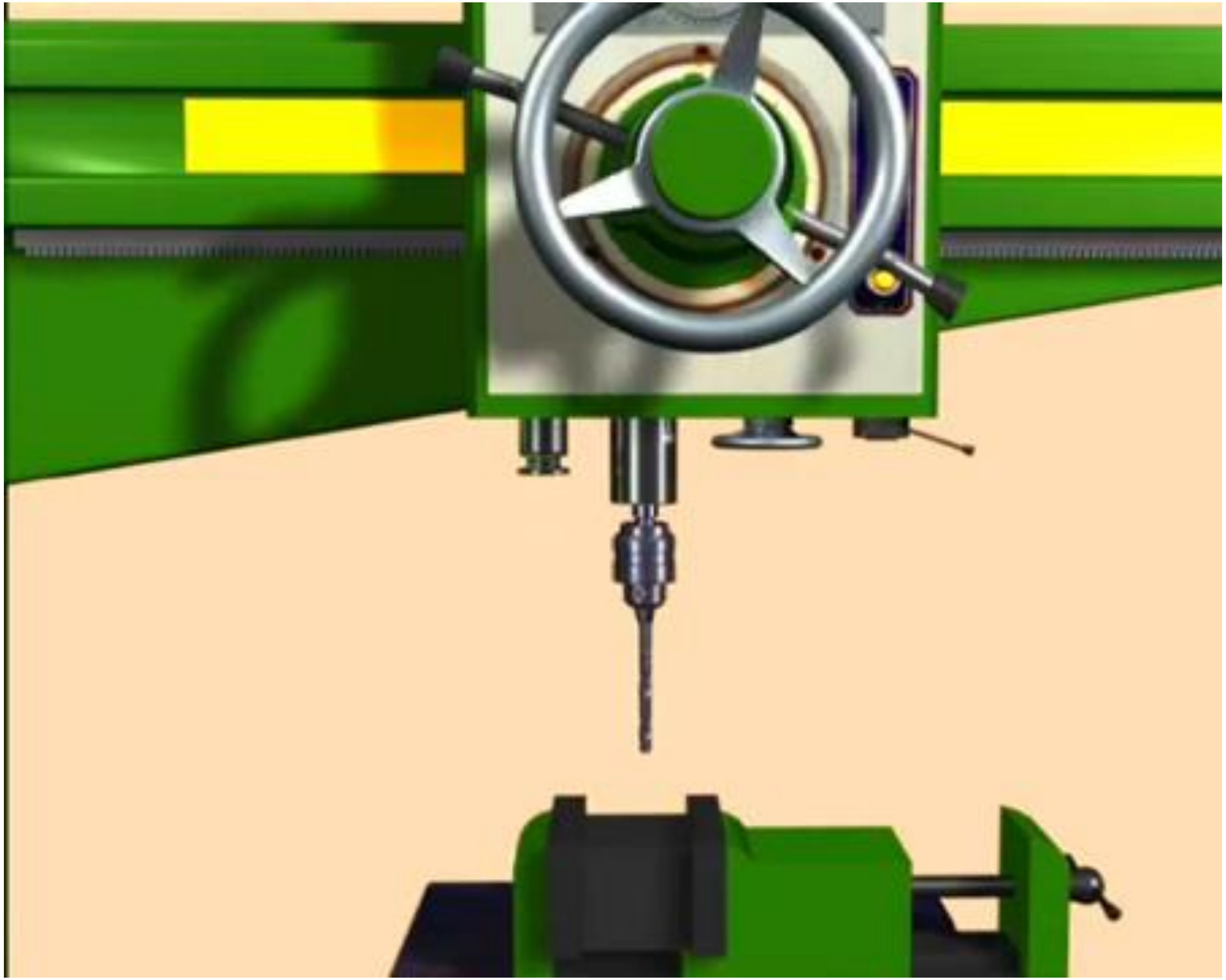


Drilling Jig

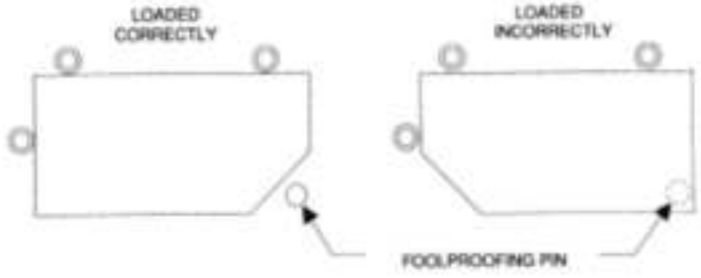





Cutter
Workpiece
Table
Kay
T-Slot



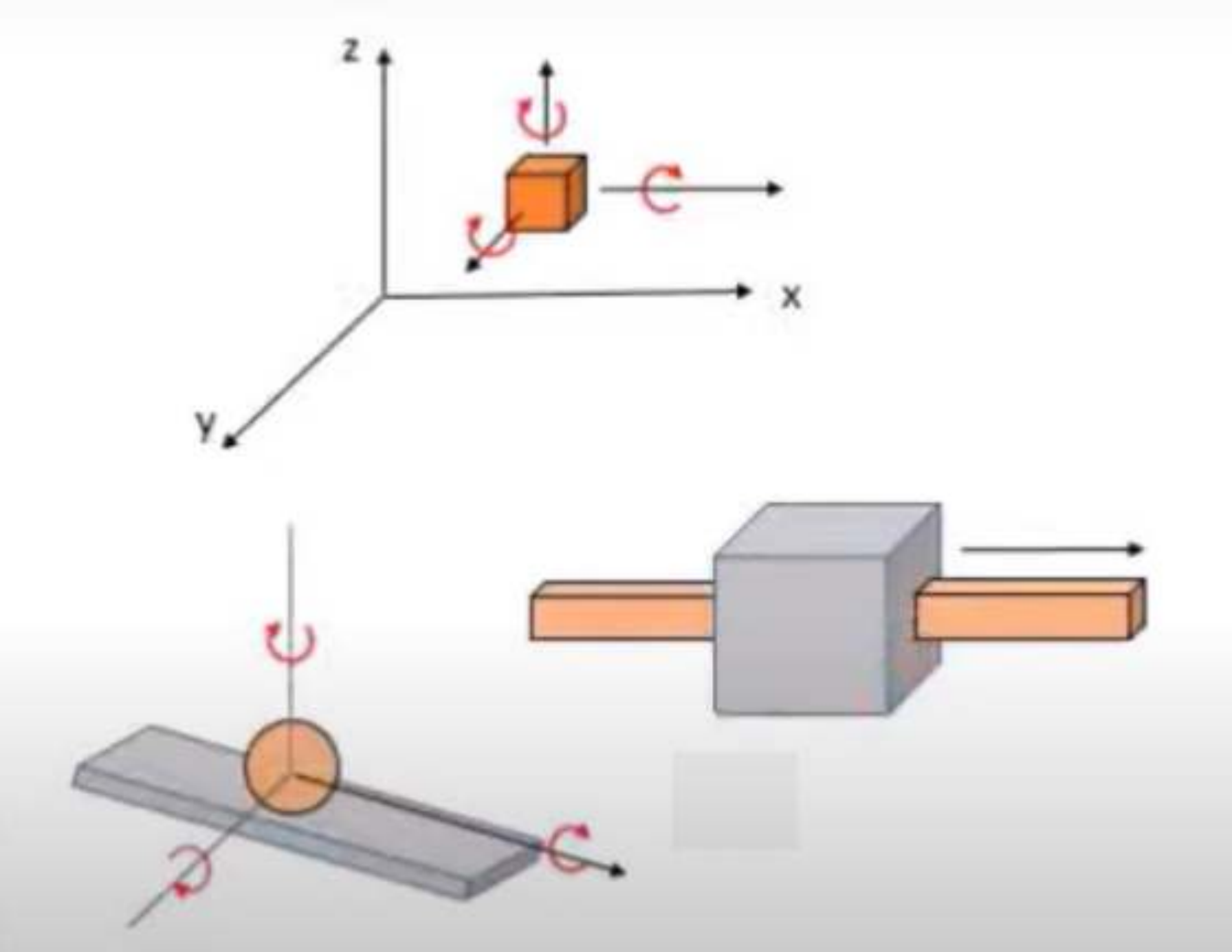
- Location must be related to the ***dimensional requirements*** stated on the work piece drawing.
- It is preferable to use a ***more accurately machined surface*** than a less accurate surface for location.
- The work piece should be ***prevented*** from moving along and rotating around the *x, y, z* axes.
- Location system should facilitate ***easy and quick loading and unloading*** of the work piece and aim at motion economy.
- ***Redundant locators*** must be avoided.
- Location system should positively prevent wrong loading of the work piece by ***fool proofing***.
- Locating ***surfaces should be perpendicular*** to each other to reduce errors.

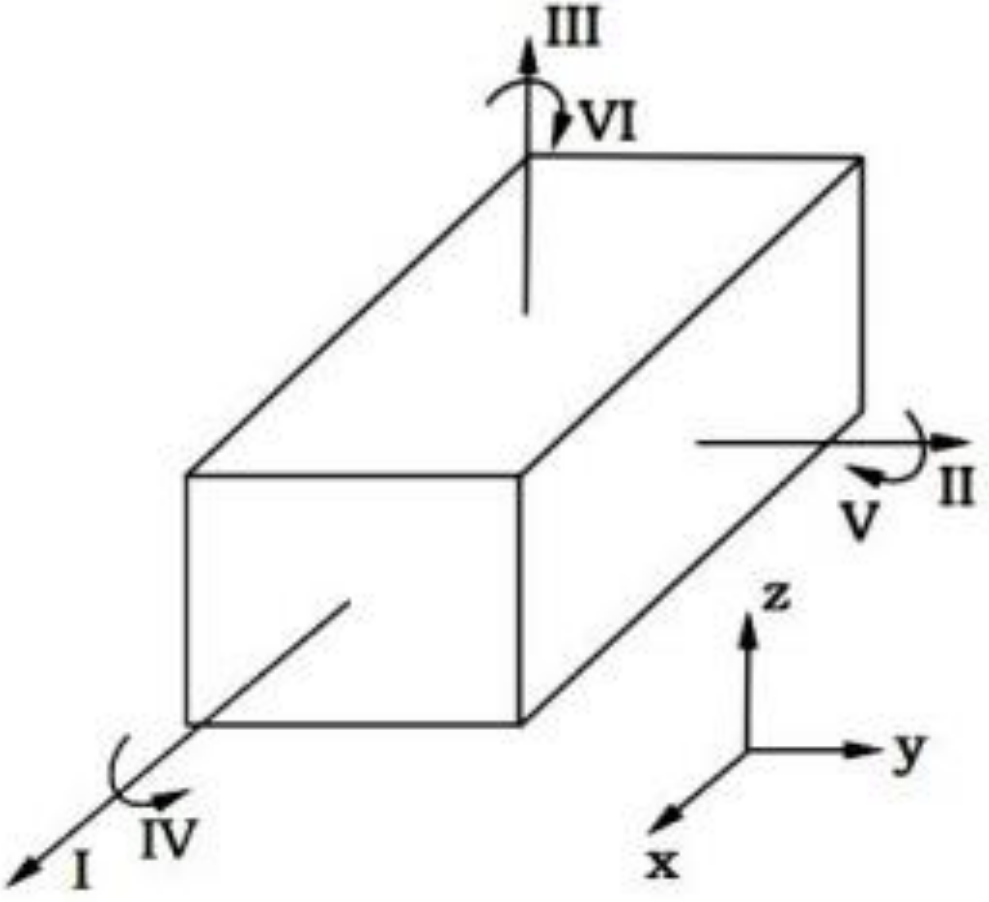


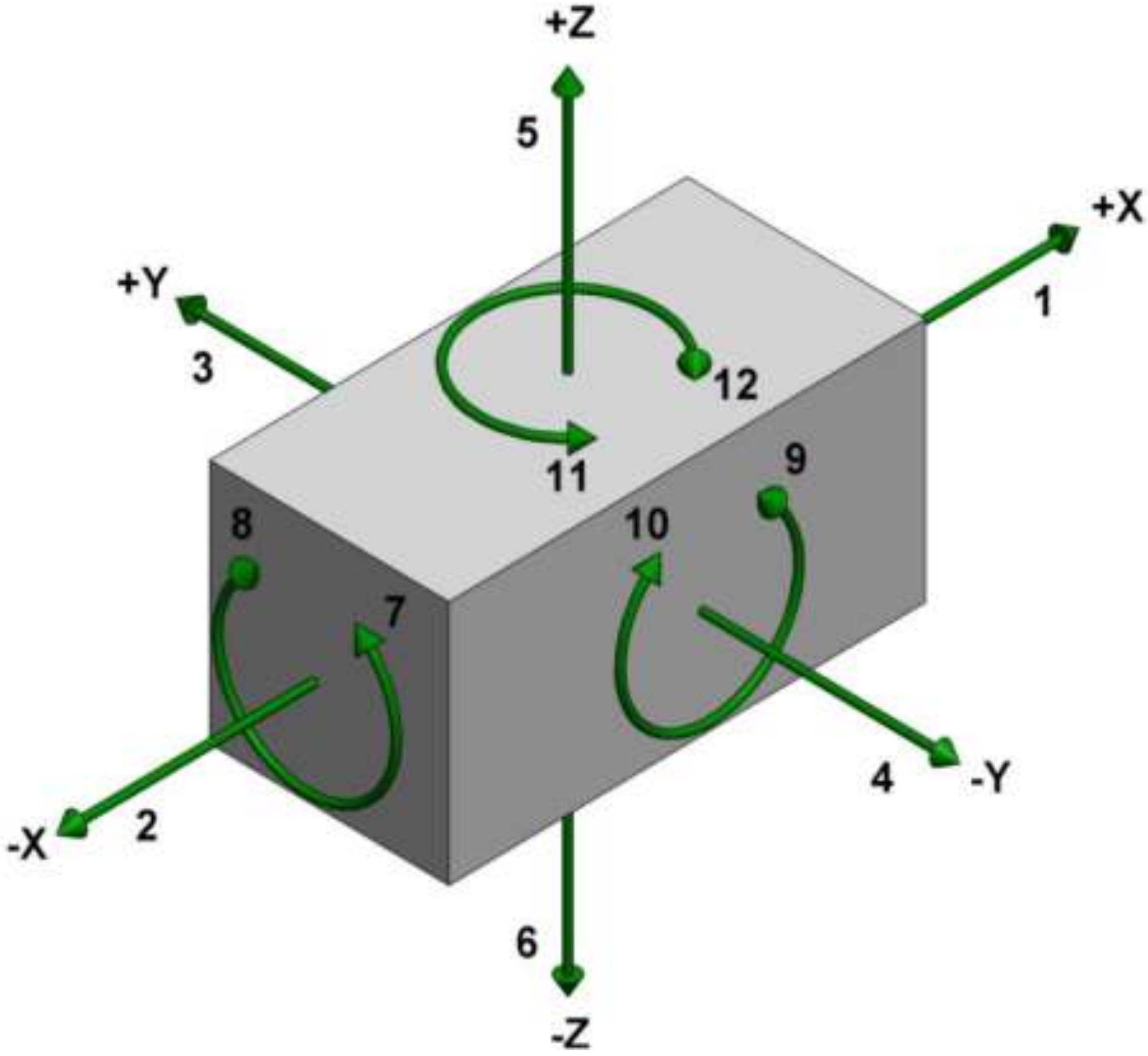
- It is necessary that the work piece need to be properly ***placed and clamped in position (location)*** so that the work piece is not dislocated by the cutting forces acting on it.
- Though ***locating and clamping*** are two distinct problems in practice, these cannot be separated and often the same device may facilitate locating and clamping a work piece.
- ***Jigs and fixtures*** the devices used for this purpose.

Degrees of Freedom

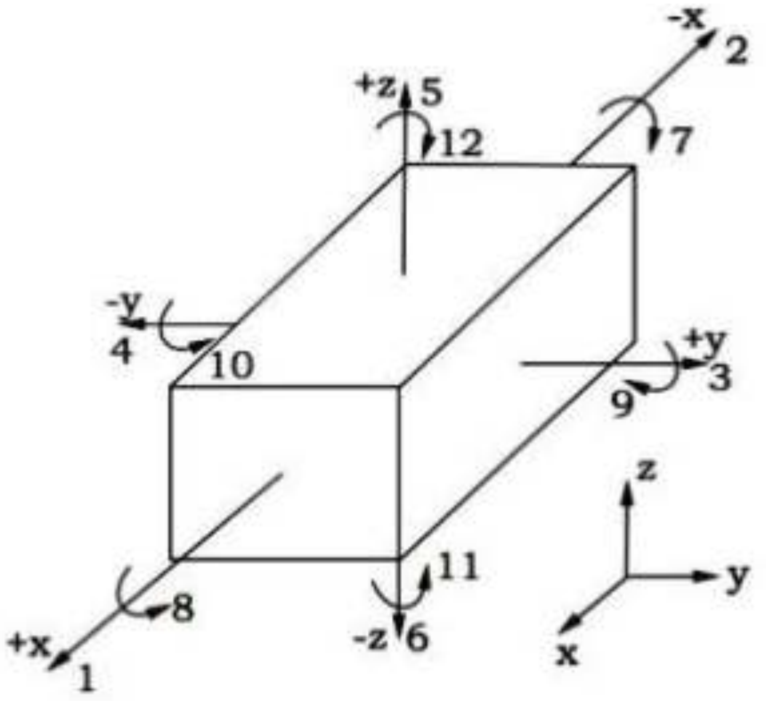
- When we consider the case of any object or body, it has the freedom to move in space unless the movement is restricted.
- With respect to a three dimensional co-ordinate system, we can define these movements as ***translational (linear) movements*** parallel to the co-ordinate axes and rotations about the co-ordinate axes.
- This means the body can have ***3 linear movements and 3 rotary movements*** with reference to the co-ordinate system. Hence, we can say that the body is having ***6 degrees of freedom***. Here, degrees of freedom means, the freedom of movement of the body with respect to the coordinate axes.
- Consider a rectangular block as shown in figure. This rectangular block has 6 degrees of freedom as shown.

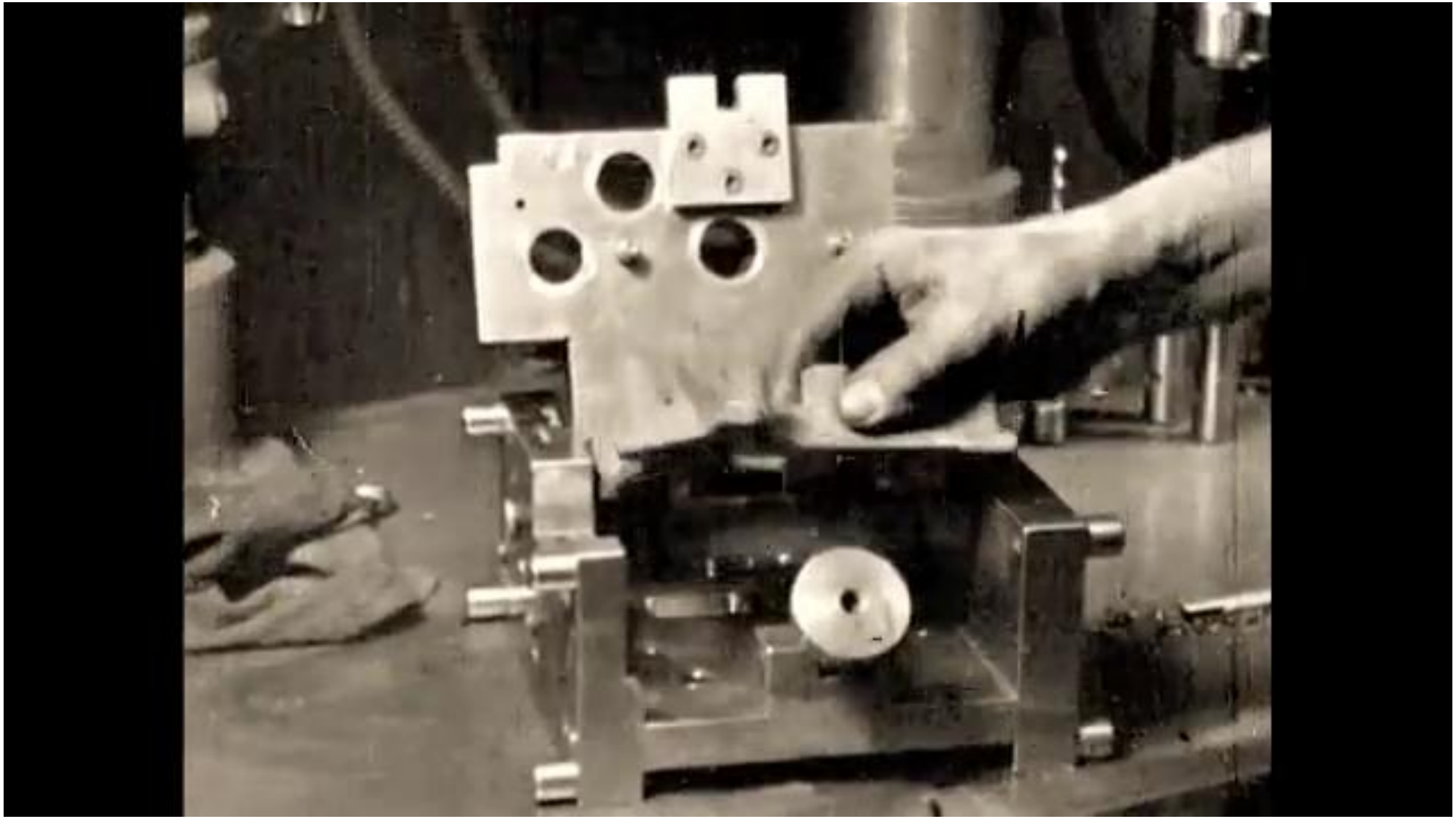

z
x
y


III
VI
II
V
z
y
x
IV
I


+Z
5
+X
1
+Y
3
12
11
9
8
10
7
2
-X
4
-Y
6
-Z

- If we examine the movements of the rectangular block in more detail, it can be said that the block can have ***6 linear*** (translational) movements along the three co-ordinate directions.
- These are along +x, *-x,* +y, *-y,* +z and -z directions.
- In addition there can be ***6 clockwise and anti-clockwise rotations*** about the *x, y, z* axes. All these ***12 degrees of freedom*** needs to be arrested for properly locating and clamping the block.



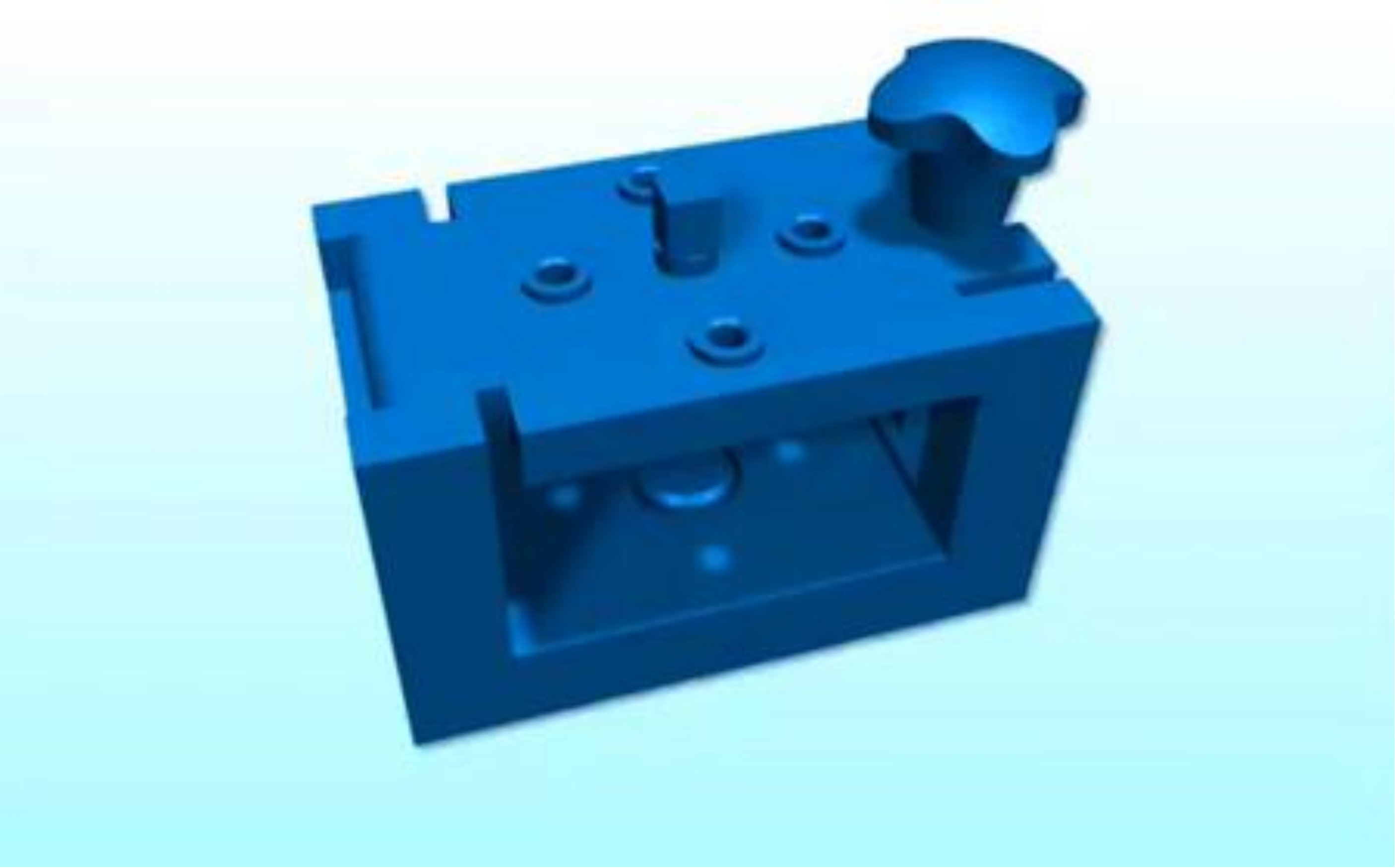


Jigs and fixtures

- Fixtures are strong and rigid mechanical devices which enable easy, quick and consistently ***accurate locating, supporting and clamping, work blanks against cutting tools*** and result faster and accurate machining with consistent quality, functional ability and interchangeability.
- Jig is also a fixture with an ***additional feature of guiding the tool*** to the correct location where machining is to be carried out.

jigs	Fixtures
Jig holds, locates and as well as guides the tool	Fixture holds and position the work but does not guide the tool
Jigs are made lighter for quicker handling and clamping with the table is often unnecessary	Generally heavier in construction and are bolted rigidly on the machine table
Used for holding work and guiding the tool in drilling, reaming or taping operations	Used for holding work in milling, grinding, planning or turning operations

JIG

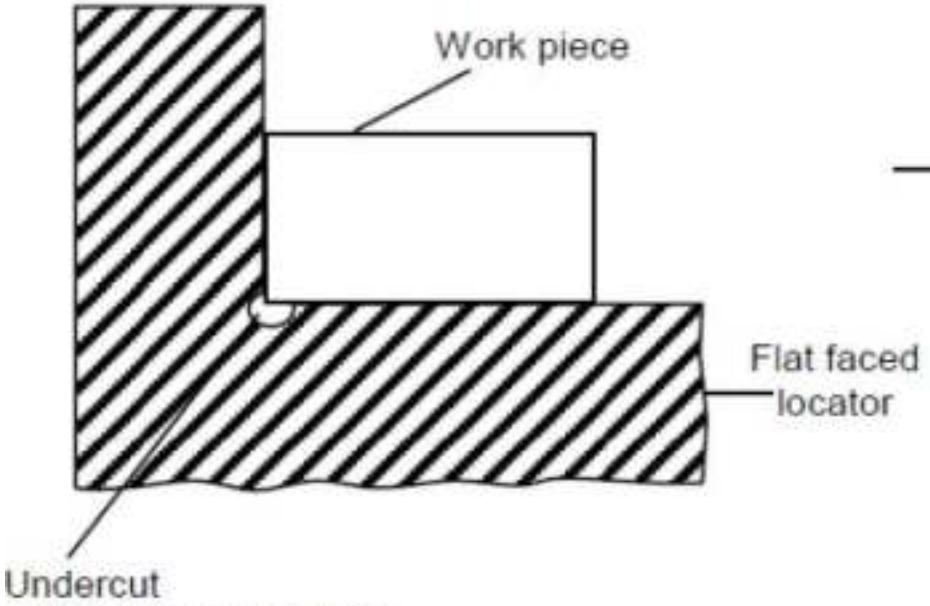


Locating Methods

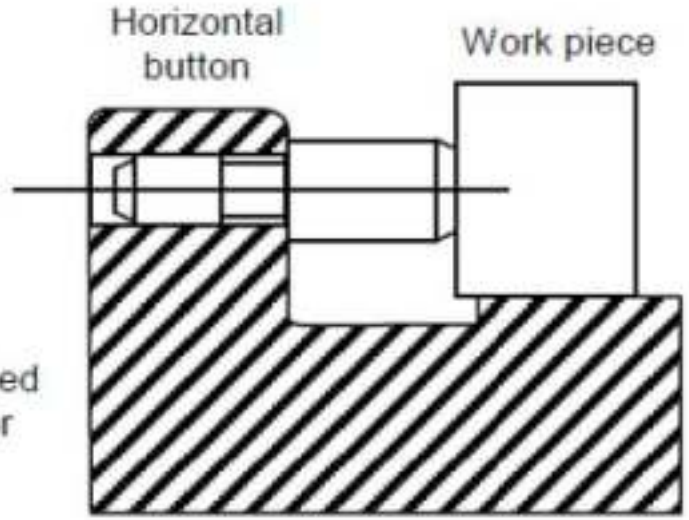
- Locating from plane surfaces
- Locating from circular surface
- Locating from irregular surface

Locating from plane surfaces

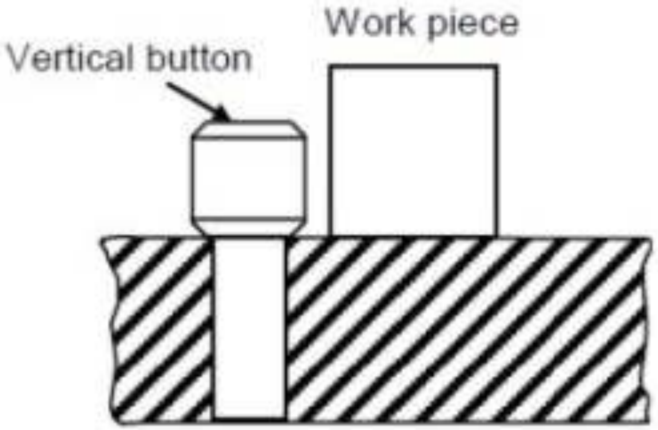
- The basic reference for locating is a flat plane, generally a machine table. The machine table is usually at right angles or parallel with the machine's feed movements.
- Most machines have three standard movements which move the workpiece up and down (vertical), right or left (longitudinal), and in or out (cross).
- All locating devices are made with regard to the basic reference plane (machine table). **If a workpiece with a plane surface is placed upon the basic reference plane (machine table), it will remain in position because of the forces of gravity acting upon it.**
- However, during a machine operation, the **workpiece may move in any direction except** toward the surface of the machine table. The machine table acts as a stop and becomes a locating surface. It prevents movement of the workpiece when forces are imposed upon it by the **vertical feed movement**.



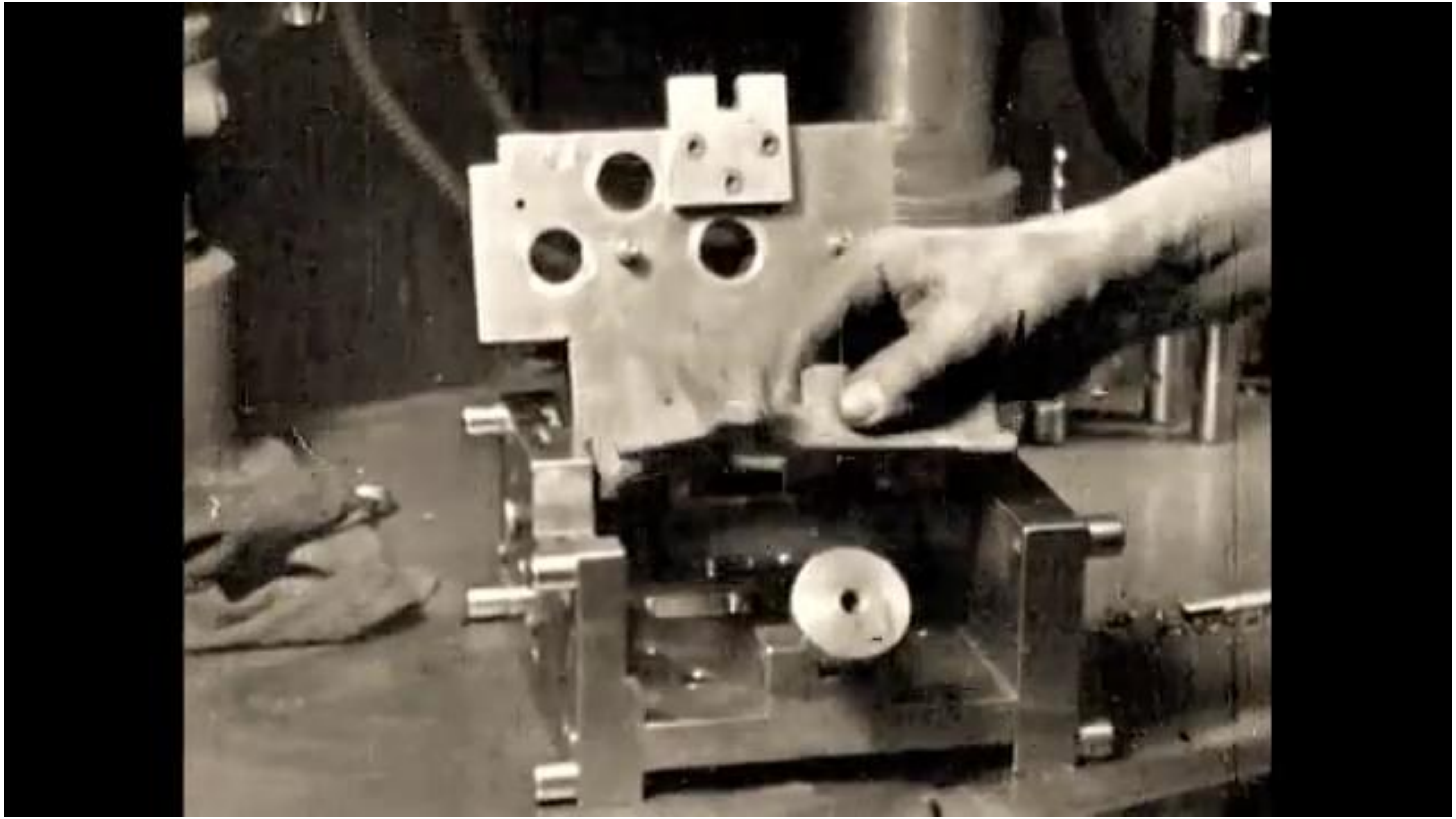
(Location by Flat Jig



Location by Horizontal
Button Type Jig



Location by Vertical
Button Type



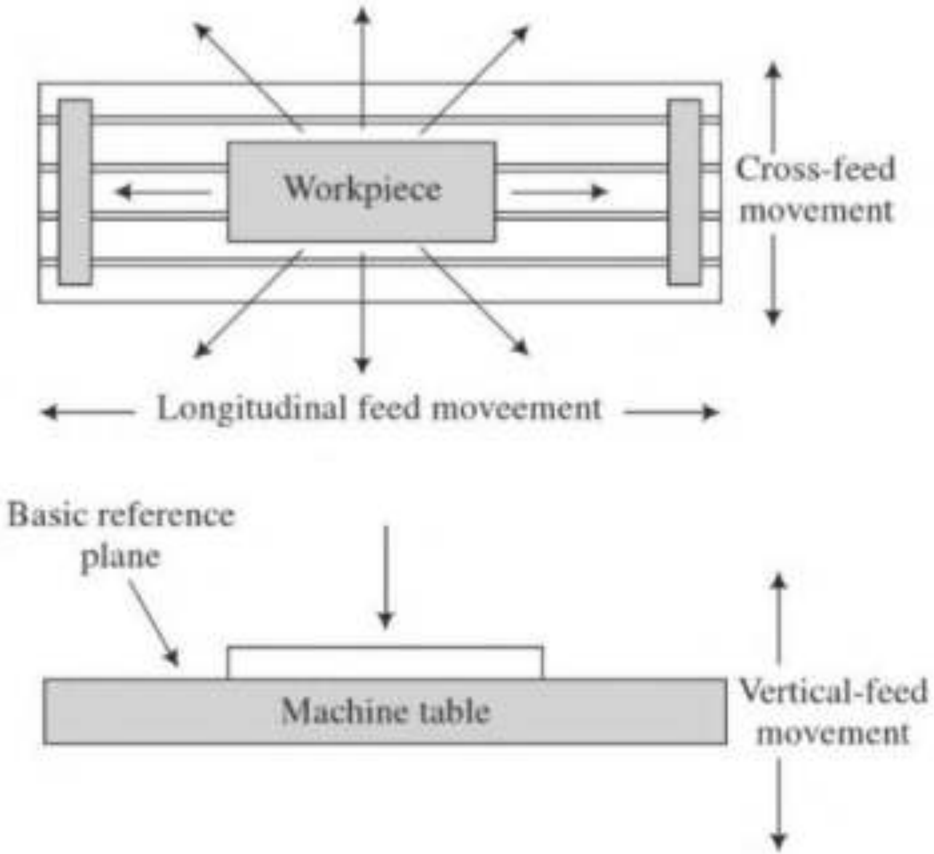


Fig. 6.4 *Workpiece may move in any direction except toward the surface of the machine table*

- If the workpiece does not have a flat side to mate with the machine table, the flat plane of the machine table cannot be used as a locating surface. It becomes necessary to reduce the contact area of the locating surface. A series of sharp points would give the theoretical minimum amount of contact area, but in practice the points must have enough body to prevent breaking and rapid wear.

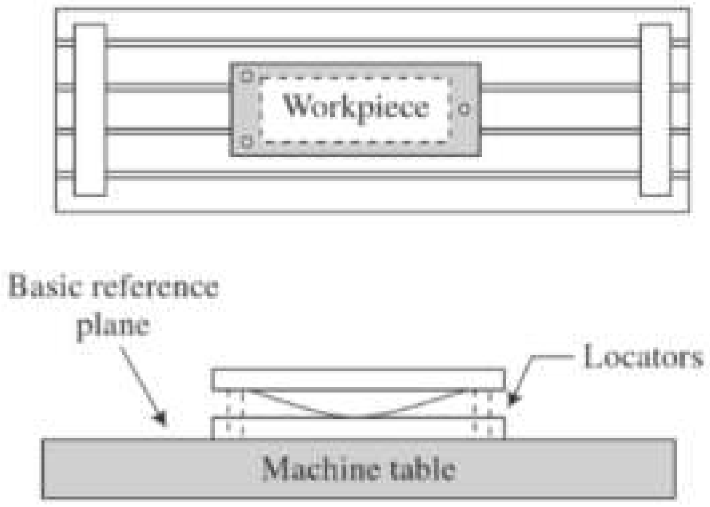
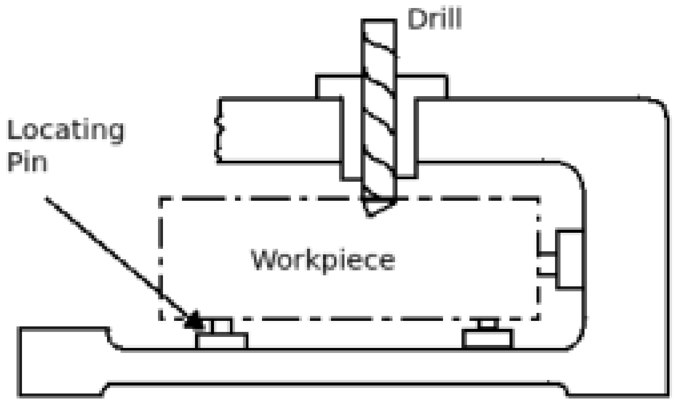
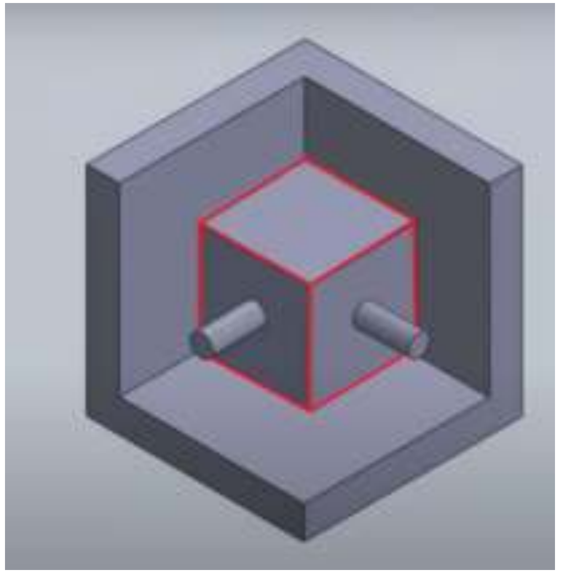


Fig. 6.5 *The use of three locators to establish the workpiece in a plane parallel to the reference plane*

- The pins should be spaced as widely as possible for more accuracy. When using the 3-2-1 principle, the three pins can define a plane, but they cannot provide adequate support to the workpiece during machining.
- With these **three pins, the movement of workpiece in vertical direction is prevented**. Still the workpiece is **free to move along the horizontal plane against the forces due to longitudinal or cross feed movement in a machine**.
- **Providing two locating points in a second plane and another locating point on a third plane would solve this.**



Drilling Jig



Locating from plane surfaces (*3-2-1 principle of location*)

- The proper location of a workpiece requires use of ***minimum number of locating points***.
- For external plain surface, ***3-2-1 principle of location*** is generally employed.
- In order to understand 3-2-1 principles of location, let us consider a rectangular block with all the planes perpendicular to each other. The rectangular block has ***12 degrees of freedom.***
- In order to properly locate the block, ***all the 12 degrees of freedom need to be restricted*** with suitable locating points.
- Location of the block can be done using ***six locating points***; three locating point in the primary locating surface, two locating points in the secondary locating surface and one locating point in the ternary locating surface.

- Placing the primary locating surface of the block on the ***three locating pins restricts five degrees of freedom***; one linear movement (along—Z direction, or 6) and four rotational movements (7, 8, 9 and 10). The two locators

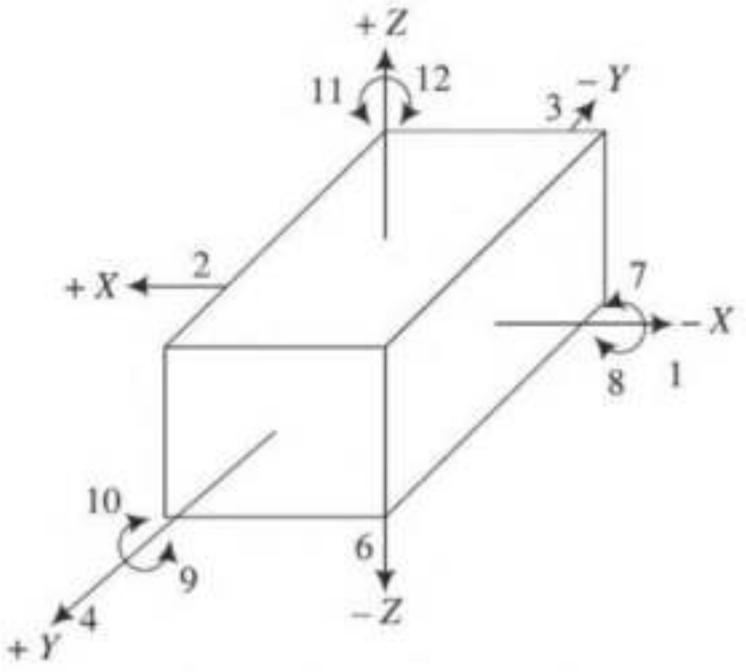


Fig. 6.1 *Twelve degrees of freedom of rectangular block*

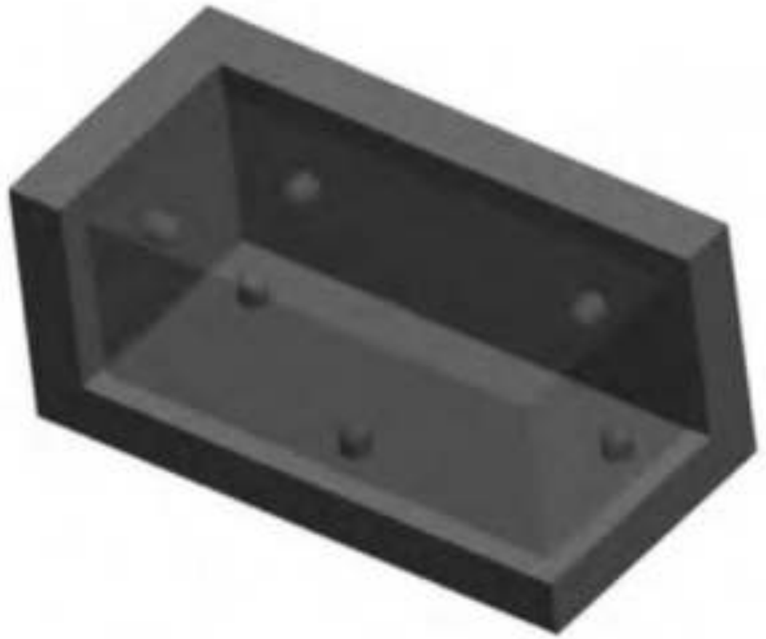


Fig. 6.2 *Six point location of a rectangular block*

- The ***two locators placed*** on the secondary locating surface restrict ***three more degrees of freedom***; one linear movement (along + X direction, 2) and two rotational movements (11 and 12).
- The ***one locator positioned on the ternary surface*** of the block restricts one linear movement (along +Y direction, 4).
- Therefore, six locators(1+2+3) restrict ***nine degrees of freedom***. Remaining three degrees of freedom is restricted by ***clamping the block***.

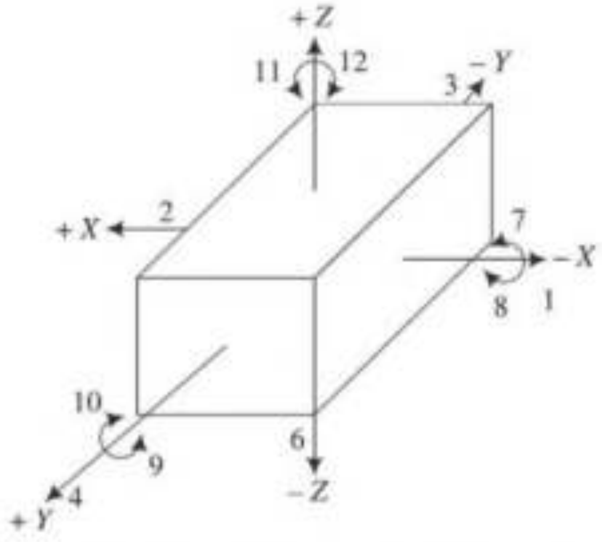
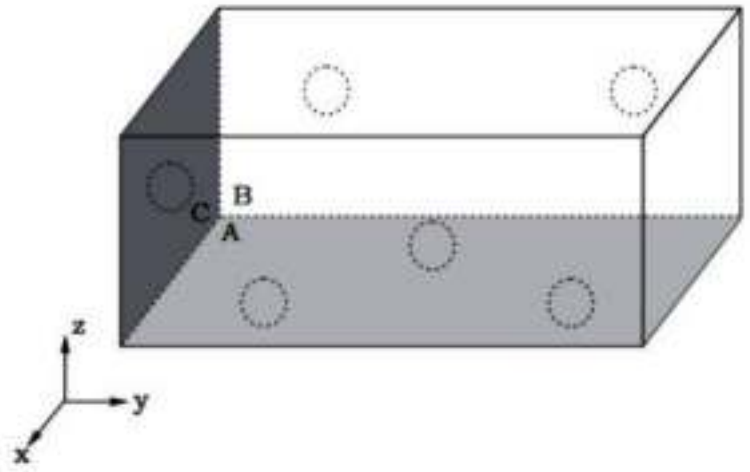
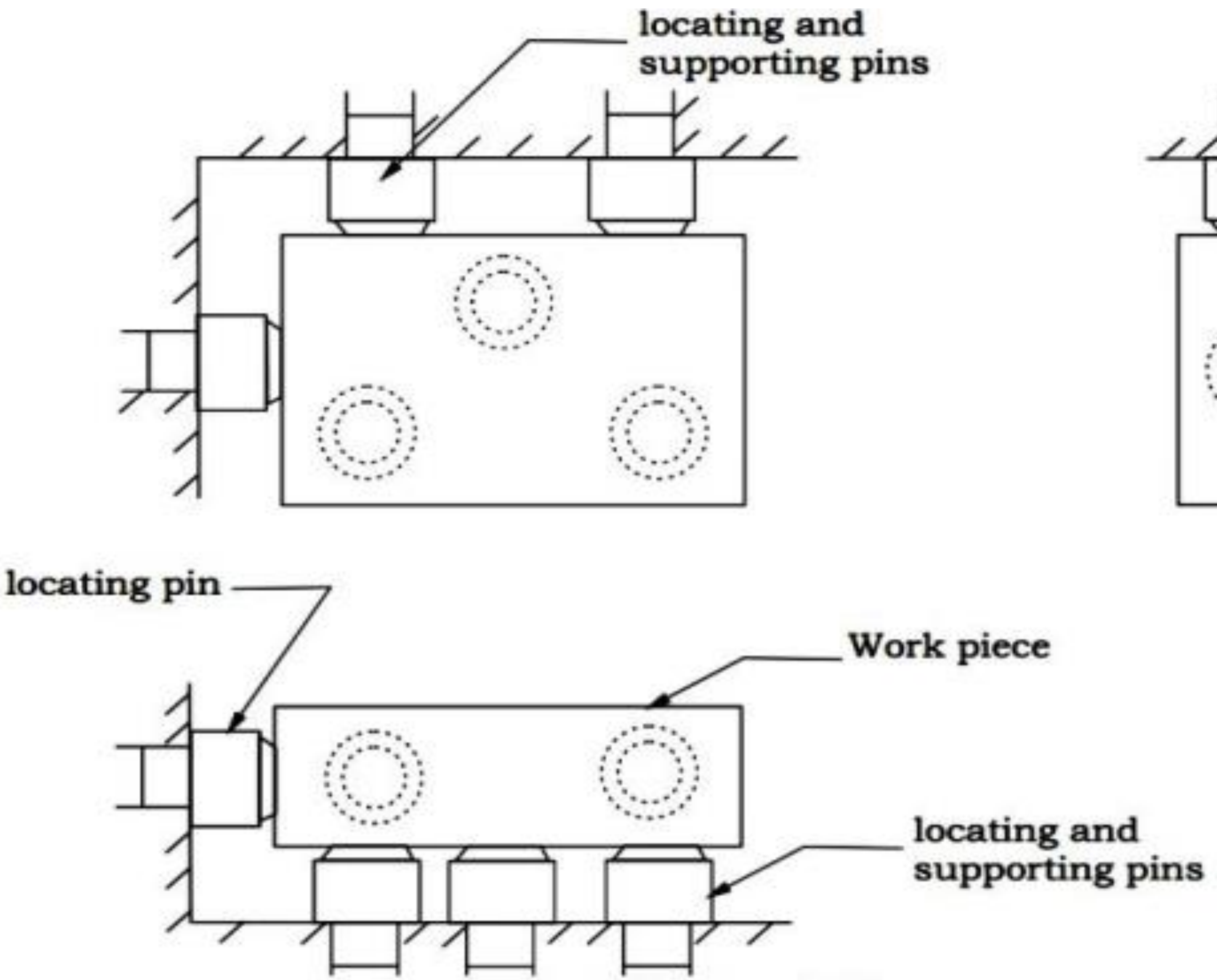


Fig. 6.1 *Twelve degrees of freedom of rectangular block*

Fig. 6.2 *Six point location of a rectangular block*

- Here the movements of the block are arrested by three locating points on the primary locating surface marked A, two locating points on the adjacent surface marked B and another one locating point on the ternary locating surface marked C.
- Hence, location of the ***rectangular block can be done using six locating points***. This method of using 3-2-1 locating points on three adjacent sides is known as the **3-2-1 principle of locating**.
- ***When the workpiece is removed from this position, every time it can be replaced exactly in the same position. But the workpiece needs to be properly clamped to retain it in this location during the machining.***





locating and
supporting pins
locating pin
Work piece
locating and
supporting pins

LOCATING FROM CIRCULAR SURFACE

- Location from cylinder is the most common and convenient form of location. Here also we can take the ***flat plane of machine tool table*** as the basic reference for location.
- Here we have to ***locate the base and axis of circular workpiece***, then it can only rotate about its axis.

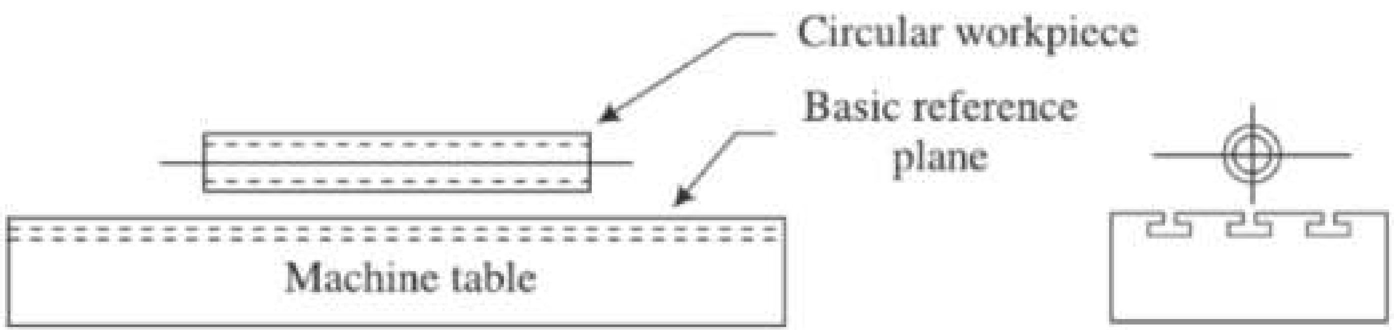


Fig. 6.9 *Circular workpiece must be located with its axis parallel with the basic reference plane*

LOCATING FROM CIRCULAR SURFACE

- One of the common methods of locating from a circular surface is by ***using cones,*** a method commonly referred to as ***conical location*** and usually employed when locating is done from a hole.
- The same system may be used when locating on the outside of a circle, except that the **cones are inverted to form cups.**

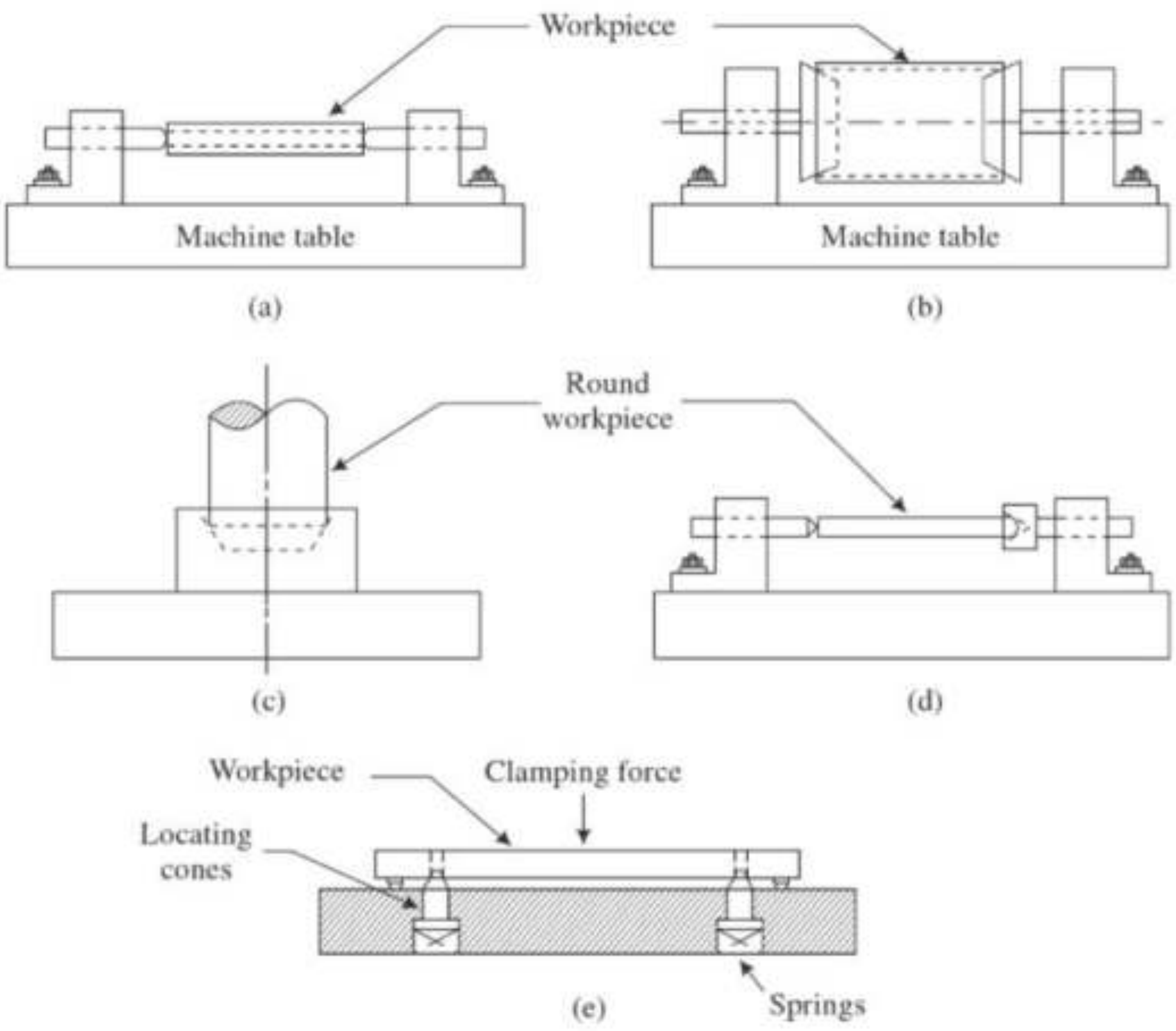


Fig. 6.10 *Methods of conical location*

- The ***V method*** is also used to locate round workpieces. An angle of 90° is best suited for the V blocks.
- The V block should be positioned in such a way that the changes in ***workpiece diameter*** will not affect location on the workpiece.

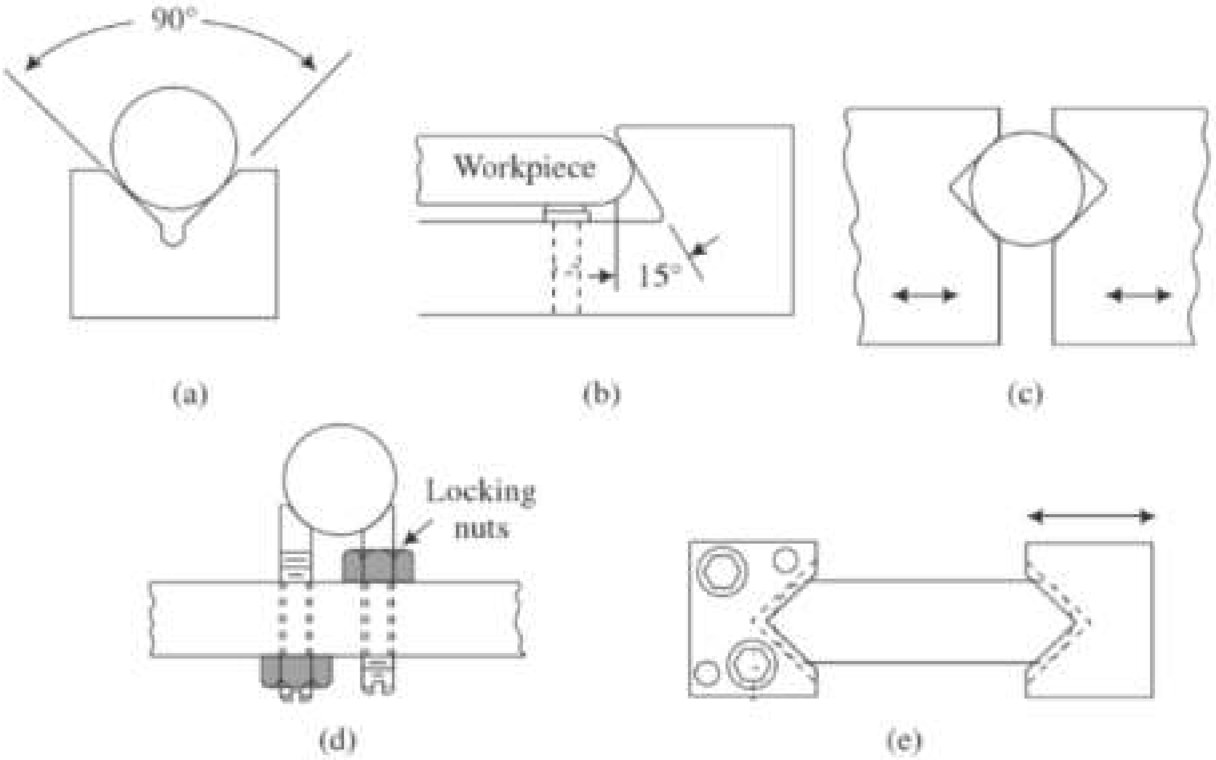


Fig. 6.11 *Methods of V location*

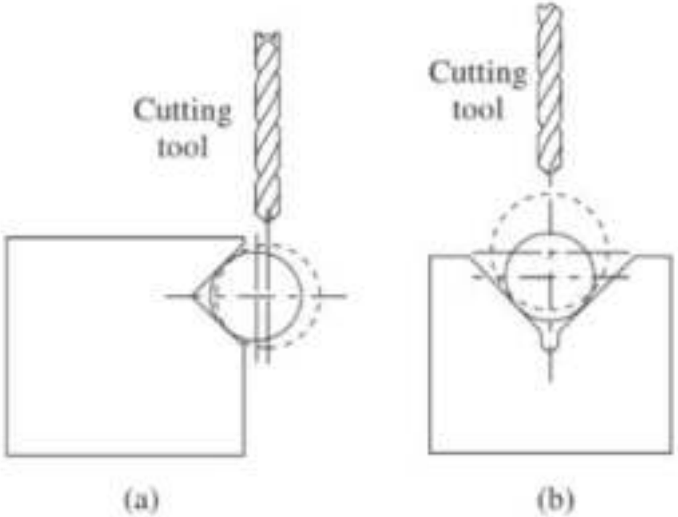
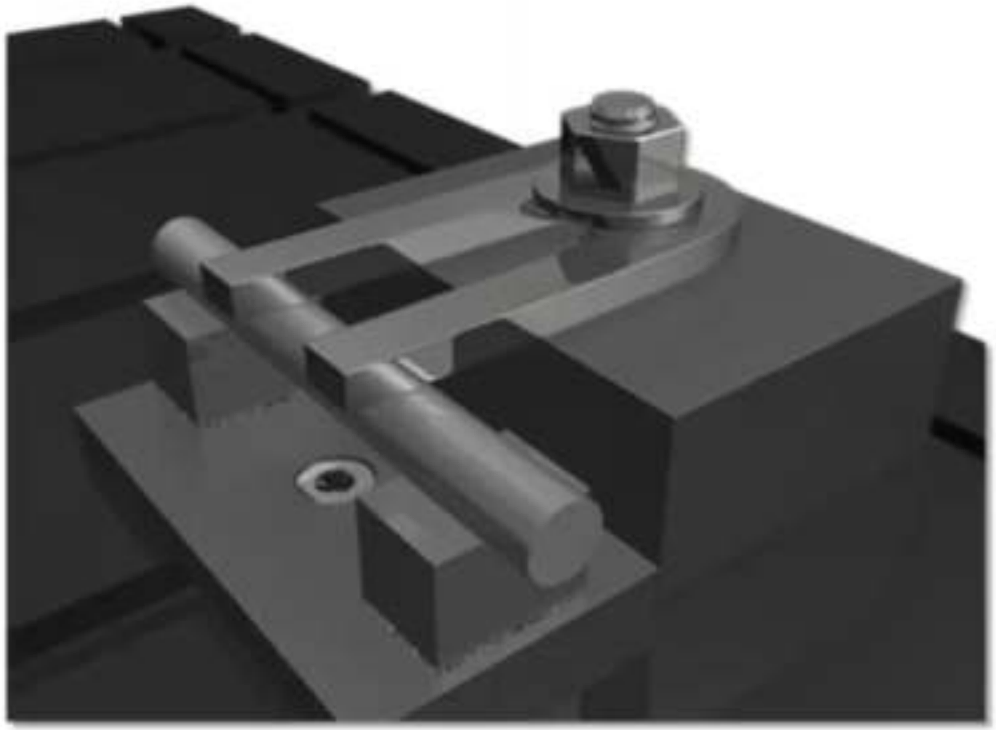


Fig. 6.12 *V should be directed in such a way that variations in workpiece size will not affect location*

CLAMPS AND BOLTS



- Conical locators are used mainly to locate **rough unmachined cylinders in castings and forgings.**
- V locators are used extensively to locate cylindrical surfaces from outside. Fixed V blocks are used for approximate location.
- For precise location, **adjustable, guided V blocks** are used, which are adjusted by a screw or a cam.

- ***Concentric Locating*** method combines both locating and clamping since the work is usually positioned to a ***common centre.***
- ***Chuck is a commonly used clamping and locating device***, where both the chuck and workpiece rotates. **Chuck is also used to clamp and locate idle workpieces** to machine tables.
- In the case of a self centering chuck, it is easy and quick to locate and clamp round workpieces of various diameters.

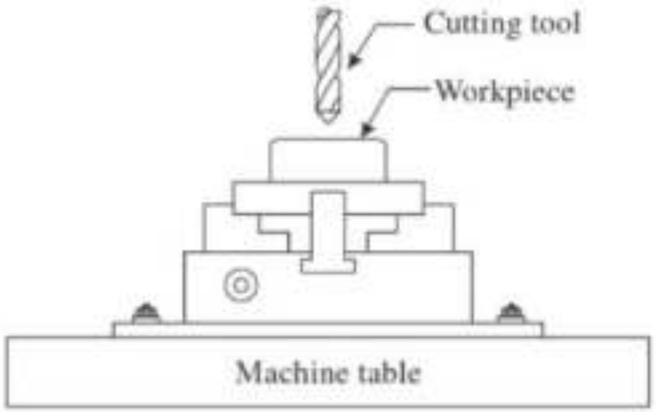


Fig. 6.13 *Use of a three-jaw universal chuck as a work-locating and clamping device*

LOCATING FROM IRREGULAR SURFACE

- Those surfaces which are neither ***flat nor circular*** are treated as irregular. They may or may not be ***geometrically true***. For example, a parabolic or ***elliptical*** surface would be considered an irregular surface.
- ***A surface of a workpiece that may vary dimensionally from time to time would also be an irregular surface***. An example would be the raw edge or surface of a casting.
- The ***degree of roughness*** may also determine whether a surface would be considered flat, circular, or irregular.
- A rough flat surface may have to be considered as an irregular surface when determining locating methods, especially ***when workpiece dimensions vary from part to part***.

- Locating methods used for flat and circular surfaces may be used for some irregular surfaces that are finished and geometrically true. For example, ***V locating methods*** may be used to locate certain parabolic surfaces, and ***button locators*** may be used to locate certain elliptical surfaces.
- ***It may be necessary to locate from an irregular surface only during the first machining operation***, as it should produce holes or surfaces that can be used as reference or locating points for subsequent operations.
- The unevenness of the surface of a casting will allow a ***maximum of three contact points***. If more than three points are used, the work piece will deform when clamping pressure is applied.
- It is therefore necessary to use adjustable rest pins or equalisers to compensate for the unevenness of the work piece surface.

- One of the simplest types of adjustable rest pins, commonly called *a **fixture jack***.
- During usage, the workpiece is positioned on three non-adjustable locators, and the ***jacks are adjusted until they touch the workpiece surface.***
- The contact pressure between the jacks and the workpiece depends upon the judgment of the operator.

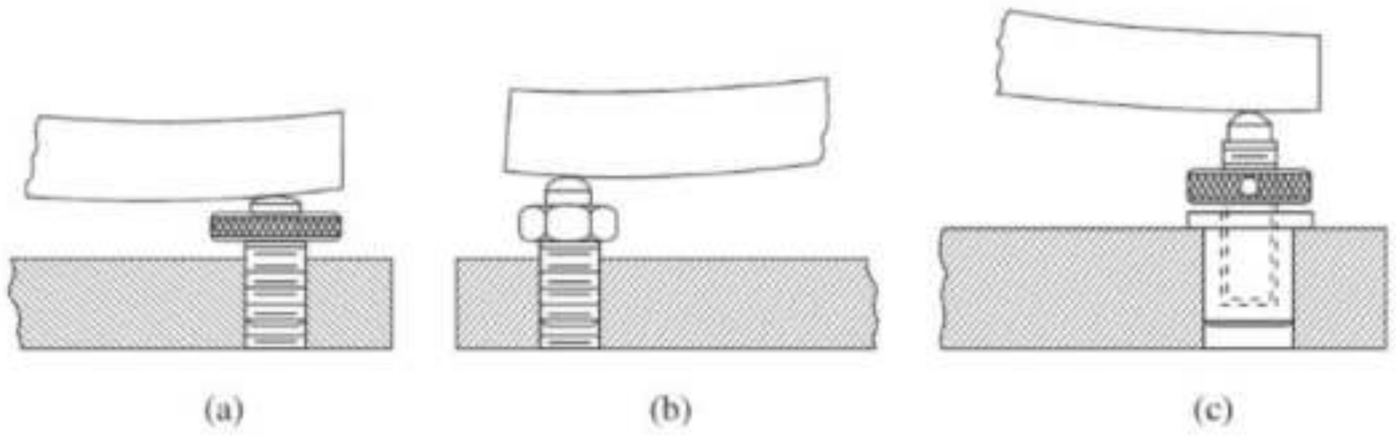
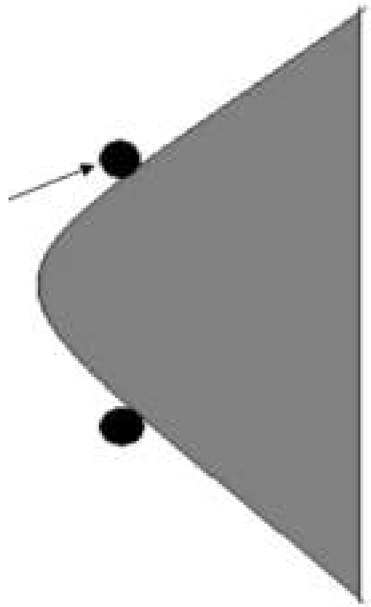
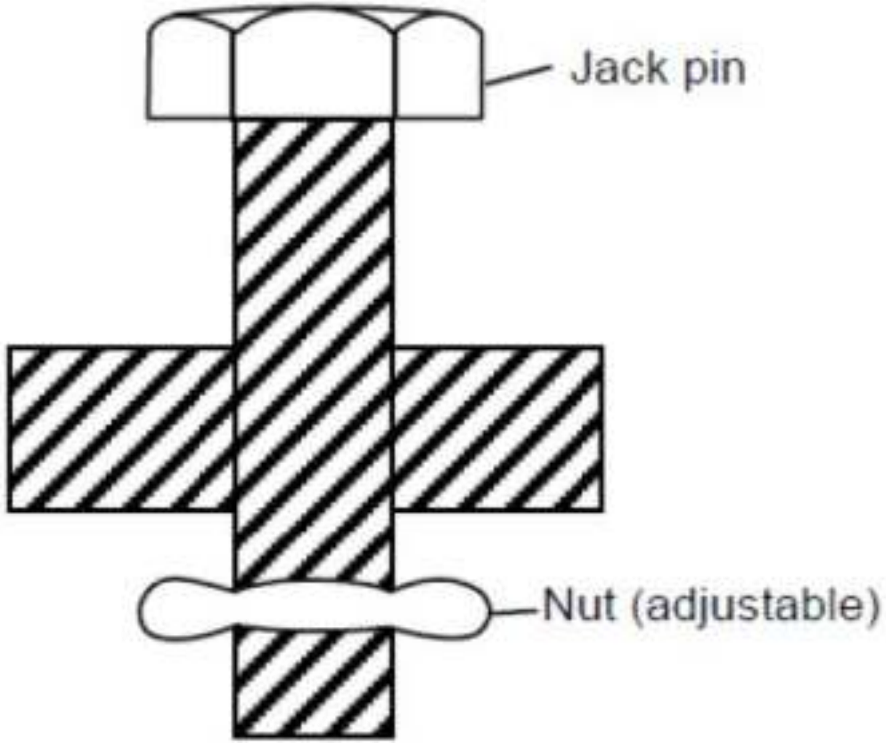


Fig. 6.14 *Types of adjustable rest pins or fixture jacks*




Jack pin
Nut (adjustable)

- Modified versions of fixture jacks which can be placed under the workpiece and easily accessed by the operator are also used.
- In addition to fixture jacks, mechanical ***equalising jacks*** are also used in combination with rest pins or cone locator pins.
- After locating the irregular surface in one plane, the same steps are to be extended to the two remaining planes.

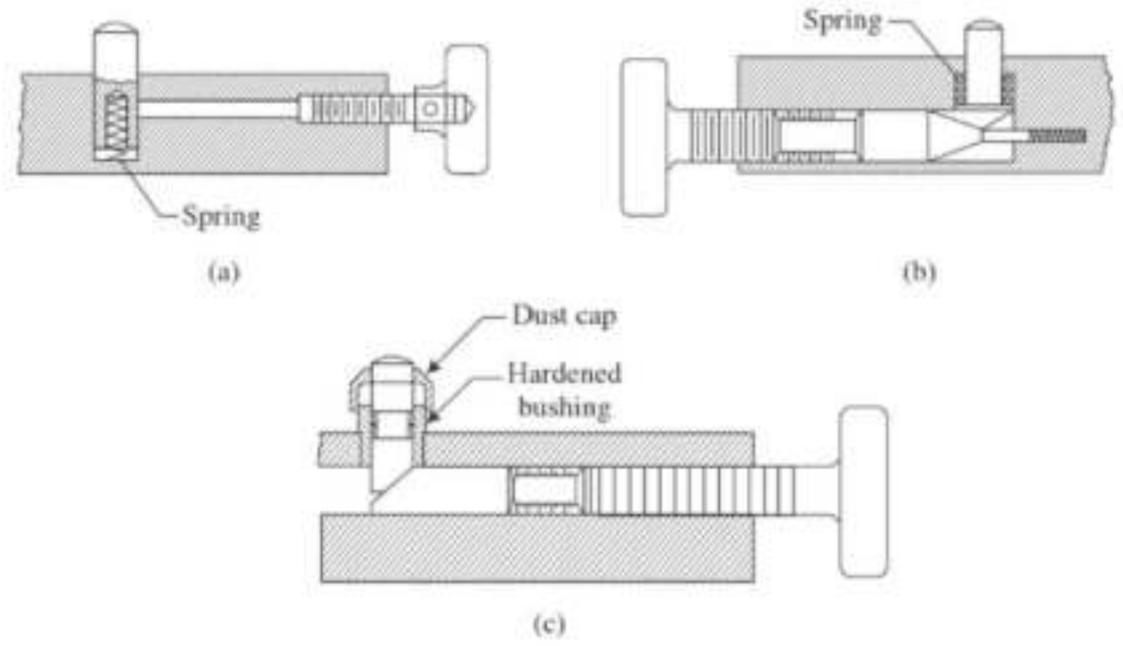
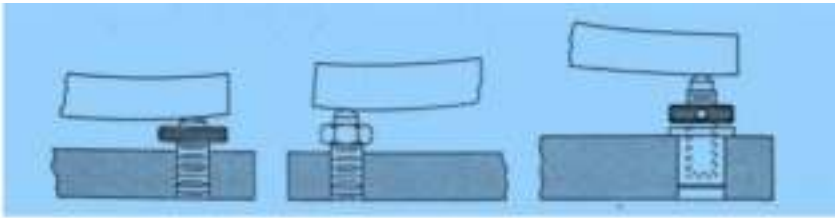
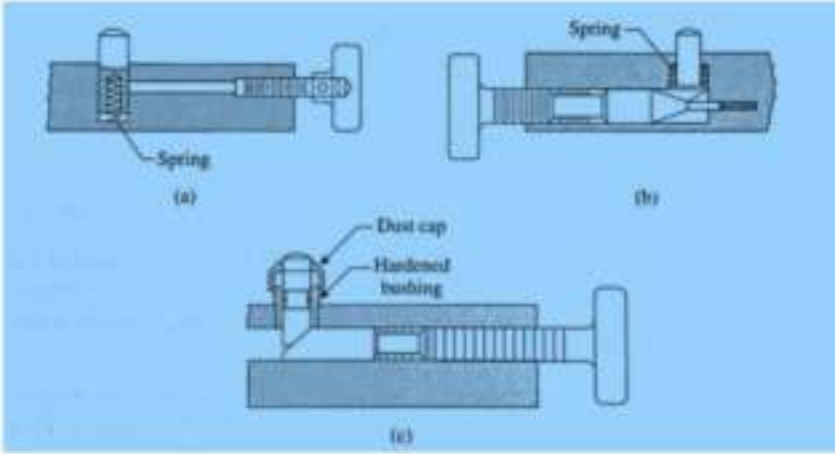
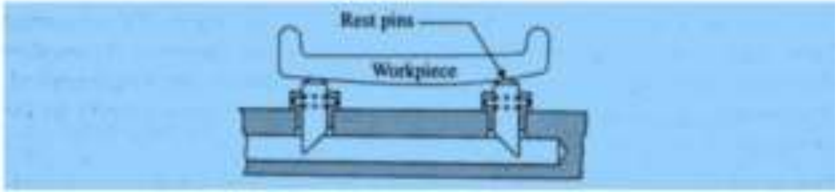


Fig. 6.15 *Fixture jacks that can be placed well under the workpiece*

- ***Adjustable pins***: The workpiece of any geometry can be located with adjustable pins.
- ***Fixture jack***:The workpiece is positioned on three non adjustable locators and jacks are adjusted until they touch the workpiece surface.
- ***Mechanical equalizing jack***: They give nearly equal contact pressure between the two locators.







Locating methods and devices

Three most common types of locating points are buttons, pins and pads. Buttons are made of steel, of round cross section and have either a flat or spherical head.

1. Pin and button locators

- One of the common methods of location is to **use pins and buttons**.
- A round pin or button is used to firmly support or hold the workpiece in position.
- The main difference between pins and buttons is in **length**.
- Buttons are generally **shorter than pins** and are used for vertical location. Pins are usually used for **horizontal location**.
- Larger sizes are sometimes referred to as **plugs**.

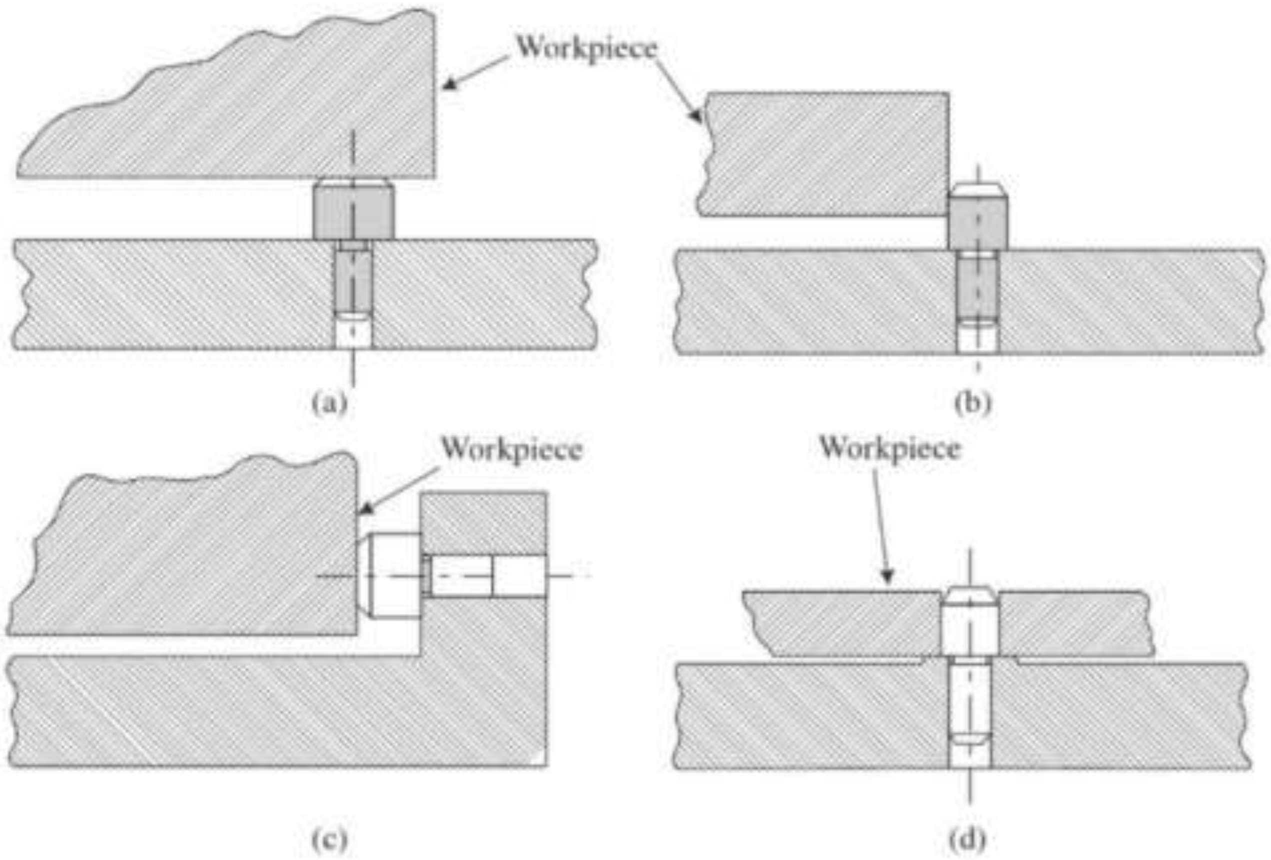


Fig. 6.21 *Use of pins and buttons as locators*

Fig. a, the button is used for workpiece support (vertical location). In **b** and **c**, the button and pin are used to locate the edge of the workpiece (horizontal location). The pin in **d** is used to locate from a hole produced by a previous operation.

- Pin and button locator can again divide to **fixed type and adjustable type**. The fixed type pin and button has a fixed length while in adjustable type, the length of pin/ and button is adjustable according to needs.
- The adjustable model is used where the surface of component is rough and uneven.

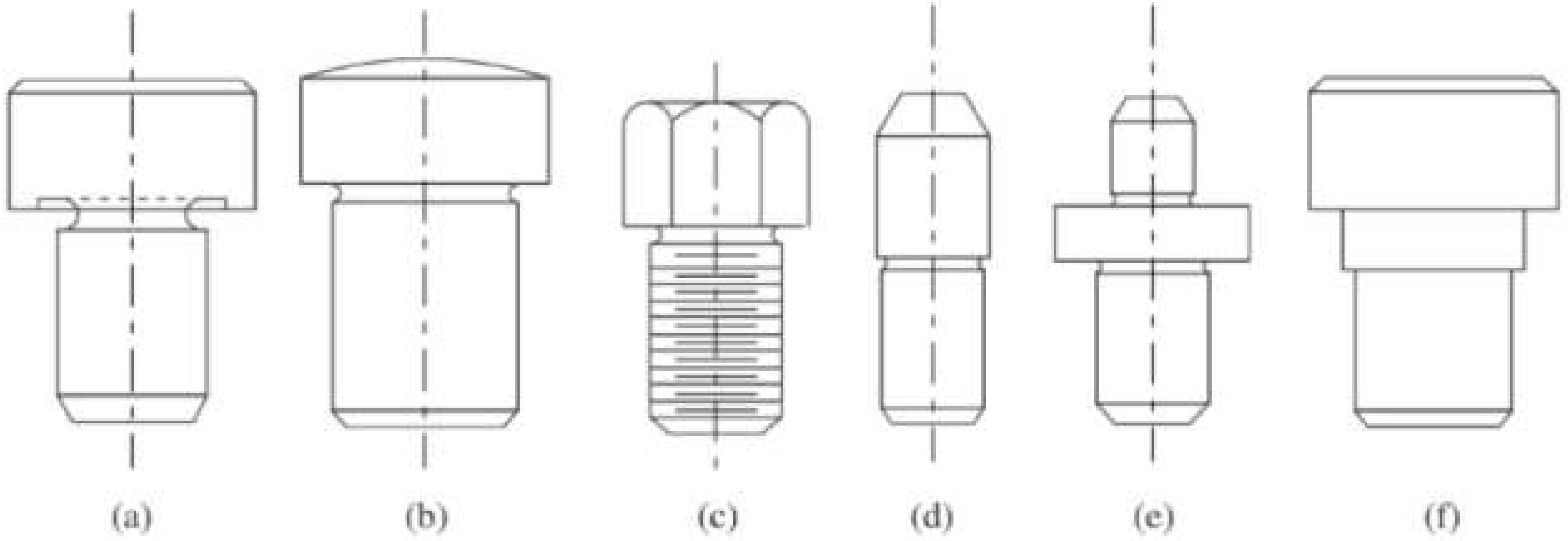


Fig. 6.22 *Standard buttons and pins*

- The rest button in **Fig (a)** is used when the workpiece surface is flat, while the spherical-radius button in **b** is used when the workpiece surface is rough and irregular. The screw rest button in **c** is used when a through hole is not possible and therefore provides a means of easily removing the button. The pin in **e** serves as a workpiece support as well as a locating pin, while the button in **f** contains a dirt groove when installed in a jig or fixture baseplate.

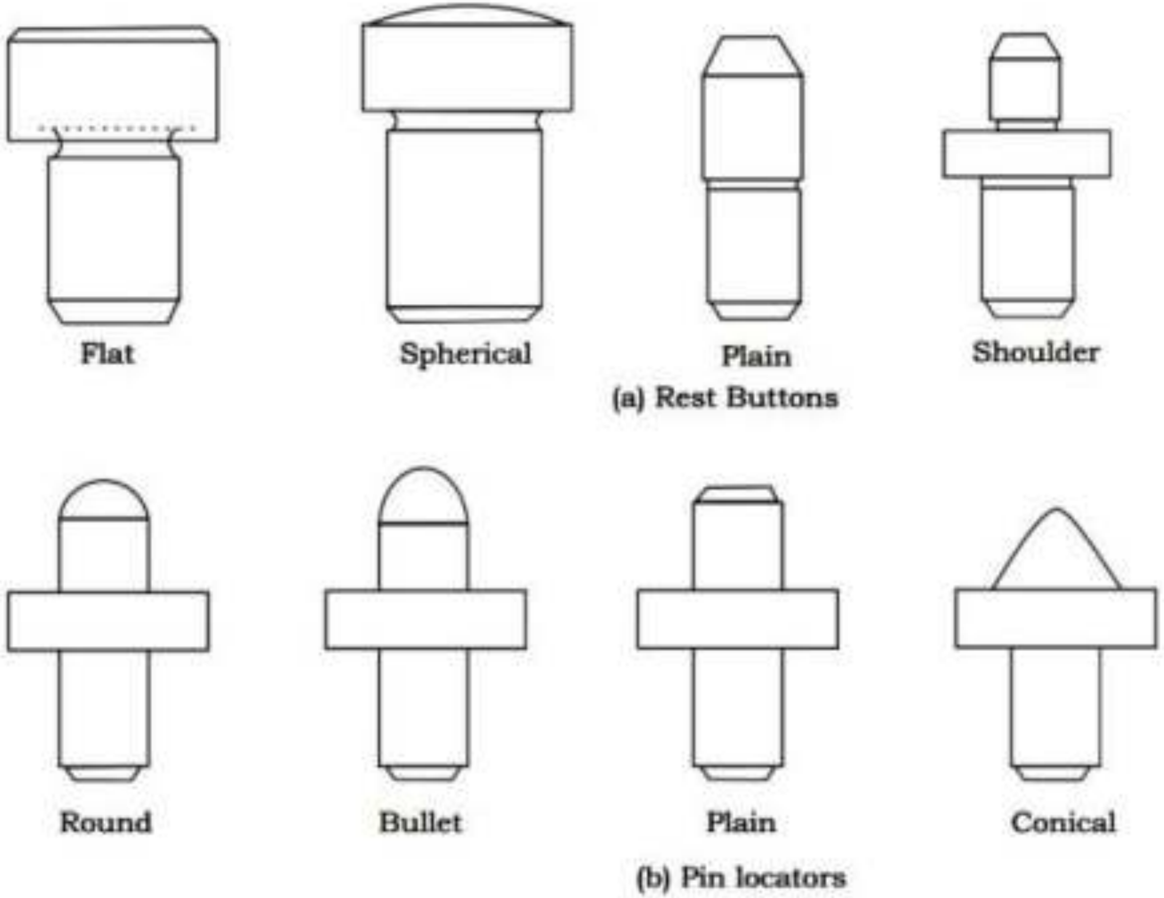

Flat
Spherical
Plain
Shoulder
(a) Rest Buttons
Round
Bullet
Plain
Conical
(b) Pin locators

Figure 5.4

Pin Locators

2. Rest pads and plates

- **Rest pads and plates** are used to support and locate work vertically in a **manner similar to rest buttons**, but the**y are used with larger and heavier workpieces**.
- Rest pads are similar to rest buttons but do not have a shank. They are held to the jig or fixture baseplate by socket-head cap screws.
- Pads are flat components made from sheets. These are used as base locators when rest buttons do not provide sufficient bearing area.

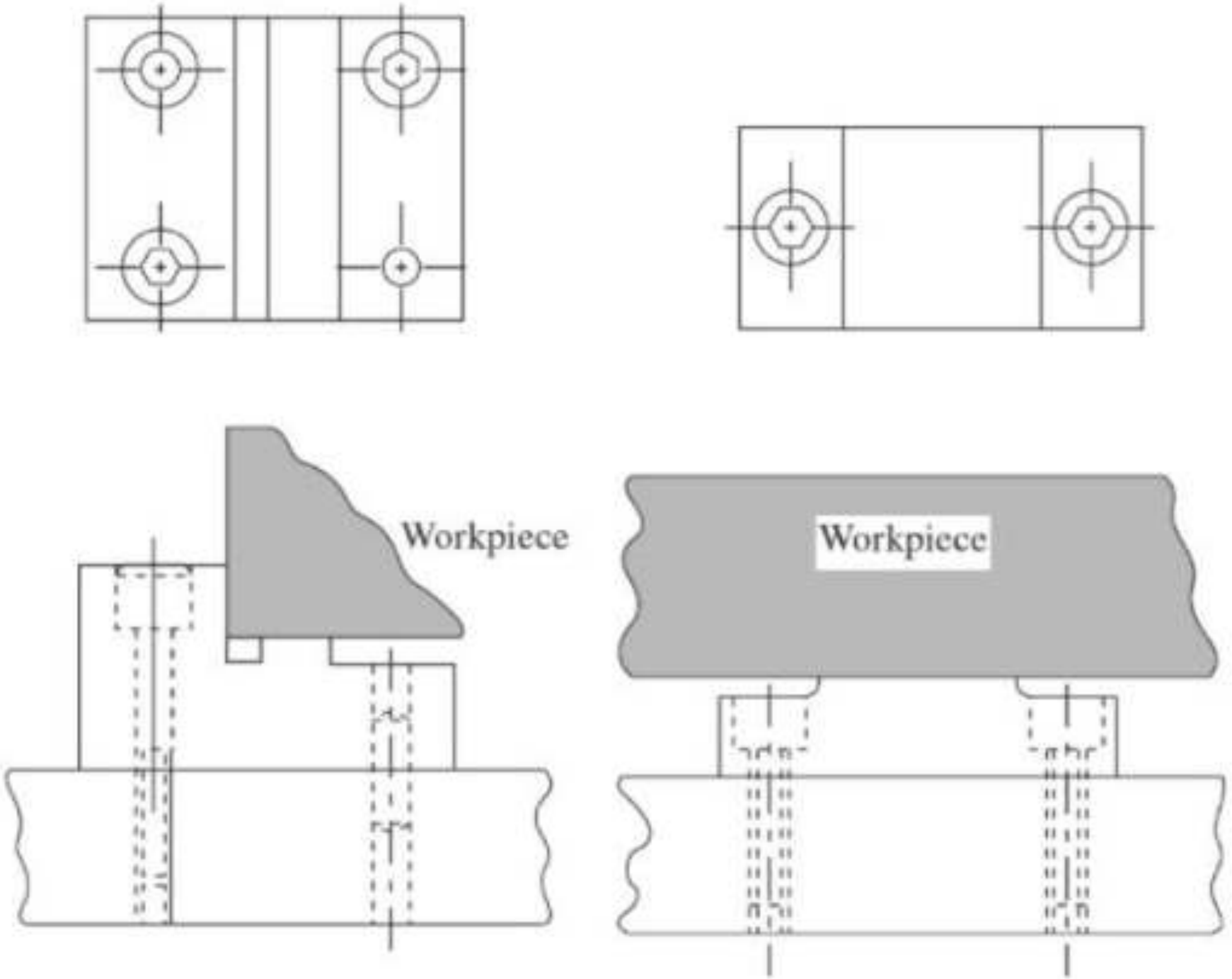
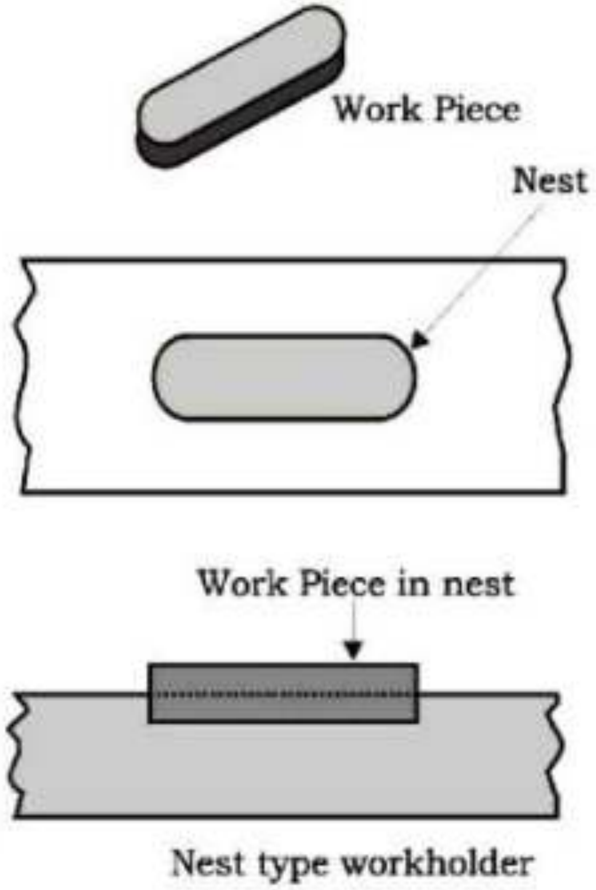


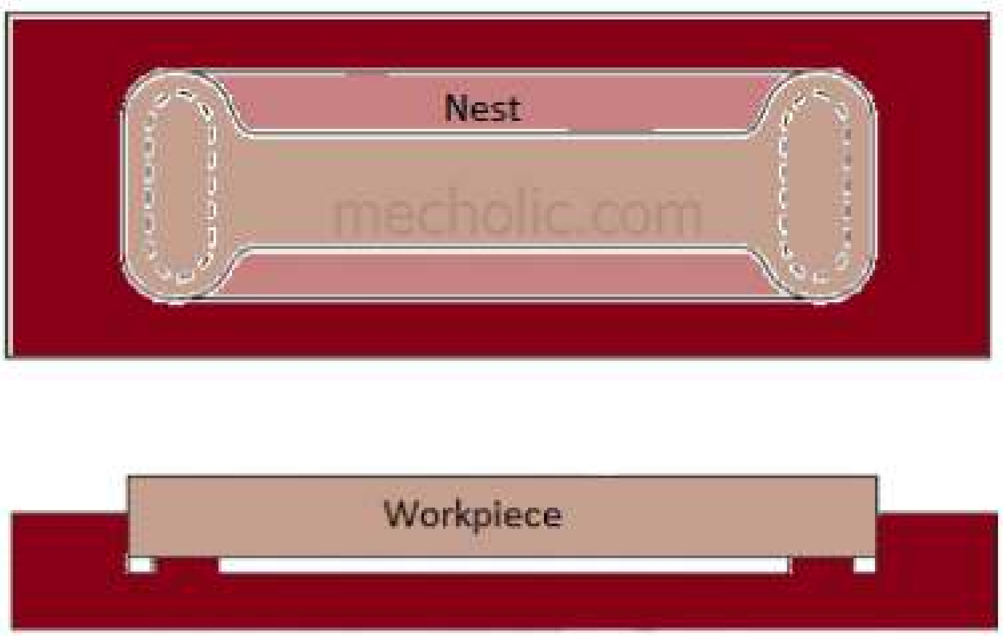
Fig. 6.28 *Using rest pads and plates for work support and positioning*

Nesting or Cavity Locating

- The nesting method of locating makes use of a **cavity in the work holding device into which the workpiece is placed and located.** This is an effective means of locating when the cavity is of the same size as that of workpiece.
- Figure 5.13 shows an example of nest enclosing a workpiece on its bottom surface. The only freedom available to the workpiece is in the upward direction.
- Nests of the cavity type are used to locate a wide variety of workpieces including a cylindrical one. No additional locating devices like pins are not required here.

- As the workpiece is completely surrounded by the cavity, it may not be easy to lift it and remove from the cavity.
- The presence of burrs and chips from machining operation also tend to lock the workpiece into the nest. These are some disadvantages of the cavity locating.

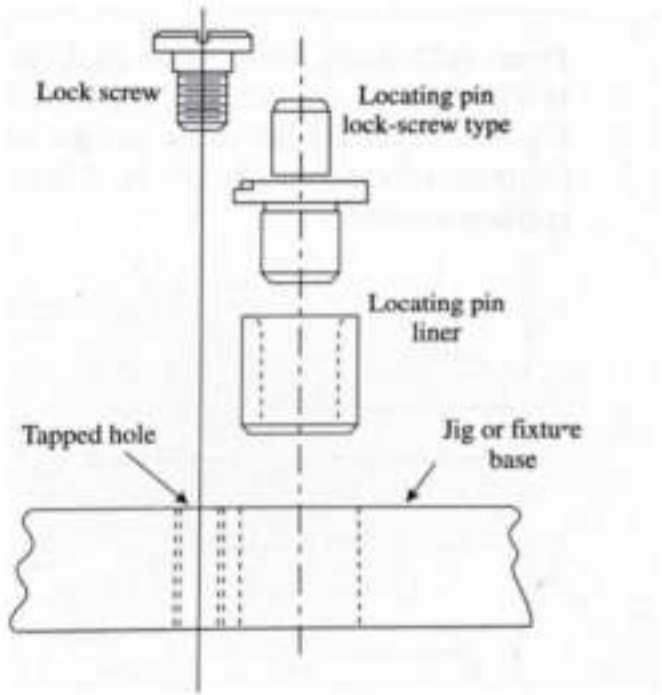




Lock screw button and pins

Used in case of

- wear environment
- Frequently replaced



Diamond pins

- Diamond pins are used for radial location in conjunction with round locating pins.
- It is possible to accurately locate a workpiece with two round pins, but allowances must be made for the variations encountered in hole sizes and locations.

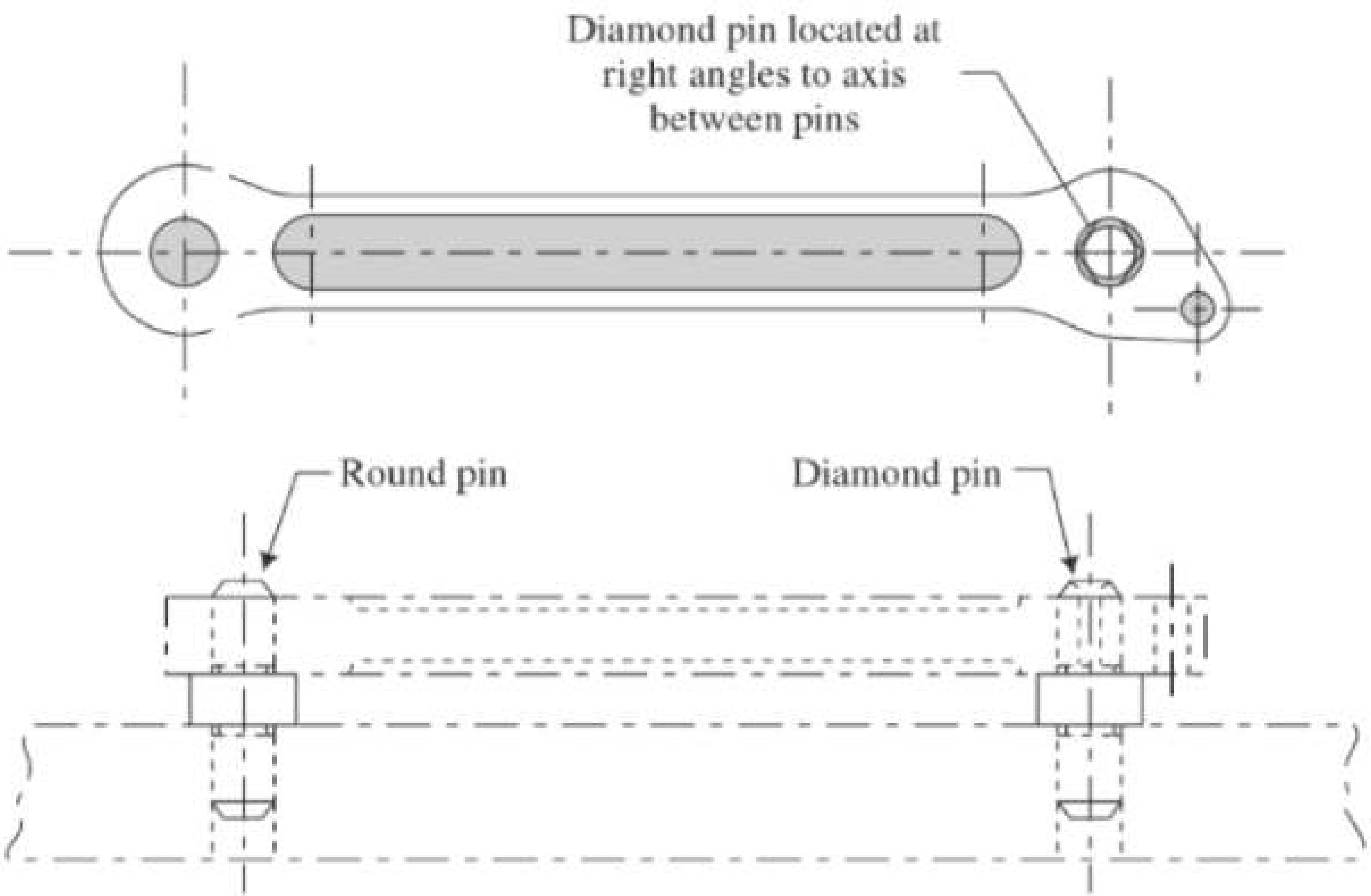


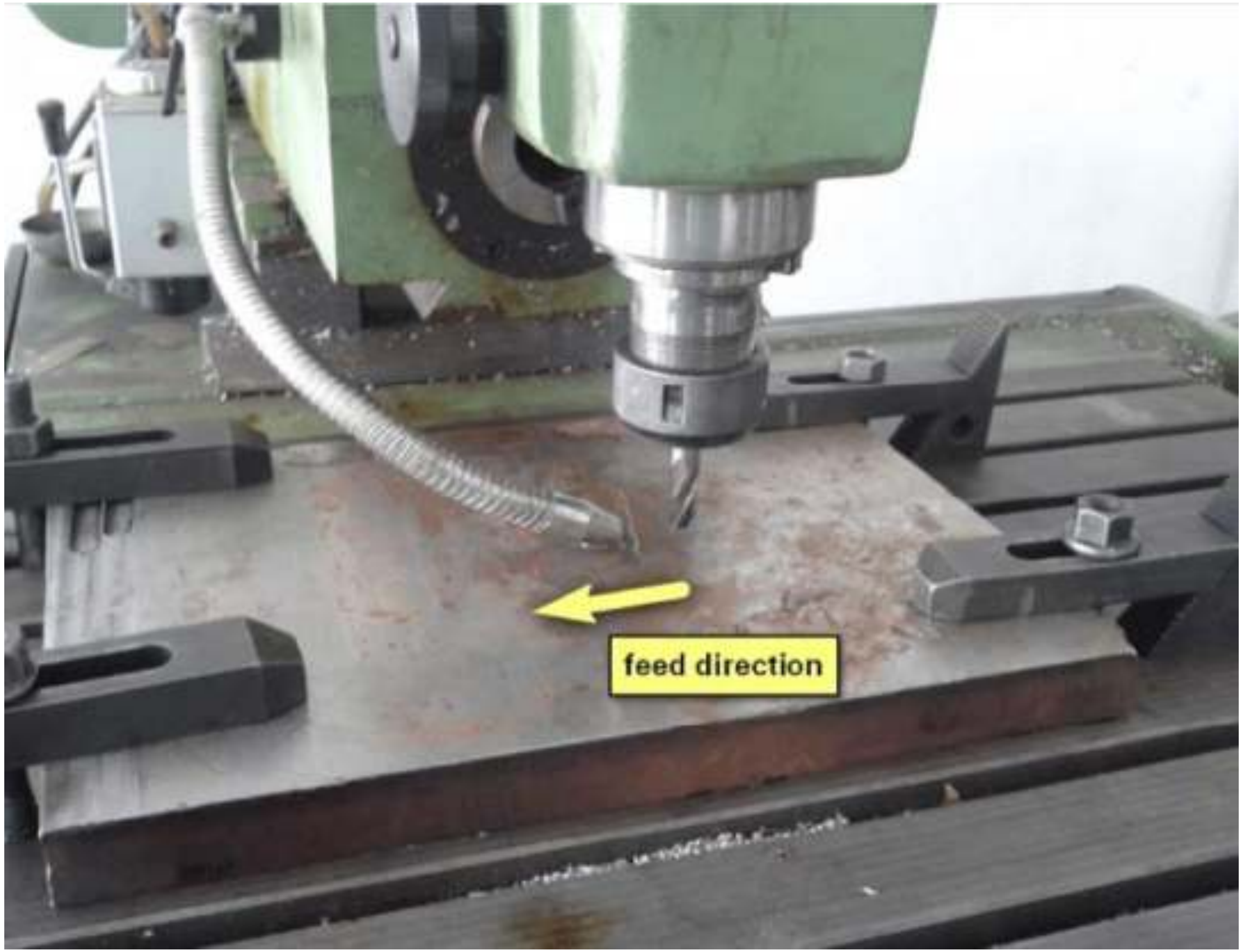
Fig. 6.24 *Use of one round and one diamond locating pin*

CLAMPING

PRINCIPLES OF CLAMPING

- When the workpiece is properly by located it needs to be clamped so that it is **firmly held in position against the forces acting on it**.
- This step of pressing the workpiece against locating surfaces to hold it there is called **clamping and the tools used for this are called clamps.**
- There are numerous types of clamps in use today. The essential requirements of clamps are:

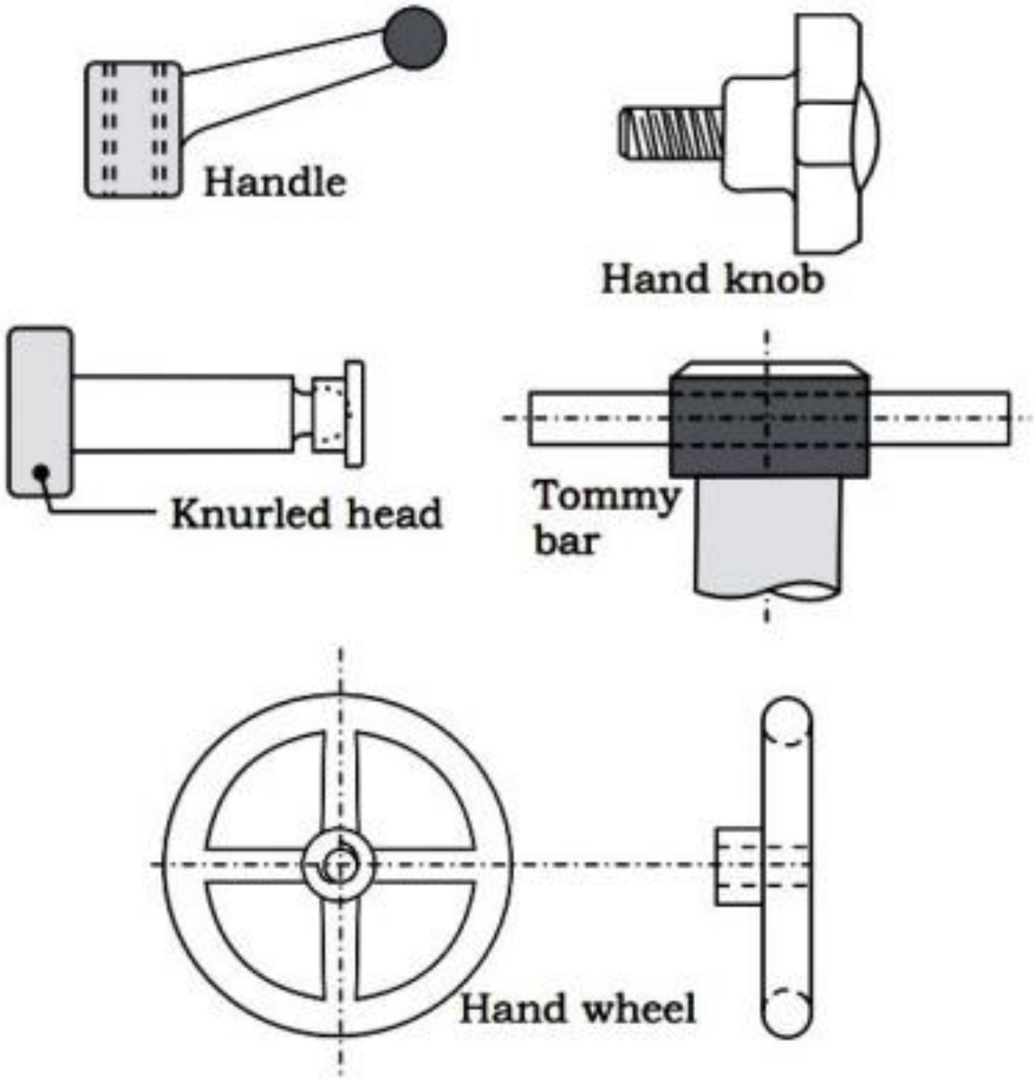
1. The workpiece must be ***held rigidly*** while the cutting tools are in operation.
2. The clamp should be ***quick acting*** so that the time required for loading or unloading must be minimum.
3. The clamp must be ***able to withstand vibration***, chatter and heavy pressure.
4. The clamp ***must not damage*** the workpiece.


feed direction

The main principles of clamping are the following.

- ***Position:*** Clamping should be positioned to direct the clamping force on a strong supported part of the workpiece. Clamps should ***not obstruct path of the cutting tool***. The clamp should not ***obstruct the loading and unloading of the workpiece***.
- ***Strength:*** The clamping system should have ***sufficient strength to hold*** the workpiece firmly against the cutting forces. At the same time, the clamping force should ***not make damages to the workpiece.***
- ***Productivity:*** The clamping time should be minimized by using knobs, knurled screws, tommy bars, hand wheels and handles. A clamp which can be tightened or loosened ***without using spanners*** will have more productivity as the setup time is reduced.

Hand operated clamping devices



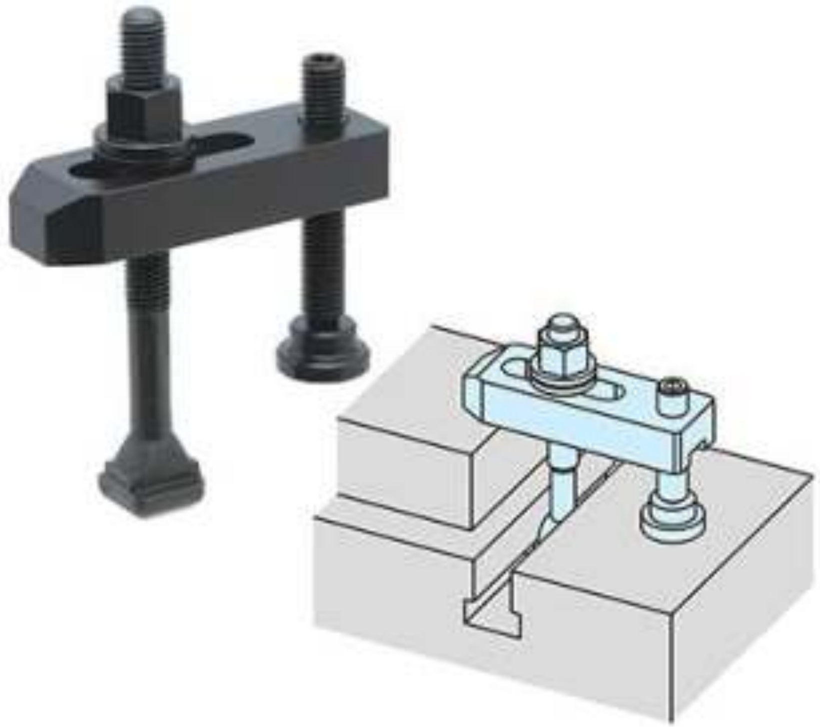
- ***Operator fatigue:*** Pneumatic or hydraulic clamping is to be used when the number of clamps to be set up is more. This reduces operator fatigue and setup time.
- ***Workpiece variation:*** The clamping design should be able to accommodate variations in the workpiece dimensions.

TYPES OF CLAMPS

- There are numerous types of clamps in use today. The basic classification is into the following categories. ***Strap, cam, screw, latch, wedge, toggle and rack & pinion***.
- Most clamping devices contain one or more of these elements. Another general classification is based on the ***usage features of the clamps*** into: Strap, side, hinge and swing clamps.
- In addition to these ***mechanical clamping types, vacuum clamping and magnetic clamping*** are also being used.

Strap Clamps

- In the simplest form, the clamp is ***tightened by rotating a hexagonal nut on a screw***. One end of the clamp presses against the workpiece and the other on a ***head pin***.
- In order to accommodate variation in workpiece dimensions, the clamping face of the clamp is ***made curved*** and the top face of pin is made spherical in shape.



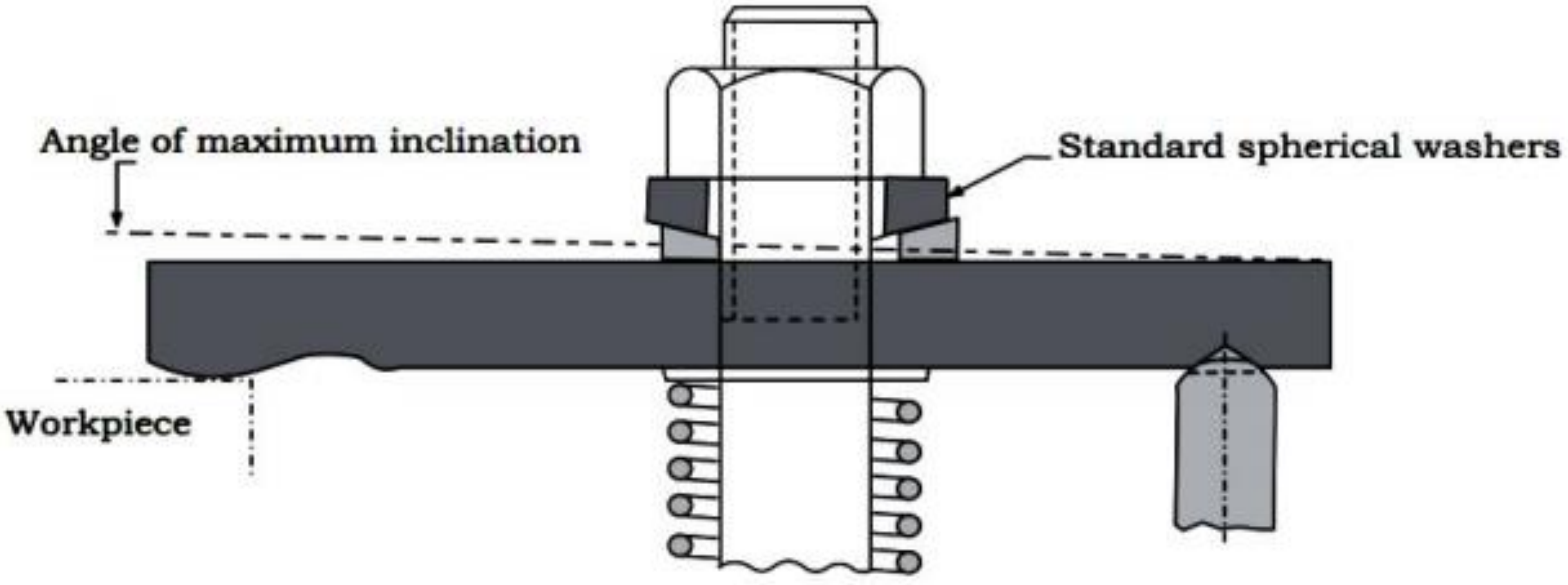
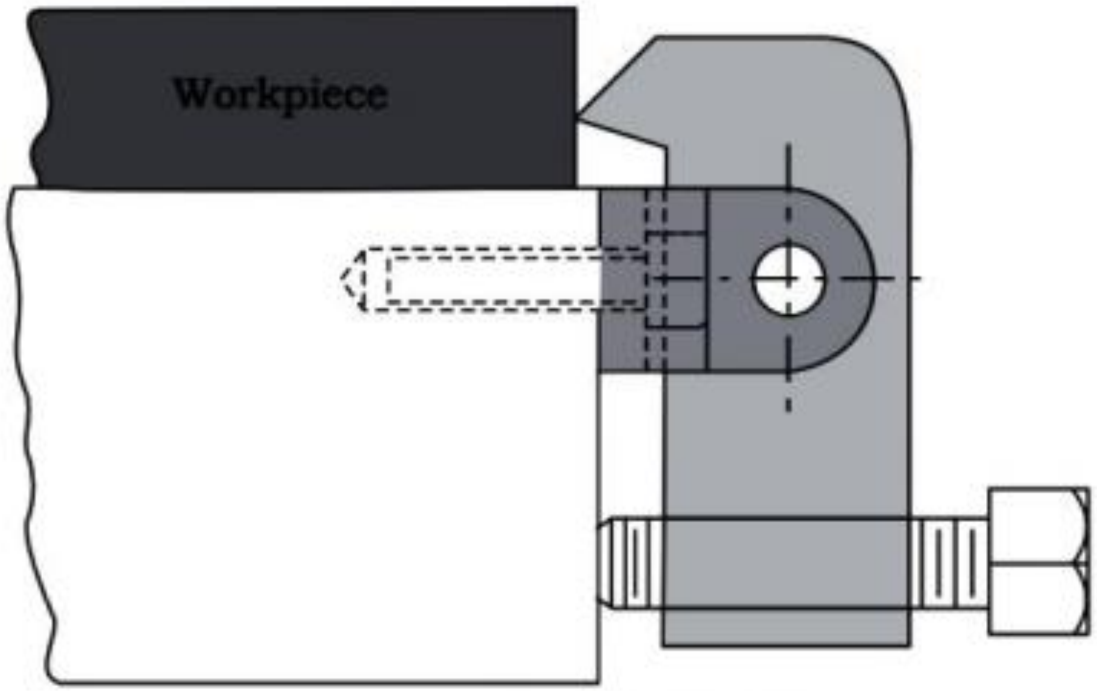

Angle of maximum inclination
Standard spherical washers
Workpiece

Figure 5.15

- Another feature which supports variation in workpiece dimension is the provision of spherical washers between clamp and the hexagonal nut.
- The strap clamps are also provided with a ***washer and spring below the clamp***. This makes the loading and unloading of the workpiece easier.
- Many variants of strap clamp like retractable strap clamp, slotted strap clamp, swinging strap clamp and special strap clamps are in use for various types of workpiece configurations.

Side Clamps

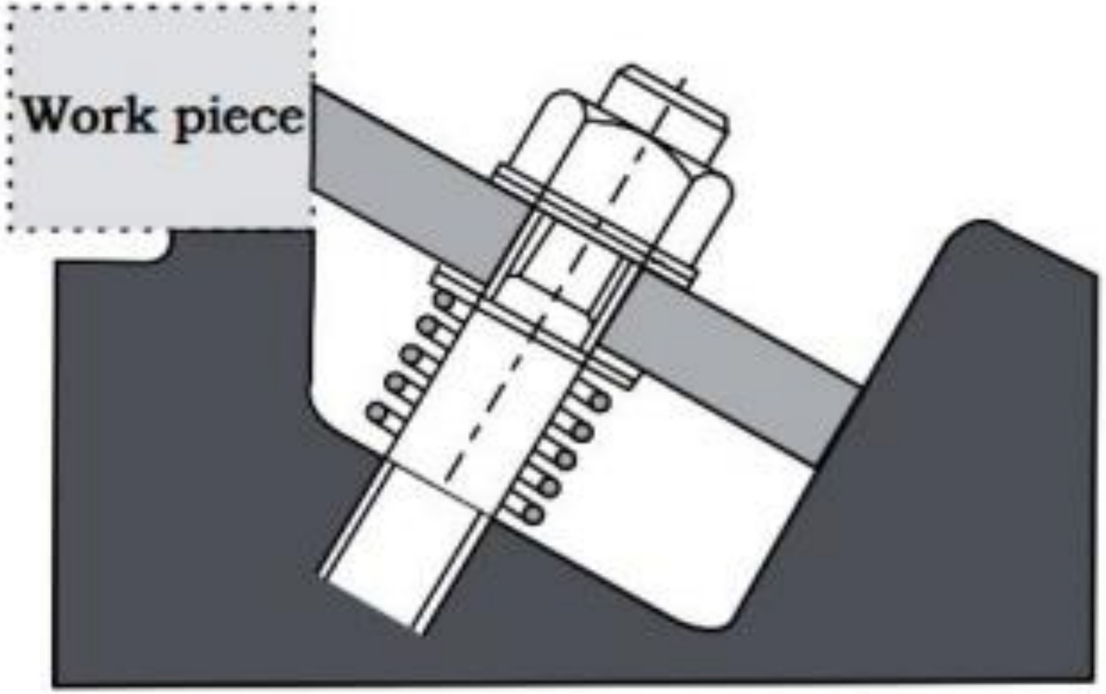
- Side clamps are preferred when the ***top surface of workpiece needs to be free and unobstructed for machining***.
- For milling, plaining and broaching, this type of clamping may be necessary.




Value Creator
IMAO
IMAO CORPOR

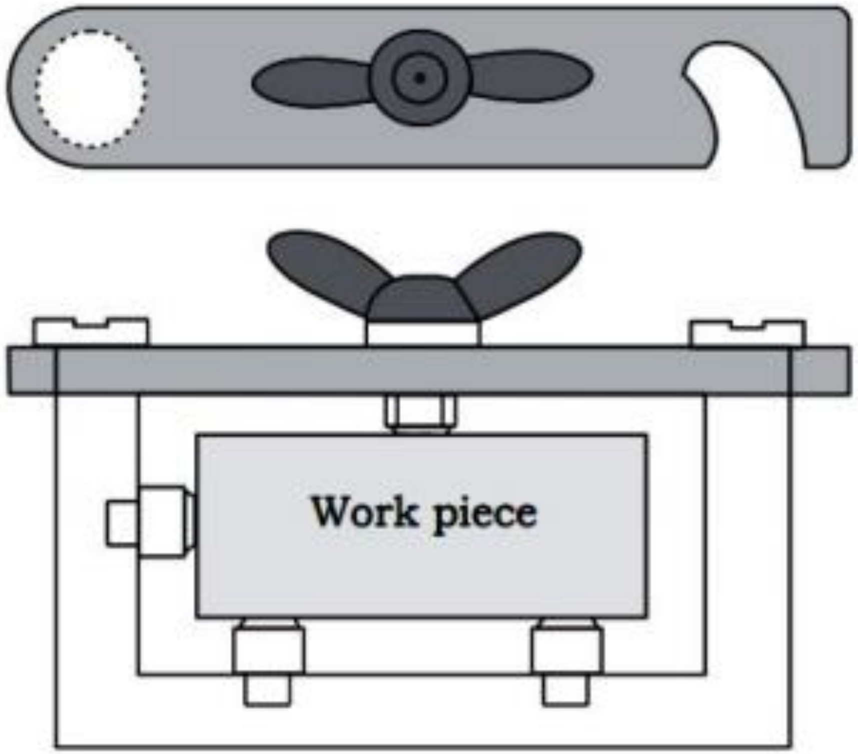

StrongHandTools
Side Clamp
SIDE CLAMP
0:00
Hold, stop, or locate parts with horizontal clamping force.
0:04 / 0:19

- The figure shows a simple side clamp. By tightening the nut, the wedge shaped clamp presses the workpiece against locating surface and keeps it in position.

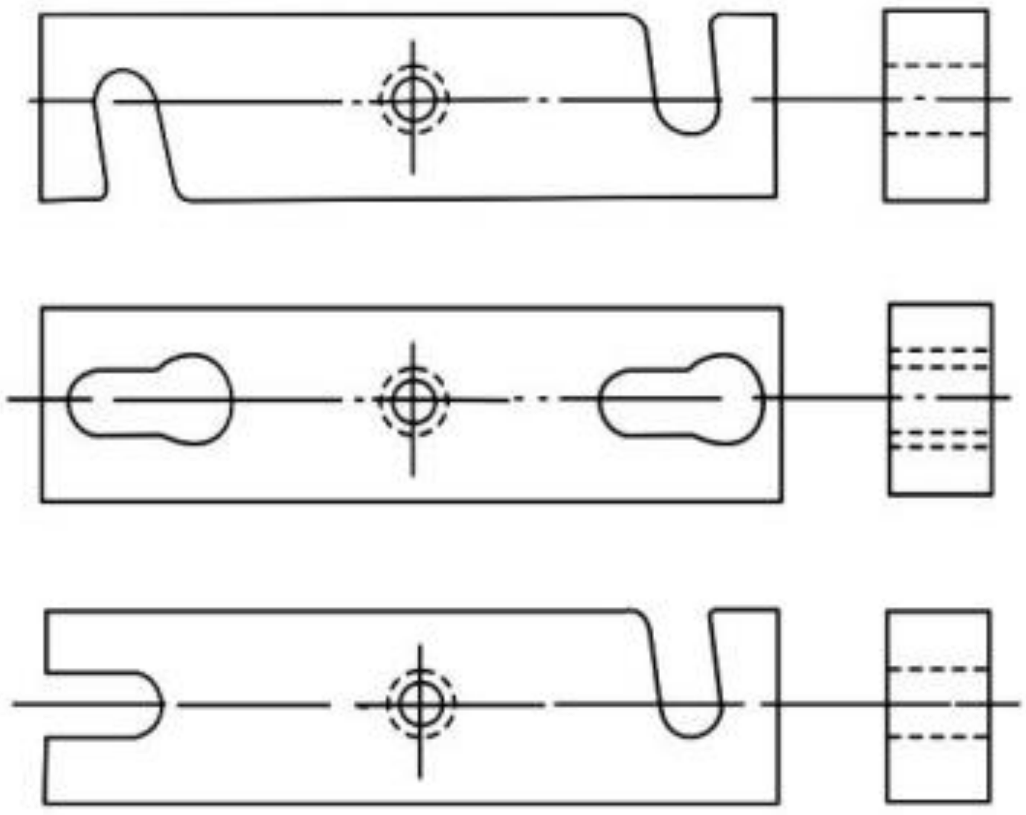


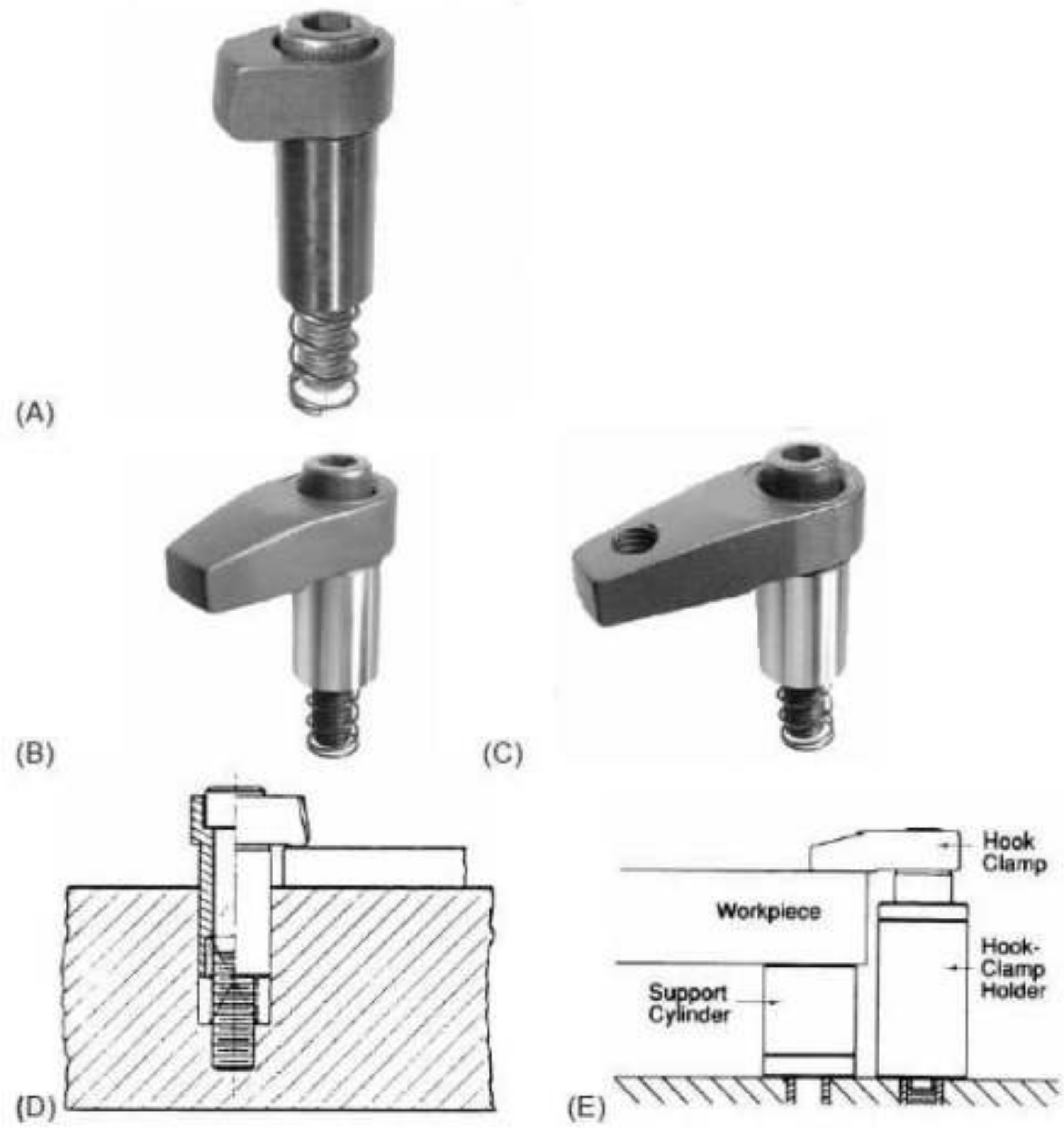
Latch Clamps

- This type of clamps are ***simple and relatively quick in operation***. These are suitable only for smaller size, simple shaped workpieces requiring lower clamping forces.



- The latch clamps are also called ***swing clamps*** as these are to be swung to the working position. The axis of rotation of swing plates is such that they rotate in the planes of their plates. Figure shows strap plates with different types of slots for easy removal.



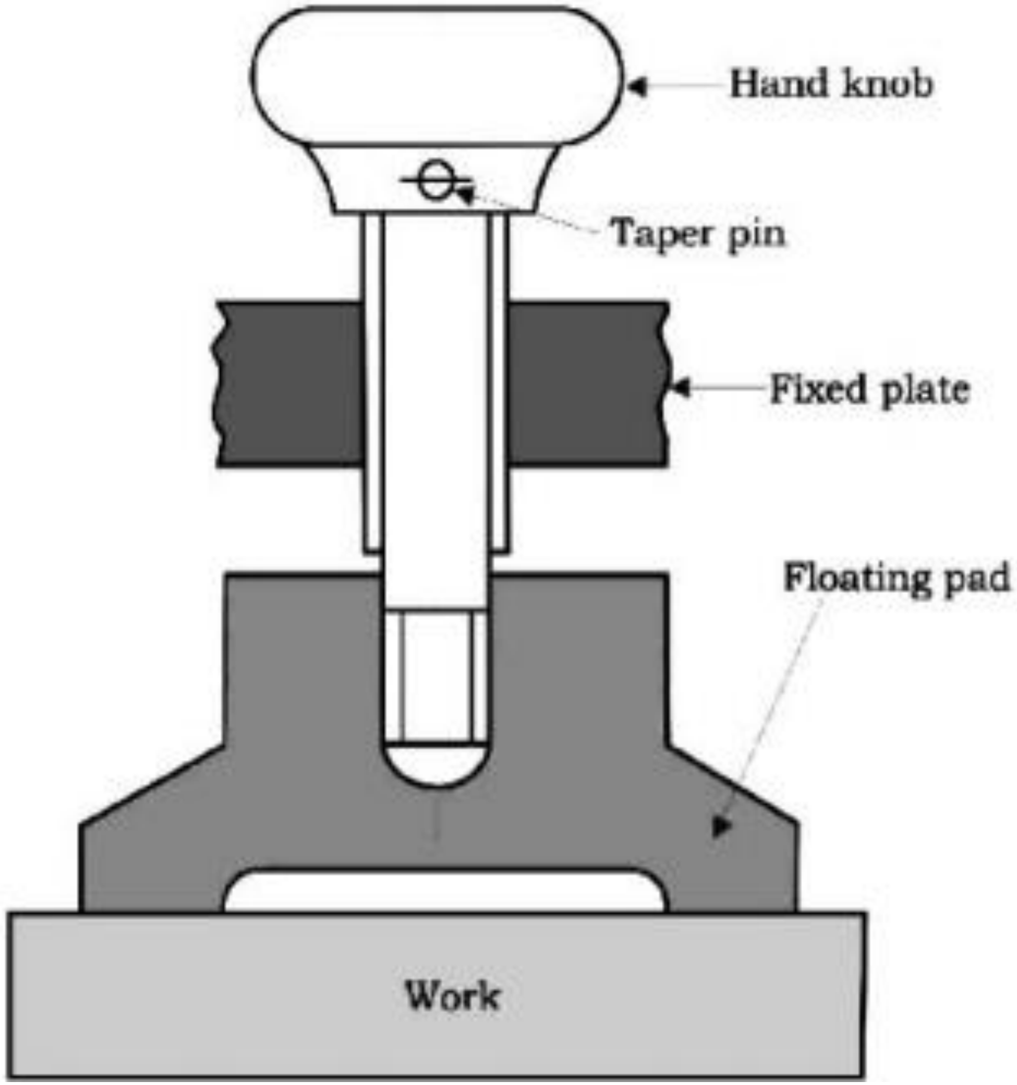

(A)
(B)
(C)
(D)
(E)
Hook
Clamp
Workpiece
Hook-
Clamp
Holder
Support
Cylinder

The right clamp for tight spaces


BLICK
INDUSTRIES

Screw Clamps

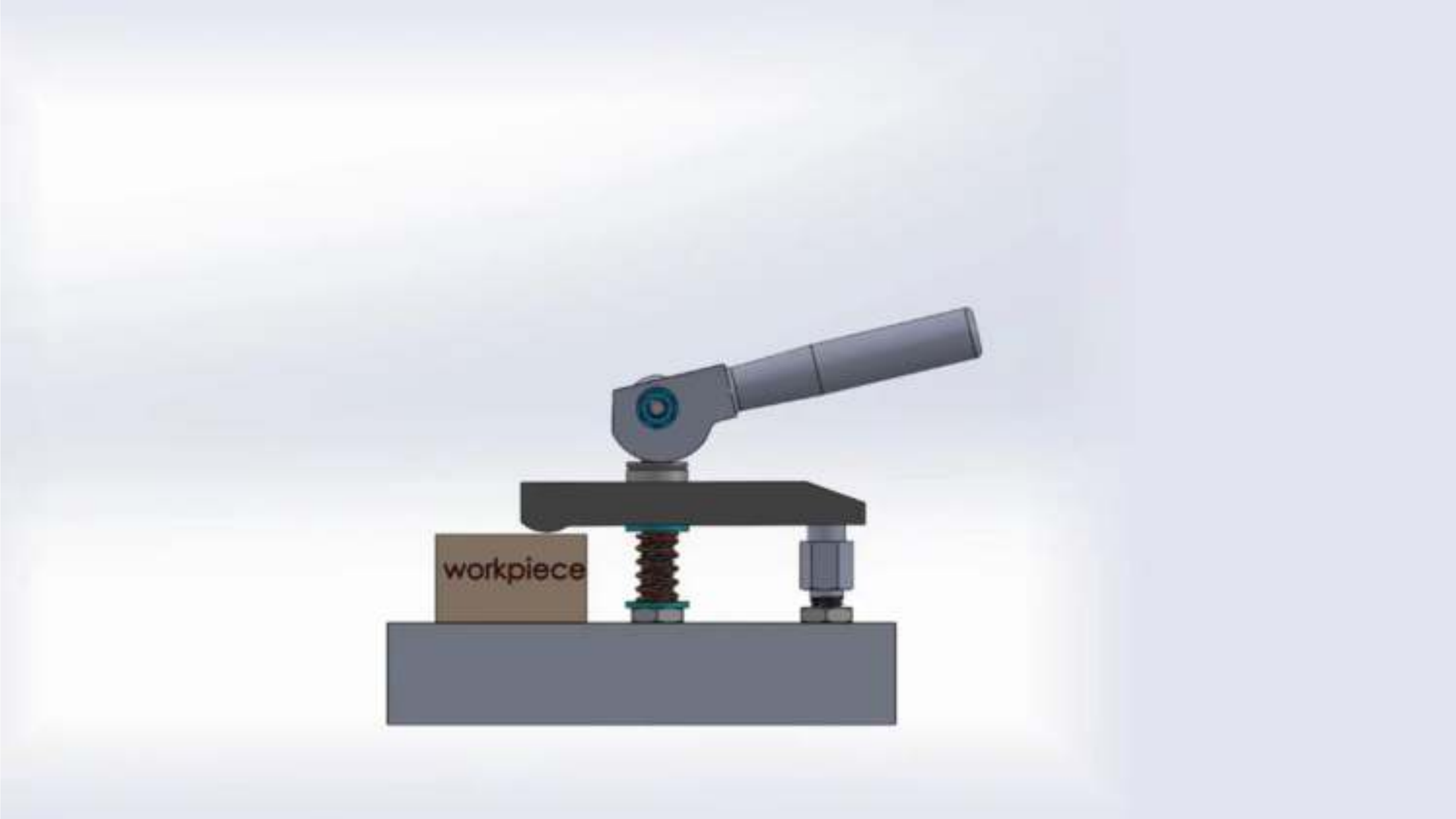
- A screw clamp is provided with a ***screw thread*** to clamp a workpiece. The screw clamp can exert adequate force and remains in position preventing loosening due to vibrations.
- The ***clamping action takes more time*** compared to strap and cam clamps, and may not be suitable for mass production.
- The basic screw clamp comprises of a screw, hand knob and pressure.
- **The clamp uses the torque developed by the screw thread to hold the workpiece in position.**

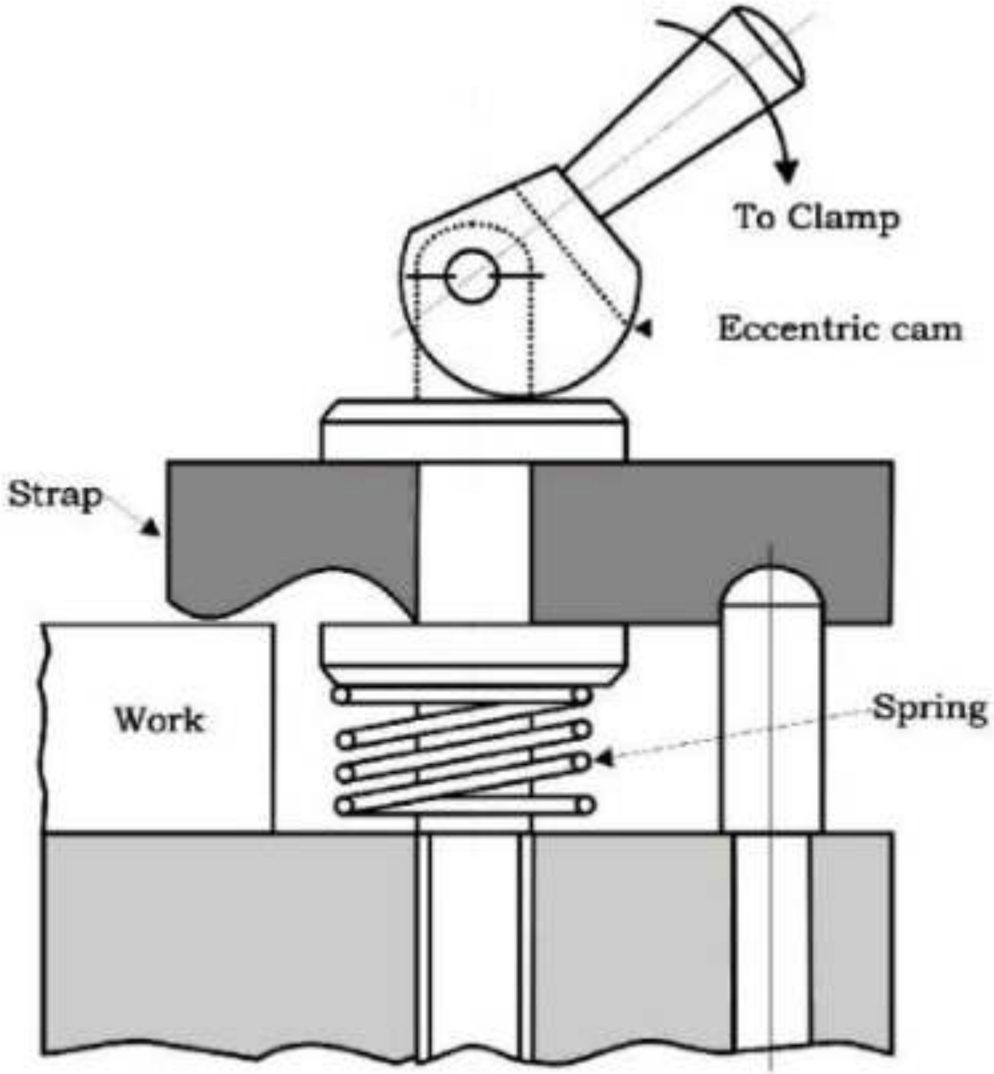

Hand knob
Taper pin
Fixed plate
Floating pad
Work

- Screw clamps make use of simple setscrews to complicated clamping assemblies actuated by screw threads.
- Standard items like handles, hand knobs, knurled head, tommy bar, hand wheel etc. are used for the construction of screw clamps.
- There are numerous ***other devices developed to speed up the clamping action of screw clamps***. Quick acting screw clamp and quick acting knob are two popular devices used along with screw clamps.

Cam Clamps

- Cam clamps are simple to use and provide an effective and faster method of clamping.
- The ***clamping may loosen under vibrations***. Hence this type of clamp can not be used where heavy clamping forces are needed.
- Cam clamps are available in two types, ***spiral and eccentric camp*** clamps. The spiral cam provides better locking as compared to the eccentric one.
- Eccentric cam clamps are easier to manufacture. The construction is similar to the strap clamp, where the hexagonal nut of the strap clamp is replaced by an eccentric cam.


workpiece


To Clamp
Eccentric cam
Strap
Work
Spring

Wedge Clamps

- A simple wedge clamp consists of a ***movable wedge*** which forces the workpiece against a fixed stop.
- The ***horizontal movement of wedge causes upward vertical clamping force on the workpiece***.
- Wedges with angle of 1 to 4 degree are self locking type. Wedges with larger angles need another holding device like a screw or cam to hold the wedge and workpiece in position.
- In the side jaw wedge clamp, the clamp slides down as the hexagonal nut is tightened. Now the ***jaw is pushed against the workpiece to clamp it firmly.***
- In another type of wedge clamp in which a screw is used to force the wedge end of clamp upward causing the clamping action.

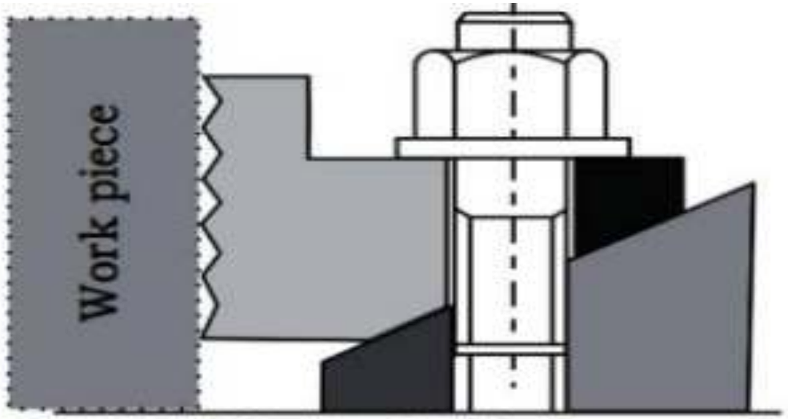
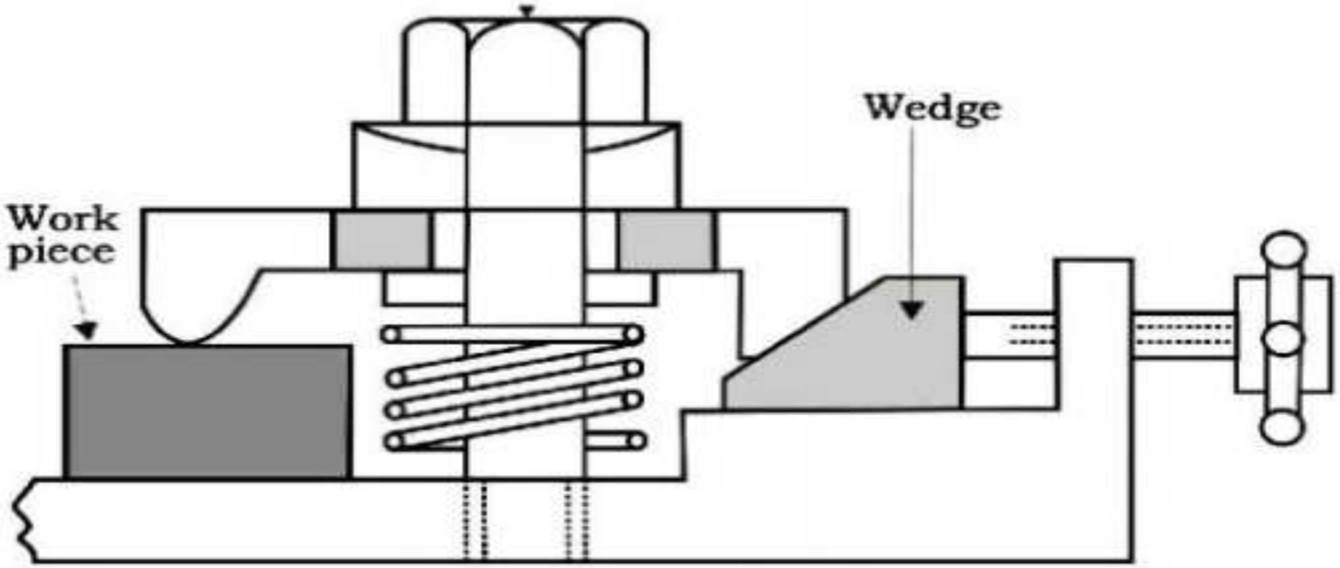
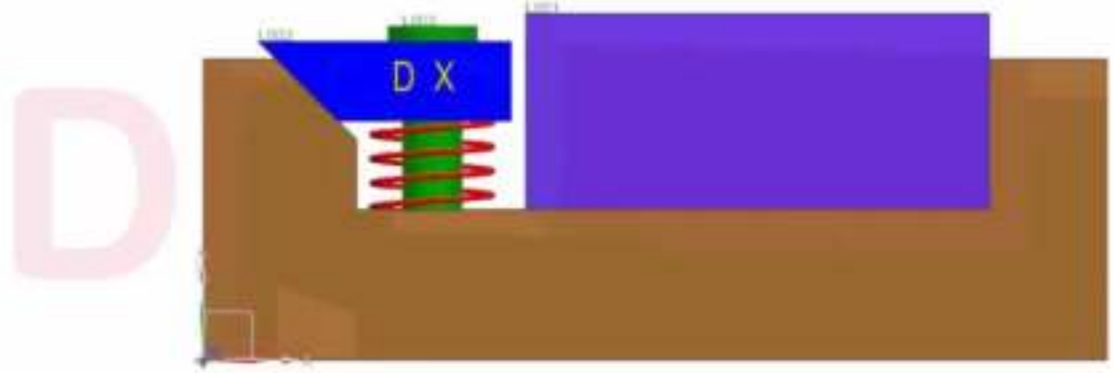


Figure 5.22

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POWER CLAMPING

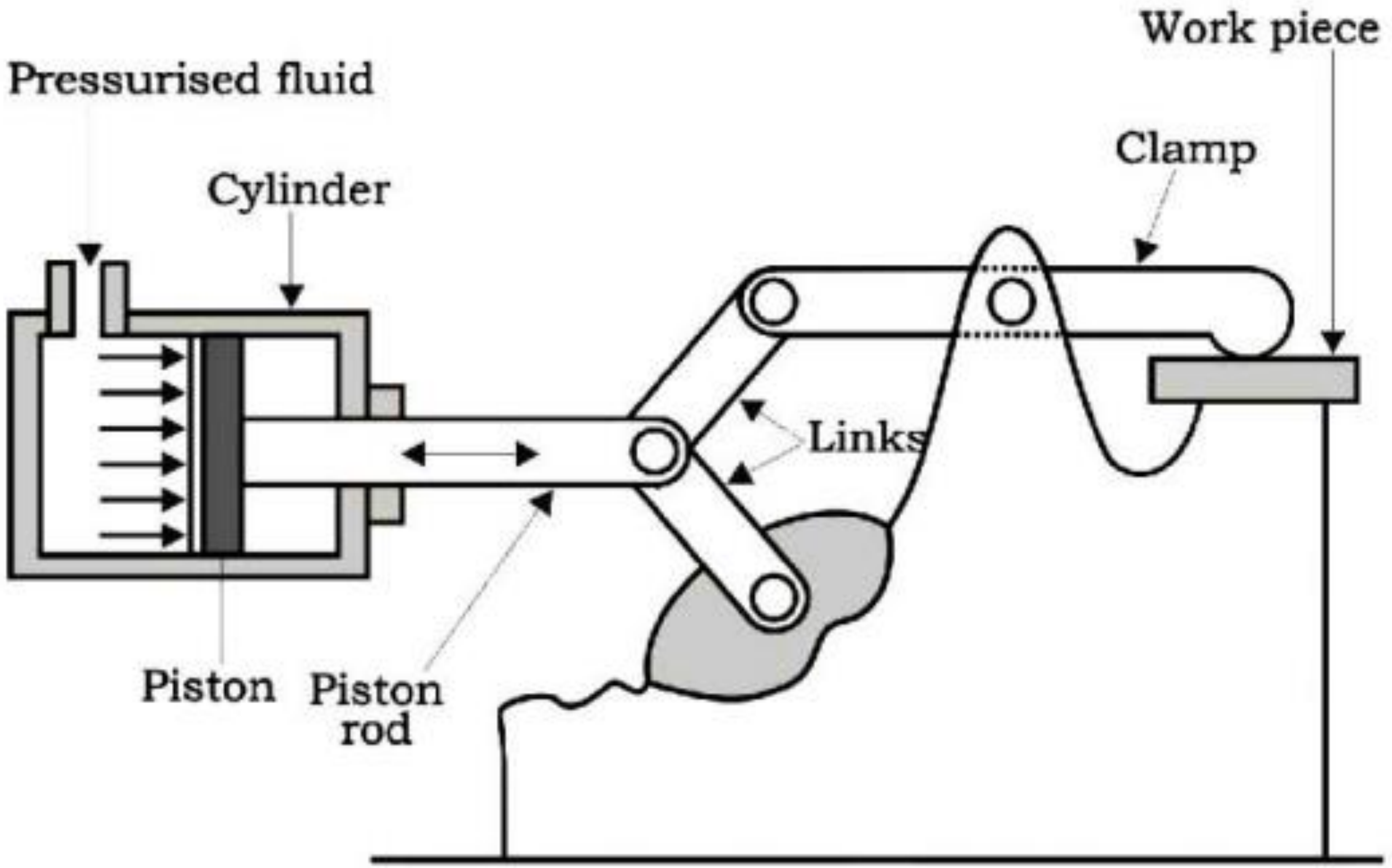
- Using power clamping a number of clamps of various types can be operated simultaneously. Power clamping can be implemented using the following means.
- Pneumatic clamping
- Hydraulic clamping
- Vacuum clamping
- Magnetic clamping
- Electrostatic clamping
- Many of the types of clamps explained earlier can be operated using ***a few of the power clamping methods***. Some power clamping methods are employed for specific applications involving special clamps or even without any clamps at all.

Hydraulic and Pneumatic Clamping

- These two are grouped under ***fluid power clamping methods*** since both are using fluids to generate clamping force. The advantages of using these clamping methods ***are faster clamping, uniform and equalised clamping pressure and less operator fatigue***.
- Working principle of these are similar, but the pneumatic system needs larger cylinders to develop higher pressures. With a smaller cylinder, the hydraulic system will be able to develop such higher pressures to operate the clampling devices.


ROEMHELD
HILMA • STARK

- Supply of compressed air may be available in most manufacturing industries and it is convenient to use pneumatically operated clamping devices.
- The low pressure air available can be given a pressure boosting with the help of an ***air to hydraulic booster.*** The booster is used to convert the lower pneumatic pressure into higher hydraulic pressure to operate the hydraulic powered clamping system.
- During clamping, the ***piston inside the cylinder is actuated by fluid pressure***. ***The piston rod is connected to levers of the clamp, which exerts the necessary pressure to workpiece***. As the piston moves back, the levers release the clamping pressure on the workpiece and it is released for unloading.

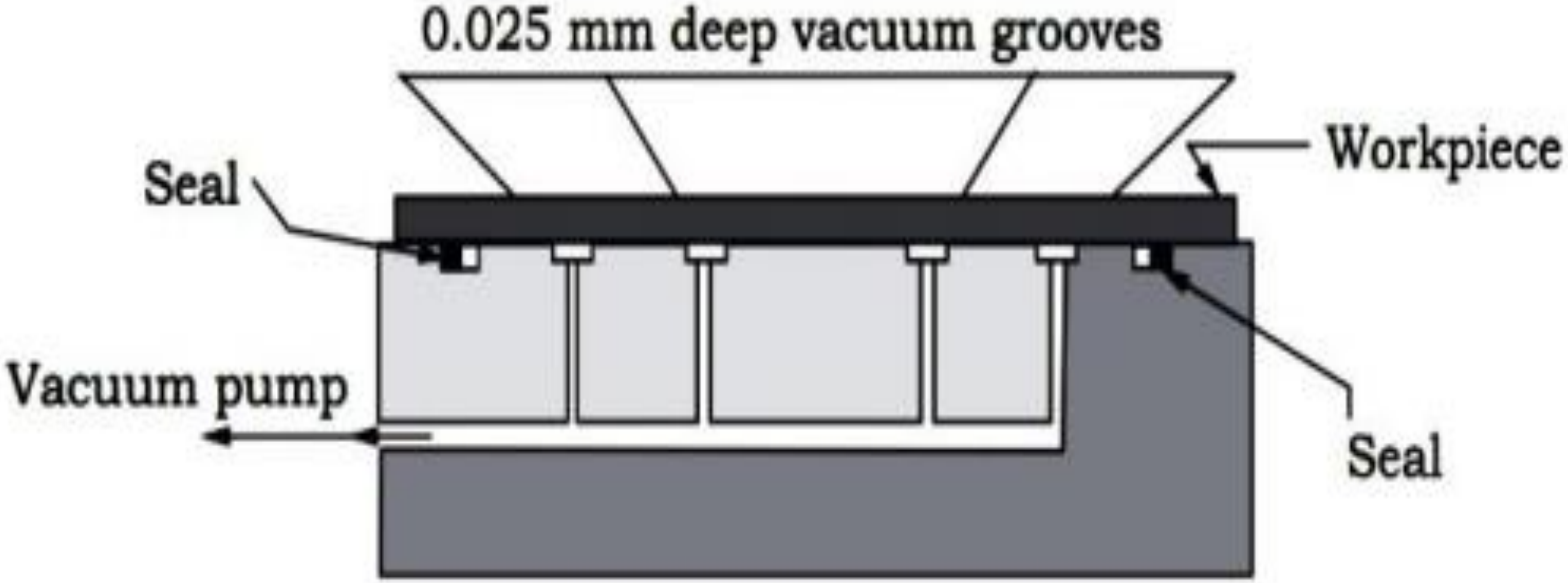


Pressurised fluid
Cylinder
Work piece
Clamp
Links
Piston
Piston rod

- When there are a number of clamps actuated by a single hydraulic system, clamping pressure of all ***clamps will be equal***.
- By ***regulating the pressure of the fluid***, clamping pressure can be varied.
- Higher pressure can be used for heavy cuts and lower pressure can be used for finishing operations.
- The risk of sudden pressure drops can be eliminated by providing ***non return valves along the hydraulic circuit***.

Vacuum Clamping

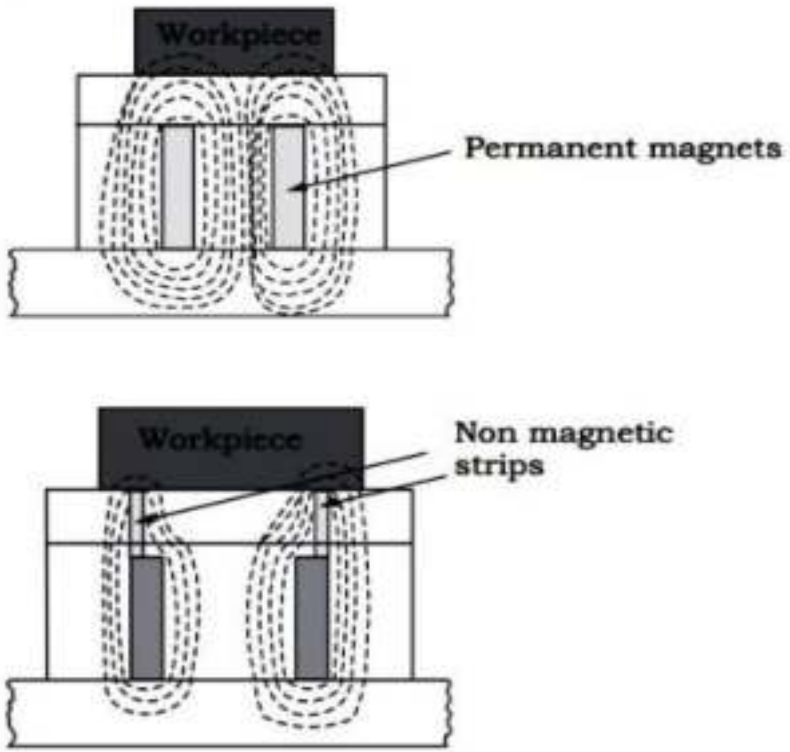
- An application of vacuum clamping is for ***securing thin sheets*** which cannot take up heavy clamping forces. Vacuum clamping provides ***only light clamping***.
- The holding face is provided with small vacuum ducts of around 0.25mm depth. In addition, there will be a rubber seal covering the periphery of the holding face and acts as the boundary of vacuum clamping area.
- When the vacuum pump is operated, the ***vacuum ducts are evacuated and develops a clamping force on the flat thin workpiece***.
- Upon stopping the vacuum pump, the clamping is released.


0.025 mm deep vacuum grooves
Workpiece
Seal
Vacuum pump
Seal

Magnetic Clamping

- Similar to vacuum clamping, ***magnetic force*** can be made use to clamp the workpiece in position.
- Permanent magnets or electromagnets are used for this purpose.
- Permanent magnets are mounted on a sliding member and moved under a non magnetic material to block the magnetic flux. The permanent magnets are slid into the clamping and unclamping position by a lever.
- The workpiece to be clamped is placed on the surface of clamp. There are a number of permanent magnets below the surface of clamp. A lever is used operate the clamp. In the ON position, magnetic flux passes through the workpiece to complete the magnetic circuit.

- When in the OFF position, the flux passes through the clamp surface only and not through the workpiece. Thus the workpiece is undamped. This is done by aligning the magnets with a number of non magnetic separators.
- **Electromagnetic tables** use solenoid coils as temporary magnets. The solenoid coil acts like a magnet when DC current is supplied. When current is switched off, the table is demagnetized and workpiece is released.
- By varying the current through the solenoid coil, the magnetic clamping force can be varied. These magnets are more powerful than permanent magnets.



PRESS WORKING (Sheet metal operations)

- Sheet forming, unlike bulk-deformation processes, involves workpieces with a ***high ratio of surface area to thickness***.
- Sheet thicker than 6 mm is generally called ***plate***; If the sheet is thin, it is generally coiled after rolling and is often decoiled and flattened prior to further processing.
- The mechanics of all sheet forming processes basically consists of ***stretching and bending.***

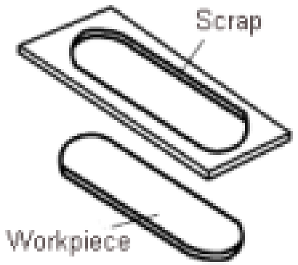
Sheet-Metal Parts

(a)

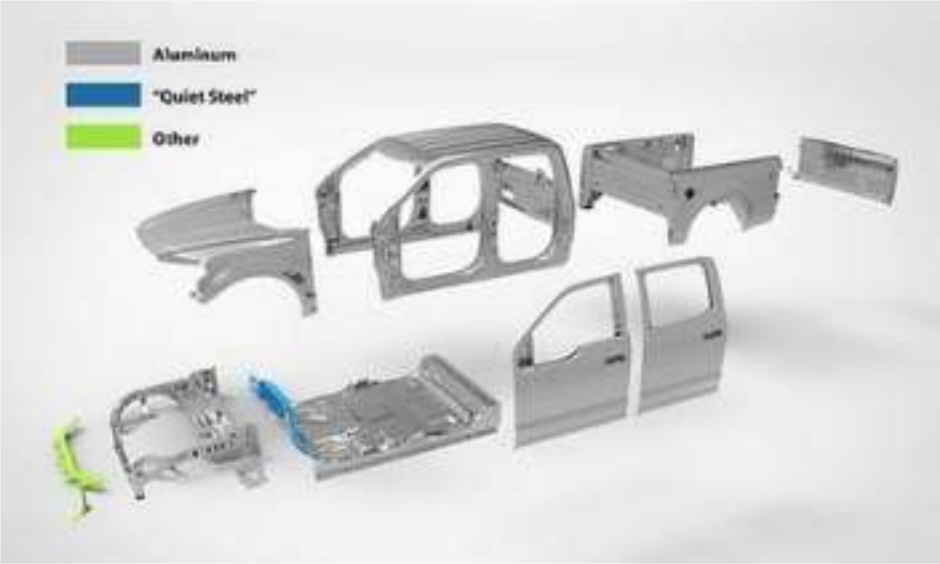
(b)

Figure 16.1 Examples of sheet-metal parts. (a) Die-formed and cut stamped parts. (b) Parts produced by spinning. *Source:* (a) Courtesy of Aphase II, Inc. (b) Courtesy of Hialeah Metal Spinning, Inc.

- Products made by casting or forging are of simple design and are heavier. For making ***light weight and versatile products like appliances, automotive bodies, cans, household utensils etc., sheet metal is used***.
- From a large sheet of metal, a ***blank of suitable dimensions is cut and removed by shearing operation***. This blank is then formed into various shapes, by stretching and bending the sheet.



Blanking



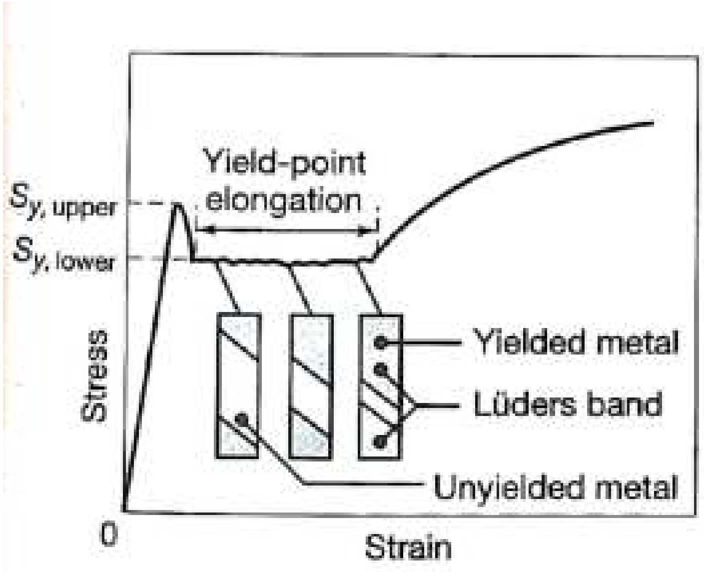
- Low carbon steel is most commonly used ***sheet material***.
- It is a low cost material with ***good strength and formability***. For aircraft and aerospace applications sheets of aluminium and titanium are used.
- Certain characteristics of sheet metal which are having important effects on the sheet metal forming are explained here.

1. **Elongation:** Since the sheet metal is usually being stretched during sheet forming, ***high uniform elongation*** is desirable for good formability.

   A ***higher value of strain hardening exponent (n) and strain rate sensitivity index (m) are desirable***. Along with elongation, necking also occurs, but a diffused necking is desirable in sheet forming operations. Another related factor is total elongation of the material.

- Total elongation is the sum of ***uniform and post-uniform elonation***. Uniform elongation is governed by the ***strain-hardening exponent, n,*** whereas post-uniform elongation is governed by the ***strain- rate sensitivity index, m***.
- The higher the m value, the more diffuse the neck is, and hence the greater the post-uniform elongation prior to fracture. Consequently, the ***total elongation of the material increases with increasing values of both n and m***.

- **Yield point elongation:** Low carbon steels exhibit a behaviour called ***yield point elongation***. Aluminium and magnesium alloys also exhibit this behaviour. Once the material yields, the sheet stretches more in certain regions while in other regions sheet has not at all yielded.



- **Anisotropy:** Another important factor that influences sheet metal forming is anisotropy of the sheet. Due to this property, the material exhibits ***different behaviors in different planar directions***, which can be reduced or eliminated by annealing.

- **Grain size:** The grain size of sheet metal is important due to two reasons. Grain size affects mechanical properties and influences the surface appearance. In a coarse grained sheet, surface appearance will be rougher.

- **Residual stresses.** Residual stresses can develop in sheet metal parts because of the nonuniform deformation that the sheet undergoes during forming. Tensile residual stresses on surfaces can lead to ***stress-corrosion cracking*** of the part.

- **Spring back:** Caused by ***elastic recovery*** of the plastically deformed sheet after removing the applied loads. This leads to distortion of the part and ***loss of dimensional accuracy***. This behavior is particularly significant in simple bending and other forming operations where the ***bend radius-to-sheet thickness ratio is high***.

General Characteristics of Sheet-metal Forming Processes (in alphabetic order)	
Forming process	**Characteristics**
Drawing	Shallow or deep parts with relatively simple shapes, high production rates, high tooling and equipment costs
Explosive	Large sheets with relatively simple shapes, low tooling costs but high labor cost, low-quantity production, long cycle times
Incremental	Simple to moderately complex shapes with good surface finish; low production rates, but no dedicated tooling required; limited materials
Magnetic-pulse	Shallow forming, bulging, and embossing operations on relatively low strength sheets, requires special tooling
Peen	Shallow contours on large sheets, flexibility of operation, generally high equipment costs, process also used for straightening formed parts
Roll	Long parts with constant simple or complex cross sections, good surface finish, high production rates, high tooling costs
Rubber	Drawing and embossing of simple or relatively complex shapes, sheet surface protected by rubber membranes, flexibility of operation, low tooling costs
Spinning	Small or large axisymmetric parts; good surface finish; low tooling costs, but labor costs can be high unless operations are automated
Stamping	Includes a wide variety of operations, such as punching, blanking, embossing, bending, flanging, and coining; simple or complex shapes formed at high production rates; tooling and equipment costs can be high, but labor cost is low
Stretch	Large parts with shallow contours, low-quantity production, high labor costs, tooling and equipment costs increase with part size
Superplastic	Complex shapes, fine detail and close dimensional tolerances, long forming times (hence production rates are low), parts not suitable for high-temperature use

Shearing Action

- Shearing is the basic operation of cutting sheet metal to the required dimensions and shape. The sheet is subjected to ***shear stresses*** developed between a die and a punch.
- This is typically done with a punch and a die that subject the sheet to ***shear stresses in the thickness direction***, an operation similar to the action of a paper punch.
- Important variables in the shearing process are the ***clearance***, ***punch speed***, the ***corner radii of the punch and the die*** the of the sheet the punch and die materials, and lubrication condition.

- The clearance c, is the major parameter that determines the shape and quality of the sheared edge.
- As ***clearance increases***, the edges become rougher and the deformation zone in the sheared region becomes larger.
- Also, with a high clearance, the sheet is pulled more into the cavity, and the sheared edges become more and more rounded.
- In fact, if the ***clearance is too large***, the sheet metal is bent and thus is subjected to tensile stresses.
- In practice, clearances typically range between ***2 and 8% of the sheet thickness***, but may be as small as 1% in fine blanking.
- In general, clearances are smaller for softer materials; they are higher as the sheet thickness increases.

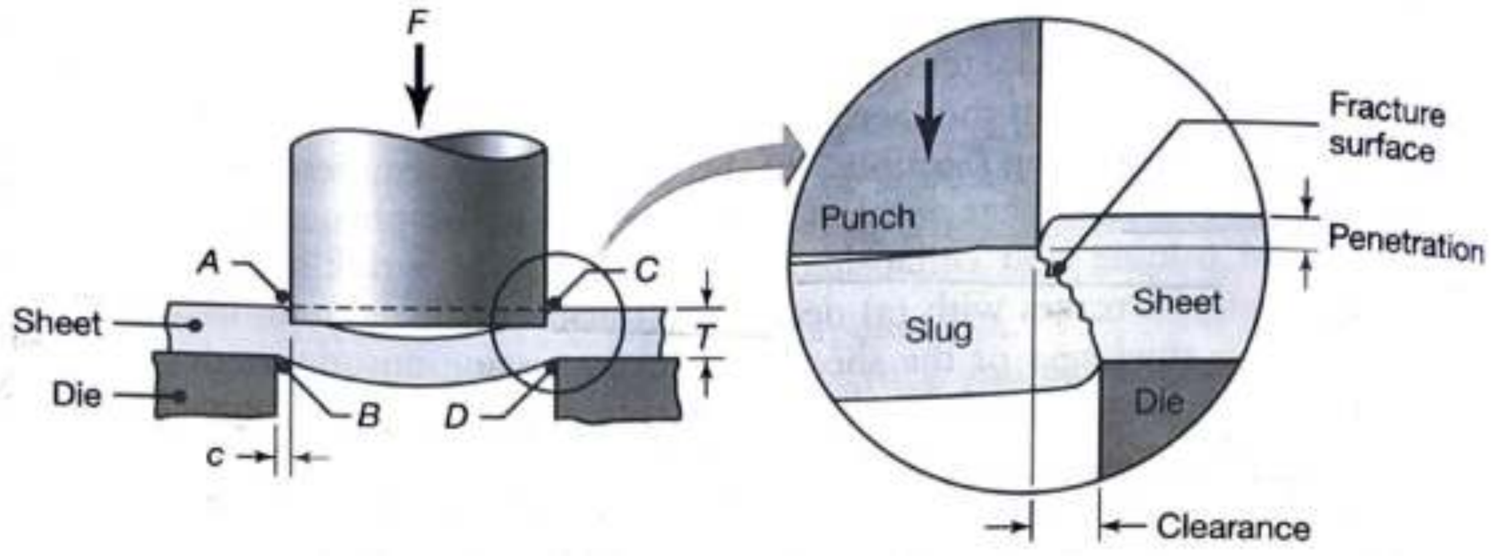
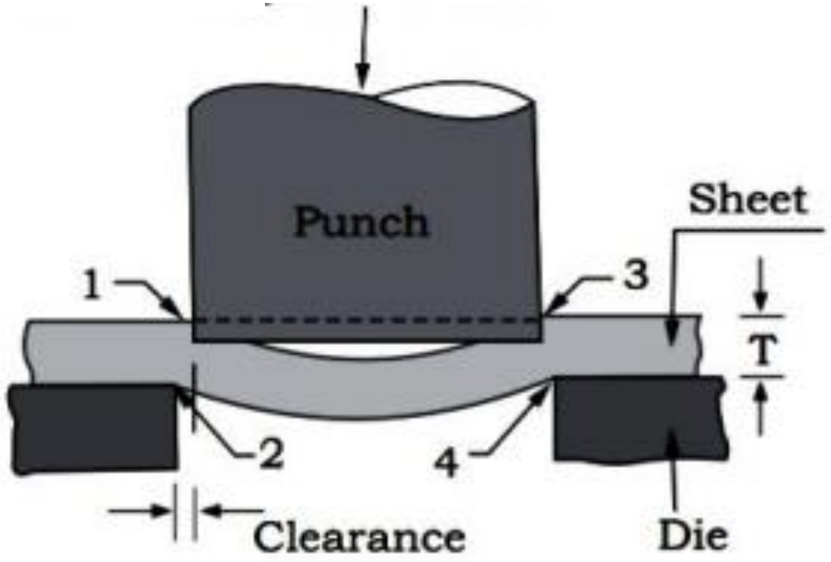


FIGURE 7.4 Schematic illustration of the shearing process with a punch and die, indicating important process variables.



- During the shearing process, initially cracks are formed on the top and bottom edges of the workpiece. These points are marked as 1, 2, 3, 4 in figure.
- As shearing proceeds, the points 1 and 2 move towards each other and meets, so does the points 3 and 4 and form ***rough fracture surface***. This leads to separation of materials and creation of a hole on the workpiece.

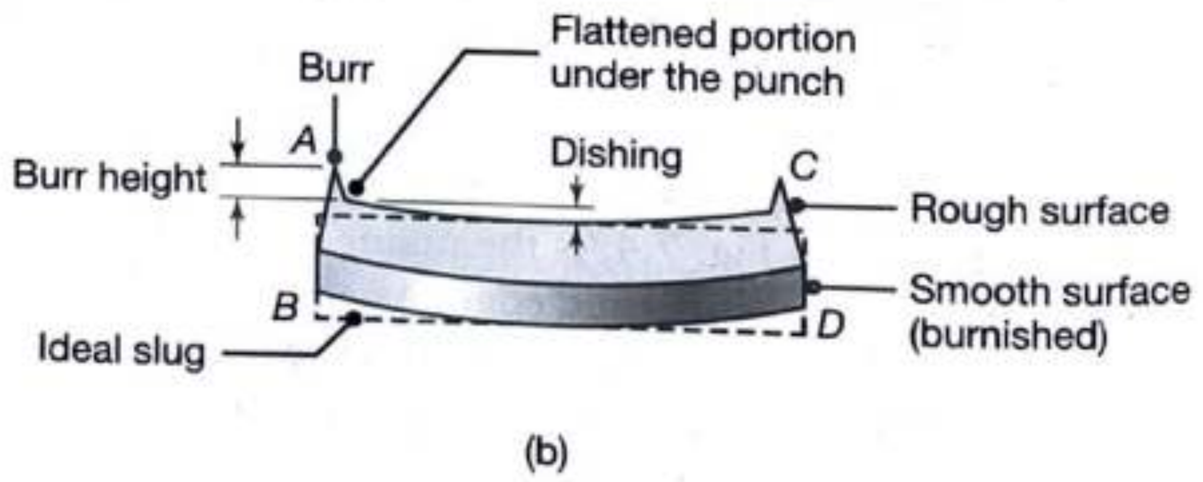


FIGURE 7.5 Characteristic features of (b) a punched slug. Note that the slug has been enlarged with features exaggerated for emphasis.

- **Punch force.** The punch force, F, is basically the ***product of the shear strength of the sheet metal and the cross-sectional area being sheared***; friction between the punch and the sheet can increase this force significantly.
- Because the sheared zone is subjected to a combination of plastic deformation, friction, and development of cracks, the punch-force vs. stroke curves can have a variety of shapes.
- The area under the curve is the ***total work done in shearing***.
- An approximate empirical formula for estimating the maximum punch force F

$$F_{max} = 0.7 S_{ut} t L,$$

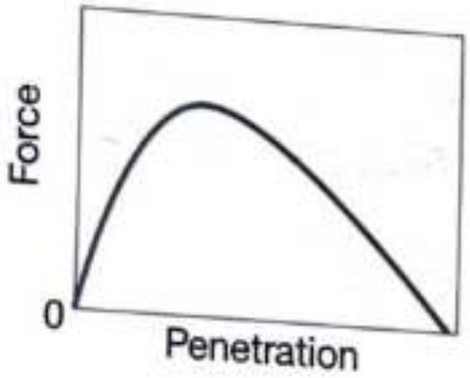


FIGURE 7.7 Typical punch force vs. penetration in shearing. The area under the curve is the work done in shearing. The shape of the curve depends on processing parameters and material properties.

EXAMPLE 7.1 Calculation of Maximum Punch Force

Given: A 25 mm diameter hole will be punched in a 1.6 mm thick, 5052-O aluminum sheet a
room temperature.

Find: Estimate the force required.

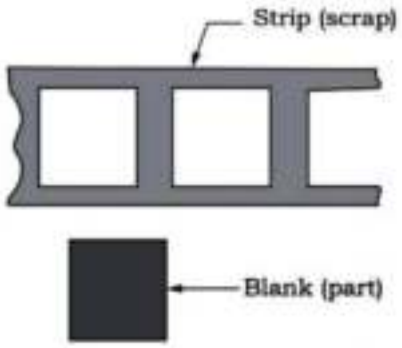
Solution: The force is estimated from Eq. (7.4), where S_{ut} for this alloy is found in Table 3.5 a
190 MPa. Therefore,

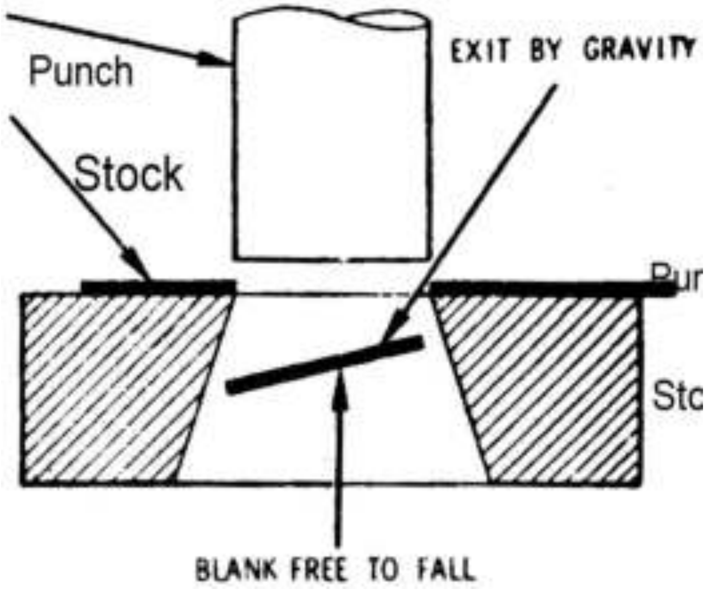
$$F = 0.7\,(0.0016)\,(\pi)(0.025)\left(190 \times 10^6\right) = 16.7\ \text{kN}.$$

Shearing Operations

- A typical application of shearing process is to ***cut large sheets into smaller sections*** for subsequent press working operations. Based on shearing process, there are several operations performed on sheet metals.

1. ***Blanking*** is the process of cutting sheet metal along a closed outline in a single step. Here the part cut out from the sheet is called ***blank*** and it is the desired product and the remaining portion is discarded.
   - The piece detached from the strip is called ***Blank***.
   - The remaining metal strip is called ***scrap***.

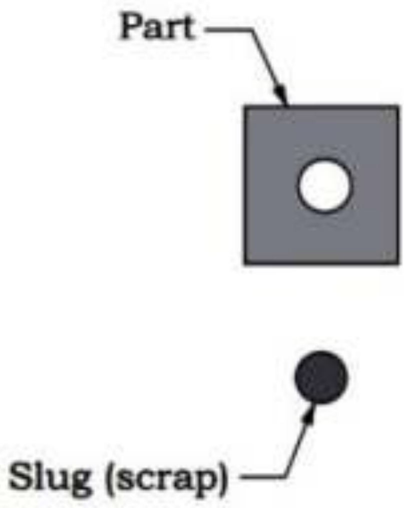


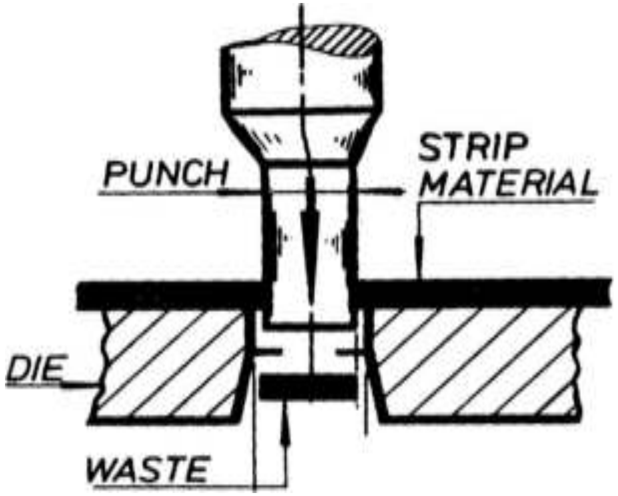


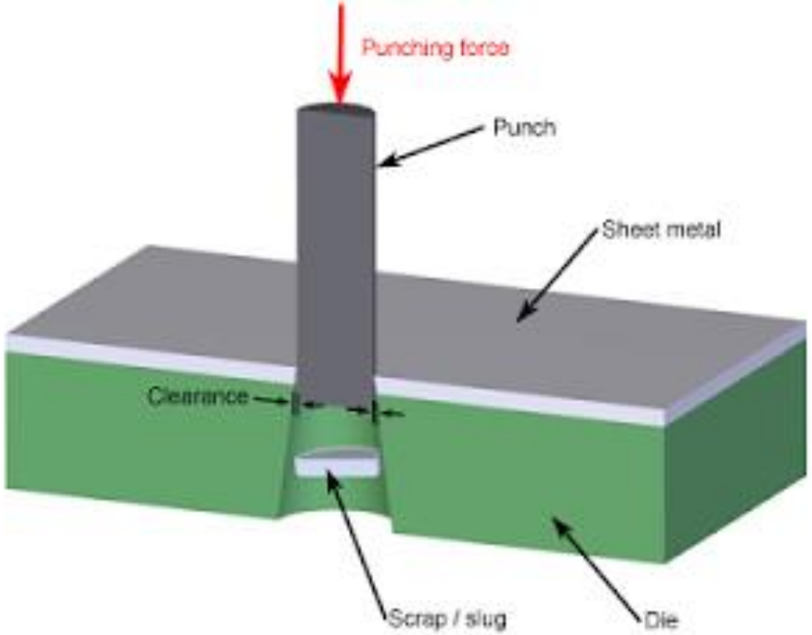
PUNCHING

2. ***Piercing or punching*** is similar to blanking except that the part cut and separated is (slug) discarded. Punching is used to create cut outs of different shapes in sheet metal.

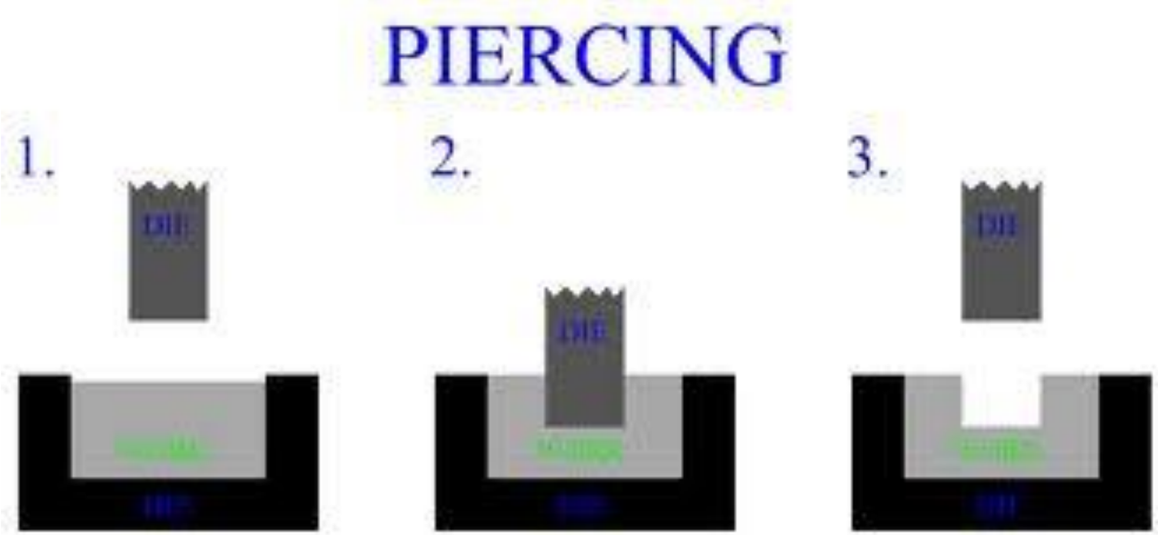
- Piercing is also a shearing process in which raw metal is pierced with a punch, resulting in the creation of a circular or other shaped hole.
- As the raw metal is pierced, the metal from the newly created hole is considered scrap.



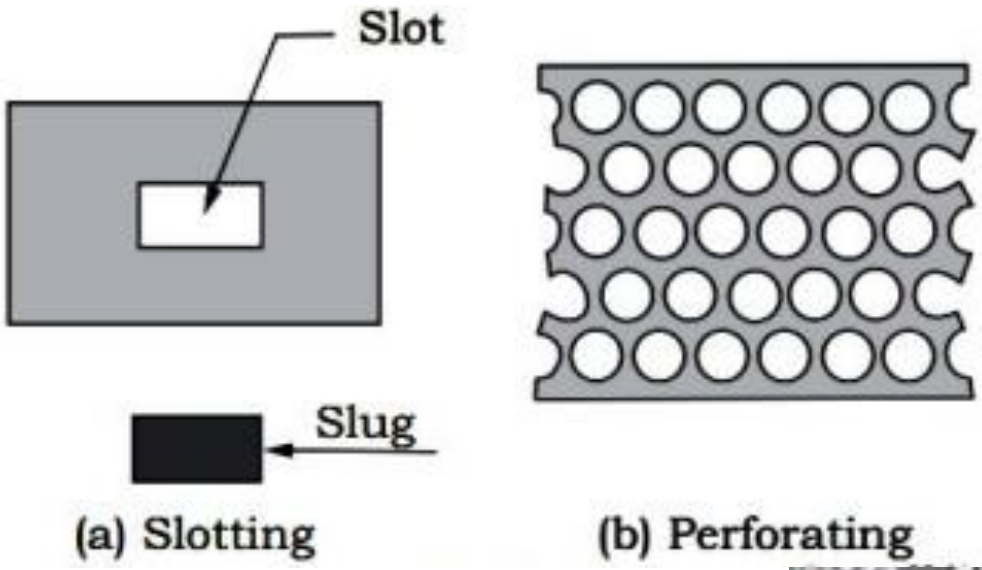


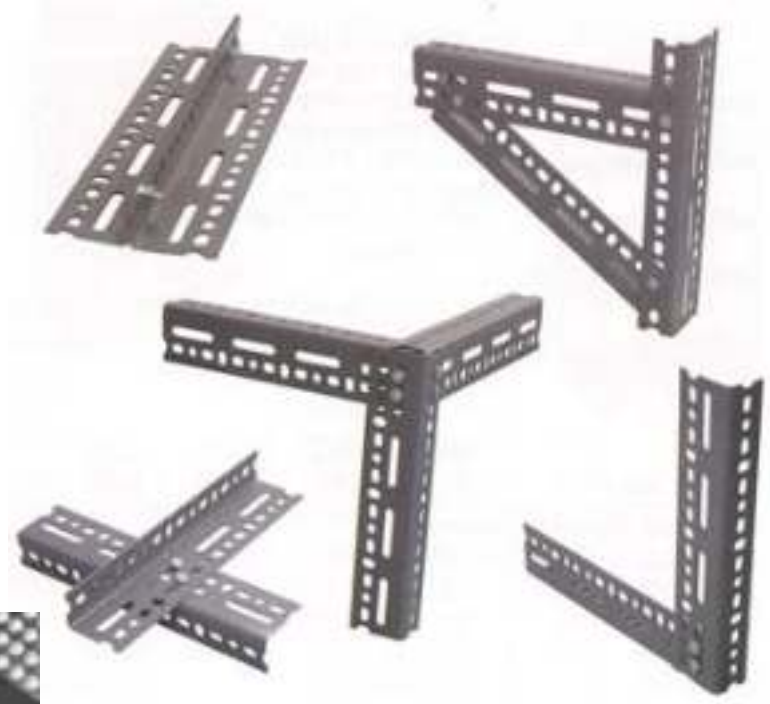


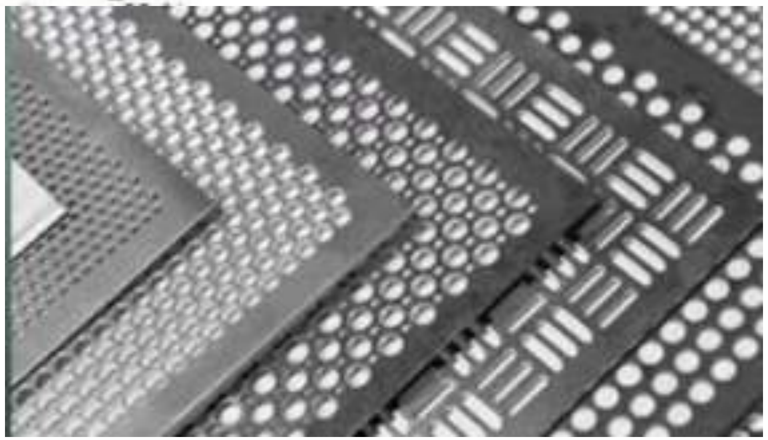
• In Piercing operation there won't be any scrap metal (waste metal) produced.



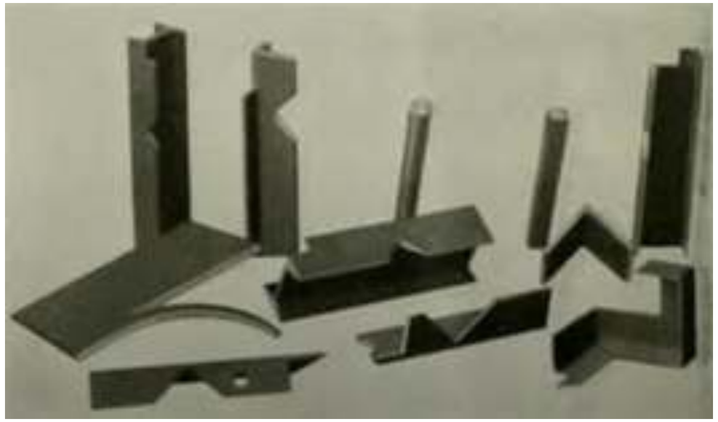
3. ***Slotting*** is the term used to call the punching operation for cutting rectangular holes. ***Perforating*** involves cutting a number of holes in sheet metal for decorative purpose or for passage of light or air.

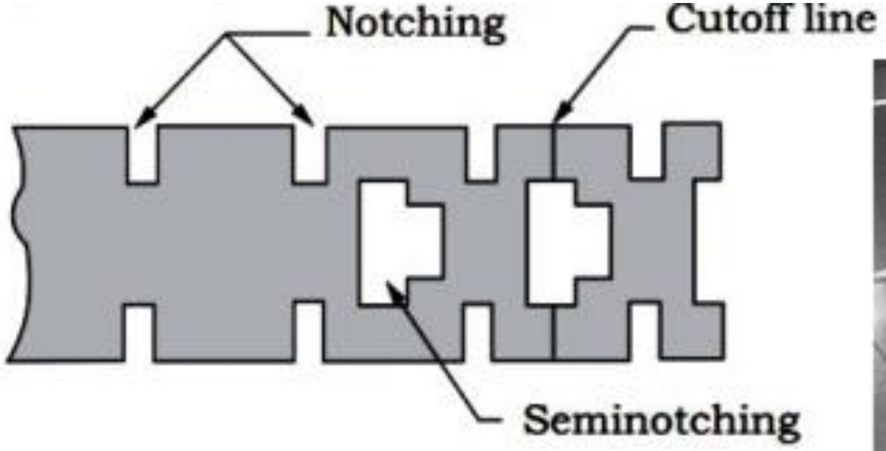


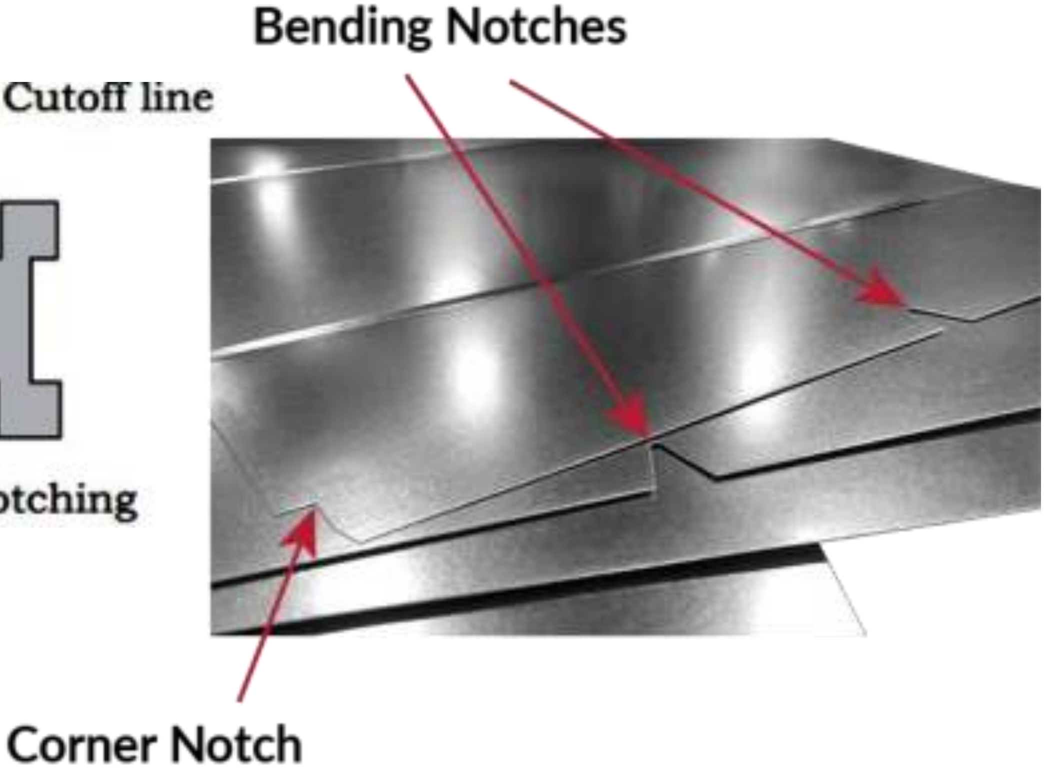




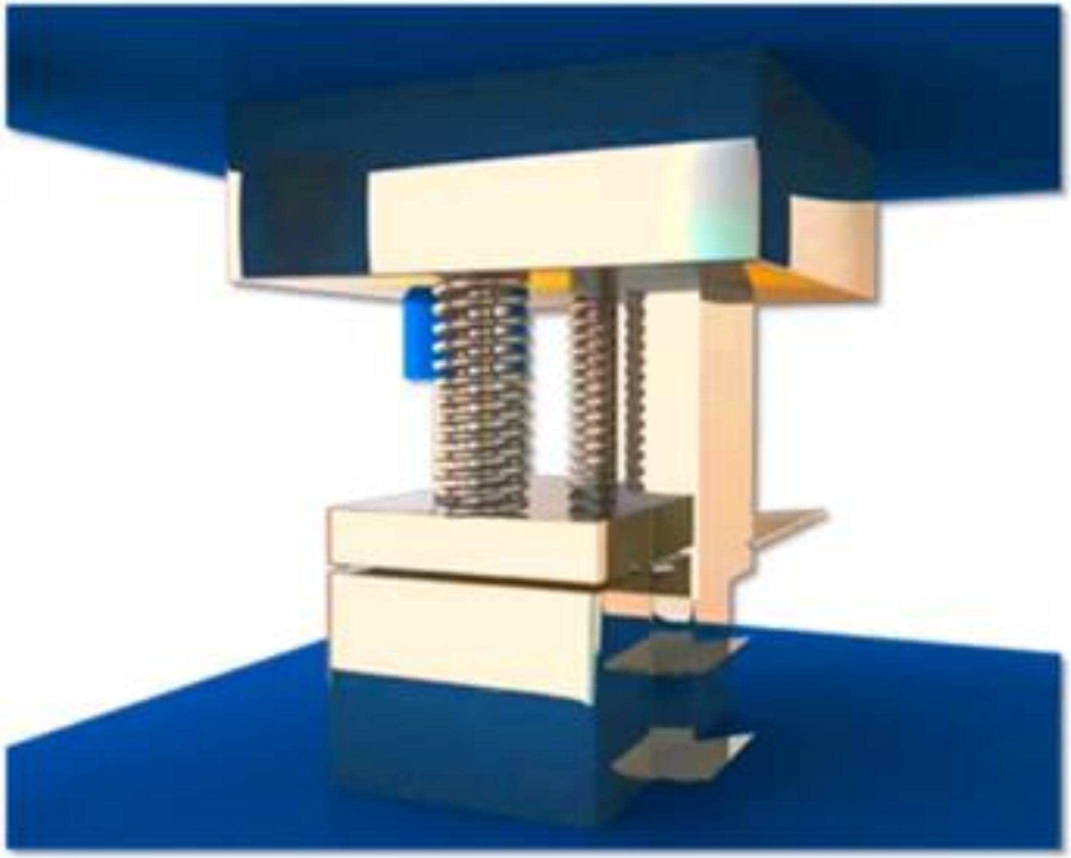
4. ***Notching*** is another kind of shearing process by which pieces of metal of various shapes are removed from the edges of sheets.
    - Semi notching removes a portion of metal (blank) from the interior of sheet to create a part of the blank outline.
    - This is different from punching and slotting as these processes create holes in sheets.







NOTCHING



5. ***Fine blanking*** is another shearing operation by which holes with ***very smooth and square edges*** are produced in sheet metal. Though this process is carried out as a single step process, it is limited to sheets of relatively small thickness.

- V shaped stringer used.
- Very low clearance, 1% of sheet thickness.

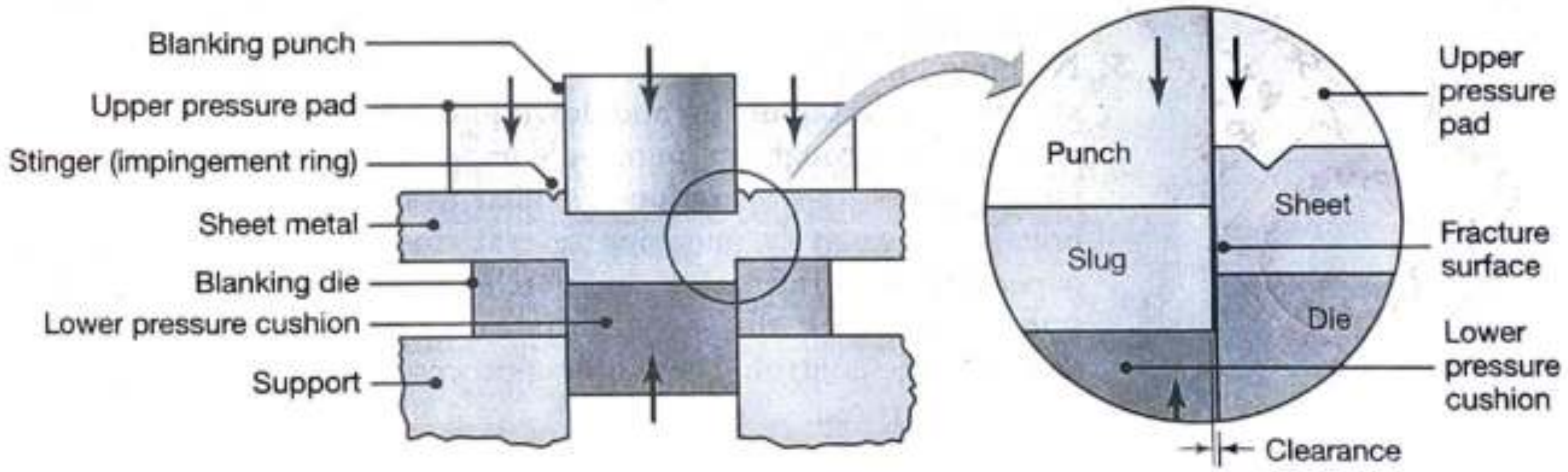
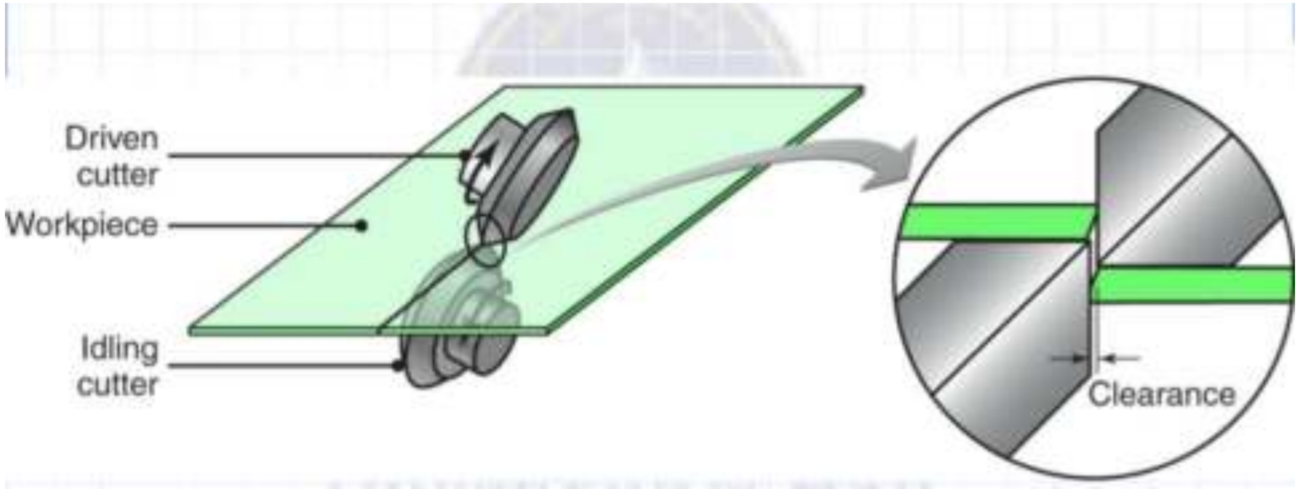


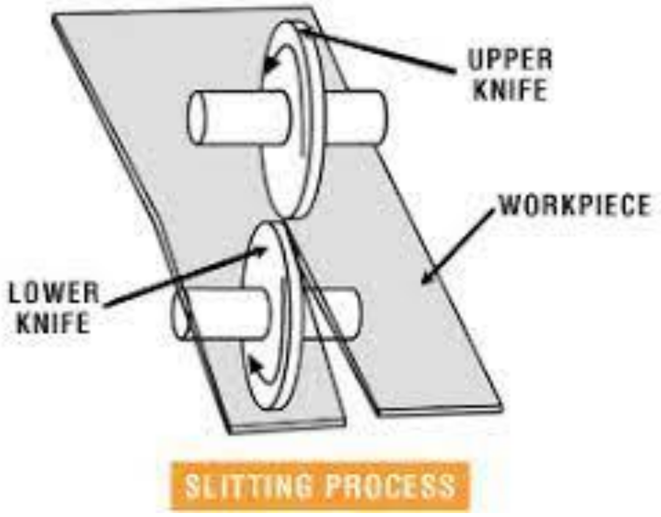
FIGURE 7.9 Schematic illustration of a setup for fine blanking. *Source:* Feintool International Holding.

6. ***Slitting and Lancing*** involves leaving a tab on the sheet without removing any metal.

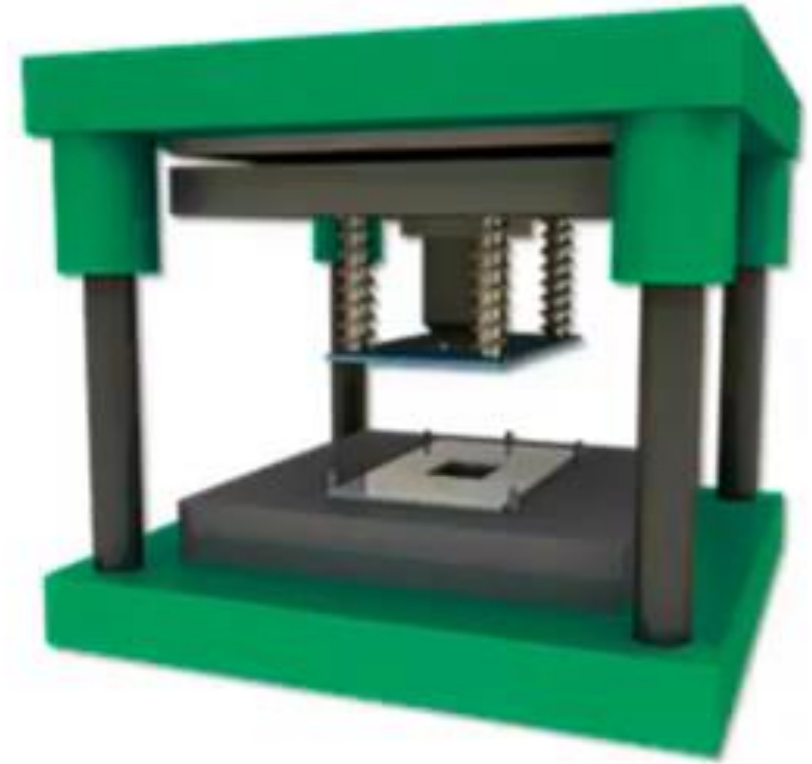
Lancing

Slitting

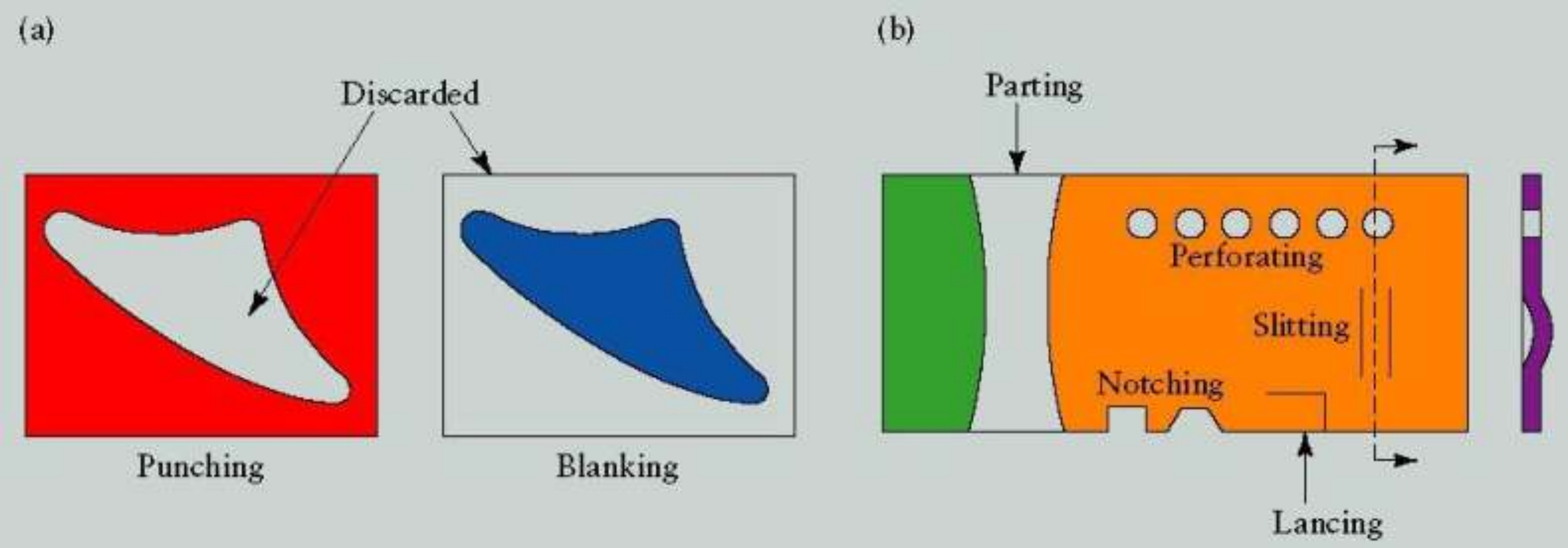




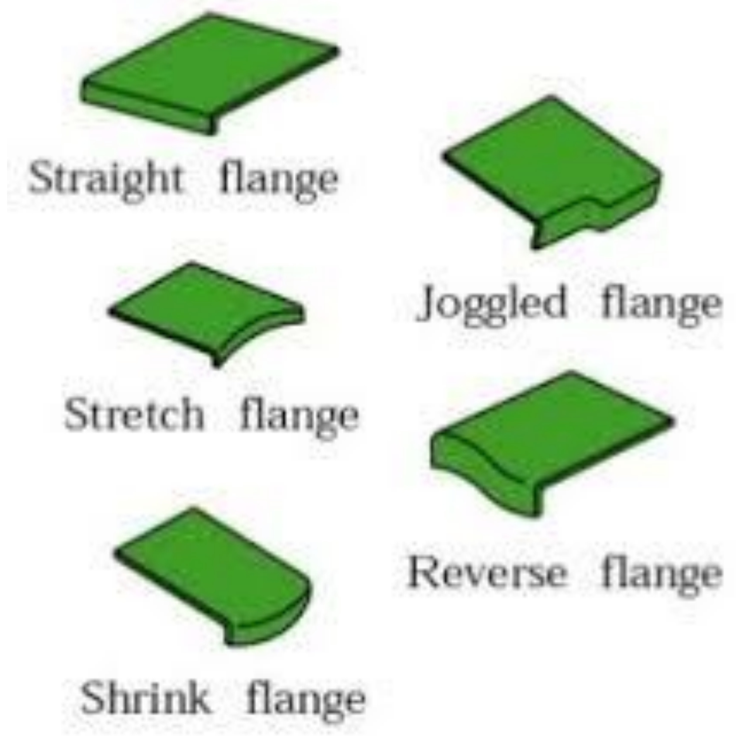
LANCING



7. ***Parting*** is the shearing the sheet into two or more pieces.

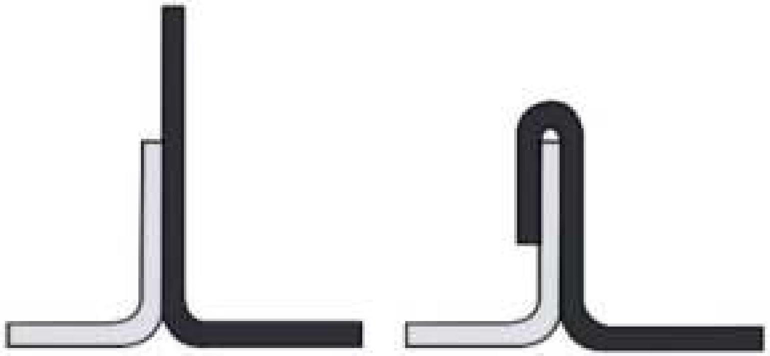


8. ***Flanging*** is the process of ***bending edges of sheets at 90°. This is done prior to*** joining two sheet metal parts or to increase stiffness

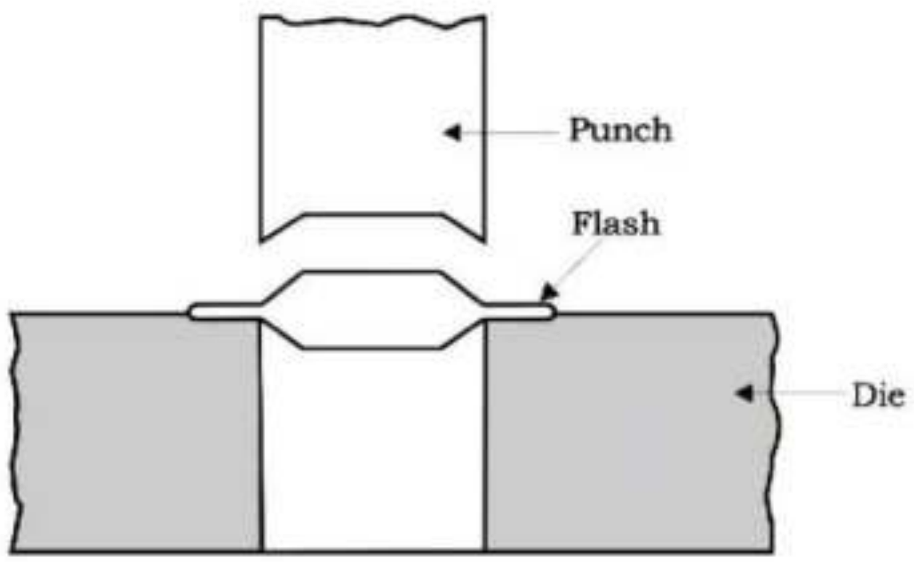


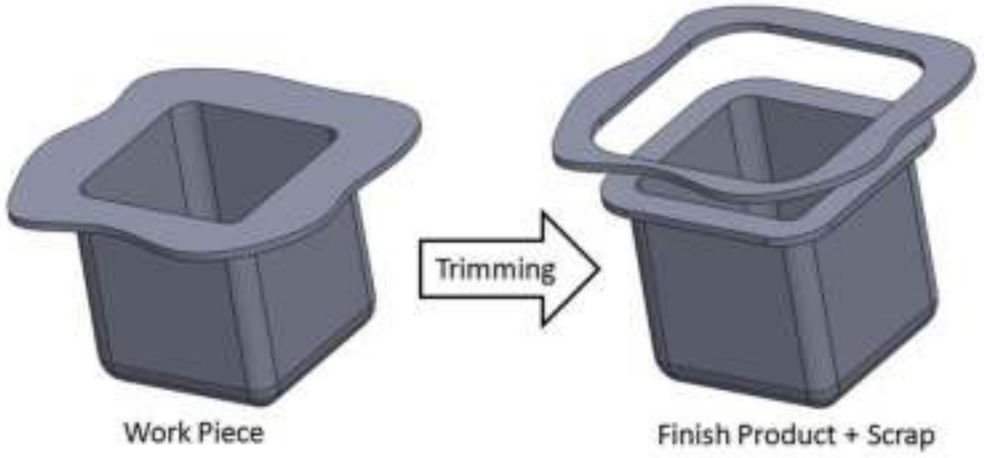
9. *Hemming* is the process of folding over the edge of a piece of sheet metal and then ***pressing it to make it flat***. This is done to stiffen the edges of sheets.

10. ***Seaming*** is done to ***join two sheets without use of fasteners*** or welding. One or both sheets are flanged before seaming and a joint is made.



11. ***Trimming*** is used to remove flash (small ***fin like extra material spread out near parting line***) in products made by die casting and drop forging process. The flash is trimmed before the forging is used. Dies similar to blanking dies are used for this. But the presses used for trimming process usually have a larger table.





12. **Shaving**. The edges of blank or hole produced by blanking or piercing operations, may have some burrs created by the shearing process. The ***shaving operation is used to remove these burrs***, following the blanking or piercing process. The shaving dies usually have very small clearances.

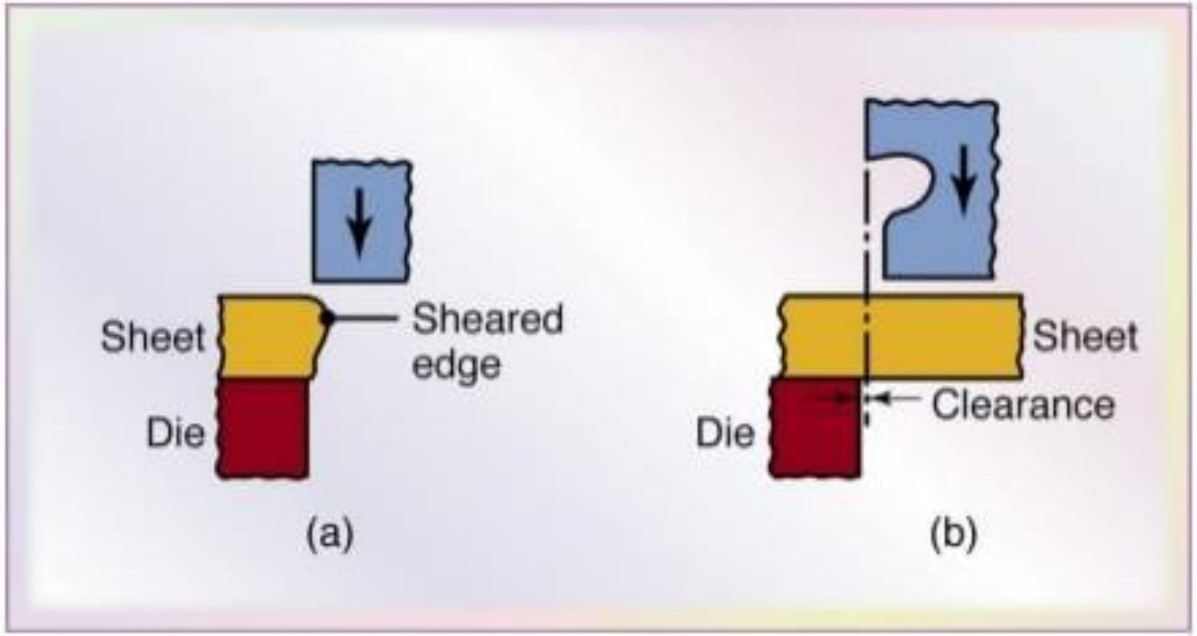
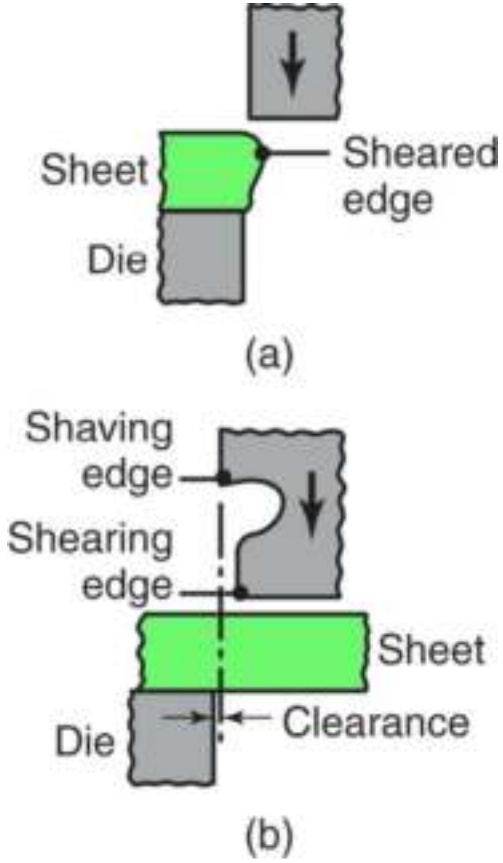
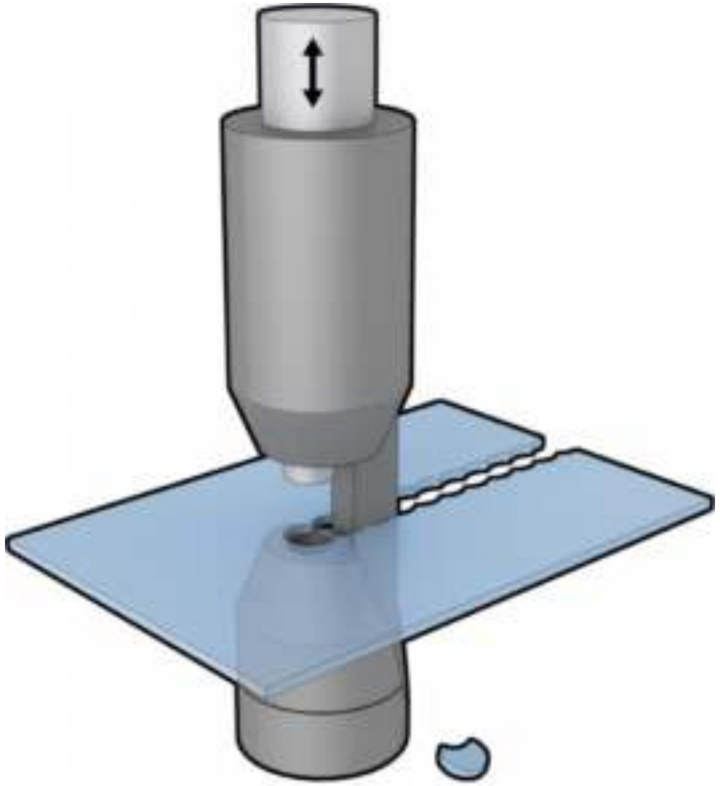
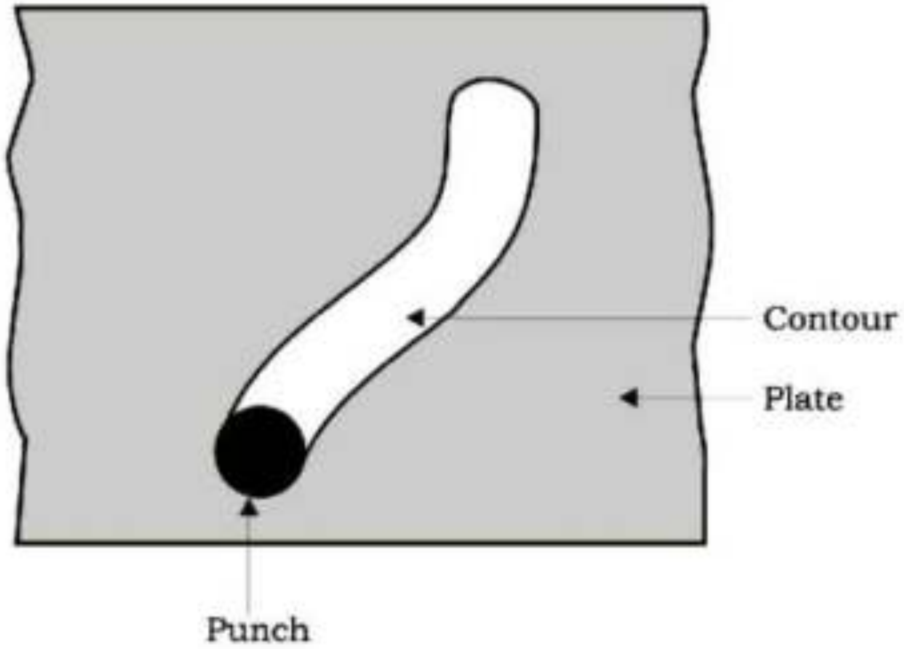


Figure 16.9 Schematic illustrations of the shaving process. (a) Shaving a sheared edge. (b) Shearing and shaving combined in one stroke.



13. ***Nibbling*** is used to remove metal from a sheet metal in small increments to form a specific contour. This process is used when the ***contour is long and a single punch*** may not be economical. Round or square punches can be used to punch the plate repeatedly to develop the required profile.



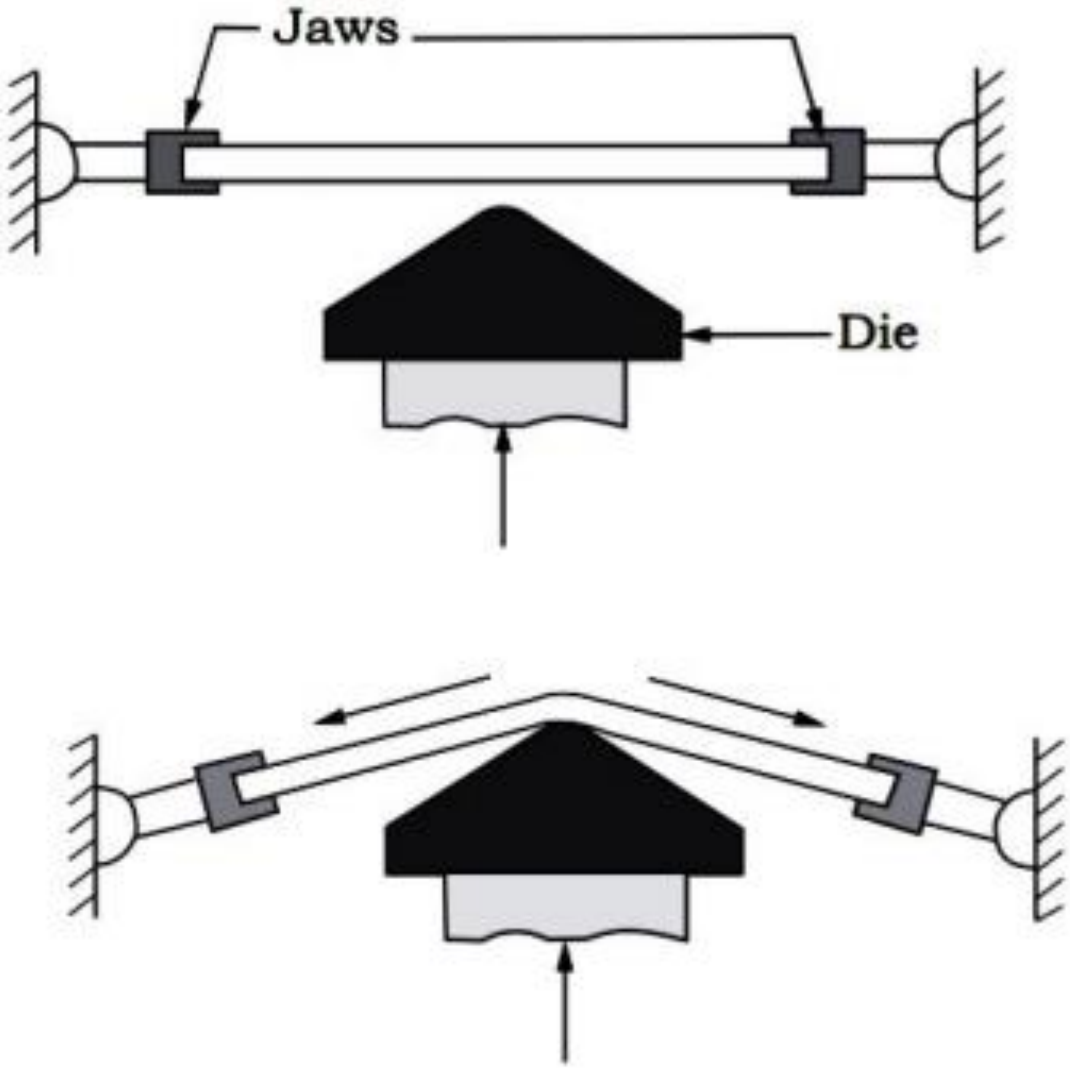


TENSION OPERATIONS

- These press working operations subject the workpiece to ***tensile stress*** to deform it as per the needs.
- Eg. Stretch Forming

Stretch Forming

- In stretch forming, the sheet metal is ***clamped along its edges and stretched over a die or form block***. There are different types of machines in which the form block moves forward, backward or sideways.
- Rectangular sheets are usually the work materials for stretch forming. The sheet is clamped **along** its narrower edges and stretched lengthwise. The rectangular sheet gets elongated in length and shortened in width. Stretch forming cannot be used for products with sharp corners.
- Popular applications of stretch forming are for making ***automobile door panels, window frames and aircraft wing panels***.


Jaws
Die

- Stretch forming operation is ***carried out in plastic state only***, and spring back effect is eliminated. The sheet is held between two jaws of hydraulic cylinders and stretched **beyond elastic limit.**
- Then the die moves forward to come in contact with the sheet and give it the shape of die. This is a ***simple and inexpensive process***.
- An estimate of force required in stretch forming can be obtained from the expression.

$$F = Lt\sigma_f$$

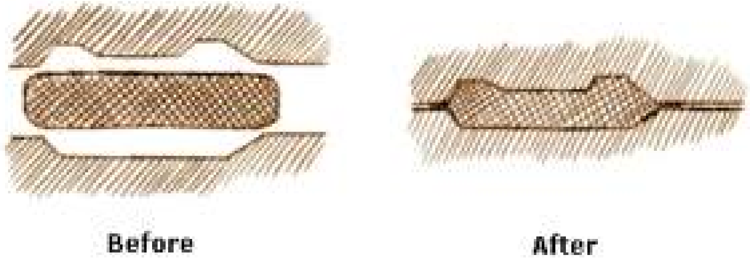
where L-Dimension of sheet in the direction perpendicular to stretching (mm); t-instantaneous thickness of sheet (mm); σ_f -flow stress of work material (MPa).

COMPRESSION OPERATIONS

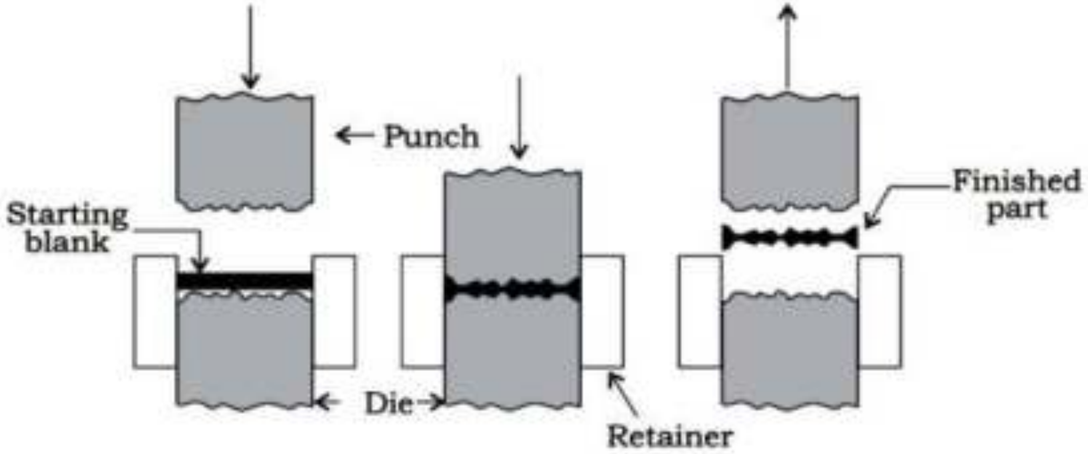
- These operations are earned out by applying compressive stress on the work material.
- Compression operations are,
  - Coining
  - Sizing
  - Ironing
  - Hobbing

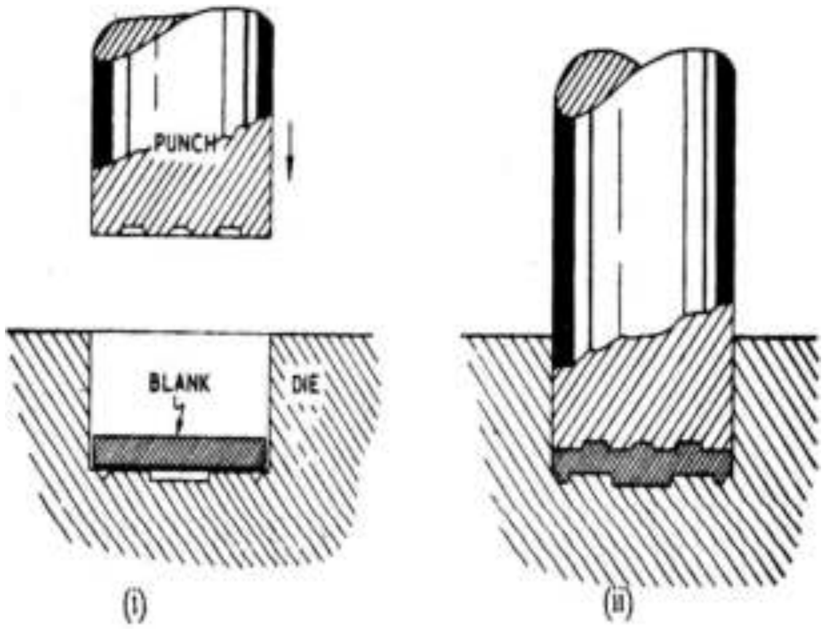
Coining

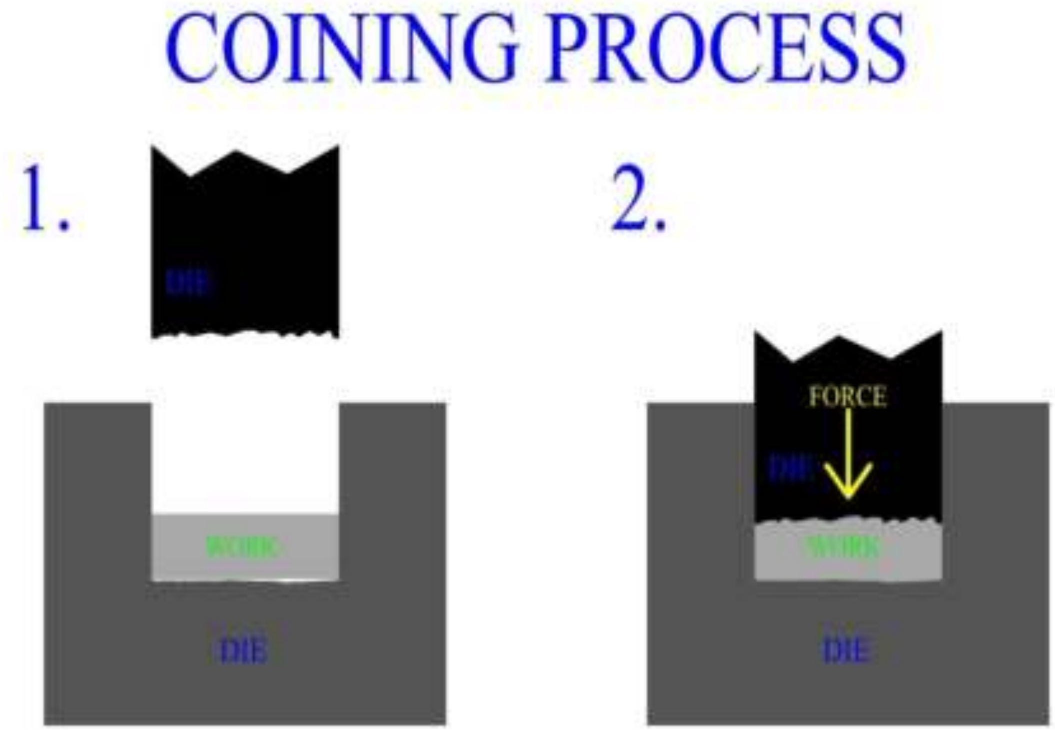
- Coining is the process of ***pressing material in a die*** so that it flows into the cavities in the die face.
- Coining operation is to **force the impressions on the die to the surface of the metal**.
- Make use of blank sheet metal.
- In this process, metal flows as per the contour of the die and there is **significant changes in metal thickness**.
- Coining operations are generally carried out in cold condition using Closed Dies.



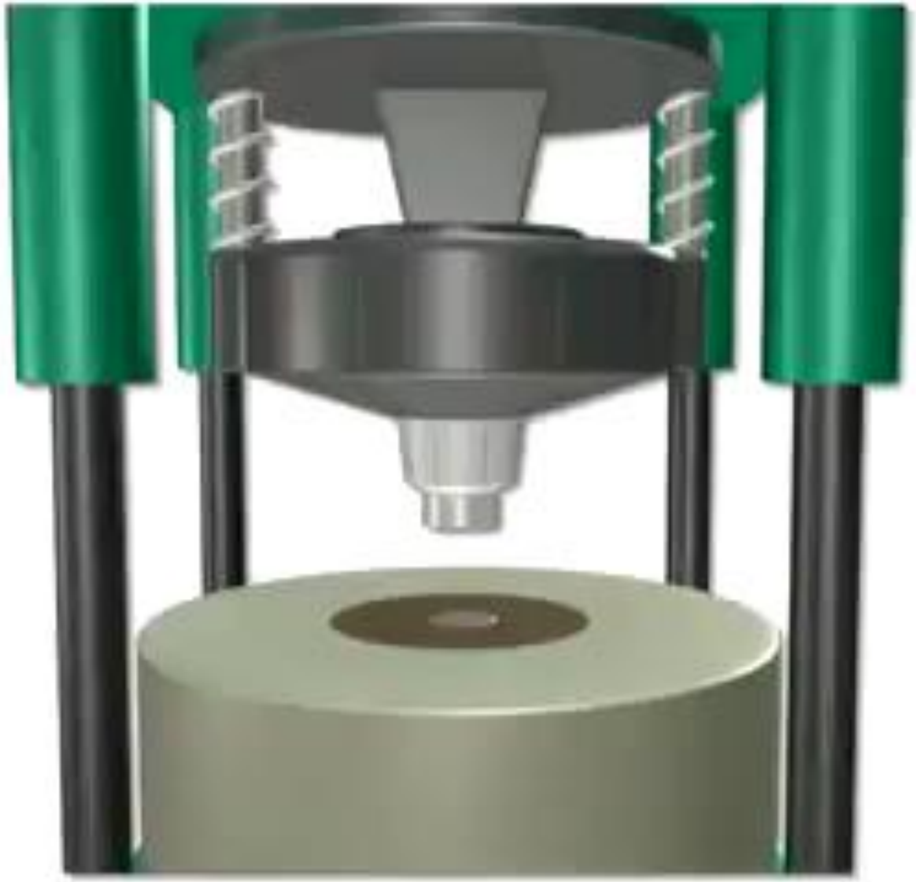
COINING




PUNCH
BLANK
DIE
(i)
(ii)


COINING PROCESS
1.
2.
DIE
WORK
DIE
FORCE
DIE
WORK
DIE

COINING

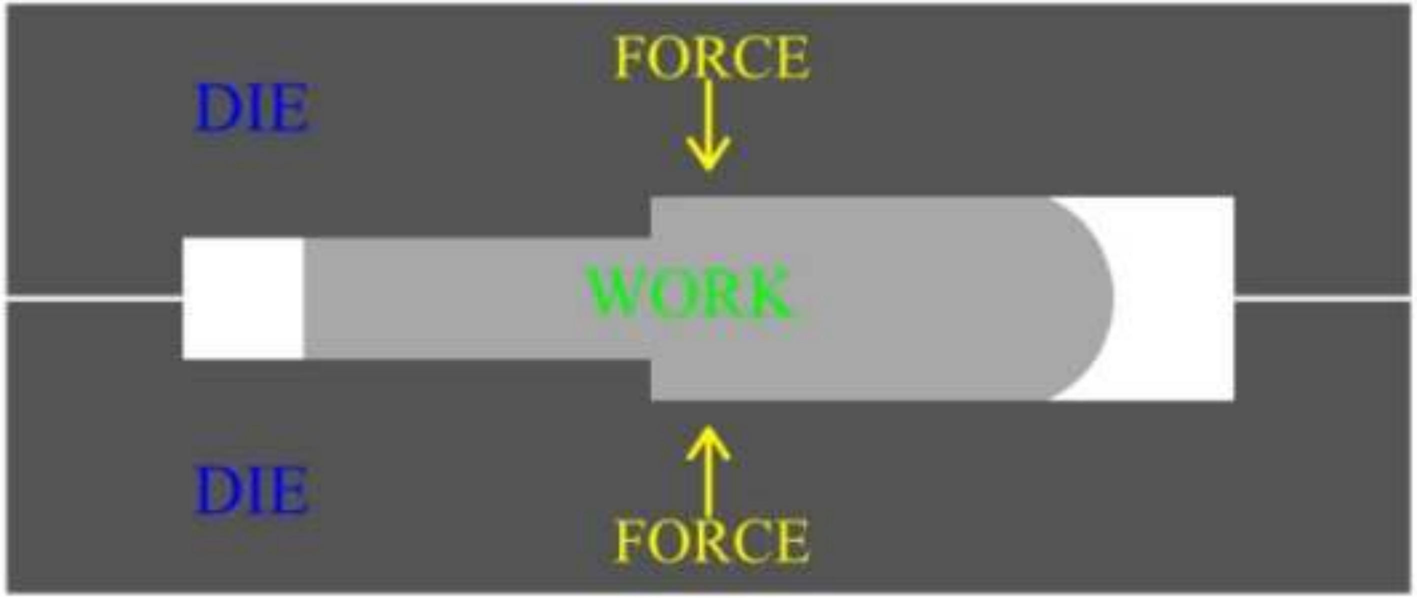


ELDHO PAUL,MACE

- Coining is used to reproduce ***ornate details with excellent surface finish and very close tolerances***. Some examples of products made by coining process are metal buttons, medals, coins, jewellry, tableware and decoration items.
- In order to impart good surface finish, the coining dies must be highly polished and free from scratches and tool marks.
- During the coining operation, the part must be ***properly confined***. The die block surfaces will have the details to be inscribed on the part and will control the thickness of the part. The sides of the die control the outside contour of the part.

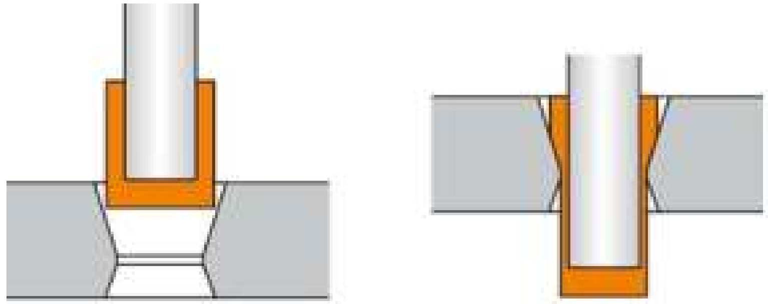
Sizing

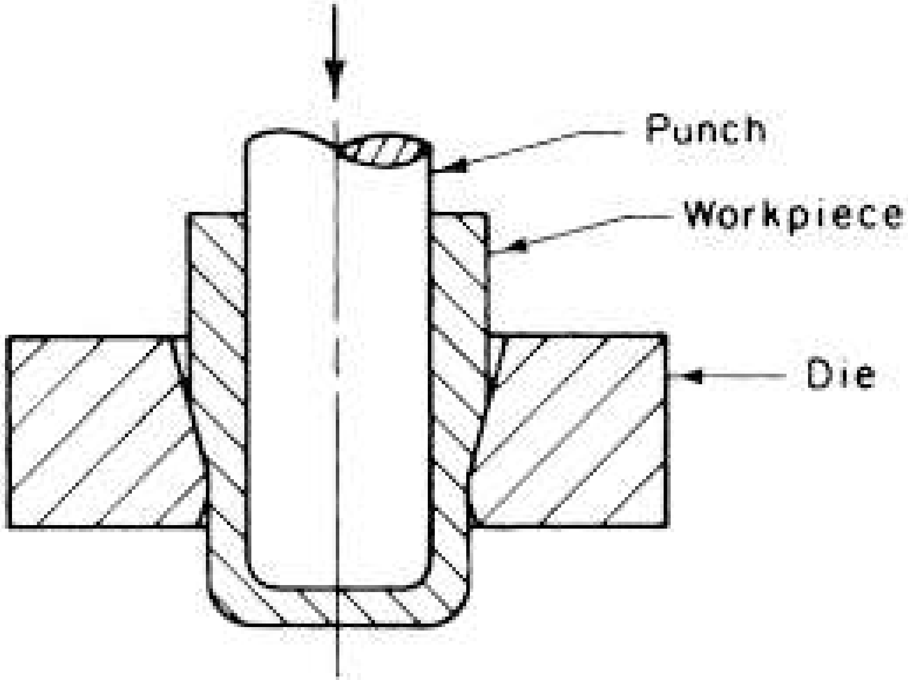
- Sizing is a metal forming process that is used mainly to finish work that has already been manufactured.
- It is a cold forming process.
- Metal sizing uses a lot of force over a short distance, producing very accurate dimensions in the finishing of these parts.
- This manufacturing technique can also be used to create work with excellent surface quality.
- Sizing is characteristic in that during the operation, the flow of work material is unrestricted in all directions except that over which the force is applied.

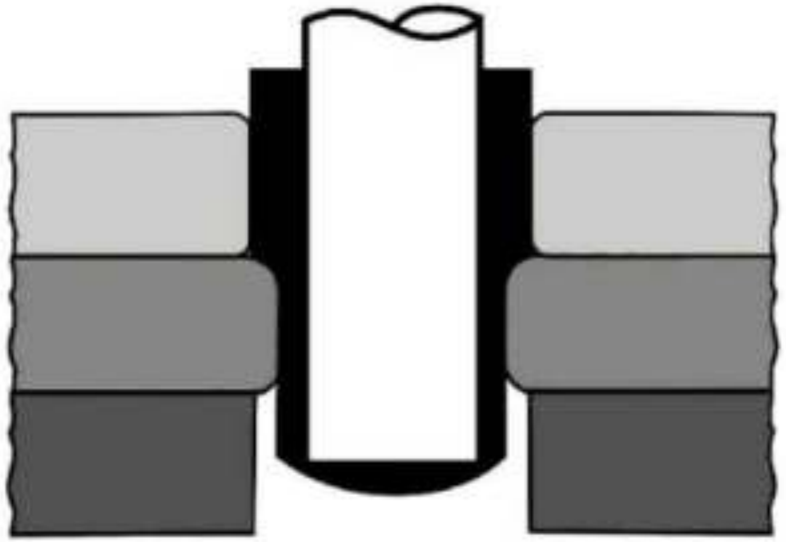

FORCE
DIE
WORK
DIE
FORCE

Ironing

- Ironing is a method of ***redrawing a tubular shell to reduce the wall thickness*** to ensure a smooth uniform wall surface with only a minor reduction in the inner diameter. ***The ironing process is also called as thinning***.
- Ironing is done as a ***secondary step after drawing process***. Purpose of ironing are to correct the natural thickening of the wall and to reduce its wall thickness to a uniform level.
- ***This is done by making the clearance between the punch and die less than the wall thickness of work.***
- The metal is thinned and length is increased as it is forced through the die and punch.

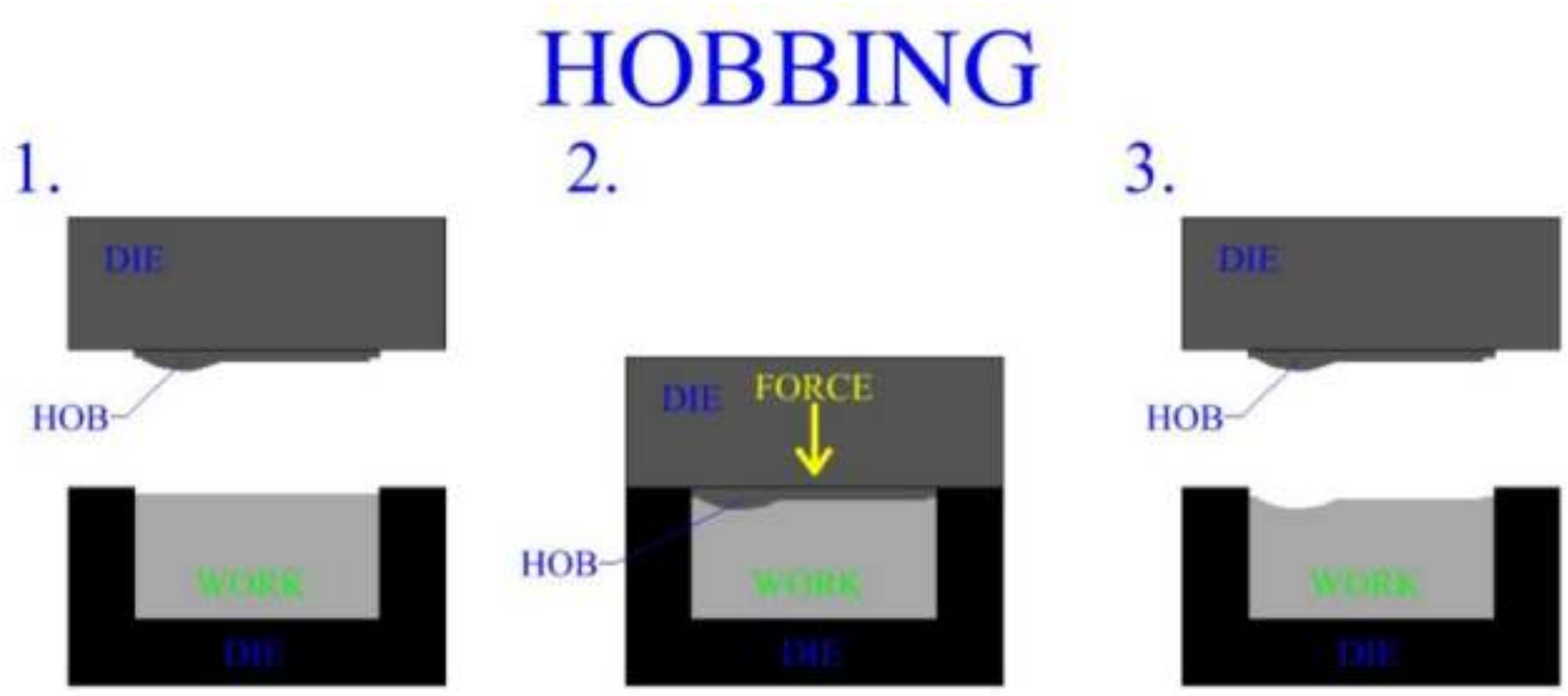



Punch
Workpiece
Die



Hobbing

- The process of hobbing is uses a very hard piece of steel, previously ***engraved or embossed with specified details, known as the master hob***, and pushes it into an unhardened steel blank by way of hydraulic press. This produces a hob with a reverse image of the specific details either ***impressed or raised on the blank*** depending on the job requirement.
- The hobbing process is performed at room temperature with the required pressure varying from 1380 MPa to 2760 MPa depending on both the hobbing metals and blanking material.
- This is a ***cold forming process*** which is generally done with steel in a fully annealed state. Cold hobbing makes very efficient use of material while producing very strong parts, as the material flows into the desired shapes, maintaining its grain structure.



- Very accurate dimensions and surface quality are obtained within the cavity.
- A common application of hobbing in modern industry is to produce ***molds or die cavities*** for other manufacturing processes such as plastic molding, die casting, and other metal forging processes.

TENSION & COMPRESSION OPERATIONS

- In this category of press working, the work material is subjected to tensile and compressive stresses.
- The dies used here are designed so as to distribute the applied load into tensile and compressive stresses properly as per the design requirements.

Bending

- In sheet metal work, bending is denned as straining of metal around a straight axis.
- During bending, the outer fibres of the metal are in tension and the inner fibres are in compression. The neutral plane with no stresses separates these different zones.
- The length of neutral axis in the bend is called bend allowance and is used to determine length of blank for bending.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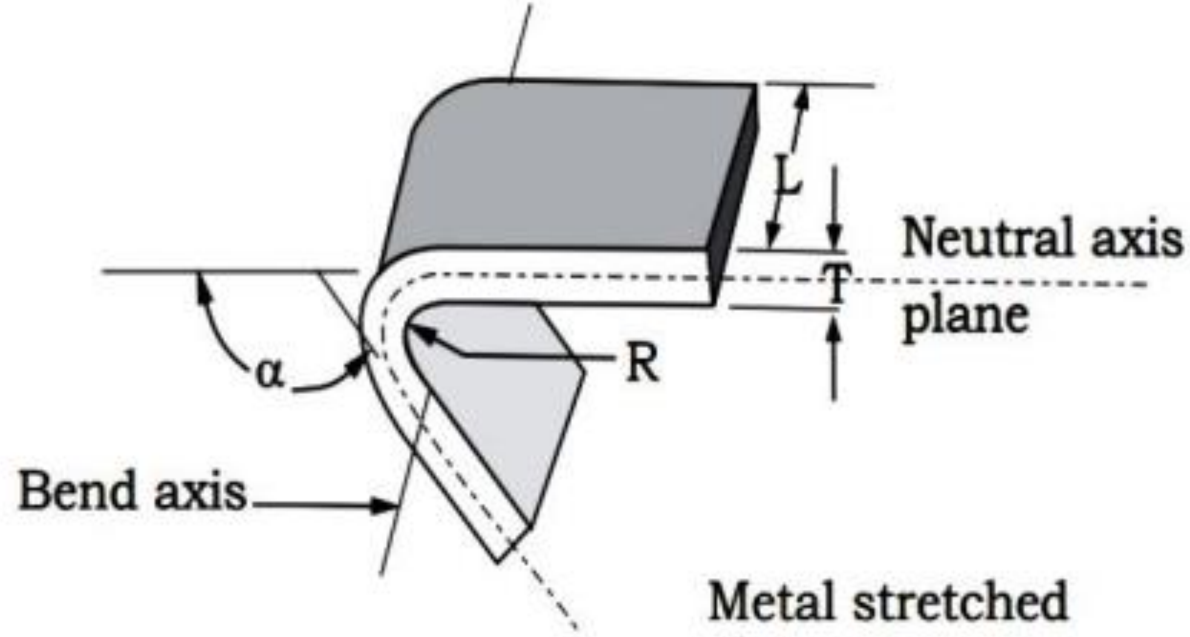
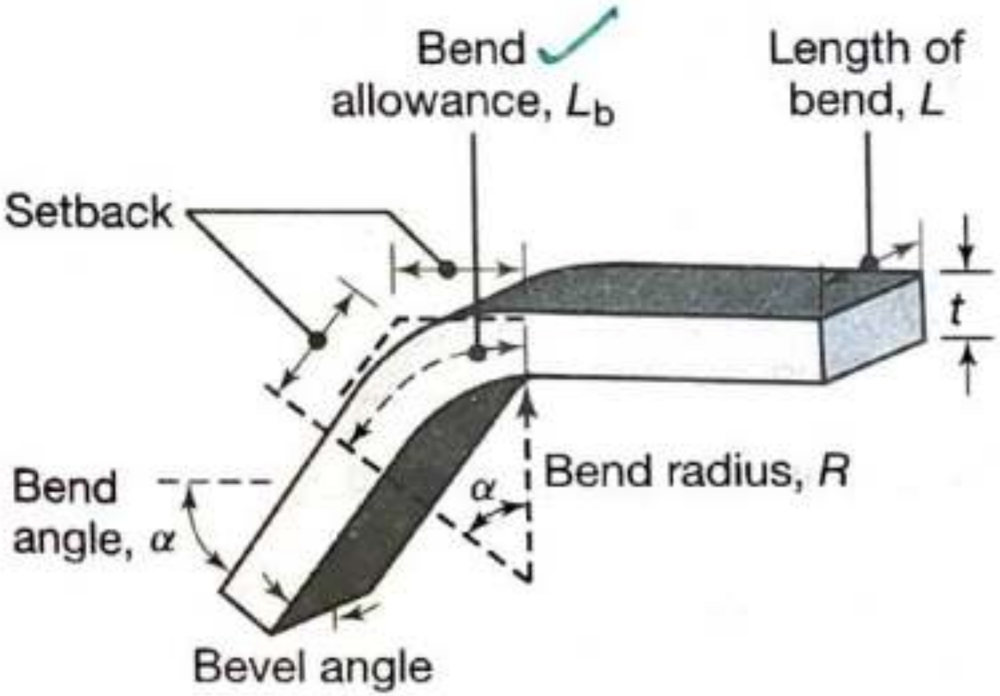
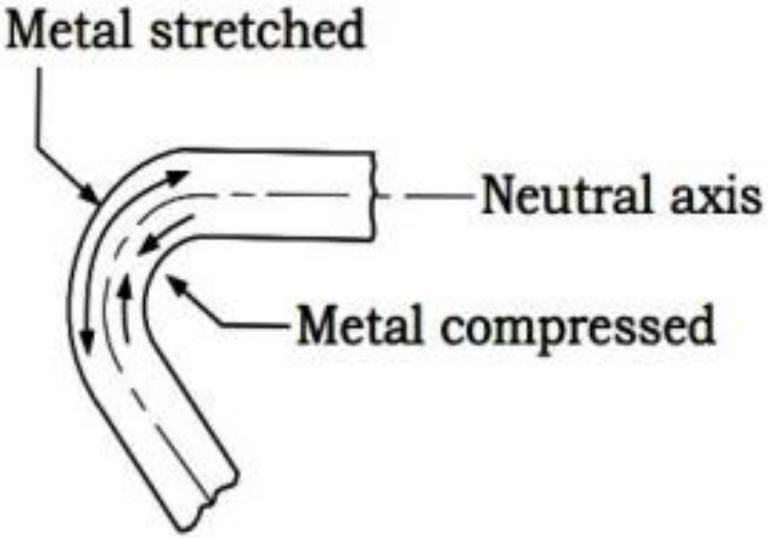


L
T
Neutral axis
plane
R
α
Bend axis

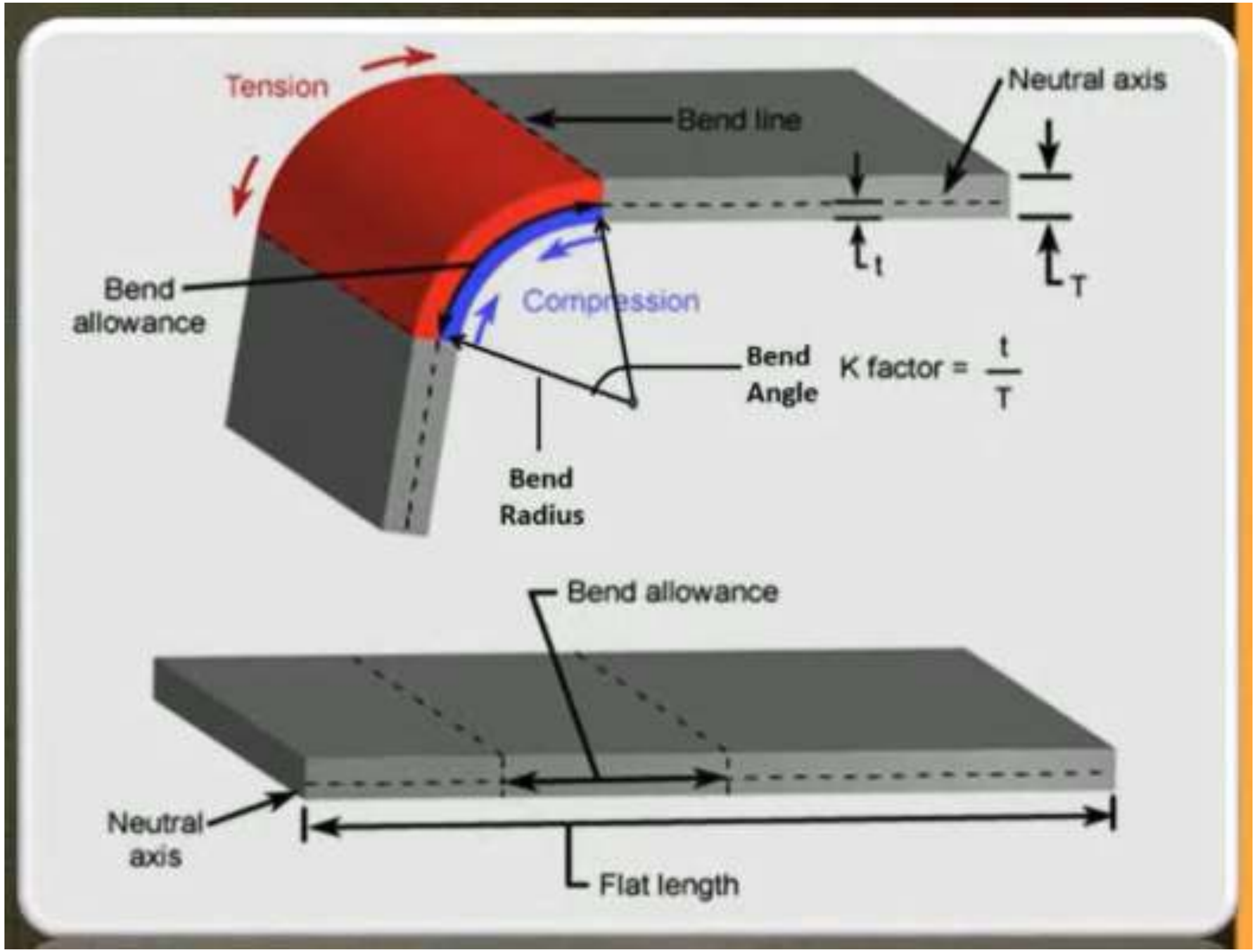


Bend
allowance, L_b
Length of
bend, L
Setback
t
Bend radius, R
α
Bend
angle, α
Bevel angle



Metal stretched
Neutral axis
Metal compressed

ELD
PAUL,



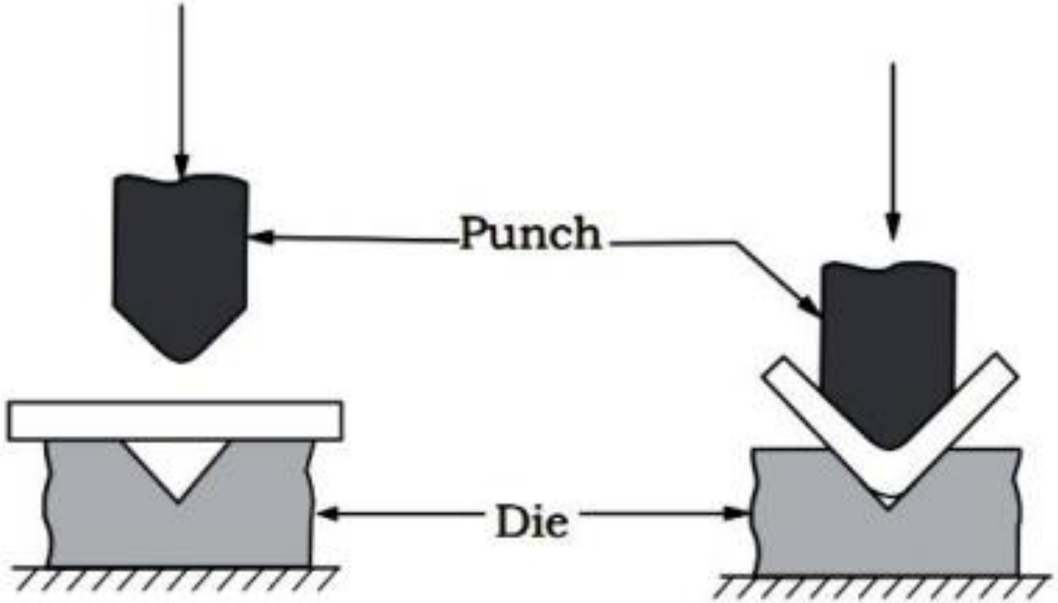
Tension
Bend line
Neutral axis
t_t
t_T
Bend allowance
Compression
Bend Angle
K factor = $\frac{t}{T}$
Bend Radius
Bend allowance
Neutral axis
Flat length

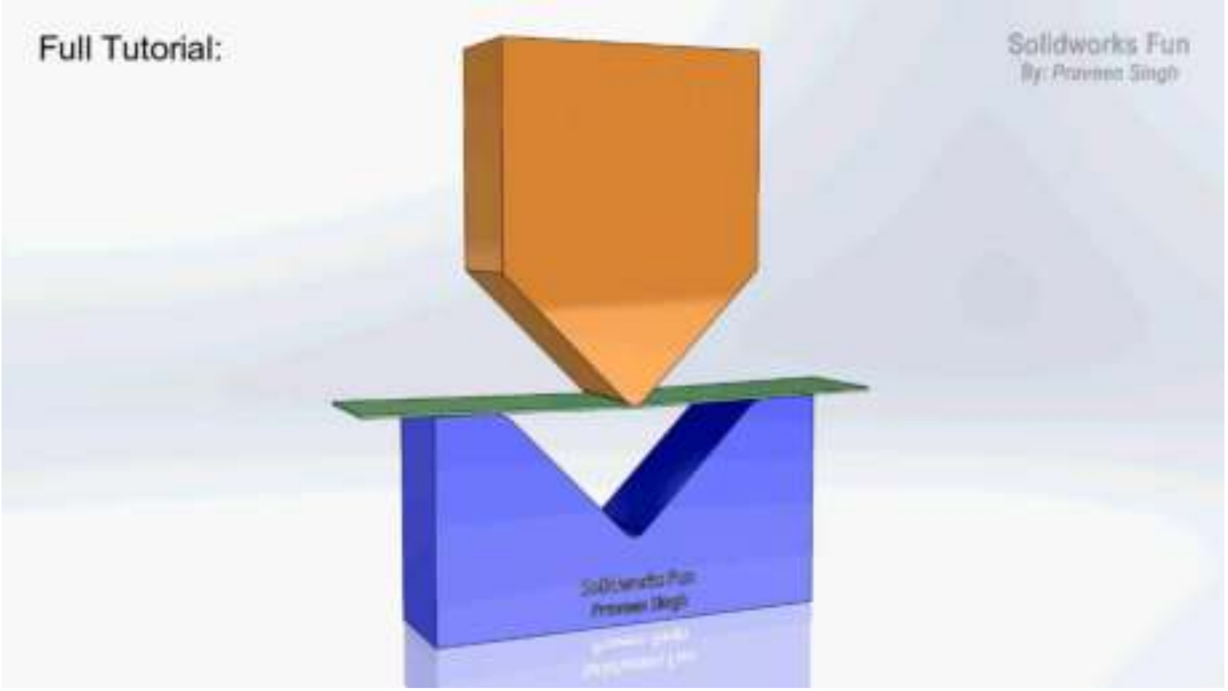
- An approximate value for bend allowance is given by

$$L_b = \alpha\left(R + kt\right)$$

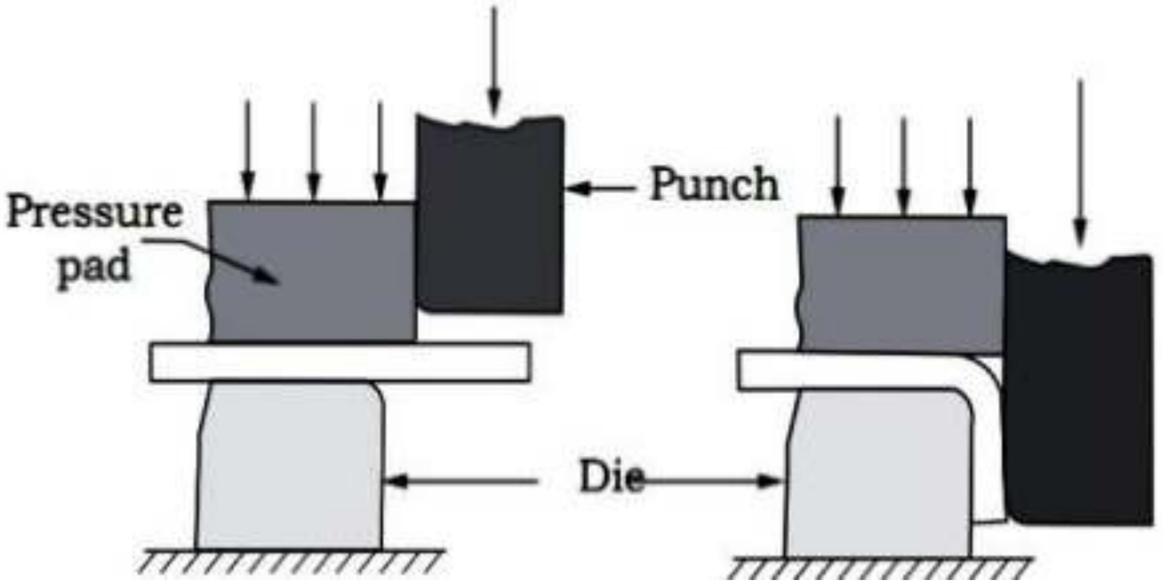
- where a is the bend angle in radians, *R* is bend radius, *T* is sheet thickness and *k* is a constant. In an ideal case, neutral axis is at the centre of sheet thickness and k=0.5, but *k* ranges from 0.3 (for *R*< 27) to 0.5 (for *R* >27).
- When R/t ratio decreases, the tensile strain at the outer fiber increases; the sheet may thus begin to crack after a certain strain is reached. The radius, R, at which a crack first appears on the outer surface of the bend is called the minimum bend radius.
- This minimum bend radius is generally expressed in terms of its thickness, such as 2t, 3t, 4t, and so on. Thus, for example, a bend radius of 3t indicate that the smallest radius to which the sheet can be bent, without cracking is three times its thickness.

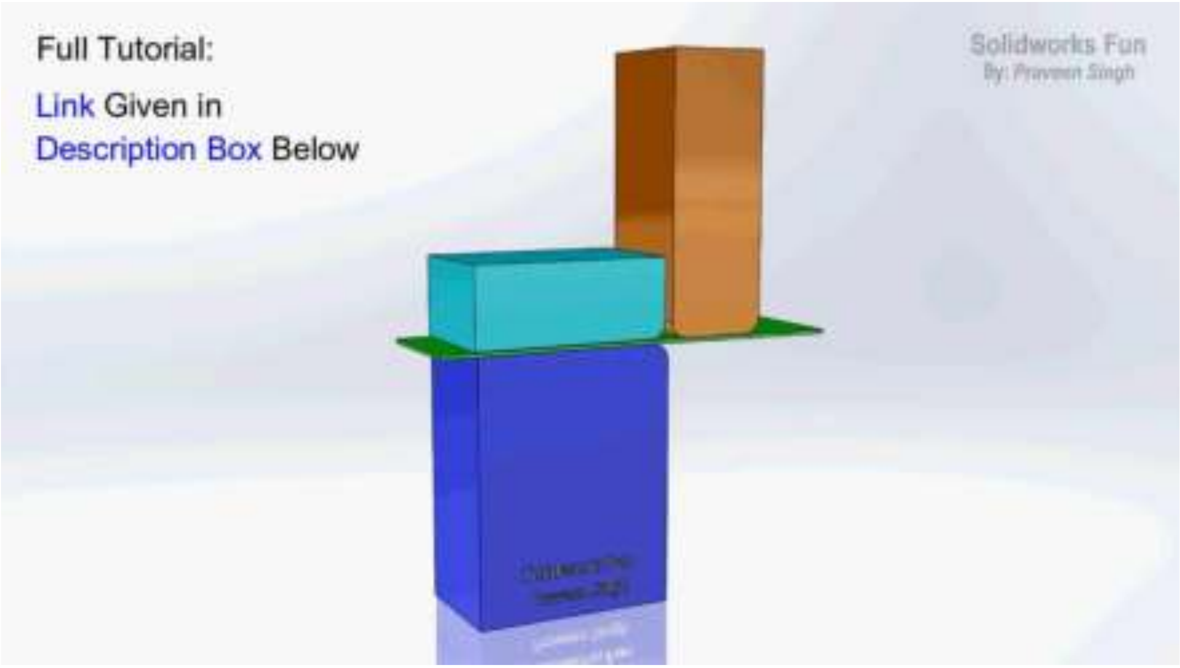
- Bending operations are carried out using properly designed punch and die set. There are two common methods of bending;
  - V-bending and
  - Edge bending
- In V-bending, the metal is bent between a V shaped punch and die.
- The V-dies can be used to make bends of various included angles.





- Edge bending is done using a wiping die. Here sheet metal is held in position by the application of force by the pressure pad. The punch now forces the sheet to yield and bend over the edge of the die. Figure shows the wiping punch and die set for edge bending of 90° or less. These are expensive than the V-dies.





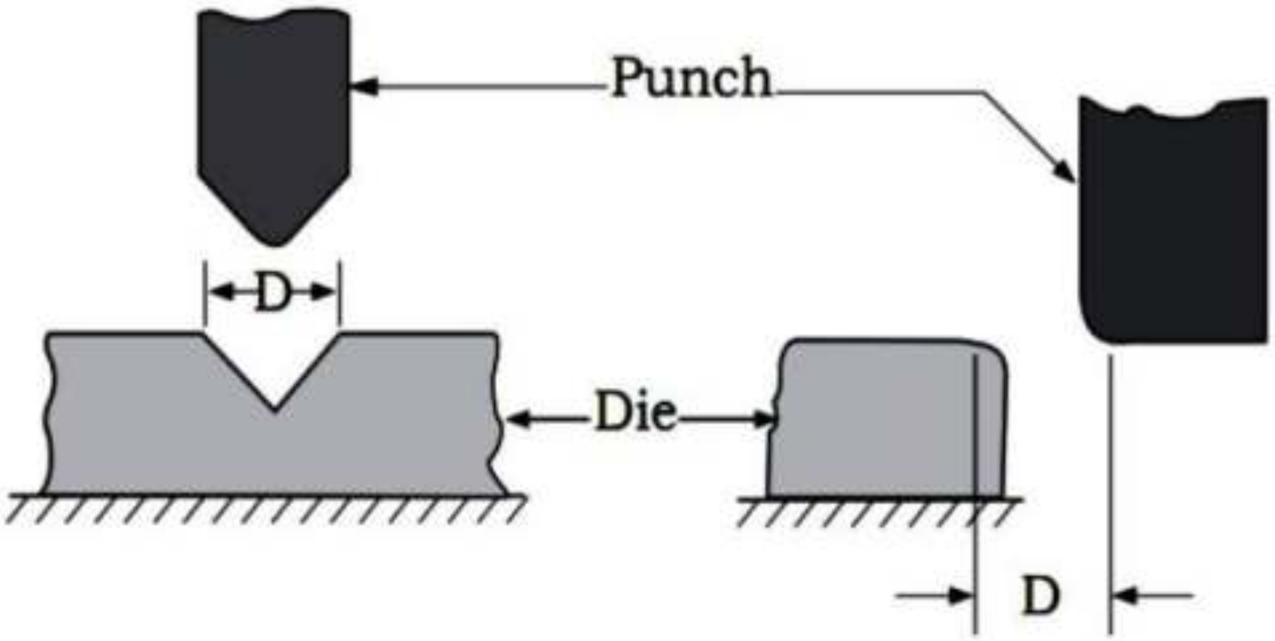
Bending Force

- The bending force can be determined from die characteristics and the material properties.

$$F_b = \frac{KL\sigma_u T^2}{D}$$

where L is width of part in the direction of bend axis, T is blank thickness, D is width between contact points (die opening dimension), σ_u -ultimate tensile strength and K is a constant (see figures 5.41 and 5.44).

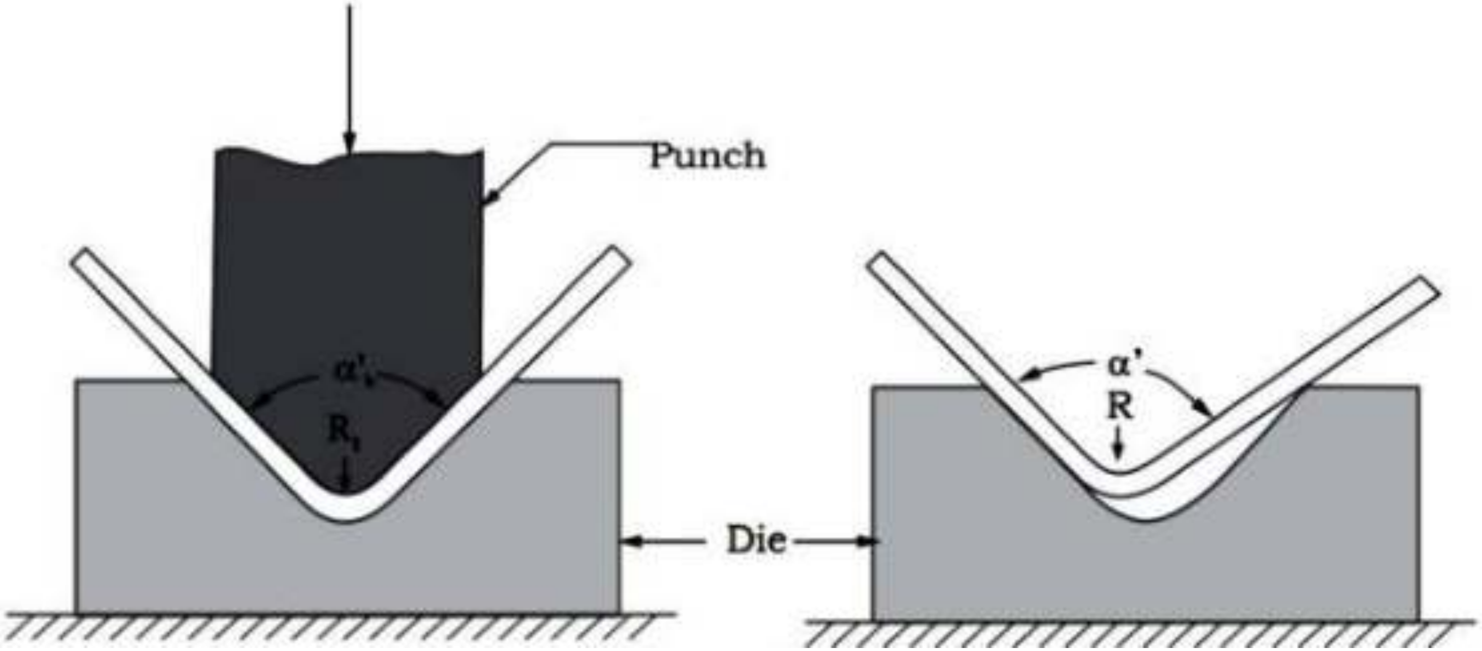
K=1.33 for die opening of 8T; K=1.20 for die opening of 16T; K=0.67 for U bending and K=0.33 for a wiping die.



Spring Back

- In a bending operation, the load applied by punch is removed at the end of deformation. At this time, some ***elastic energy remains in the bent part and it causes partial recovery of the deformation***. This partial recovery towards original shape is called spring back in bending.
- Because all materials have a ***finite modulus of elasticity, plastic deformation is always followed by elastic recovery upon removal of the load***; in bending, this recovery is known as springback.
- The final bend angle after springback is smaller than the angle to which it is bent and the final bend radius is larger than the radius to which it is bent.
- Spring back in bending is not easily to estimate theoretically. But it can be compensated by different means.

How do you compensate for springback when bending high strength steel?



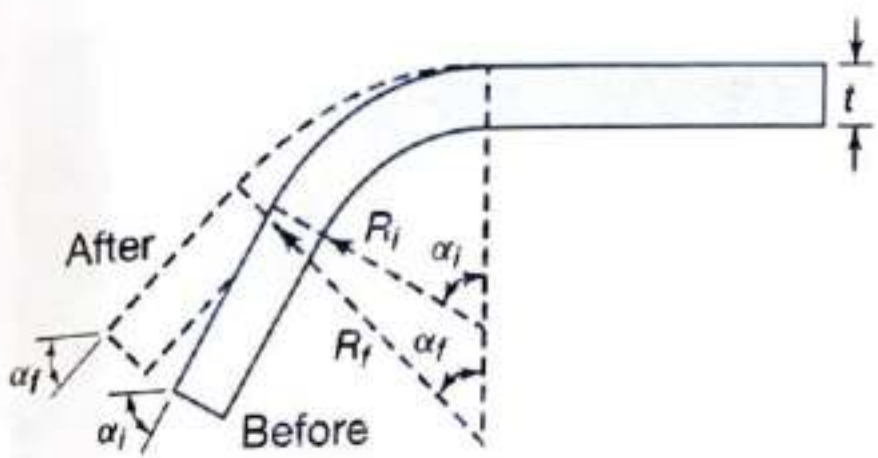
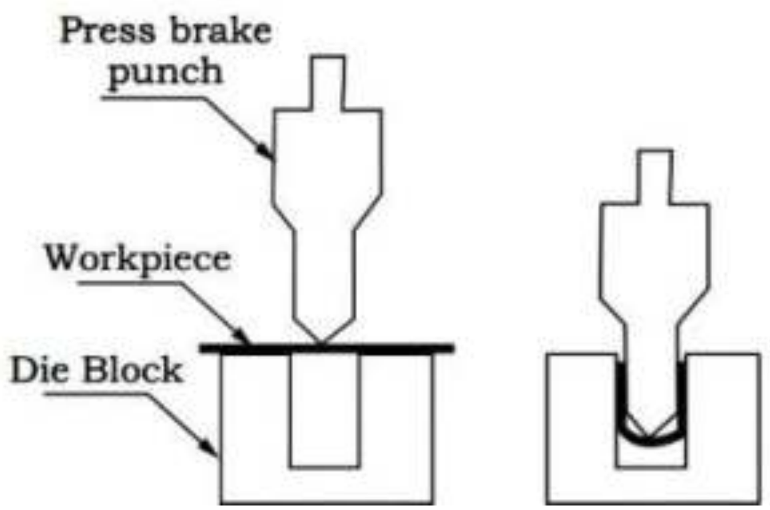


FIGURE 7.18 Terminology for springback in bending. Note that the bend angle has become smaller after the sheet is bent. There are situations whereby the angle becomes larger, called *negative springback* (See Fig. 7.20).

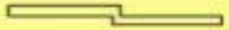
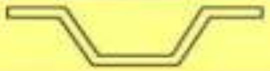
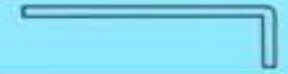
- ***Over bending and bottoming*** are two common methods for compensating spring back. In over bending, the punch angle and radius are fabricated slightly smaller than the angle required on the final product.
- Here, the metal springs back to the desired value. **Bottoming** involves subjecting the bend area with high localized compressive stress using the punch to deform the bent region again.
- Another method is stretch bending where the part is subjected to tension while being bent.

Press Brake Bending

- Press brakes along with simple fixtures can be used to bend sheet metal and plates having 7m or longer dimensions. This machine uses long dies in a mechanical or hydraulic press and is suitable for small lots.
- Press braking is a metal forming process that uses an open frame single acting press used to bend, blank, curl, corrugate or punch sheet metal or plate.
- This is one of the oldest mechanical metal deformation processes. A die and punch set of V, U or channel shape is used to carry out the metal forming.



- The process can produce a variety of shapes.

Shape	Type of Bend
	90° Rib Form
	90° Bottom / V Bottom
	Channel
	Closing
	Double Form
	Hat Channel
	M.T. Offset
	Offset
	Open Hat Channel
	Radius
	Single Form
	Wipe Die

Tube Bending

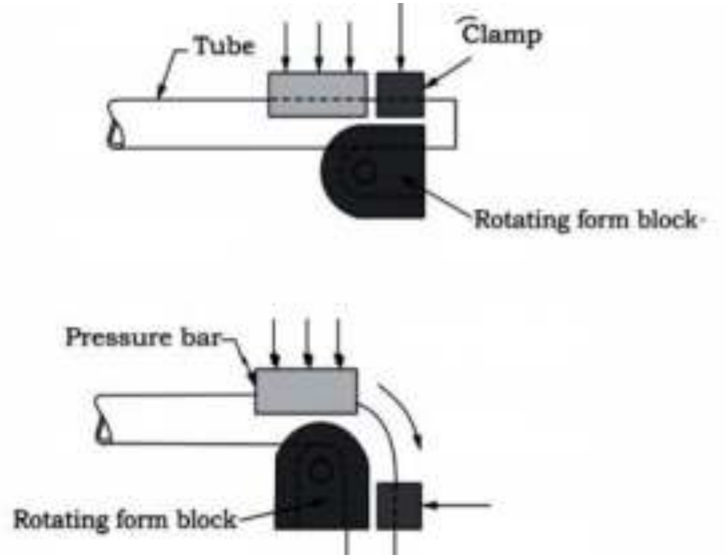
- Metal tubes made of ***steels, aluminium, copper, and brass*** are being used for a wide variety of industrial and commercial products. Tubes of various shapes like ***round, square, rectangular, oval, and special shapes*** are in use for various applications.
- For bending tubes to a specific shape or geometry, force must be applied so as to exceed the yield point of the material, but below the ultimate tensile strength of the material.
- As the tube is bent over a specific radius, the ***outside wall will stretch in tension while the inside wall bends under compressive forces.*** The boundary line through the centre of the tube, between the tension and compression zones is called the neutral axis where the material will be free from all forces.

- There are different bending methods, the use of which depends upon the tube diameter, wall thickness, minimum bend radius required, and part complexity. These bending methods include:
- Rotary draw bending
- Compression bending
- Ram bending
- Roll bending


sme

Rotary draw bending

- Rotary draw bending uses a movable bending die or form block, along with a clamping die, and a pressure bar. The process begins by clamping the tube against the form block and clamp.
- Then the form block and clamp together is rotated to bend the tube. The pressure bar is used to support the unbent region of the tube during the process.
- Rotary draw bending can produce bends up to 180° with standard tooling.



Compression bending

- Compression bending is similar to rotary draw bending except that the bending form block remains stationary rather than rotating with the tube.
- A wiper shoe is used to hold the tube and bend it around the contour of the fixed form block. This method is used where there is minimum clamping space between bends.

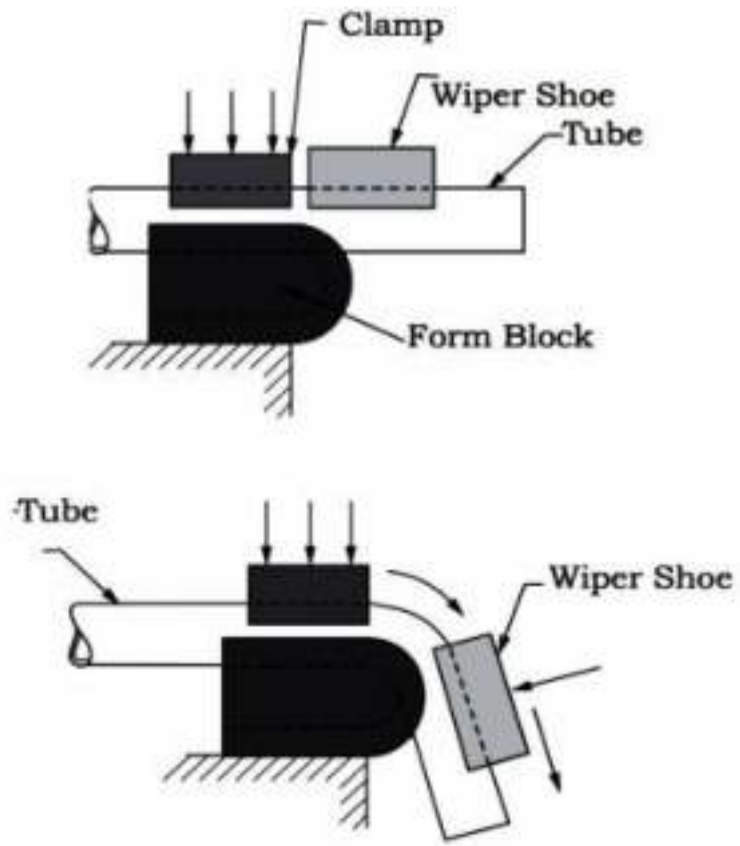
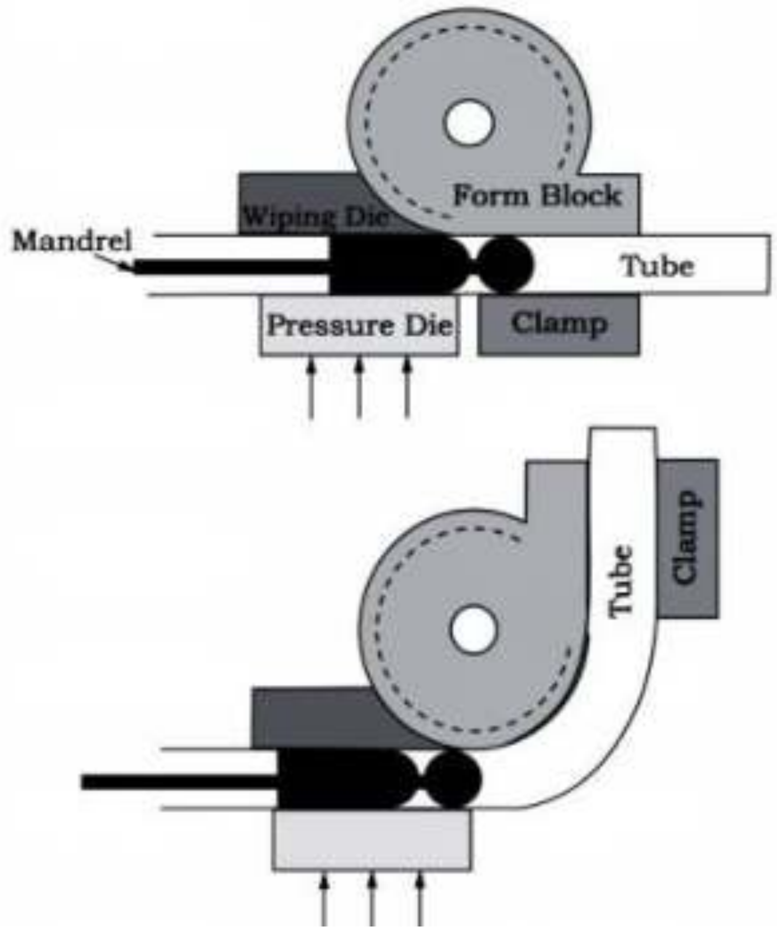


Figure 5.48

Mandrel bending

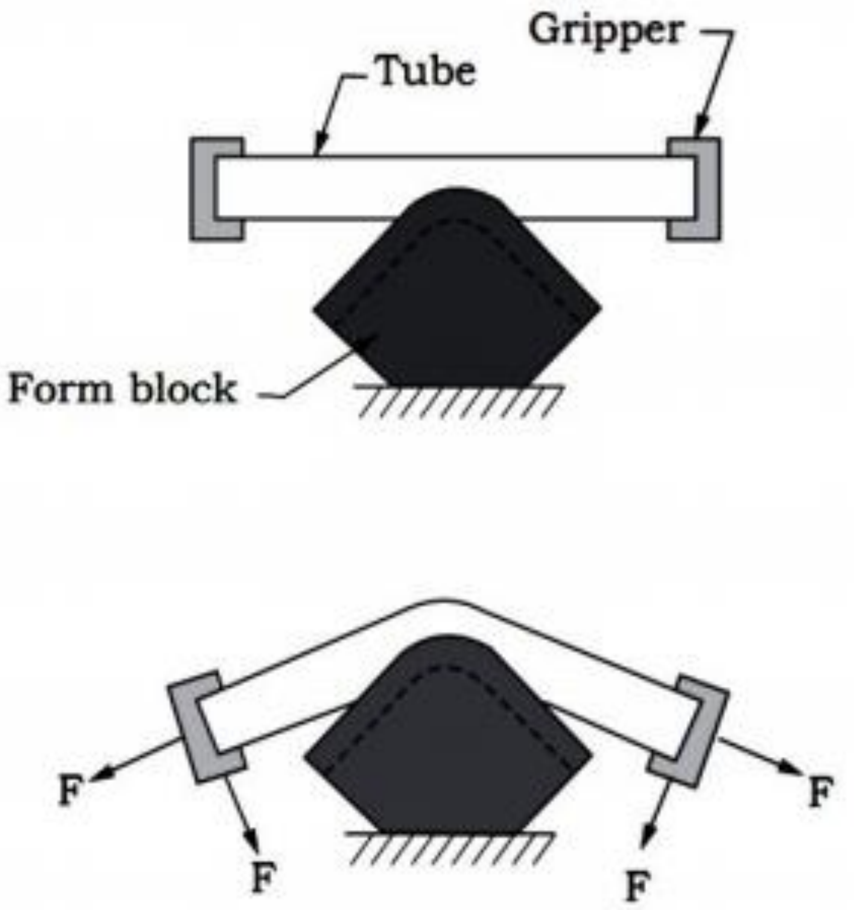
- Mandrel bending is another modified form of rotary draw bending.Here, a ***mandrel is inserted into a pipe*** or tube during bending so that the shape and diameter is maintained.
- The mandrel supports the pipe internally and ***ensures that the interior curvature of the*** pipe is the best possible bend and is not deformed.
- Mandrel bending maintains a good finish and is best used for handrails, ornamental iron work, exhaust pipes, roll cages and all stainless steel and aluminium tubing.


Form Block
Wiping Die
Mandrel
Tube
Pressure Die
Clamp
Tube
Clamp

Stretch bending

- The tube or pipe is held at two ends by two grippers and it is stretched by force applied through the grippers.
- At the same time, force is applied through the grippers perpendicular to the length of tube also.
- As the tube is supported by the form block, ***it gets bent as per the contour of the form block***. The pipe or tube is deformed inside and outside of the curvature.
- Depending on the thickness of the pipe or tube material, this process will deform the tube or pipe into an oval shape.

- A similar bending process is ***ram bending***. Instead of the fixed form block, here a movable ram is used to apply bending stress to the tube stretched by the end grippers.
- This is the easiest and least expensive bending process. The process is best used for electrical conduits and similar light gauge products.


Gripper
Tube
Form block
F
F
F
F

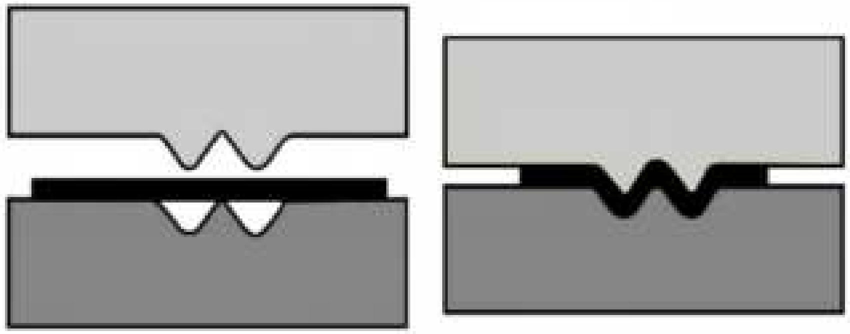
- ***Roll bending*** is used to produce large radius bends on heavy walled tubing. Roll bending is not typically used to bend thin wall tubing due to the high degree of wall stretching and thinning that occurs with the process.
- Roll bending uses three forming rolls arranged in a pyramid configuration, either in a horizontal or vertical position. Each roll has approximately the same diameter and all are contoured to match the cross-sectional shape of the tube.
- Two of the rolls are fixed while the third is adjusted to determine the finished bend radius. Roll bending can produce a multiple radius part, full circles, and helixes on tube, pipe, as well as extruded material.
- Unlike mandrel bending, the inside of the tube or pipe is not supported. The top roller exerts downward pressure, while the two bottom rollers push up to deform the pipe.

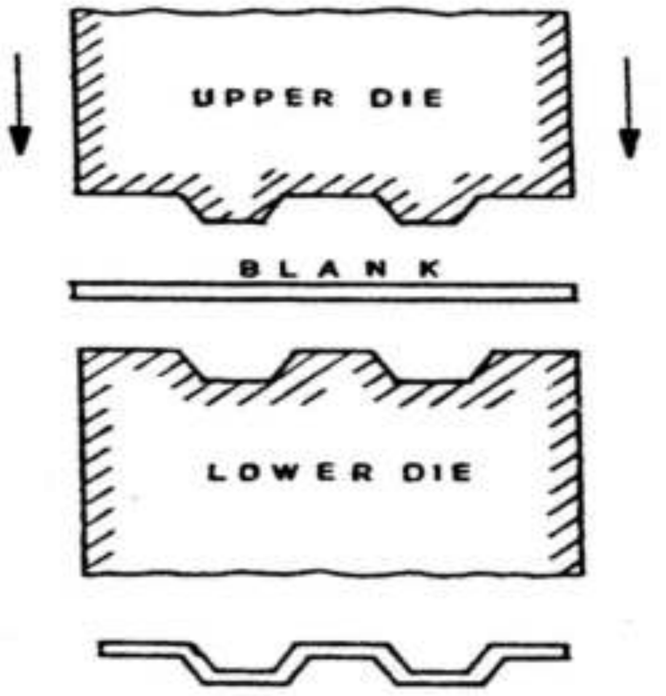
Forming

- The forming operation is generally along a curved axis rather than a straight axis. Here, the shape of die and punch are reproduced in the work material.
- There will be minimum metal flow in forming process and there won't be excessive thinning or shearing of the material.
- Forming operations may strengthen the workpiece, add rigidity, remove sharp edges and improve the appearance of the workpiece. Embossing and coining are examples for two forming operations.

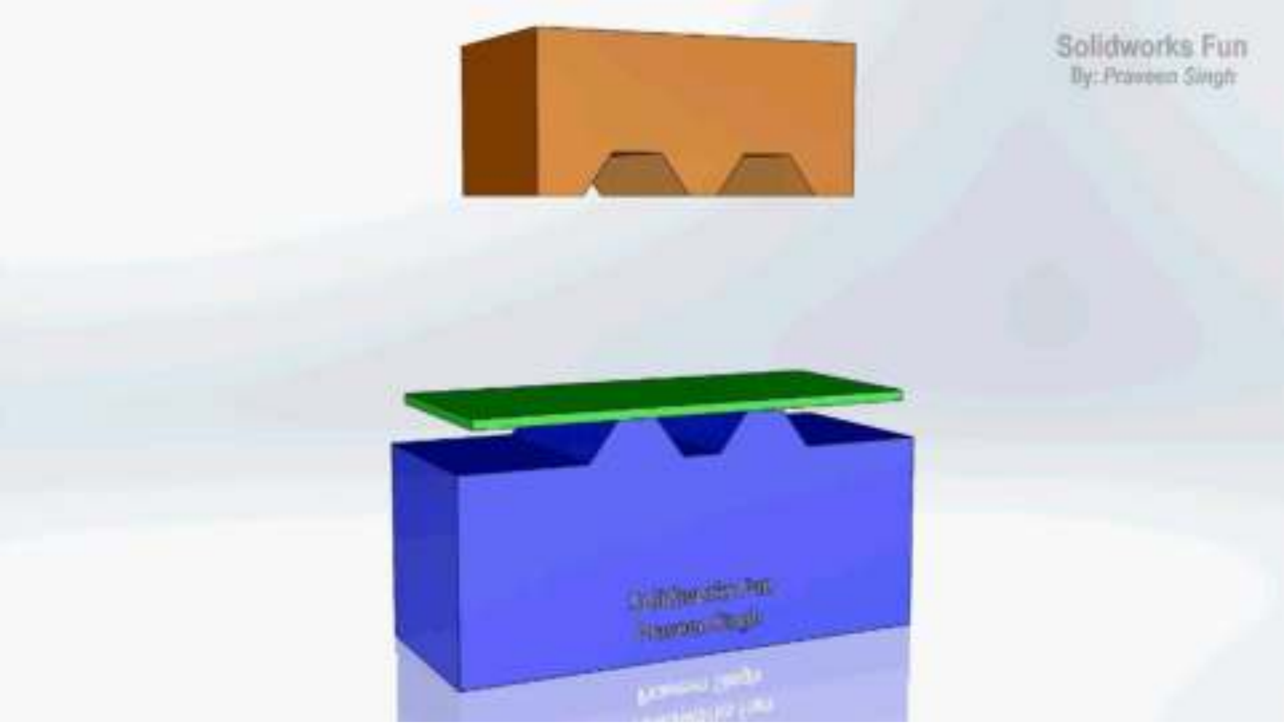
Embossing

- Embossing is a shallow forming operation in which the work material is displaced between a male and female surface. The finished part will have a depressed surface on one side and a raised surface on the other. A typical embossing die will have a male die with the exact reverse pattern of the female die, with allowances for the thickness of work material.
- ***Thickness remain the same in embossing***, where as in coining, thickness changes.





- This process consists of forming a number of shallow shapes, such as numbers, letters, or designs, on sheet metal, for decorative as well as specific purposes. Parts may be embossed with male and female dies, or by various means

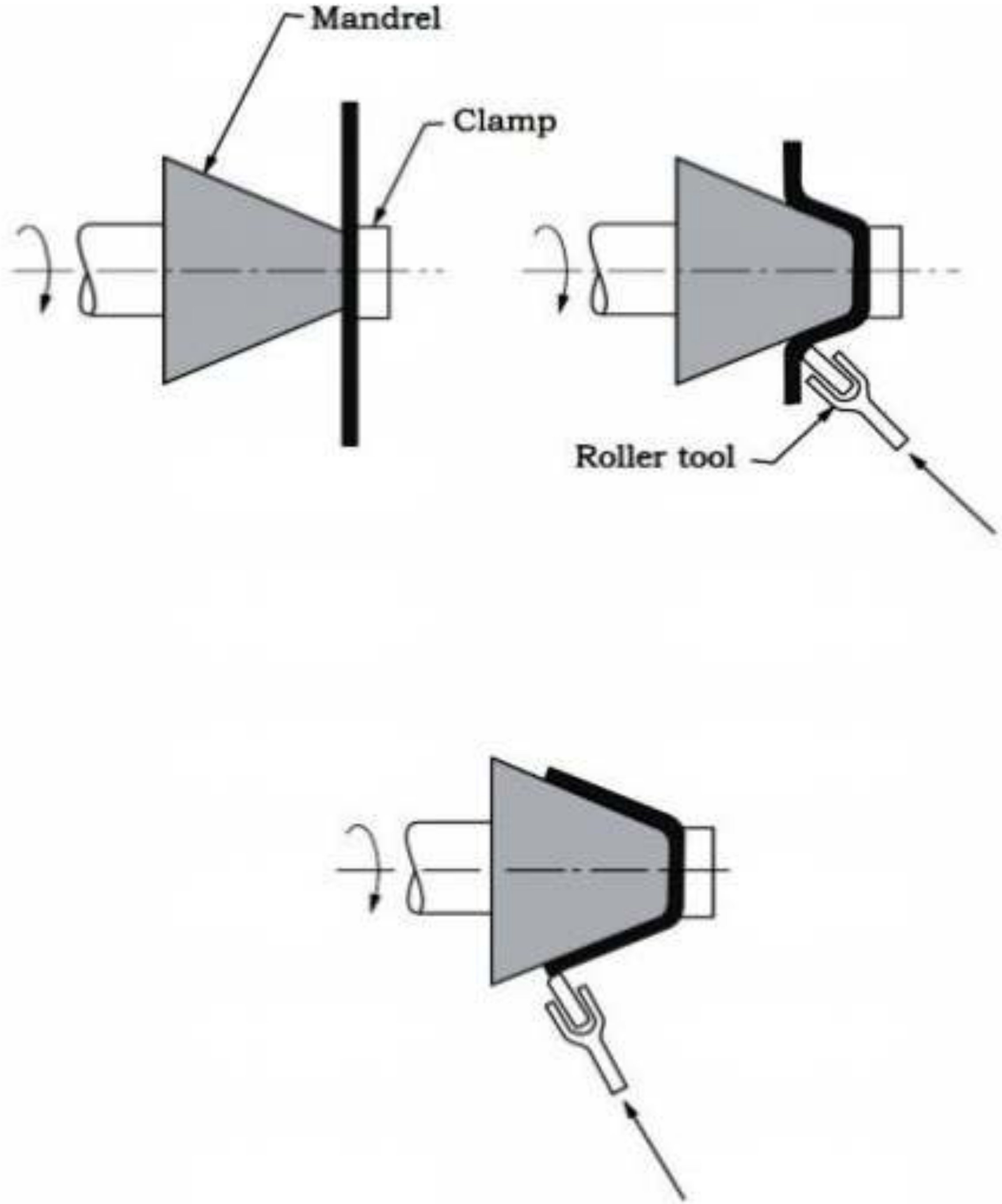


Spinning

- This metal forming process is used to make ***axially symmetric parts by gradual forming*** over a rotating mandrel by means of a rounded tool or roller.
- The process is somewhat similar to that of forming clay pots on a potter's wheel.
- There are three basic types of spinning process, namely conventional spinning, shear spinning and tube spinning.

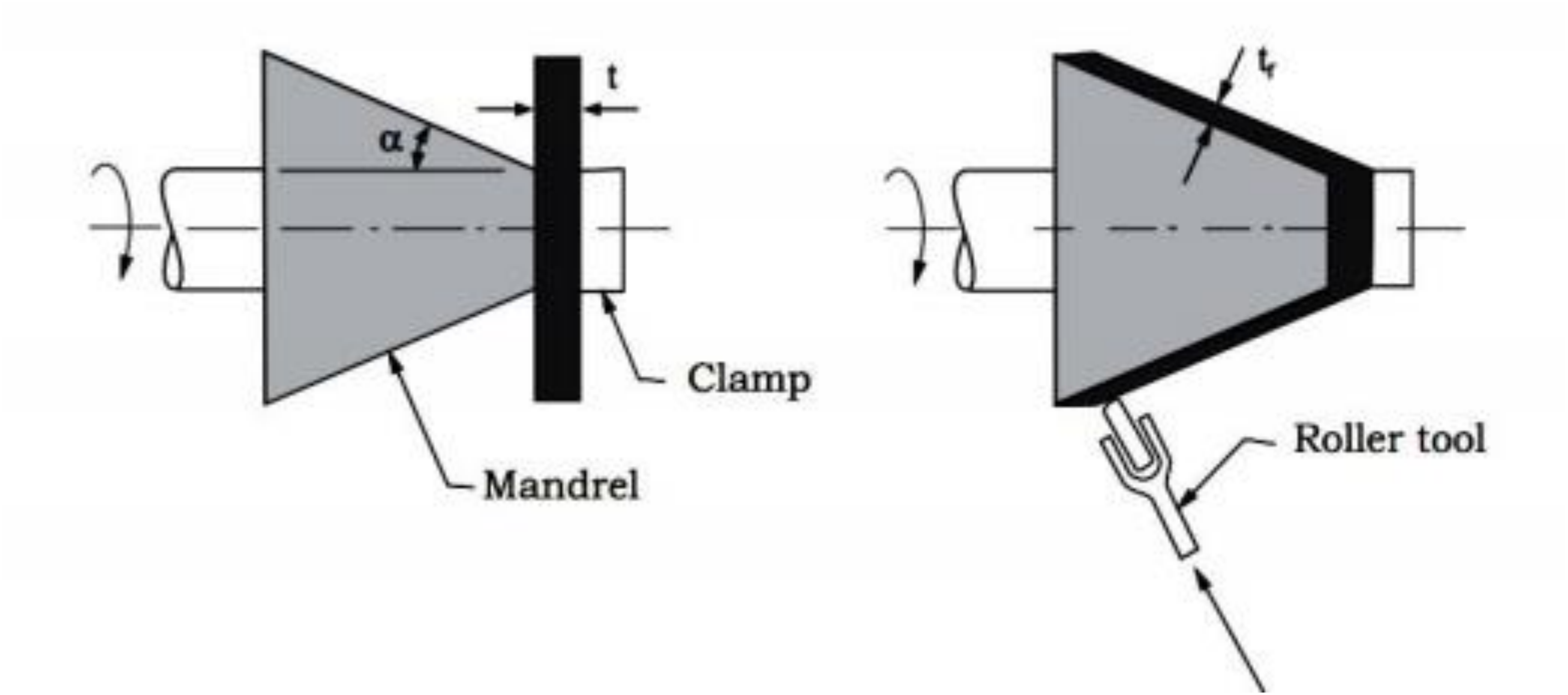
- **Conventional spinning**

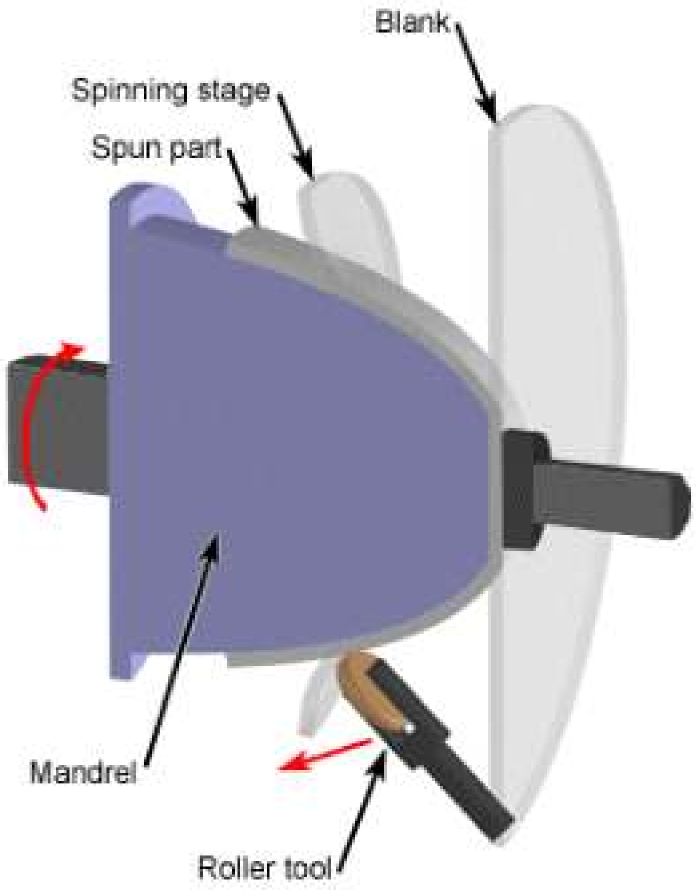
- In this process, a circular blank of sheet metal is held against a rotating mandrel of the desired shape of final product. A tool or roller is pressed against the rotating blank to deform it as per the shape of mandrel.
- Here the metal is bend around a moving circular axis conforming to the shape of rotating mandrel. The thickness of metal remains unchanged during the forming process.
- The process is used to make conical and curved shapes in smaller quantities.


Mandrel
Clamp
Roller tool

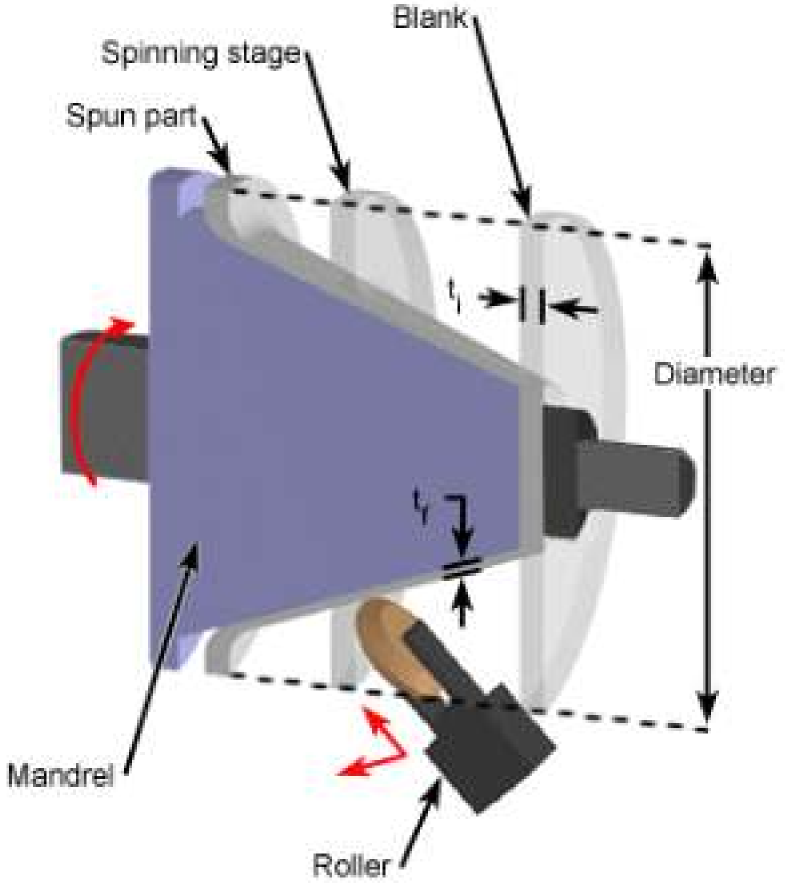
Shear spinning

- This process is also called as power spinning, flow turning, shear forming, hydro spinning and spin forging. As in the conventional spinning, here also a circular blank is deformed as per the shape of a rotating mandrel.
- But, here a shear deformation occurs and the thickness of blank is reduced during the process.
- Only bending of the blank occurs in conventional spinning while ***deformation due to shear stress occurs here and the metal deforms into the shape of mandrel.***


t
α
Clamp
Mandrel
t_f
Roller tool



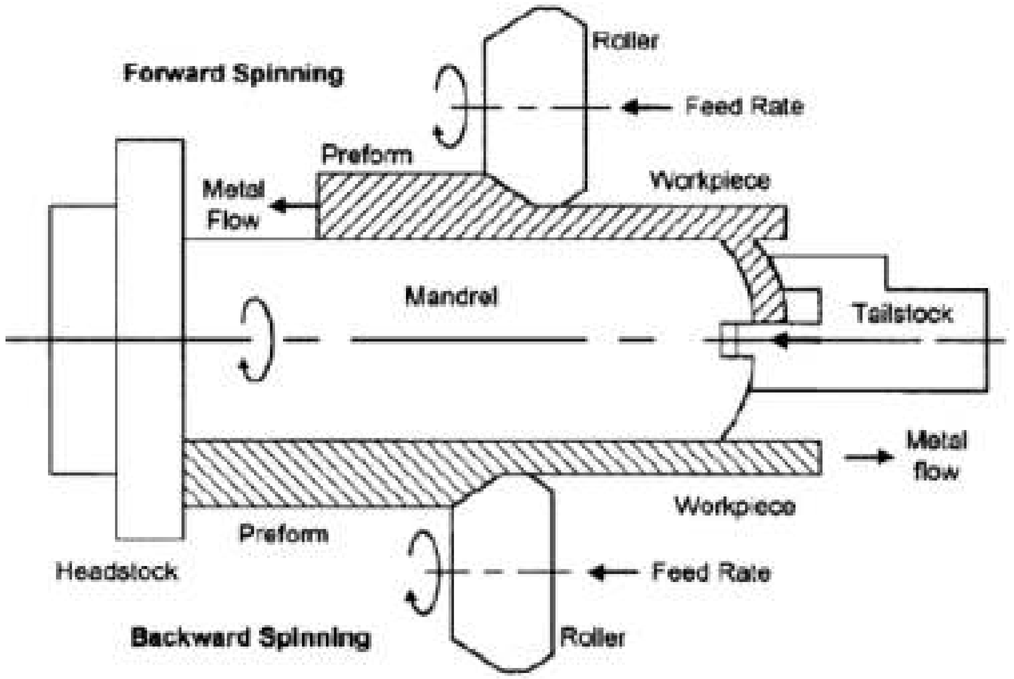
Conventional Spinning

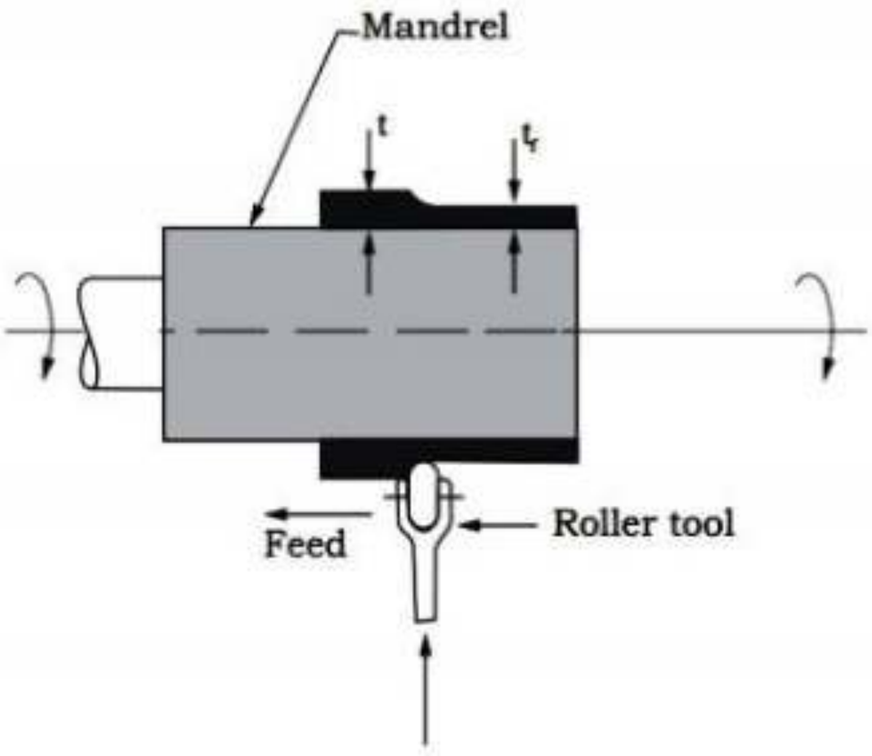


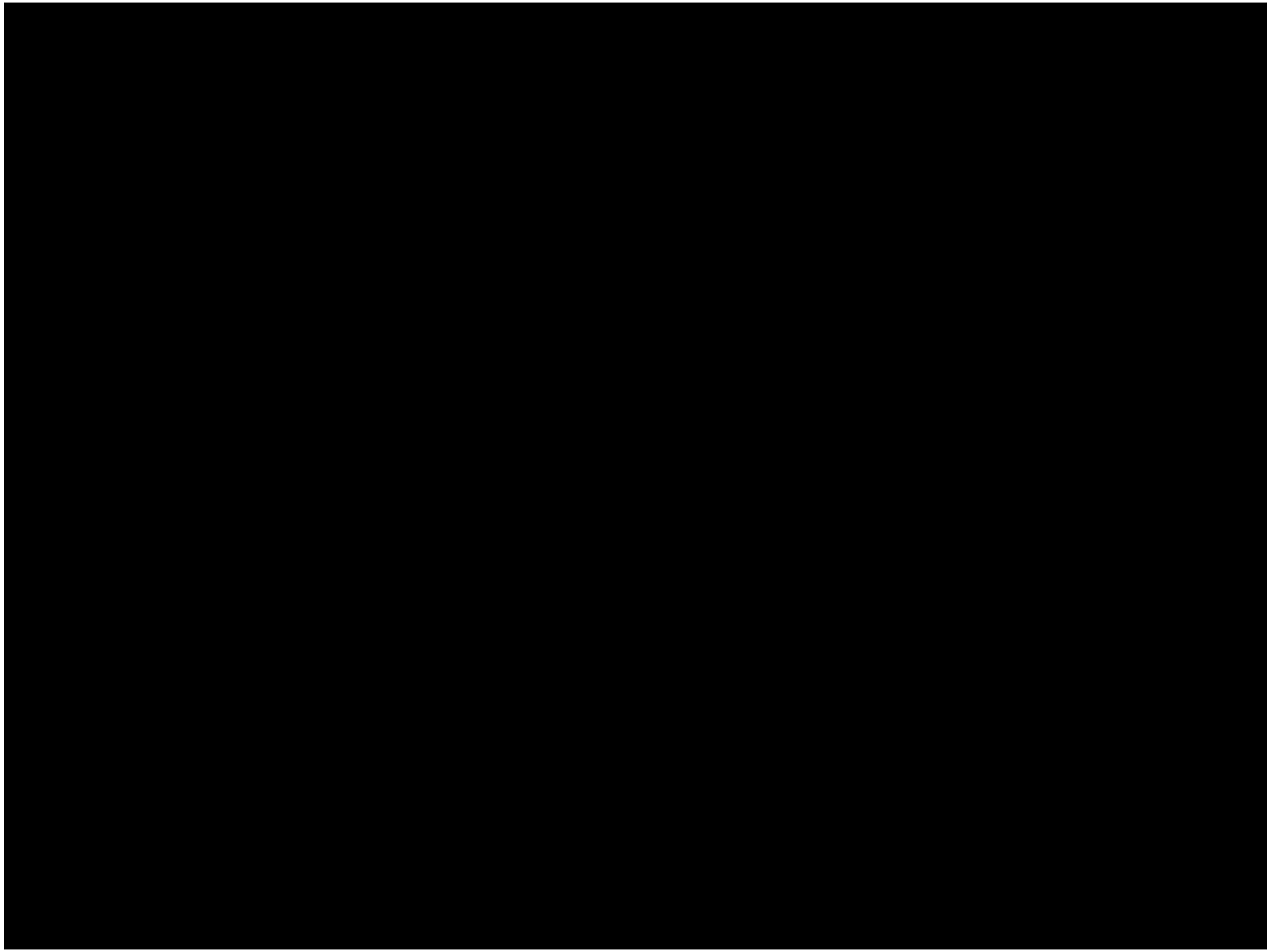
Shear Spinning

Tube Spinning

- Tube spinning is used to reduce the thickness of cylindrical parts like tubes by spinning them on a cylindrical mandrel and using roller tools. This can be done on the internal or external surface of the tube.
- Tube spinning is used to make pressure vessels, automotive wheels and components of aerospace products.







DIE CUTTING OPERATIONS

- ***Die is a tool used to cut or shape the work material in a press***. Dies are designed according to the parts to be produced. In a die set, the punch is set in a punch holder and the die in the die shoe. Usually the die is set in the lower half and the punch in the upper half of the die set.
- The upper half is called upper shoe and the lower one, the lower shoe. The die set will have guide pins which keep the upper and lower shoes in proper alignment.
- A stripper is used to pull the part off the punch on the upward stroke of the press.
- Simple die sets are made to perform a single press working operation like punching or bending that is done in one stroke of the press. Inverted dies, compound dies and progressive dies are used for various other press working operations.

Inverted Dies

- Based the type of operations performed and the type of construction, dies can be classified into various types.
- In the simple type of dies, the punch is mounted on the ram and is given a vertical movement, while the die is stationary and attached to die shoe.
- This arrangement is reversed in an inverted die. Here the punch is mounted on the die shoe, as shown in figure 5.55. As the ram moves down, the blank is sheared from the strip.
- Main advantage of inverted die is that, there is little chance of the thin blanks being bent. In an inverted die, the blank is removed by means of a knockout pin as it is cut by the punch and die.
- **The** opening in the die shoe is too small to permit the finished part to pass through the opening on the die shoe or bolster.
- Main disadvantage of the inverted dies is that the cost of construction is very high.

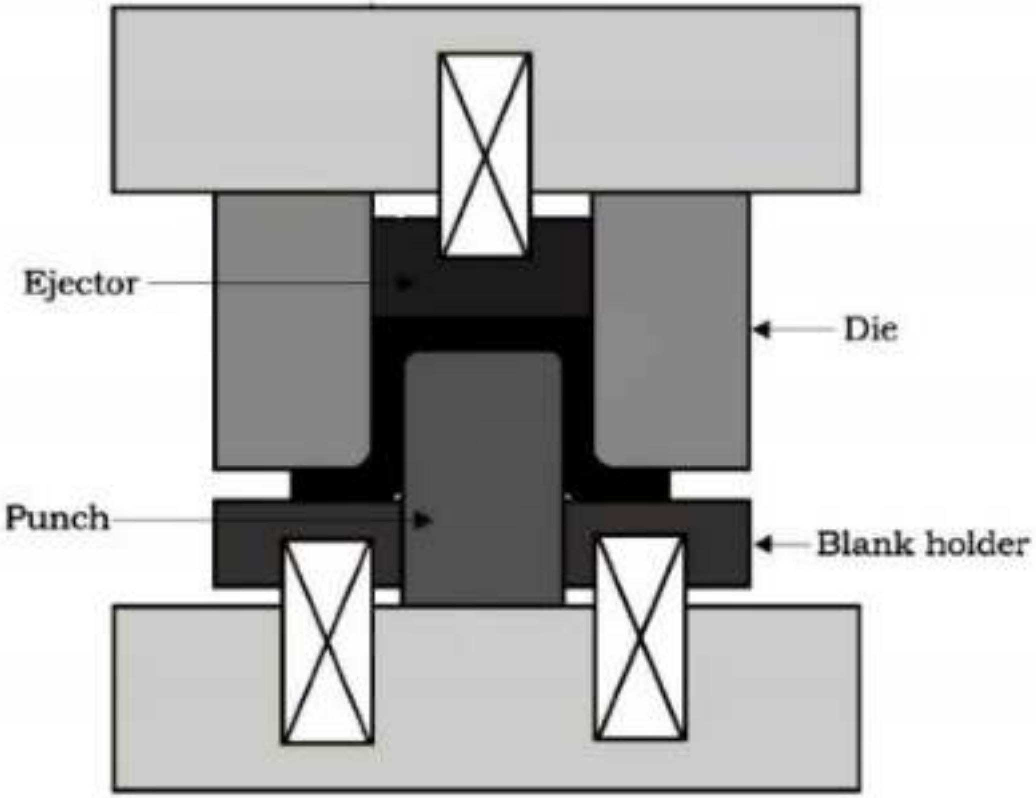


Figure 5.55

Progressive Dies

- Progressive dies are used to perform two or more operations at a time, at different locations on the stock strip (workpiece).
- Parts requiring multiple operations like punching, blanking, notching, piercing etc can be done at a faster rate using progressive dies.
- A continuous stock strip (plate) is passed through the progressive die in such a manner that different operations are carried out one after the other as the plate advances through the progressive die.
- There will be two or more stations in a progressive die which does different operations like punching, blanking etc. on the same stock strip.
- The stock strip is then advanced to move through each succeeding station to produce the complete workpiece.

- Progressive die is also known as cut-carry die. It is a multi station die that performs several operations in a single stroke of the ram in a press. Figure 5.56 shows a progressive die to carry out piercing and blanking operations.
- At first, the stock strip is positioned manually to pierce a hole using the piercing die set in the first cutting stroke of ram.
- Then the stock is advanced to the next station where the stopper pin will ensure correct spacing.
- During the second cutting stroke of the ram, the pilot of blanking punch enters the previously pierced hole and ensures correct alignment. Now the blanking punch moves down and shears the metal to form a washer.
- At the same time the piercing punch produces a hole for the next washer at the first station. From the second stroke onwards a finished washer is produced by the action of progressive die.

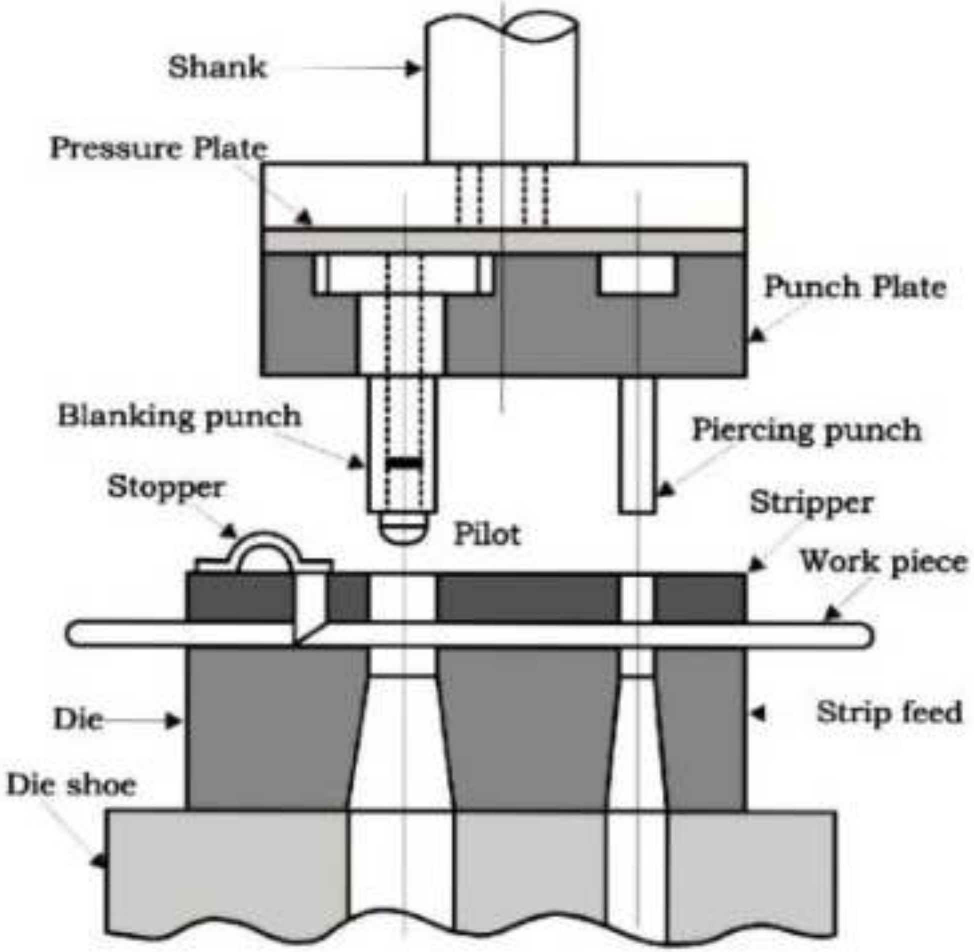

Shank
Pressure Plate
Punch Plate
Blanking punch
Piercing punch
Stopper
Pilot
Stripper
Work piece
Die
Strip feed
Die shoe

Figure 5.56

Advantages

- More number of operations can be performed on the same stock strip simultaneously.
- During every stroke of ram a finished product is made.
- Simple to construct and economical to repair.
- Suitable for mass production

Disadvantages

- Not suitable for thin or soft materials.
- Cost is more compared to simple dies.
- Design is complicated as compared to simple dies.

Compound Dies

- We have seen how two or more operations are carried out one after the other on a stock strip using a progressive die. In a compound die, such operations are combined and carried out in a single stroke of the press at the same station itself.
- For example, in order to carry out piercing and blanking operations, the upper and lower parts of the die will have piercing and blanking elements placed directly opposed to each other. During cutting stroke, the piercing punch acts in the opposite direction as that of the blanking punch. Here in a compound die, both the cutting actions are carried out simultaneously, in a single stroke.
- Figure 5.57 shows the layout of a compound die, used for producing a component like a washer. The workpiece (stock) is pierced and blanked at one station in a single stroke. The blanking punch also serves as piercing die.

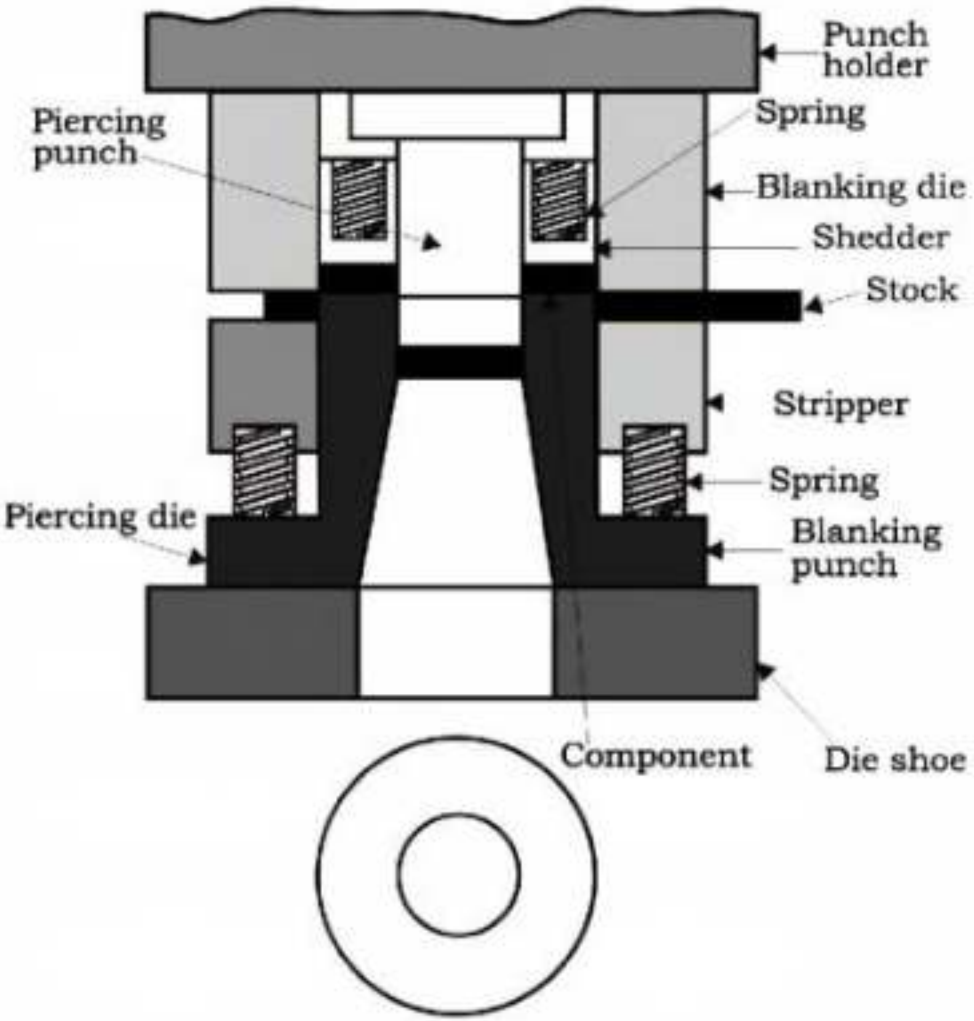

Punch holder
Piercing punch
Spring
Blanking die
Shedder
Stock
Stripper
Spring
Piercing die
Blanking punch
Component
Die shoe

Figure 5.57

- The blanking punch and die are arranged in the inverted position. During the stroke, first the hole is pierced on the stock and upon further travel, the blanking operation is done.
- The progressive and compound dies are used mainly to perform cutting operations.

Advantages

- Workpiece can be produced with more accuracy.
- Strip materials of shorter length can be used.
- Cost of production is low.
- Larger parts can be blanked using a small press when compound dies are used.

Disadvantages

- More expensive to construct and repair.
- Slower than progressive die.
- Complicated design compared to progressive dies.
- Higher power requirement.

Progressive dies	***Compound dies***
Performs one operation at a time	Performs more than one operation at a time.
Power requirement is lower	Power requirement is higher
Simple in design and construction of die set	Complicated design and construction of die set
Less expensive to construct and repair	More expensive to construct and repair