



### Objectives:

- Define manufacturing and explain its significance in engineering and society.
- Classify the major categories of manufacturing processes.
- Compare metal joining processes used in fabrication.
- Explain fixed, variable, total and average costs in manufacturing.
- Apply break-even analysis for selecting economical processes.
- Interpret cost graphs for production planning.

### 1.1 Introduction

Advanced technologies and innovations are the result of intelligently designed products that integrate functional requirements with efficient and cost-effective manufacturing practices. This synergy not only ensures economic feasibility but also drives improvements in performance, reliability, and quality, capture the core principles of manufacturing science. The functional requirements often demand the use of advanced materials and specialized processing operate under stringent conditions, and place a significant pressure on the manufacturing industry to deliver high-quality products.

Manufacturing is the process of converting raw materials into finished products exhibit advanced performance characteristics enabling them to

withstand high temperatures, pressure, and challenging working conditions. Economic considerations also play a crucial role in the manufacturing process; products must be cost-effective in the competitive market place. Consequently, engineers must thoroughly evaluate all aspects of the manufacturing process during the design phase to achieve an optimal balance between functionality and economic viability.

Manufacturing processes form an integral part of the various disciplines of engineering, facilitating the production of components essential in contemporary life. Consequently, manufacturing process occupy a vital and unifying role within the broader domain of engineering.

## 1.2 Historical overview

Historically, manufacturing was primarily a manual craft until the onset of the First Industrial Revolution in the late 18th century. During this period, production was limited to low-volume, single-piece fabrication and relied heavily on the craftsmanship of skilled artisans for the creation and assembly of components. In the absence of mechanized systems, these methods were inherently slow and labor-intensive, consequently economically unsustainable for large-scale production.

The introduction of steam engines and coal-fired furnaces marked a pivotal turning point in industrial history, enabling high-volume production. Moreover, subsequent advancements in machine tools, coupled with the advent of electricity and development of advanced materials, further enhanced the efficiency of manufacturing process. These innovations laid the foundation for modern industrialization.

By the early 20th century, rise in the automobile industry significantly accelerated evolution of manufacturing practices. Mass production techniques, including the use of assembly lines, became widespread and revolutionized the productivity and the cost-efficiency. Today, engineers utilize a wide range of

manufacturing processes; broadly categorized into four major types:

- a. Casting processes
- b. Forming processes
- c. Fabrication processes
- d. Material removal processes

## 1.3 Casting processes

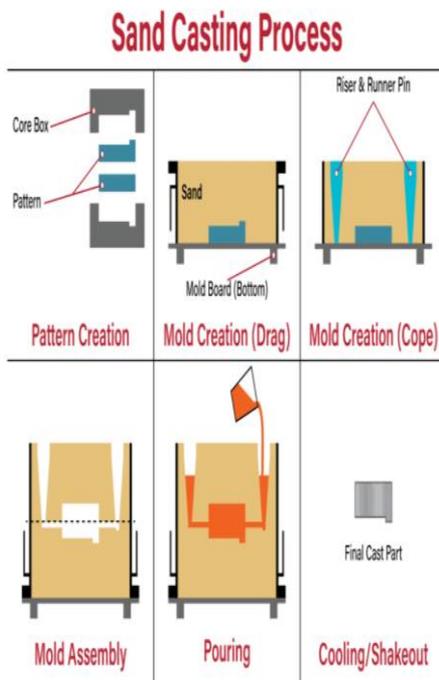
Casting is one of the oldest and most fundamental manufacturing processes, distinguished as the only technique utilizes metal in its molten state. The process involves creating a mold cavity typically made from refractory materials, replicates the shape of the final part type. Molten metal is then poured into the cavity and allowed to solidify under controlled ambient conditions. Once solidification is complete, the cast part is removed from the mold, producing a product closely conforms to the desired geometry.

Casting processes are widely utilized for manufacturing a broad spectrum of components across various industries. Among these methods, sand casting is the most commonly used technique. Due to its flexibility and cost-effectiveness, sand casting is suitable for both small-batch production and large-scale manufacturing.

### 1.3.1 Types of casting processes

Casting processes comprise a variety of methods used to shape molten material into desired forms, each method offers distinct advantages in terms of accuracy, surface finish, and production efficiency.

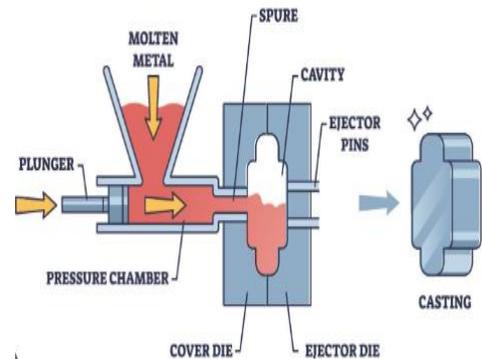
- a. **Sand casting:** uses a sand-based mold, and is compatible with both small-batch and high-volume production.



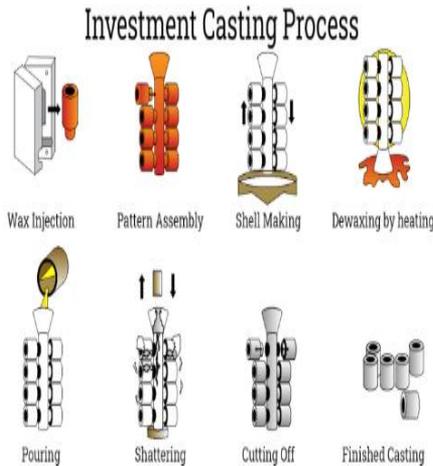
- b. **Die casting:** involves injecting molten metal under high pressure into a hardened steel mold (die), making it ideal for high-volume production of

non-ferrous components with precise dimensional accuracy and surface finish.

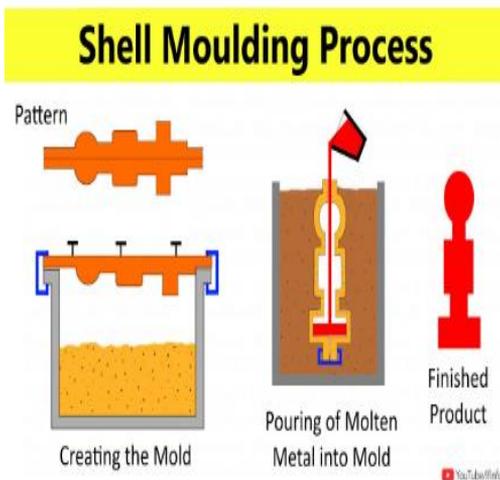
### DIE CASTING



- c. **Investment casting:** a wax pattern coated with a ceramic material to form a precise mould. After the wax is melted and removed, molten metal is poured into the cavity, making the process suitable for producing intricate and high-precision components.

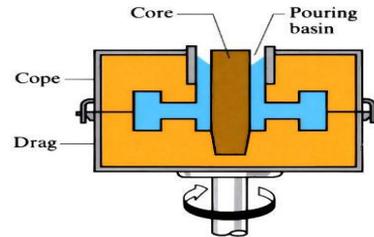


- d. **Shell molding:** a variation of sand casting that utilizes resin-coated sand to form a thin rigid shell around the pattern. This method provides improved dimensional accuracy and surface finish compared to conventional sand casting.



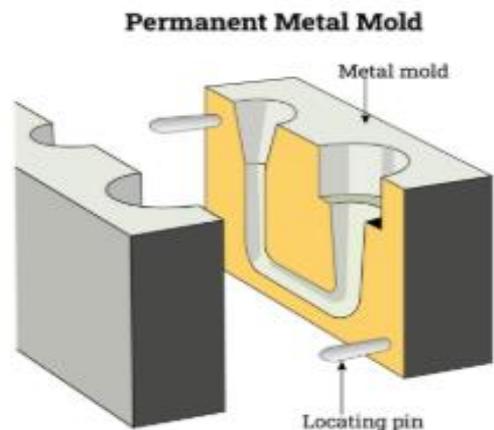
- e. **Centrifugal casting:** involves pouring molten metal into a rotating mold, where centrifugal force ensures

uniform distribution of the metal. This process is particularly suitable for producing cylindrical components such as pipes, rings, and bushings.



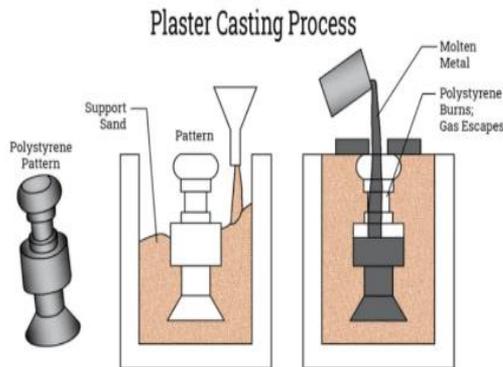
Centrifugal Casting

- f. **Permanent mold casting:** employs reusable metal molds, usually made of steel or iron, to produce components with superior mechanical properties compared to sand casting. However, it is less suited for parts with complex geometries.



- g. **Plaster mold casting:** uses plaster to form the mold, allows a smoother surface finish. It is limited to non-

ferrous metals and low-temperature alloys because plaster cannot withstand high casting temperatures.



## 1.4 Forming processes

Forming processes are solid-state manufacturing methods recognized for their high productivity and minimal material wastage. In these methods, metal is typically heated to a temperature just below the solidus point, making it malleable enough for deformation without reaching the melting stage. A large force is then applied to induce plastic deformation, shaping the metal into the desired form while simultaneously enhancing its mechanical properties.

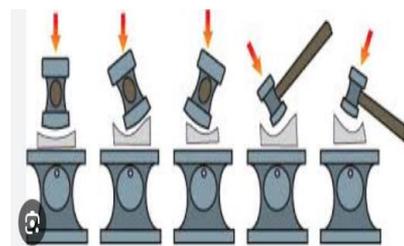
Forming processes are well-suited for high-volume production and are widely recognized as cost-effective, owing to their high efficiency, rapid operation,

and minimal material wastage. These characteristics make them a preferred choice in industries where strength, precision, and economy are critical.

### 1.4.1 Types of forming processes

Forming processes can be broadly classified into several categories based on the nature of the applied force, temperature conditions, and specific operations involved. Common types include:

- Forging:** involves shaping metal using compressive forces delivered by a hammer or press. Forging improves material strength through grain refinement and is commonly used in automotive and aerospace applications.

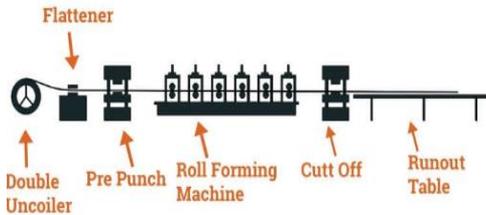


Forging Process

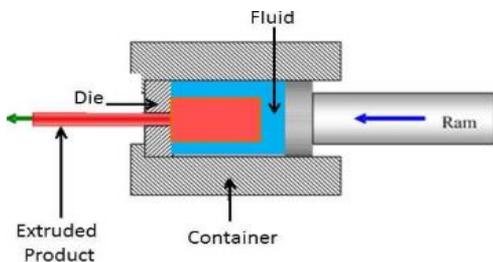
- Rolling:** reduces the thickness of metal and produces a uniform cross-section by passing it between rotating rolls. It is one of the most

efficient and economical metal forming methods, ideal for producing sheets and structural components.

### Rolling Forming Process

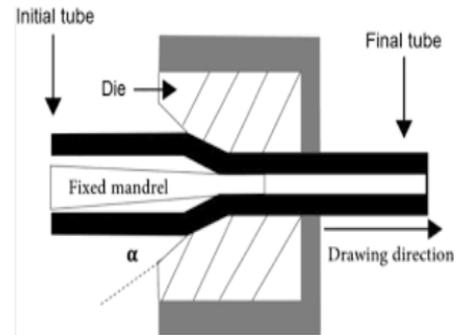


- c. **Extrusion:** forces metal through a die to create objects with a fixed cross-sectional profile. It is suitable for producing long parts with uniform cross-sections, such as rods, tubes, and channels.



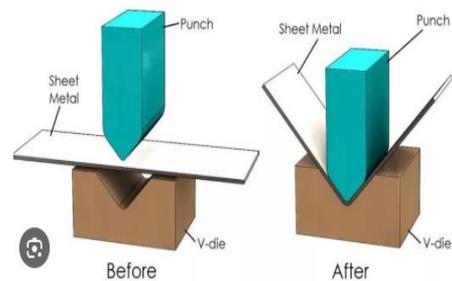
Extrusion Process

- d. **Drawing:** involves pulling metal through a die to reduce its diameter and increase length. Commonly used for manufacturing wires, tubes, and bars with high dimensional accuracy.



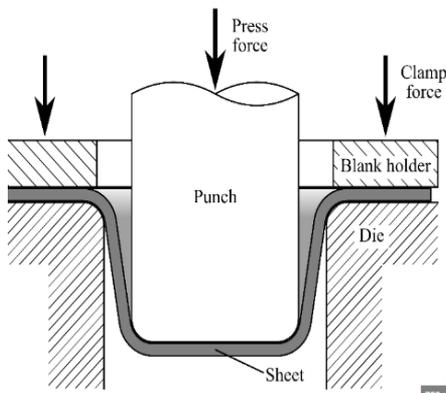
Drawing Process

- e. **Bending:** deforms metal into an angular shape without altering its thickness. Widely used in the fabrication of metal sheets for parts like brackets, enclosures, and channels.



Bending Process

- f. **Deep Drawing:** uses a punch to draw sheet metal into a die cavity, forming deep, hollow shapes. The process is commonly used for manufacturing beverage cans, kitchen sinks, and automotive components.

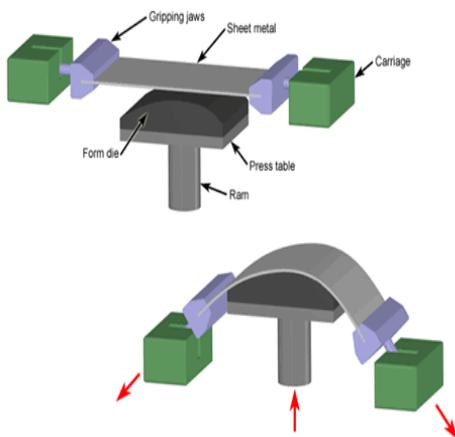


Deep Drawing

The stretch forming processes can be further categorized based on temperature requirements:

- a. **Hot forming** conducted above the recrystallization temperature, allows greater ductility.
- b. **Cold forming** performed at below recrystallization temperature, offers better surface finish and dimensional accuracy but requires higher forces.

- g. **Stretch Forming:** involves stretching the sheet metal and simultaneously bending it over a form to achieve complex, curved shapes. Frequently used in the aerospace industry for forming large panels and aircraft skins.



Stretch Forming

### 1.5 Fabrication processes

Fabrication processes are secondary manufacturing methods in which raw materials typically pre-processed by casting or forming are assembled to form the final product. These processes are essential when individual components must be joined to build larger structures or functional assemblies.

Fabrication is widely employed in steel structural applications, where components are first rolled or formed into shape and then assembled using the fabrication techniques. These processes are also critical in industries such as automotive, aerospace, construction, and manufacturing of different machinery.

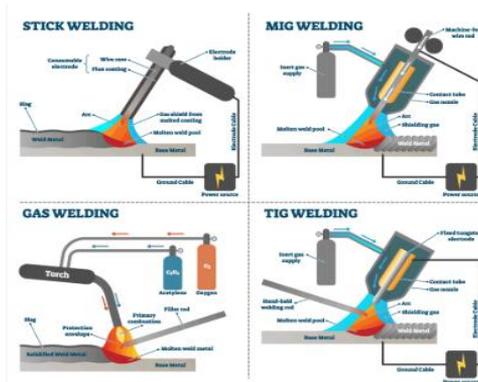
### 1.5.1 Types of fabrication process

Metal joining involves either permanent or temporary joints, depending on the design requirements and intended application.

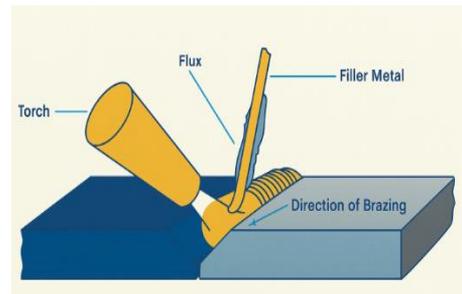
Permanent joining methods, such as welding and brazing, provide high structural integrity and are often used in load-bearing applications.

In contrast, temporary joining methods, such as bolting and riveting, are preferred where components need to be disassembled for maintenance or replacement.

a. **Welding** involves melting the base materials and often adding a filler material to form a strong joint upon cooling. Common types include ARC, MIG, TIG, and GAS welding. Widely used in construction, automotive, and shipbuilding industries.

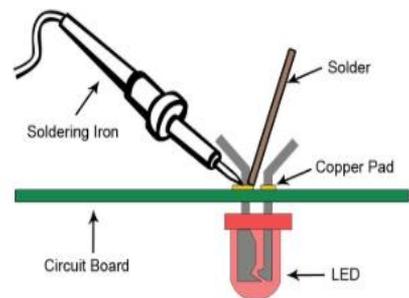


b. **Brazing:** joins two or more metals by melting and flowing a filler metal into the joint, without melting the base materials. The filler metal has a lower melting point than the workpieces. Suitable for joining dissimilar metals.



Brazing

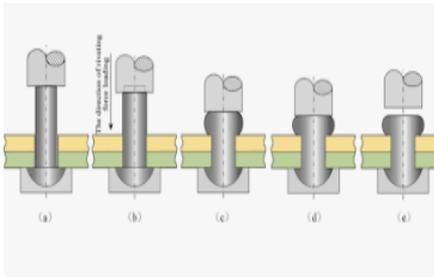
c. **Soldering:** performed at lower temperatures. Commonly used in electronics and plumbing to form precise, low-strength joints.



Soldering

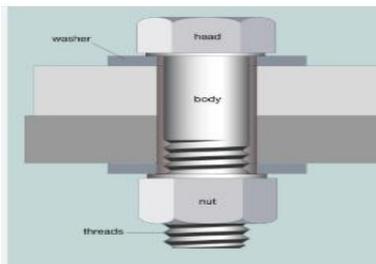
d. **Riveting:** uses metal pins (rivets) fastened metal pins (rivets) by inserting them into pre-drilled holes and deforming them to secure the

components, this method is still used in aircraft structures, shipbuilding industry and bridge construction.



Riveting

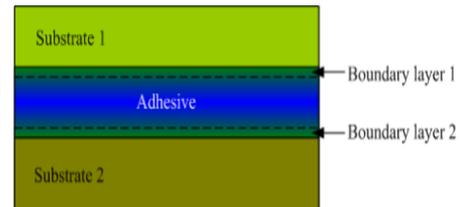
- e. **Bolting:** It is a temporary joining method uses threaded fasteners (bolts and nuts). This method is commonly used in machine frames and structural assemblies. It allows for easy disassembly and maintenance.



Bolting

- f. **Adhesive bonding:** uses chemical adhesives to join materials. Provides smooth surfaces and useful for joining dissimilar or thin materials. This method is common in

aerospace, automotive industry, and widely used in consumer electronics.



Adhesive bonding

## 1.6 Material removal processes

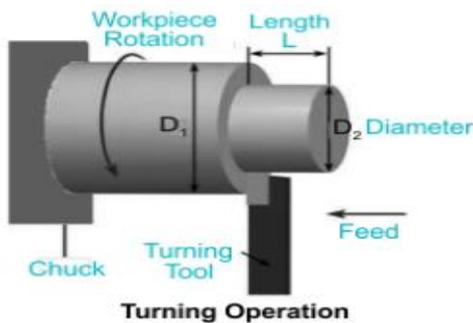
The material removal processes are commonly known as subtractive manufacturing methods where excess material is systematically removed from a workpiece to achieve precise dimensions, shapes, and surface finishes. These processes are essential in industries that require high levels of precision and accuracy, such as aerospace, automotive, and medical device manufacturing. Machining often complements primary processes like casting or forming, enabling the production of components to meet the stringent design specifications.

### 1.6.1 Types of machining processes

Machining processes comprise a range of material-removal operations, each employing specific tools and techniques

to achieve the desired shape, dimensions, and surface finish of a workpiece.

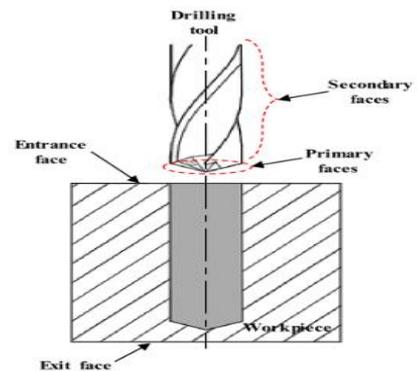
- a. **Turning:** involves rotating the workpiece while a cutting tool moves parallel to the axis of rotation. The method is used to produce cylindrical components such as shafts, pins, and bushings. The turning operation is commonly performed on a Lathe Machine.



- b. **Milling:** removes material from the workpiece using a rotating multi-point cutting tool. Suitable for producing flat, contoured, or complex surfaces. Widely used in tool rooms and production environments for both precision and versatility.

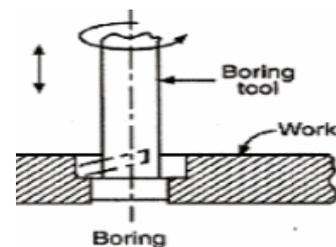


- c. **Drilling:** involves producing round holes in solid materials using a rotating drill bit. It can be carried out on drilling machines or machining centers and is often performed in conjunction with other machining operations.



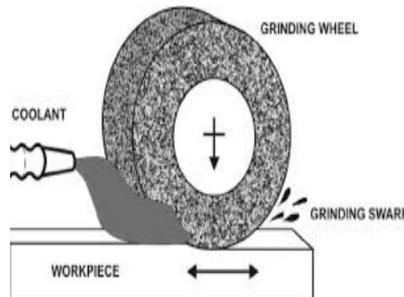
**Drilling Operation**

- d. **Boring:** enlarges existing holes using a single-point cutting tool. It offers high dimensional accuracy and is typically used as a finishing operation following drilling to improve hole size and surface quality.



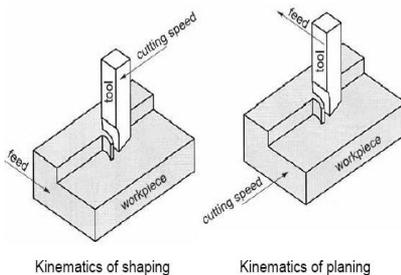
- e. **Grinding:** removes material in small increments using an abrasive wheel.

Provides tight tolerances and excellent surface finishes. Commonly used in the automotive and tool-making industries.



Grinding Operation

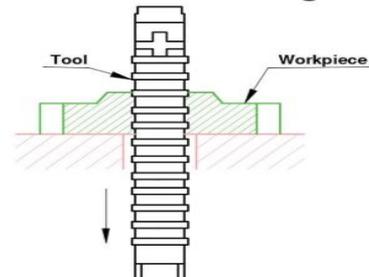
**f Shaping and planing:** involves linear relative motion between the tool and workpiece. Shaping uses a reciprocating tool; planing moves the workpiece instead. Used for flat or contoured surfaces in low-volume production.



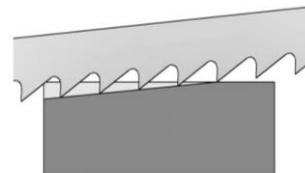
**g Broaching:** uses a multi-tooth cutting tool (broach) to remove material in a single pass. Ideal for creating

complex shapes like keyways, splines, and internal gears with high accuracy.

### Internal Broaching



**h Sawing:** uses a toothed blade to cut material into desired lengths or shapes. Common in both primary material preparation and finishing operations.



Sawing

## 1.7 Break-Even Analysis

One of the key responsibilities of an engineer is to select a manufacturing process, ensures the desired product quality minimizes production costs. A break-even analysis of manufacturing processes is essential to balance quality and cost-effectiveness to select the most

suitable production method. This analysis supports informed decision-making by identifying the most economical process for a given production volume, ensuring both technical feasibility and financial viability.

Break-Even Analysis is a financial and economic tool used to determine the production volume at which total costs equal total revenues, resulting in neither profit nor loss. It identifies the break-even point (BEP), which is the minimum number of units that must be produced and sold to cover all fixed and variable costs associated with manufacturing. This analysis plays a crucial role in comparing different manufacturing processes by evaluating their cost structures and selecting the most cost-effective option for a specific production scale.

In break-even analysis, two primary types of costs are considered:

- a. **Fixed Costs:** These are the initial expenditures required to establish the manufacturing process; includes investments in equipment, tooling, facility setup, and other capital resources. Fixed costs remain constant regardless of the level of production output.

- b. **Variable Costs:** These costs vary directly with the production volume. It includes expenses such as raw materials, energy consumption, direct labor, special tooling for each unit, and proportional administrative overheads. As production increases, variable costs increase in direct proportion to the number of units produced.

The total manufacturing cost is the cumulative cost incurred in production of certain number of units. It is the sum of fixed costs, do not change with production volume, and variable costs, vary in direct proportion to the number of units produced. This relationship can be expressed mathematically as:

$$TC = FC + VC \times Q$$

Where:

TC = Total cost

FC = Fixed cost

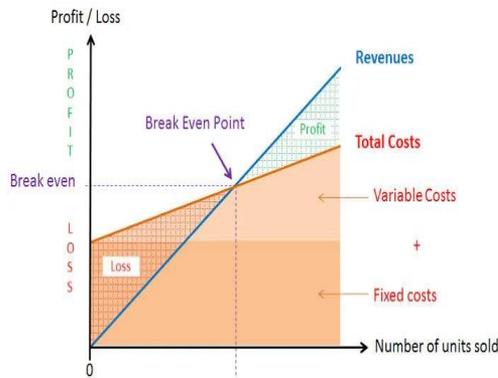
VC = Variable cost per unit

Q = Quantity of production

### 1.7.1 Graphical evaluation: cost functions

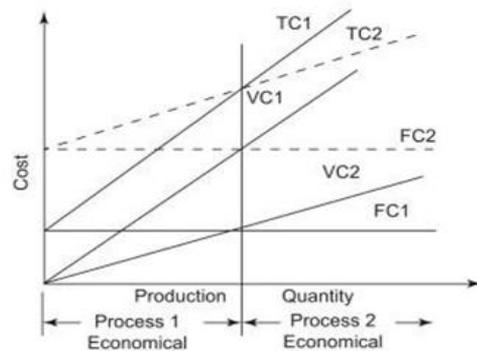
The graphical evaluation of the total cost equation is illustrated in Fig. 1.1. As the production quantity (**Q**) increases, the cost per unit part decreases. This is

because the fixed cost is distributed over a greater number of units, reducing the fixed cost component per unit. However, the total fixed cost itself remains constant regardless of the output level. The total cost curve begins at the fixed cost level and increases linearly due to variable cost accumulation.



**Figure 1.1 Total Cost Curve**

When comparing two alternative manufacturing processes for producing the same component, the engineer must first identify the fixed and variable costs associated with each process. By plotting the total cost curves of both processes on the same graph—as illustrated in Fig. 1.2 the point of intersection between the two curves represents the break-even point. This is the production quantity at which both processes incur the same total cost.



**Figure 1.2 Break Even Curve**

- Below the break-even point, the process with the lower fixed cost and relatively higher variable cost is more economical.
- Above the break-even point, the process with the higher fixed cost but lower variable cost becomes more cost-effective due to economies of scale.

### 1.7.2 Mathematical formulation for break even point

The break-even quantity ( $n$ ) refers to the production volume at which the total costs of two alternative manufacturing processes are equal. To find this point, the total cost equations of both processes are equated:

$$FC_1 + n \cdot VC_1 = FC_2 + n \cdot VC_2$$

$$\text{Break-even quantity (n)} = \frac{FC_2 - FC_1}{VC_1 - VC_2}$$

This equation yields a positive break-even quantity when one process has a higher fixed cost but a lower variable cost. If one process has both lower fixed and variable costs, it is always the preferred choice, regardless of production volume.

However, if one process has both lower fixed and variable costs than the other, it is unequivocally the more economical choice. In that case, no break-even analysis is required, as that process will result in lower total cost for any production volume. The analytic approach provides a numerical basis for identifying the economic crossover point between competing manufacturing options.

### 1.7.3 Average cost analysis for break even point

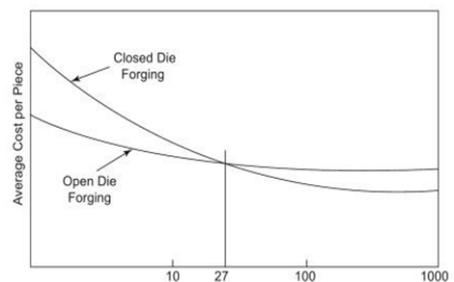
A widely used method for comparing manufacturing processes involves analyzing the average cost per unit across varying production volumes. This method provides insight into how cost efficiency improves as production scales up. The average cost is calculated by dividing the total manufacturing cost by the number of units produced:

$$\text{Average cost} = \frac{\text{Total Cost}}{\text{Quantity}} = \frac{FC + VC \times Q}{Q} = \frac{FC}{Q} + VC$$

The above mathematical expression presents, as the production quantity increases, the fixed cost per unit decreases, causing the average cost curve to decline and asymptotically approach the variable cost line.

For example, the average cost per unit curves for Open Die Forging and Closed Die Forging show how economic efficiency varies with production volume. At low production levels, Open Die Forging is typically more economical due to lower fixed costs.

However, at higher volumes, Closed Die Forging becomes more cost-effective because its lower variable cost per unit offsets its higher initial investment. This comparison helps engineers determine the optimal process based on projected production quantities. A representative curve is shown in Fig. 1.3.



**Figure 1.3 Break Even Chart**

### 1.7.4 Relative cost comparison

To compare two or more processes, a useful technique is the relative cost approach. In this method, the total cost of one process is taken as a reference (or base), and the relative costs of other processes are plotted accordingly. The relative cost is defined as:

$$\text{Relative cost} = \frac{\text{Cost of Process A}}{\text{Cost of Reference process}}$$

By plotting relative cost curves as shown in Fig. 1.4 with cost per unit on the vertical axis and production volume on the horizontal axis. The figure emphasizes the importance of performing a break-even analysis when selecting manufacturing processes. It clearly shows that Shell Moulding is preferred for high-volume production, while Green Sand Moulding suits low-volume runs.

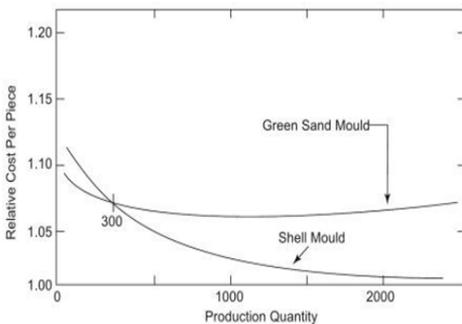


Figure 1.4 Relative Cost Comparison

This method simplifies comparison and highlights the production ranges where one process becomes more cost-effective than others.

### Example 1: Basic BEP Calculation

A manufacturer produces plastic containers.

- Fixed cost (FC) : ₹50,000
- Variable cost per unit (VC) : ₹20
- Selling price per unit (SP) : ₹50

### Break-even quantity (Q):

$$\text{BEP} = \frac{\text{FC}}{\text{SP} - \text{VC}} = \frac{50000}{50 - 20} = 1667 \text{ units}$$

Interpretation: The company must produce and sell at least 1,667 containers to cover all costs.

### Example 2: Comparing Two Processes

Two manufacturing processes are available for making the same part:

Cost Type	Process A	Process B
Fixed Cost (₹)	80,000	40,000
Variable Cost/unit (₹)	25	40

To find the break-even point between both processes:

$$FC_A + n.VC_A = FC_B + n.VC_B$$

$$80000 + 25n = 40000 + 40n \Rightarrow 15n = 40000 \Rightarrow n = \frac{40000}{15} = 2667 \text{ units}$$

**Interpretation:** For production less than 2,667 units, Process B is cheaper. For production more than 2,667 units, Process A becomes more economical.

### Example 3: Break Even Point with Graphing Insight

A company wants to determine the BEP for a new automated line:

FC	:	₹2,00,000
VC/unit	:	₹10
SP/unit	:	₹25

$$\text{BEP} = \frac{200000}{25 - 10} = \frac{200000}{25 - 10} = 13,334 \text{ units}$$

10. What are forming processes, and how do they differ from casting?
11. Why is metal heated below its solidus temperature during forming?
12. List any four common forming processes used in high-volume production.
13. What is meant by fabrication in manufacturing?
14. Differentiate between temporary and permanent joining in fabrication.
15. What is the primary objective of material removal processes?
16. Name four common machining operations and the type of tools used.
17. Define fixed cost and variable cost with examples.
18. How is break-even quantity calculated? Write its mathematical formula and explain each term.

### Questions

1. What is manufacturing? How does it contribute to modern comforts and conveniences?
2. Why is economic viability as important as functional design in manufacturing?
3. Name at least three engineering disciplines that rely on manufacturing processes.
4. Describe how manufacturing evolved during the First Industrial Revolution.
5. What role did the automobile industry play in advancing manufacturing?
6. List the four broad categories of modern manufacturing processes.
7. Why is casting considered one of the oldest manufacturing methods?
8. Name three specialized casting processes and their typical applications.
9. What are the advantages of sand casting in terms of production volume and cost?

## Objectives:

- Define and categorize various classes of engineering materials.
- Identify and describe key mechanical, thermal, and electrical properties.
- Interpret stress–strain behavior in relation to material performance.
- Analyze the influence of composition, manufacturing processes, and operating conditions on material properties.
- Evaluate materials for suitability in specific applications based on property requirements.

## 2.1 Introduction

The performance and reliability of materials in manufacturing processes are fundamentally determined by their mechanical and thermal properties. These properties govern how a material responds under various service conditions, such as applied stresses, mechanical deformation and elevated temperatures. Since manufacturing processes can alter a material's intrinsic properties, it becomes essential to understand these characteristics thoroughly. Such comprehension enables engineers to make informed decisions while selecting materials best suited for specific functional requirements. This chapter focuses on the critical mechanical properties that directly influence a material's strength,

durability, and overall performance in service environments.

## 2.2 Material strength

Strength is one of the most fundamental mechanical properties of materials. It refers to a material's ability to resist deformation or failure when subjected to external forces. Depending on the type and direction of the applied load, strength is commonly classified into three primary categories:

- **Tensile strength** : resistance to pulling forces
- **Compressive strength** : resistance to pushing forces
- **Shear strength** : resistance to sliding forces

When an external force is applied, the material develops an internal resisting force known as **stress**;

$$\text{Stress}(\sigma) = \frac{\text{Applied Load (F)}}{\text{Cross-Sectional Area (A)}}$$

Simultaneously, the deformation of material is quantified as **strain**, given by:

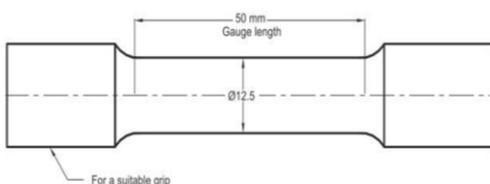
$$\text{Strain}(\varepsilon) = \frac{\text{Change in Length } (\nabla L)}{\text{Original Length } (L_o)}$$

Deformation may occur in two distinct forms:

- **Elastic deformation** – Temporary change in shape. The material returns to its original form once the load is removed.
- **Plastic deformation** – Permanent change in shape. The material does not return to its original shape after the load is removed.

### 2.3 Tensile testing of materials

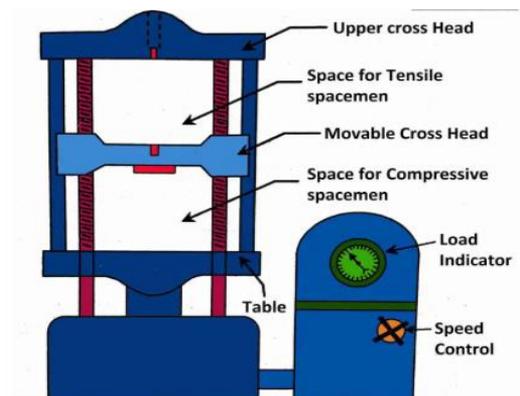
A tensile test can be conducted using a Universal Testing Machine (UTM) to evaluate a material's mechanical strength. This test involves preparing a standardized specimen either rectangular or cylindrical in shape and of specified dimensions as shown in Fig 2.1.



**Figure 2.1 Standard specimen for tensile test**

To ensure consistency and accuracy, the surface of the specimen must be smooth and free from notches, cracks, or deep scratches, as these can act as stress concentrators and adversely affect the test results.

The Universal Testing Machine comprises a robust test frame with a fixed lower beam and a movable upper crosshead. The crosshead applies a controlled tensile force to the specimen, as illustrated in Figure 2.2. The specimen is firmly held between two grips, one connected to the fixed beam and the other to the moving crosshead. An extensometer is mounted on the gauge length to accurately measure the elongation of the specimen during loading.



**Figure 2.2 Universal Testing Machine**

This setup enables precise evaluation of the material's deformation and tensile behavior under applied stress.

The Universal Testing Machine (UTM) is used to evaluate the mechanical behavior of materials under a controlled tensile load. The resulting stress–strain curve begins at point **O** and rises linearly to the **proportional limit (A)**. Between **A** and **B**, the curve gradually departs from linearity as the **elastic limit** is approached. At point **B**, the **yield point** is reached. From **B** to **C**, the curve displays yielding, characterized by a substantial increase in strain with minimal change in stress. Between **C** and **D**, strain hardening occurs, culminating at the **ultimate tensile strength (D)**, represents the maximum stress sustained during the test. Beyond **D**, localized necking begins, causing a significant reduction in cross-sectional area.

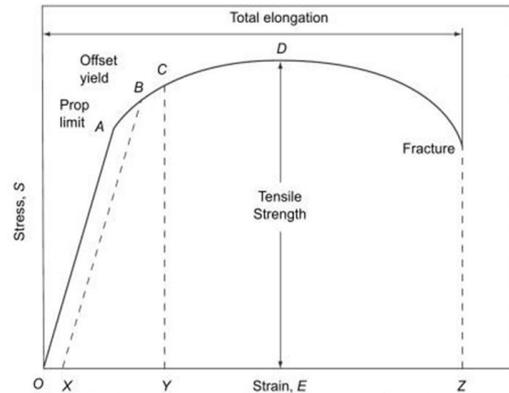


Figure 2.3 Stress and Strain Curve

This localized deformation leads to a rapid loss of load-bearing capacity, ultimately resulting in fracture. The test concludes at point **Z**, where fracture occurs. The total elongation at break, incorporating both elastic and plastic deformation, is determined by measuring the final distance between the gauge marks after carefully rejoining the fractured ends of the specimen. This value, typically expressed as percentage elongation at break, is a key indicator of ductility, reflecting the material's capacity for plastic deformation prior to failure.

Similar experimental procedures can be adapted to assess other mechanical properties, including compressive strength and shear strength, by varying the nature of the applied load.

## 2.4 Hardness

Hardness refers to a material's resistance to plastic deformation, typically in the form of indentation, scratching, or abrasion by a harder material. It is a critical property in materials science and engineering, as it strongly influences a material's ability to resist wear, surface deformation, and mechanical damage under various service conditions. Hardness is especially important in applications involving friction, contact loading, or surface durability.

### 2.4.1 Definition and measurement

Hardness is defined as the ability of a material to withstand permanent surface deformation. It is typically evaluated using standardized testing methods, such as:

- **Brinell Hardness Test (BHN)**- uses a hardened steel or carbide ball under a standard load.
- **Rockwell Hardness Test (HR)**- uses different indenter shapes (spherical or conical) with varying loads; offers rapid measurement.
- **Vickers Hardness Test (VHN)**- uses a diamond-shaped indenter and is suitable for very hard or thin materials.



Figure 2.4 Hardness tester

### 2.4.2 Factors affecting hardness

The hardness of a material is governed by several key factors; composition, microstructure, temperature, and work hardening, influence its resistance to plastic deformation, wear, and surface damage.

Material composition plays a primary role; materials with strong atomic bonds and dense crystal structures generally exhibit higher hardness. The microstructure is equally critical as finer grain sizes and the presence of hardened phases, such as a martensitic microstructure, enhance hardness by impeding dislocation movement and increasing resistance to localized deformation.

Temperature also affects hardness, as elevated temperatures typically reduce it

by lowering resistance to plastic flow; increased atomic mobility at higher temperatures facilitates deformation.

Finally, work hardening (or strain hardening) occurs during plastic deformation in cold working, where dislocation density increases within the crystal lattice. This accumulation of dislocations restricts further movement, thereby improving the material's resistance to deformation and enhancing surface hardness.

## 2.5 Ductility

Ductility is the capacity of a material to undergo substantial plastic deformation before fracture when subjected to tensile (pulling) forces. It is a critical property in applications that demand flexibility, stretchability, or the ability to be shaped without failure. Ductility is commonly quantified through percentage elongation and percentage reduction of area, as determined from tensile test measurements.

$$\text{Percentage Elongation} = \frac{\text{Final Gauge Length} - \text{Initial Gauge Length}}{\text{Initial Gauge Length}} \times 100$$

$$\text{Reduction in Area} = \frac{\text{Initial Area} - \text{Final Area}}{\text{Initial Area}} \times 100$$

At the atomic level, ductility arises from the ability of atoms within a

material to rearrange via slip systems under applied stress. In metals, metallic bonding permits atoms to slide past one another without disrupting the overall crystal structure, enabling sustained plastic deformation. Materials with face-centered cubic (FCC) crystal structures: such as gold, aluminum, and copper exhibit high ductility due to the presence of multiple slip systems, whereas materials with body-centered cubic (BCC) or hexagonal close-packed (HCP) structures possess fewer slip systems and generally display lower ductility.

Highly ductile materials can be readily formed into wires (drawing), sheets (rolling), or complex shapes (forging), owing to their ability to sustain large deformations without cracking. Their capacity to absorb significant energy before fracture makes them essential in applications where resistance to sudden, catastrophic failure is critical, such as in structural components for bridges, buildings, and pressure vessels. By allowing localized deformation, ductility also helps components accommodate stress concentrations and thermal expansion during service.

## 2.6 Malleability

Malleability is a physical property of metals that describes their ability to be deformed or shaped under compressive stress, such as hammering, rolling, or pressing, without cracking or breaking. It reflects a material's capacity to be flattened into thin sheets or reshaped through compression while maintaining its structural integrity. Malleability is a key indicator of a material's workability, particularly in manufacturing processes like sheet metal forming, coin stamping, and forging.

Malleable metals can be rolled into sheets, stamped, or pressed into complex shapes, making them essential for the production of foils, plates, panels, coins, and architectural elements. Their ability to resist cracking under compressive loading makes them particularly suitable for applications involving static or impact forces, where maintaining structural integrity during deformation is critical.

## 2.7 Brittleness

Brittle materials tend to fracture or shatter abruptly without undergoing significant elongation, bending, or yielding. They lack the ability to absorb strain through plastic deformation and typically fail suddenly under stress, often

without warning. Brittleness is a mechanical property that describes a material's tendency to break with little or no plastic deformation, often occurring with minimal warning. In simple terms, a brittle material fractures rather than bends, unlike ductile or malleable materials, which can undergo significant deformation before failure.

Material selection is especially critical in cold environments, where even normally ductile materials can exhibit brittle behavior. For instance, steel may become brittle in Arctic conditions due to reduced atomic mobility at low temperatures. In structural applications such as buildings and bridges, brittle failure of materials like concrete during earthquakes can lead to catastrophic consequences. To mitigate this risk, steel reinforcement is incorporated to provide ductility, enabling the structure to absorb energy and deform safely under dynamic or impact loading.

## 2.8 Toughness

Toughness is a critical property in materials science that describes a material's ability to absorb energy and undergo plastic deformation before fracturing. It reflects resistance to fracture under conditions of shock loading, sudden impact, or high-stress concentrations. A

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tough material does not fail abruptly; instead, it bends, stretches, and experiences substantial deformation before breaking, making it ideal for applications requiring both strength and durability under unpredictable loading conditions. There are two key types of toughness:

- **Fracture toughness** refers to a material's ability to resist the propagation of cracks, especially when flaws or pre-existing defects are present. It is a critical parameter for evaluating structural integrity under stress.
- **Impact toughness**, on the other hand, measures a material's capacity to absorb energy during sudden loading or impact. This property is typically evaluated using standardized tests such as the Charpy or Izod impact tests, providing insights into a material's performance under dynamic or shock conditions.

## 2.9 Creep

Creep is a time-dependent and permanent (plastic) deformation that occurs in a material when subjected to a constant load or stress over an extended period, particularly at elevated

temperatures. This phenomenon is critical in high-temperature applications such as turbines, boilers, and engines, where maintaining long-term dimensional stability is essential. Once creep deformation occurs, the material does not return to its original shape upon removal of the load, as the change is irreversible.

Creep becomes particularly significant at temperatures exceeding approximately  $0.4 \times T_m$  (melting temperature in Kelvin), where increased atomic mobility accelerates deformation. Under these conditions, the material's microstructure undergoes gradual changes such as grain boundary sliding, dislocation climb, and void formation contribute to a progressive loss of mechanical integrity over time.

## 2.10 Fatigue

**Fatigue** refers to the progressive weakening and eventual failure of a material due to repeated or fluctuating stress cycles, even when the applied stresses are below the material's yield strength. It is a time-dependent and localized form of structural damage that accumulates under cyclic loading, often leading to sudden failure without significant prior deformation. Fatigue is

a critical consideration in structural, aerospace, automotive, and mechanical engineering, where components are frequently subjected to cyclic loading. To evaluate a material's resistance to fatigue, engineers use S–N curves (stress versus number of cycles), which help determine the number of load cycles a material can endure before failure at a given stress level.

## Ductility vs Malleability vs Brittleness vs Toughness vs Creep vs Fatigue

Property	Definition	Type of Stress	Key Feature	Example Materials	Failure Mode
<b>Ductility</b>	Ability to <b>stretch</b> or <b>elongate</b> without breaking	Tensile (pulling)	Drawn into wires	Copper, Gold, Aluminum	Elongation before fracture
<b>Malleability</b>	Ability to <b>deform</b> under <b>compression</b> without cracking	Compressive	Formed into thin sheets	Gold, Lead, Silver	Flattening without cracking
<b>Brittleness</b>	Tendency to <b>break suddenly</b> without significant deformation	Any stress (primarily tensile)	Fractures with little warning	Glass, Ceramics, Cast Iron	Sudden fracture
<b>Toughness</b>	Ability to <b>absorb energy</b> before breaking	Impact / High stress	Combines strength and ductility	Mild Steel, Rubber, Titanium	Deforms before fracture
<b>Creep</b>	<b>Slow deformation over time</b> under constant load	Constant stress (high temp)	Time-dependent, long-term strain	Lead, Aluminum (high temp), Plastics	Gradual elongation
<b>Fatigue</b>	<b>Crack formation</b> under repeated loading	Cyclic stress	Repetitive loading causes failure at low stress	Aircraft wings, Bridges, Gears	Micro-crack to fracture over time

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## Questions

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1. What is ductility?
2. Define malleability.
3. What is meant by toughness in a material?
4. Explain brittleness with an example.
5. What is creep in materials?
6. Define fatigue failure.
7. How does ductility differ from malleability?
8. Differentiate between toughness and strength.
9. How is brittle material behavior different from ductile material behavior?
10. Compare creep and fatigue in terms of loading conditions.
11. Which property is important for drawing a metal into wires?
12. Why is toughness important in automotive crash zones?
13. Why are ceramics not suitable for applications involving tensile loads?
14. Which mechanical property is tested using the Charpy impact test?
15. What property should a metal possess to be rolled into thin sheets?
16. How is ductility measured in a tensile test?
17. What test is commonly used to assess fatigue life?
18. What is the typical condition for creep to occur?
19. How can surface finish affect fatigue life?
20. What is fracture toughness?

## Objectives:

- Provide a comprehensive understanding of the fundamental principles and industrial relevance of metal casting processes.
- Explain the sequential stages of casting, including pattern making, molding, melting, pouring, and solidification.
- Differentiate and categorize major casting methods, and critically evaluate their characteristics, applications, and limitations.
- Identify common casting defects and propose effective corrective measures to enhance product quality.
- Analyze critical process parameters that affect the quality, performance, and efficiency of casting operations.
- Build expertise in selecting the most appropriate casting techniques based on specific industrial requirements and application criteria.

### 3.1 Introduction

Casting is a fundamental manufacturing process involving the heating of a metal or alloy beyond its melting point, followed by pouring the molten material into a mold cavity resembles the desired component's shape and dimensions. As the metal cools and solidifies, it adopts the form of the cavity, resulting in a near-net-shape product with minimal finishing. The area in a workshop dedicated to performing casting operations is known as a foundry. The production of a metal casting typically involves the following sequential steps:

1. **Pattern Preparation** – Designing and fabricating a replica of the desired component, known as a pattern, establishes the shape and size of the mold cavity.
2. **Mold Making** – Forming the mold by packing molding material around the pattern to create a cavity into which the molten metal will be poured.
3. **Melting** – Heating the selected metal or alloy in a furnace until it reaches a fully liquid state suitable for casting.
4. **Pouring** – Transferring the molten metal into the prepared mold cavity under controlled conditions to ensure complete filling.
5. **Solidification and mold removal** – Allowing the metal to cool and solidify, followed by breaking or separating the mold to extract the casting.
6. **Fettling** – Cleaning the casting by removing unwanted projections such

as risers, runners, and flash, and smoothing the surface.

7. **Inspection** – Evaluating the casting through dimensional checks and quality control techniques to ensure it meets specified standards and tolerances.

Castings can be manufactured using a broad spectrum of ferrous and non-ferrous metals, selected based on the specific performance requirements of the application. Grey cast iron is widely used for general-purpose components due to its good castability and damping properties.

Steel castings are preferred in applications demanding high mechanical strength and toughness. Bronze and brass offer excellent corrosion resistance, making them suitable for marine and plumbing applications. Aluminium and aluminium-magnesium alloys are extensively used in the automotive and aerospace industries owing to their lightweight and high strength-to-weight ratio. Stainless steel is frequently employed in the production of consumer goods such as kitchenware and cutlery, where both corrosion resistance and aesthetic appeal are important.

Casting is a cost-effective method for manufacturing parts in both small and

large quantities. Although cast components generally have lower mechanical strength compared to wrought components (e.g., those produced by forging), certain casting techniques—such as the use of chills can enhance localized properties. Moreover, casting results in minimal material waste, making it a relatively efficient production process.

### 3.2 Patterns in casting

A pattern is a precisely crafted replica of the component to be cast, serving as the model around which the mold cavity is formed. While it closely resembles the final product in terms of shape and dimensions, it is not an exact copy. The pattern is intentionally designed with allowances to account for material shrinkage during solidification, dimensional changes due to cooling, and any subsequent machining requirements.

Building on the pattern, mold preparation typically employs moist sand commonly known as green sand mixed with a binder to promote adhesion among the sand particles and retain the mold's shape. The pattern is carefully withdrawn from the compacted sand to ensure the cavity remains intact and accurate. Once the mold is complete, molten metal is poured into the cavity under controlled conditions. As the metal cools and solidifies, it conforms to

the mold geometry of the desired casting.

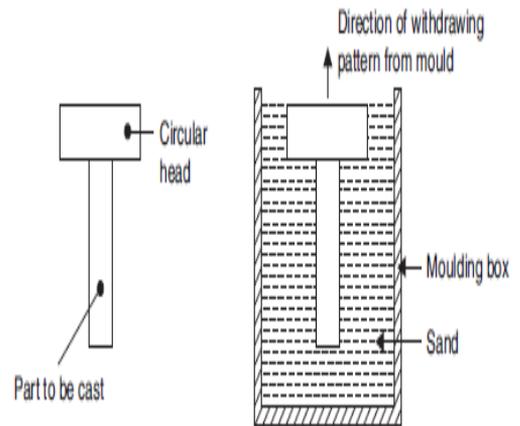
### 3.2.1 Types of patterns

Patterns are commonly made from high-quality, well-seasoned wood due to its ease of fabrication, smooth surface finish, dimensional stability, and cost-effectiveness. Wood is readily available and can be shaped with relative simplicity, making it suitable for low to moderate production volumes. However, applications need large number of castings, metal patterns are preferred for their durability, dimensional accuracy, and longer service life. These are typically manufactured from aluminium-magnesium alloys which offer a good balance of strength, machinability, and resistance to wear.

1. **Single-Piece Pattern:** A solid or single-piece pattern is constructed as one complete unit and is typically used for simple castings. It does not include provisions for runners, risers, or cores, making it suitable only for uncomplicated shapes.

Molding with this type of pattern can be carried out either directly on the foundry floor (referred to as pit molding) or within a molding box.

Pattern withdrawal is generally easy, especially when the widest section is at the top, reducing the risk of damaging the mold cavity.



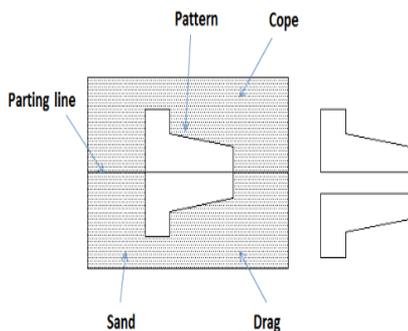
**Figure 3.1 Single-Piece Pattern**

**Example:** Casting a cylindrical pin with a circular head can be accomplished using a single-piece pattern, as it does not require complex features or internal cavities as shown in Fig 3.1.

2. **Split Pattern:** The mechanical components of intricate shape often make it impractical to use a single-piece pattern, as it cannot be withdrawn from the mold without damaging the cavity. In such cases, a split pattern also known as a two-piece pattern is employed to facilitate

easy removal and accurate mold formation.

For instance, if a circular head is added to the bottom of a cylindrical pin (as in Fig. 3.2), it becomes necessary to divide the pattern into two halves. Each half is placed in a separate molding box one in the cope (top box) and the other in the drag (bottom box). After making the impressions, the pattern halves are withdrawn, and the boxes are reassembled and clamped, forming a complete mold cavity for pouring molten metal.

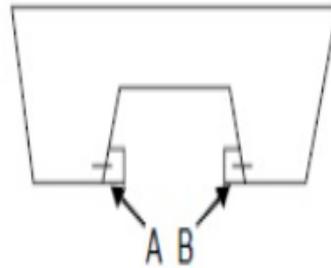


**Figure 3.2 Split Pattern**

In some cases, especially with highly intricate castings, the pattern may be split into three or more pieces to allow proper molding and withdrawal.

**3. Loose piece pattern:** In certain castings, projections, undercuts, or overhanging features make it difficult

or even impossible to withdraw the pattern from the mold as a single unit. In such situations, a loose piece pattern is employed.



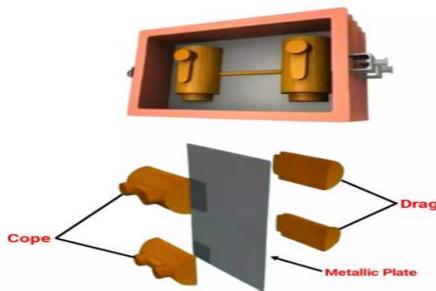
**Figure 3.3 Loose Piece Pattern**

This pattern type is particularly useful for components with non-uniform geometries or internal features that cannot be molded using standard patterns.

The complex features are designed as separate, detachable parts, known as loose pieces (Fig 3.3), which are temporarily affixed to the main body of the pattern. The mold is then prepared in the usual way, ensuring accurate cavity formation while allowing for the safe removal of all pattern components.

**4. Match plate patterns:** are commonly used with mechanized molding machines to efficiently handle the cope and drag sections of the molding box.

A match plate pattern consists of the two halves of a split pattern (Fig 3.4), mounted on opposite sides of a flat metal plate typically made of aluminium.

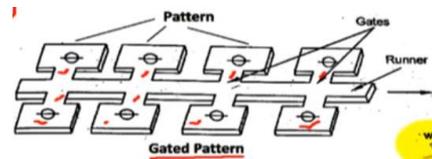


**Figure 3.4 Match plate patterns**

The alignment of these pattern halves is precisely maintained on the match plate to prevent any mismatch during mold preparation.

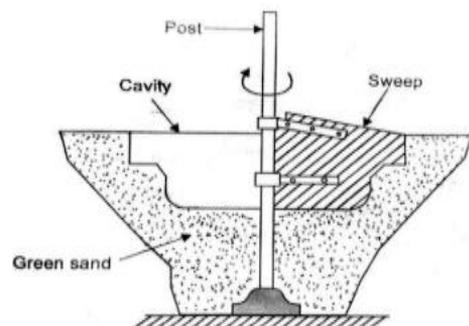
Once both impressions are made, the cope and drag are aligned and clamped together, creating a complete mold cavity ready for metal pouring. Match plate patterns are ideal for mass production, as they offer high dimensional accuracy and faster mold setup compared to conventional hand molding.

**5. Gated Pattern:** Simultaneous casting of multiple identical components maintain consistent metal flow to each cavity. A gated pattern is a modified pattern uses shallow channel to direct molten metal into the mold cavities (Fig. 3.5). The main cavities and the gates are formed simultaneously, ensures time saving, uniformity, and molding efficiency.



**Figure 3.5 Gated Pattern**

**6. Sweep Pattern:** The production of large, symmetrical castings typically with cylindrical or circular cross-sections are too big or uneconomical to be made using a full solid pattern (Fig 3.6).



**Figure 3.6 Sweep Pattern**

Instead of a complete model, a sweep is a wooden or metal template represents a cross-sectional profile of the casting. This sweep is rotated about a central axis (called a spindle) within a mold box filled with sand. As the sweep rotates, it removes excess sand and shapes the mold cavity to the desired profile.

Sweep patterns are ideal for simple, rotationally symmetrical shapes like bells, pulleys, or large pipes. They are cost-effective, especially for large castings made in small quantities, where making a full pattern would be expensive and time-consuming.

### 3.2.2 Pattern Allowances

During the casting process, various allowances are incorporated into the pattern design to compensate for material behavior and post-processing requirements. These allowances ensure the final casting meets the desired shape, size, and quality.

**1. Shrinkage Allowance :** Most metals shrink as they solidify and cool. To compensate for this volumetric contraction, patterns are made slightly larger than the final casting dimensions. This difference is known as shrinkage allowance.

- For cast iron, shrinkage allowance is typically 1%.
- For aluminium, it is around 1.6%.

**2. Machining Allowance:** Castings often require machining to achieve precise dimensions and a smooth surface finish. To accommodate this, an extra layer usually 1.5 to 2.5 mm, is added to the pattern dimensions on all machined surfaces. This is called the machining allowance.

**3. Draft Allowance:** To facilitate easy removal of the pattern from the mold without damaging the cavity, a taper is provided on all vertical surfaces. This draft angle, typically 2–3 degrees, ensures smooth withdrawal.

**4. Distortion and Radius Allowances:** In some cases, allowances are also provided to compensate for warping or distortion during cooling. Additionally, sharp corners are avoided and replaced with fillets or radii to improve mold strength and casting integrity.

### 3.3 Moulding sand and its properties

In foundries, sand is the primary material used for making molds. Natural sand, typically sourced from river beds and banks, is abundantly available and widely used, though high-quality silica

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sand is also mined for specialized applications. Chemically, sand is primarily composed of silicon dioxide ( $\text{SiO}_2$ ) in granular form.

Natural river sand contains silica with varying amounts of clay, non-metallic impurities, and traces of magnesium and calcium salts. After appropriate conditioning and treatment, this sand becomes suitable for mold-making.

### 3.3.1 Properties of moulding sand

A good moulding sand must exhibit a combination of physical and chemical properties ensure the production of defect-free castings with high dimensional accuracy. These properties determine the sand's ability to withstand the thermal, mechanical, and chemical conditions encountered during the moulding and casting processes. The essential properties of a good moulding sand include:

1. **Refractoriness:** The sand must withstand the high temperatures encountered during metal pouring without fusing or breaking down.
2. **Permeability:** It should allow the escape of gases, air and water vapour generated during casting to avoid defects such as blowholes.
3. **Green Strength:** When moist, the sand must have sufficient strength to retain the mold shape during handling and metal pouring.
4. **Flowability:** The sand should be capable of filling all cavities, corners, and fine details of the pattern to produce an accurate mold impression.
5. **Collapsibility:** After solidification of the metal, the sand should collapse easily, making it easier to remove the casting and minimize stress on the part—especially critical in core making.
6. **Cohesiveness:** Refers to the sand's ability to stick together, ensuring the mold remains structurally stable during handling and pouring.
7. **Adhesiveness:** The ability of the sand to stick to the mold box walls, preventing the mold from shifting or collapsing during pouring.

### 3.3.2 Factors influencing sand properties

Properties such as permeability, green strength, and cohesiveness depend on:

- Size and shape of sand grains
- Type and amount of binder (clay or bentonite)
- Moisture content

**Table 3.1 Moulding sand composition**

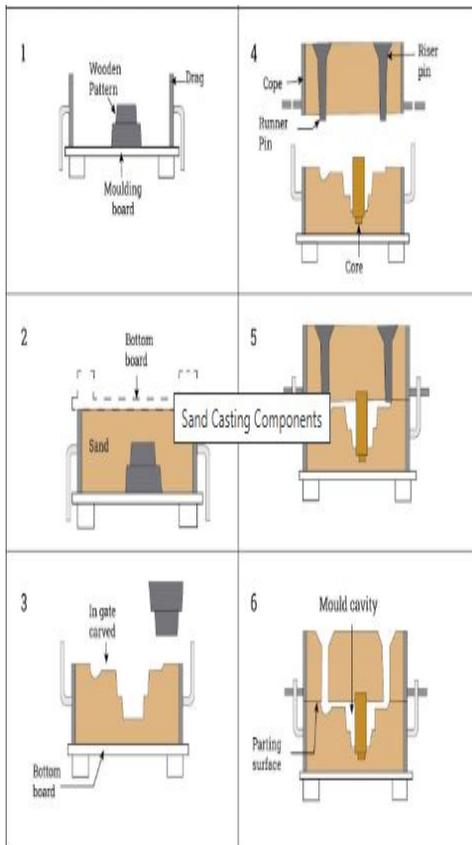
Component	Proportion (%)
Silica	~75%
Clay	10–15%
Bentonite	2–5% (as needed)
Coal dust	5–10%
Moisture	6–8%

Clay acts as a natural binder, but when its content is insufficient, chemical binders like bentonite are added to enhance bonding strength.

### 3.4 Mould making technique

Mould making is a critical operation in the sand casting process, requiring accuracy to ensure the final casting meets dimensional and surface quality standards. The following steps outline the standardized procedure using a split pattern and green sand.

1. **Pattern Placement:** The lower half of the split pattern is placed on a moulding board with the parting surface facing downward. Parting sand, a fine binder-free silica sand, is applied to prevent adhesion between the moulding sand and the pattern. The drag box is then positioned over the pattern.
2. **Sand ramming in the drag :** A 20–25 mm layer of facing sand is placed over the pattern to capture fine details. The remaining volume is filled with backing sand, typically reclaimed and conditioned. Uniform compaction is achieved through controlled ramming to avoid cavity distortion. The surface is leveled with a trowel, and vent holes are created to facilitate gas escape during pouring.
3. **Cope Assembly and Ramming:** After inverting the prepared drag, the upper half of the pattern is aligned with the lower. The cope box is placed above and temporarily clamped. Parting sand is reapplied to prevent sticking. A fresh facing sand layer is added, followed by the insertion of taper pins at runner and riser locations. The cope is filled with backing sand, rammed uniformly, leveled, and vented. Taper pins are then withdrawn.



**Figure 3.7 Steps In Mould Making**

- 4. Pattern with-drawal:** The cope and drag boxes are separated, and pattern halves are removed. Tapped holes in the pattern allow lifting rods to be inserted. Gentle rapping is used to loosen the pattern, which is then withdrawn vertically to avoid damaging the cavity.

**5. Finishing the cavity surface:** Minor imperfections in the mould cavity are corrected using small tools. Loose sand is removed manually or with compressed air to ensure a clean cavity.

**6. Core placement :** For castings with internal cavities, sand cores are inserted and supported by core prints or chaplets to prevent movement during pouring.

**7. Mould surface coating and assembly:** Graphite powder or mould wash is applied to the cavity surfaces to improve finish and facilitate pattern removal. A gate is cut in the drag below the runner. The cope is then reassembled and clamped over the drag.

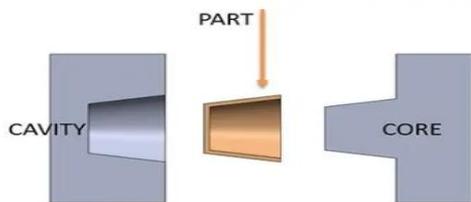
Dry moulds offer superior strength and reduce moisture-related casting defects. Once the mould is assembled and secured, it is ready for molten metal pouring, initiated through the runner until metal appears in the riser, indicating complete cavity fill.

### 3.5 Cores in sand casting

Cores are used in casting processes to form internal cavities, holes, recesses, or

undercuts that cannot be produced directly by the pattern. Typically composed of refractory materials such as oil-bonded sand, cores are inserted into the mould cavity at the designated location prior to final mould assembly.

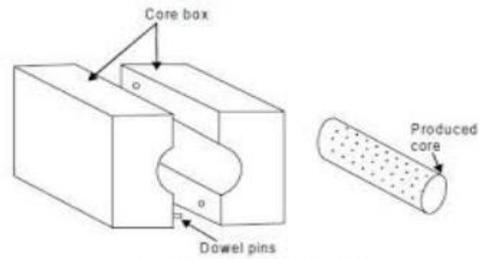
Because they are entirely surrounded by molten metal during pouring, cores must exhibit high thermal resistance. Additionally, they require adequate structural integrity and mechanical support to resist displacement due to buoyant forces exerted by the molten metal. Improperly supported cores may shift, resulting in casting defects. As the metal solidifies and contracts, the core should have sufficient collapsibility to prevent the formation of hot tears or internal stresses within the casting (Fig. 3.8).



**Figure 3.8 Core**

Cores are fabricated using core boxes (Fig. 3.9), usually made of wood, which contain the negative impression of the core shape. The sand mixture is packed and rammed into the core box, which is typically split into two halves to

facilitate removal. After forming, cores are dried in ovens to remove moisture and improve strength.

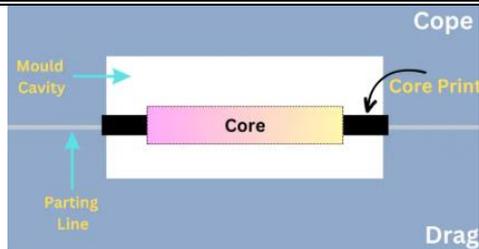


**Figure 3.9 Core Boxes**

In cases requiring additional structural stability, cores may be reinforced with wires or nails. These reinforcements are embedded within the sand and are extracted along with the spent core material after the casting is complete.

### 3.5.1 Core prints

Core prints are essential features in sand casting used to support cores within the mould cavity. They are designed as extensions or projections at the ends of the core, which rest in corresponding recesses or impressions in the mould. These recesses, also called core seats, ensure the core remains accurately positioned and suspended within the cavity, preventing it from shifting or settling due to gravitational forces during pouring.

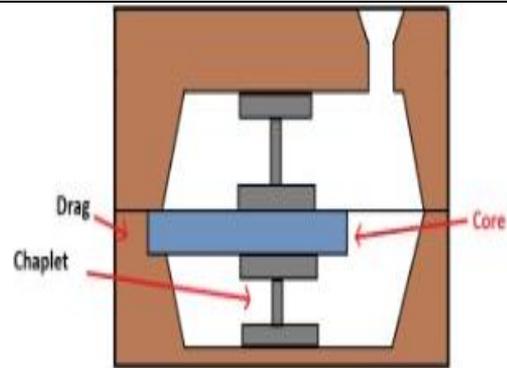


**Figure 3.10 Core Prints**

By providing mechanical support at both ends, core prints help maintain the dimensional accuracy of the intended hollow features and ensure proper alignment throughout the casting process. For instance, in the case of a cylindrical casting with a central hole, the core that forms the hole can be supported at both ends by core prints integrated into the mould design.

### 3.5.2 Chaplets

Chaplets are small metal supports used in sand casting to maintain the position of cores within the mould cavity when adequate support cannot be provided by core prints alone. They are especially necessary for large, heavy, or horizontally oriented cores, which may be prone to displacement due to buoyancy forces exerted by the molten metal during pouring (Fig. 3.11).



**Figure 3.11 Chaplets**

Chaplets are typically made of same or a compatible metal as the casting, and become part of the final product as they fuse with the molten metal during solidification. To function effectively, chaplets must be designed to:

- Withstand high temperatures without melting prematurely.
- Provide stable mechanical support without causing core movement.
- Avoid introducing defects such as porosity or inclusions.

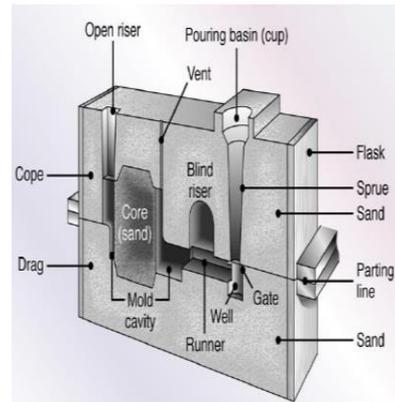
### 3.6 Gates, Runners, and Risers

In a sand casting process, the gating system refers to the network of channels through which molten metal flows from the pouring basin into the mold cavity (Fig. 3.12). This system ensures smooth metal flow, minimizes turbulence, and helps in the removal of impurities before

the metal enters the mold cavity. The key components of the gating System are described below:

1. **Pouring Basin:** located at the top of the mold (in the cope), it receives the molten metal and directs it downward into the runner via the sprue. It helps prevent splashing and reduces the chances of air entrapment.
2. **Sprue:** a vertical passage through which molten metal descends from the pouring basin. Often connected to a well at the bottom to absorb the kinetic energy of falling metal and reduce turbulence.
3. **Runner:** a horizontal channel distributes molten metal from the sprue to the gates. Helps in controlling the direction and speed of the metal flow.
4. **Gates:** small openings through which metal enters the mold cavity from the runner. Designed to regulate the flow and filter out slag or impurities. Without proper gates, molten metal could directly strike the mold cavity and cause erosion or damage.
5. **Risers:** serves as a visual cue that the mold cavity has been completely filled. More importantly, it acts as a reservoir of molten metal to

compensate for shrinkage during solidification and cooling of the casting.



**Figure 3.12 Sand Mold**

### 3.7 Cupola furnace

The cupola furnace is extensively used for melting cast iron in foundry operations due to its cost-effectiveness, continuous melting capability, and structural simplicity. Among various types of furnaces, it remains one of the most economical and efficient methods for producing molten cast iron in large volumes.

#### 3.7.1 Fuel and material considerations

The cupola uses coke as its primary fuel, which is produced by carbonizing steam coal in an oxygen-deficient (inert) environment. Coke provides a more intense and consistent heat source compared to conventional coal, making

it highly suitable for high-temperature melting processes.

### 3.7.2 Constructional features

The furnace comprises a vertical cylindrical steel shell lined internally with refractory fire bricks to withstand the elevated temperatures generated during operation. The entire structure is mounted on short steel columns approximately 0.85 meters above ground level to allow discharge and maintenance operations. The base of the cupola includes drop-bottom steel doors, also lined with refractory material and covered with a layer of high-quality molding sand, which forms the working bottom during operation.

A charging door is provided at the upper section of the furnace, through which the fuel, metal charge (usually scrap iron, pig iron, and steel scrap), and flux are introduced. A wind belt, connected to a motorized air blower, is installed approximately 1 meter above the furnace bottom. From this wind belt, a series of tuyeres (small air inlets) are positioned around the shell to supply combustion air uniformly into the furnace.

A tapping spout is installed at the lower section, for drawing molten metal,

and just above it, typically around 350 mm higher, a slag hole is provided to remove floating slag. The space between the tap hole and slag hole is termed the well, where molten metal accumulates before tapping. A spark arrester may be fitted at the top to prevent the ejection of sparks and fumes.

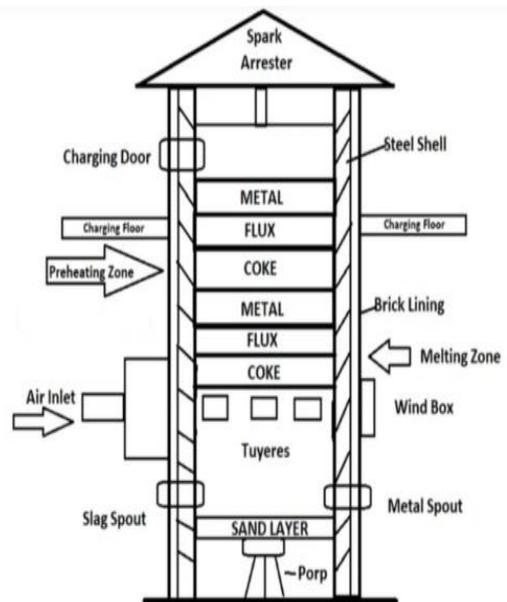


Figure 3.13 Cupola Furnace

### 3.7.3 Operating procedure

The operation of a cupola begins with inspection and repair of the refractory lining, particularly around the bottom doors. Once prepared, the hinged bottom doors are securely closed to ensure safety during operation. A wood and kerosene-soaked rag fire is initially

ignited at the base. As the fire stabilizes, coke is charged through the top until a coke bed height of approximately 0.5 meters above the tuyeres is achieved.

Following this, the air supply from the blower is initiated partially, and alternate layers of metallic charge, flux (usually limestone), and additional coke are loaded through the charging door. These materials settle on the preheated coke bed. Once the furnace is filled up to the charging level, the tuyeres are fully opened to increase combustion intensity.

The coke at the tuyere level burns vigorously, raising the temperature in the lower part of the cupola. The heat melts the surrounding metal charge, while the limestone decomposes into calcium oxide (CaO) and carbon dioxide (CO<sub>2</sub>). The CaO reacts with impurities such as silica (SiO<sub>2</sub>), forming slag (calcium silicate – CaSiO<sub>2</sub>), which being lighter, floats on the surface of the molten metal.

When sufficient metal has been melted, the slag is removed by opening the slag hole. The molten iron is tapped by puncturing the tap hole using a steel rod with a conical tip. The flowing metal is collected in refractory-lined ladles, which are then transported for pouring into molds. After tapping, the hole is sealed using fire clay.

To enhance the quality of cast iron, ferro-alloys such as ferro-manganese and ferro-silicon are added to the molten metal in the ladle. This compensates for the loss of manganese and silicon during the oxidation process inside the cupola, especially when using a charge composed of scrap iron, pig iron, and steel.

At the end of the melting session, additional coke is charged along with the final charge. After the entire metal has melted and been tapped, the air blower is switched off, and the bottom doors are opened to discharge any unburnt coke, slag, or residual metal. This prevents the formation of a solidified mass at the bottom, which would otherwise hinder subsequent operations and maintenance.

### 3.8 Casting defects

Casting defects are imperfections adversely affect the quality, dimensional accuracy, mechanical strength, and appearance of cast components. These defects may arise from improper design, poor foundry practices, or issues related to material properties and process parameters. Some of the common casting defects are described below:

- 1. Blow-Holes:** Blow-holes are spherical or elongated cavities that may appear on the surface or be

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embedded just below the surface of the casting.

They are primarily caused by entrapped gas bubbles during solidification. Contributing factors include:

- Excessive ramming pressure
- Inadequate venting
- High moisture content in the sand
- Poor sand permeability

**2. Shrinkage cavity:** Shrinkage cavities are internal voids formed due to the contraction of molten metal during solidification, especially when there is an abrupt variation in section thickness. This defect typically appears at the junction of thick and thin sections and may compromise the structural integrity of the casting.

**3. Misrun :** occurs when the molten metal fails to completely fill the mold cavity, resulting in an incomplete casting. Causes include:

- Insufficient pouring temperature
- Inadequate gating system design
- Poor metal flow or leakage at the parting line between cope and drag

**4. Cold Shut:** Cold shuts arise when two streams of molten metal fail to fuse completely upon meeting in the mold cavity, leading to a weak interface or discontinuity within the casting. Low metal temperature or poor fluidity of the molten metal are the common cause.

**5. Mismatch:** refers a misalignment between the upper (cope) and lower (drag) parts of the mold cavity, resulting in a stepped or shifted casting profile. This may occur due to improper alignment of the split pattern (e.g., loose dowel pins) and inaccurate clamping of the flask components.

**6. Drop:** occurs in a portion of the mold collapses or drops into the molten metal, creating an irregular surface impression or cavity. Likely causes include weak bonding in the mold due to inadequate ramming and low binder content or improper sand consistency.

**7 Scab:** formed in a portion of the mold face breaks away or lifts during pouring and is subsequently filled by the molten metal. The result is a metallic protrusion fused into the casting surface. This can be attributed to excessive mold expansion and inadequate mold strength or cohesion.

**8 Hot Tear :** cracks develop in long, thin sections of a casting while it is still hot and weak during solidification. These typically occur when the casting is unable to contract freely due to resistance from tightly packed or poorly yielding mold sand.

#### **Other Common Defects:**

- **Scars:** Shallow surface depressions due to inadequate mold cavity surface preparation.
- **Blisters:** Surface bubbles formed due to trapped gas near the mold-metal interface.
- **Sponginess:** Localized areas of porosity, often resulting from micro blow-holes.
- **Slag Inclusions:** Entrapped non-metallic particles (slag or

dross) introduced during pouring or melting.

### **3.9 Die Casting**

Die casting is a permanent mold casting process wherein molten metal is introduced into reusable metal molds, known as dies, to produce components with high dimensional accuracy and excellent surface finish. Unlike sand molds, which are destroyed after a single use, dies are durable and designed for repeated use in mass production.

#### **3.9.1 Working principle of die**

A typical die is composed of two halves: one fixed and one movable. These halves, when closed and locked together, form the mold cavity that defines the geometry of the casting. After the molten metal is introduced into the cavity and solidifies, the die is opened, and the casting is ejected. Die casting is classified based on the method of metal delivery into the die:

- **Gravity Die Casting:** Molten metal is introduced into the die purely under the influence of gravity.
- **Pressure Die Casting:** Molten metal is forced into the die under pressure, typically using a hydraulic or mechanical piston. This ensures

faster filling, better compaction, and higher precision.

### 3.9.2 Die material and cooling

The die material must possess a significantly higher melting point than the casting alloy. Common die materials include medium carbon low-alloy steels, which provide the necessary thermal resistance and wear durability.

Depending on the process and production rate, dies are cooled using air or water-cooled systems to enhance cycle time and maintain dimensional consistency.

#### 1. Hot chamber die casting

Hot chamber die casting operates at pressures up to 35 MPa and is primarily used for casting low-melting-point metals such as zinc, tin, lead, and their alloys. In this process, the injection chamber is immersed directly in the molten metal and kept heated, allowing rapid and efficient metal injection into the die with minimal heat loss.

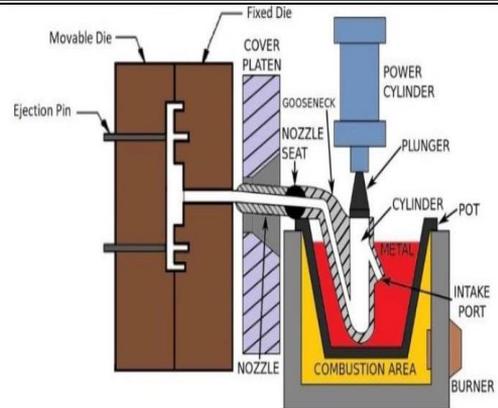


Figure 3.14 Hot chamber die casting

#### 2. Cold chamber die casting

Cold chamber die casting operates at pressures of up to 150 MPa and is suitable for metals with relatively higher melting points, such as aluminium, magnesium, and their alloys. In this process, molten metal is first ladled into a separate, unheated injection chamber and then forced into the die cavity under high pressure, ensuring precise shaping while preventing excessive heat exposure to the injection components.

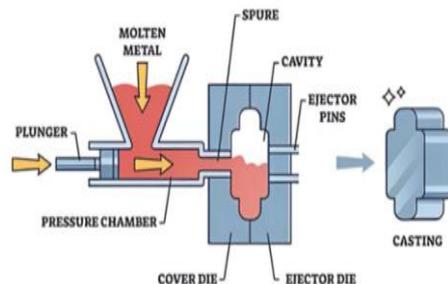


Figure 3.15 Cold chamber die casting

### 3.9.3 Advantages of Die Casting

1. **High production efficiency:** Ideal for mass production of small to medium-sized components (e.g., pistons, valve bodies, carburetor housings).
2. **Excellent surface finish:** Castings typically require minimal or no machining due to tight dimensional control.
3. **Defect-free output:** Produces castings with high integrity, free from porosity and inclusions under optimized conditions.
4. **Repeatability and uniformity:** Every casting produced is identical, enhancing quality control.
5. **No sand requirement:** Eliminates the need for molding sand, thus reducing the space requirements and environmental waste.

### 3.9.4 Limitations of Die Casting

- **Complexity limitations:** Components with intricate cores or highly complex geometries are difficult to produce.
- **Material restrictions:** Limited to non-ferrous alloys due to the thermal limitations of die materials.

### Questions

1. What is the fundamental difference between a sand mould and a die in casting?
2. Why can a die be reused multiple times unlike a sand mould?
3. How are the two halves of a die typically arranged?
4. What materials are commonly used for making dies?
5. What is gravity die casting and how is molten metal introduced in this method?
6. How does pressure die casting differ from gravity die casting?
7. Describe the basic mechanism of forcing molten metal into the die in pressure die casting.
8. Why must the die material have a much higher melting point than the casting metal?
9. List at least four metals or alloys commonly used in die casting.
10. What material is typically used to make the die for casting metals such as aluminium and zinc?
11. Why is cooling of dies (by water or air blast) important during the die casting process?
12. Why is it important to consider metal contraction during cooling?
13. What design feature is included in dies to facilitate easy removal of the casting? How does contraction affect the shape and integrity of castings during ejection?
14. What is the first step before injecting molten metal into a die?
15. When is pressure applied and for how long in pressure die casting?
16. What components are removed along with the final casting during ejection?
17. Why is the cycle in die casting repeatable and consistent?
18. What is the maximum pressure used in the hot chamber die casting method?
19. Which metals are best suited for the hot chamber process?
20. Why is the molten metal chamber heated in this method?
21. How does the cold chamber process differ from the hot chamber process?
22. What range of pressure is typically used in cold chamber die casting?

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23. Why is this method preferred for aluminium and magnesium alloys?
  24. Name three components commonly produced using die casting.
  25. What is the main economic disadvantage of die casting?
  26. How does die casting contribute to better dimensional control?
  27. Why is this process unsuitable for very large castings?
  28. What difficulties arise when producing castings with complex shapes or many cores?
  29. In what ways does die casting reduce space requirements compared to sand casting?

## Objectives:

- Develop a solid understanding of the fundamental principles of metal forming and the mechanics of plastic deformation.
- Classify and explain various forming processes, including forging, rolling, extrusion, and drawing.
- Distinguish between hot working and cold working processes, highlighting their characteristics and industrial applications.
- Analyze material behavior under compressive, tensile, and shear forces during forming operations.
- Assess the advantages, limitations, and suitable applications of different metal forming techniques.
- Select the most appropriate forming process based on material properties, part geometry, and production requirements.
- Interpret key process parameters and evaluate their impact on product quality and mechanical properties.
- Identify safety considerations and describe the equipment commonly used in industrial metal forming.

## 4.1 Introduction

Metal forming processes shape metals into functional components by applying mechanical forces cause plastic deformation, permanently alter the material's shape without cracking or breaking. The method offers high production efficiency, reduced material waste, and cost-effectiveness, making it well-suited for large-scale manufacturing. Suitable materials must possess adequate malleability and ductility, though heating can enhance formability, however, these properties may be insufficient at room temperature, leading to the use of hot or cold forming techniques. The choice of forming technique depends on material type, part geometry, and industrial applications. Cold forming methods generally provide higher dimensional accuracy and a superior

finish due to minimal thermal effects. On the other hand, hot working accommodates less ductile materials introduce oxidation, decarburization, scale formation, and dimensional variations from thermal contraction.

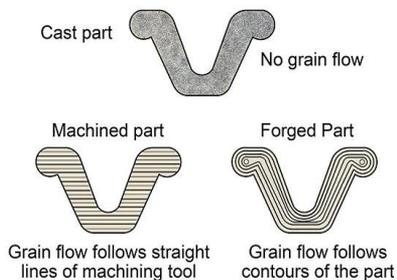
### 4.1.1 Advantages of metal forming

In addition to higher productivity, metal forming processes offer several important advantages over other manufacturing methods. These are outlined below:

1. **Improved mechanical properties:** Metal forming enhances the mechanical properties of materials, including ultimate tensile strength, wear resistance, hardness, and yield strength, though it may reduce ductility. This phenomenon is known

as strain hardening or work hardening, which results from plastic deformation during forming.

2. **Grain flow:** During metal forming, grain flow lines are aligned and elongated along the direction of material flow. This orientation improves resistance to fracture and increases structural integrity when the component is in service.



**Figure 4.1 Grain flow process**

A classic example is a V block (Fig 4.1), manufactured by machining from a solid bar, the grain flow is interrupted and does not follow the shape of the component, reducing its resistance to dynamic stresses.

If the component is manufactured by forging, the grain flow follows the full contour of the part, providing significantly higher strength and fatigue resistance.

As grains are plastically deformed and reoriented in the direction of metal flow, components produced through metal forming exhibit enhanced mechanical strength, particularly along the grain flow direction, making them more durable and reliable in demanding applications.

## 4.2 Types of metal forming

Metal forming can be classified into two types;

- (i) Cold metal forming
- (ii) Hot metal forming

Cold metal forming refers to the plastic deformation of metals and alloys below the recrystallization temperature. Deformation at lower temperatures may cause strain hardening resulting in a progressively harder material. If deformation continues without relieving the strain hardening, the metal may become brittle, eventually leading to cracking or failure. Cold forming is typically used when high strength, good surface finish, and dimensional accuracy are desired.

Hot metal forming involves plastic deformation of metals and alloys at a temperature above the recrystallization range, where strain hardening is continuously relieved due to

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recrystallization of the material. This allows the metal to retain high ductility and be formed easily under large strains. Properly performed hot forming results in a fine-grained, recrystallized microstructure improves material properties such as toughness and impact resistance.

#### 4.2.1 Recrystallization temperature

Recrystallization temperature refers to the range of temperatures at which deformed grains in a cold-worked metal are replaced by new strain-free grains. It is not a fixed value, but rather a temperature range depends on several factors, including the type of metal or alloy, the amount of prior deformation, the purity of the material, and heating rate. Recrystallization typically occurs at about one-third to one-half of the metal's melting point (on the absolute temperature scale).

The recrystallization temperature varies depending on material composition and deformation conditions:

- **Material Purity:** Pure metals tend to have lower recrystallization temperatures, typically around one-third of their melting point.

In contrast, alloys usually exhibit higher recrystallization temperatures, approximately one-half of their melting point.

- **Strain Hardening and Annealing:** Materials that have undergone significant strain hardening require higher recrystallization temperatures during annealing to restore ductility and relieve internal stresses.

- **Strain Rate:** A higher strain rate during deformation generally results in a higher recrystallization temperature, as more energy is stored in the metal's structure, promoting faster nucleation and growth of new grains. For example: Mild steel has a recrystallization temperature range of approximately 550–650°C. Low melting point metals such as lead, zinc, and tin have recrystallization temperatures close to room temperature.

To eliminate the effects of strain hardening in cold-formed metals, the material can be annealed by heating it above recrystallization temperature to restore the ductility and reduce hardness.

**Table 4.1 Comparison of cold and hot metal forming processes**

<b>Sl. no</b>	<b>Property</b>	<b>Cold Forming</b>	<b>Hot Forming</b>
1	Surface quality	Performed at room temperature; avoids oxidation, scaling, and surface tarnishing. No material loss.	High temperatures cause oxidation, scale formation, and decarburization due to carbon reacting with oxygen.
2	Dimensional accuracy	Provides high dimensional accuracy and smooth, bright surface finish. These are often called bright bars.	Lower surface finish due to oxidation. Products appear blackish and are commonly referred to as black bars.
3	Mechanical properties	Causes strain hardening, increasing strength and hardness. Requires higher deformation force and energy.	Recovery and recrystallization prevent work hardening, enabling easier deformation with lower energy and equipment load.
4	Formability	Limited ductility at room temperature restricts the formation of complex shapes.	High ductility and malleability at elevated temperatures allow easy formation of intricate shapes.
5	Internal stresses	Generates residual internal stresses. Requires stress relief (e.g., annealing) to prevent service failure.	No residual stresses remain due to dynamic recovery and recrystallization. Results in uniform, stress-free structure.
6	Tool force	Higher material strength at room temperature demands greater forming loads and heavier equipment.	Reduced material strength at high temperature allows for lower forming forces and reduced tool wear.
7	Defects	Not applicable.	Blow holes and porosity can be closed by welding action. Inclusions are broken up and chemical segregation is reduced via diffusion.

### 4.3 Classification of metal forming

Primary metal forming processes involve plastic deformation of bulk metal materials like ingots, blooms, and billets to produce basic shapes and sizes. These processes represent the first stage in shaping metal and are commonly used in industrial manufacturing to prepare raw materials for further processing.

Metal forming operations can be classified (Fig 4.2) based on the type of mechanical stress predominantly applied during deformation:

#### 1. Compressive stress based forming:

In this process, deformation is achieved primarily through compressive forces reduce thickness or change the shape of the material.

- **Forging** – Metal is shaped by compressive force using a hammer or press.
- **Rolling** – Material is passed between rotating rolls to reduce its thickness.
- **Extrusion** – A billet is forced through a die to produce objects with uniform cross-sections.

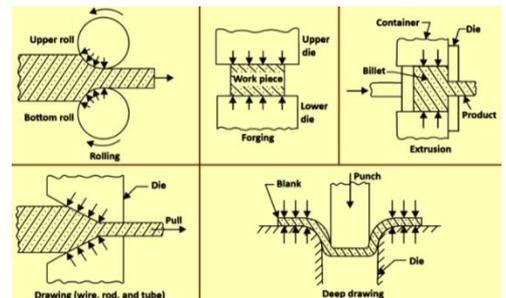
2. **Tensile stress based forming:** These processes use tensile forces to stretch the material, resulting in elongation and reduction in cross-sectional area.

- **Drawing** – The metal is pulled through a die to decrease diameter and increase length (e.g., wire drawing, tube drawing).

#### 3. Combined stresses in metal forming

Combined tensile and compressive stresses act simultaneously to achieve the desired shape. The method is used for forming thin sheets or intricate profiles.

- **Deep Drawing** – A sheet metal blank is drawn into a die cavity using a punch to form cup or box-shaped component.



**Figure 4.2** Classification of metal forming process

## Questions

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1. What is metal forming and how does it differ from machining?
2. Define plastic deformation in the context of metal forming.
3. Why are ductility and malleability important in metal forming processes?
4. What are the advantages of using metal forming over other manufacturing processes?
5. What are the primary metal forming processes?
6. Classify metal forming processes based on the type of stress applied.
7. Give two examples each for forming processes under:  
(a) Compressive stress, (b) Tensile stress, and (c) Combined stresses
8. Define hot working and cold working.
9. What is recrystallization temperature and why is it important?
10. Compare hot and cold working in terms of energy requirements and surface finish.
11. Explain how strain hardening occurs during cold working.
12. What are the typical hot working temperature ranges for steel, aluminum, and copper?
13. List three advantages of cold working processes.
14. What are the disadvantages of cold working with respect to internal stresses?
15. How does hot working help in eliminating internal porosity and inclusions?
16. Why are cold rolled steel bars referred to as "bright bars"?
17. Explain why hot forming requires lower capacity equipment.
18. What is forging and how is it classified?
19. Differentiate between open-die and closed-die forging.
20. What is the significance of grain flow in forged components?
21. Mention two applications of forged parts in industry.
22. Describe the rolling process and its purpose.
23. What is the difference between hot rolling and cold rolling?
24. Explain the term "neutral point" in rolling operations.
25. Define extrusion and mention its types.
26. What are the advantages of using extrusion in metal forming?
27. Differentiate between direct and indirect extrusion.
28. What is wire drawing and how does it work?
29. Explain the deep drawing process with a simple example.
30. What type of stress is predominant in drawing processes?
31. What is embossing in metal forming?
32. How is coining different from standard stamping processes?
33. Compare forging, rolling, and extrusion in terms of product strength and surface finish.
34. Which process would you recommend for producing hollow tubes and why?