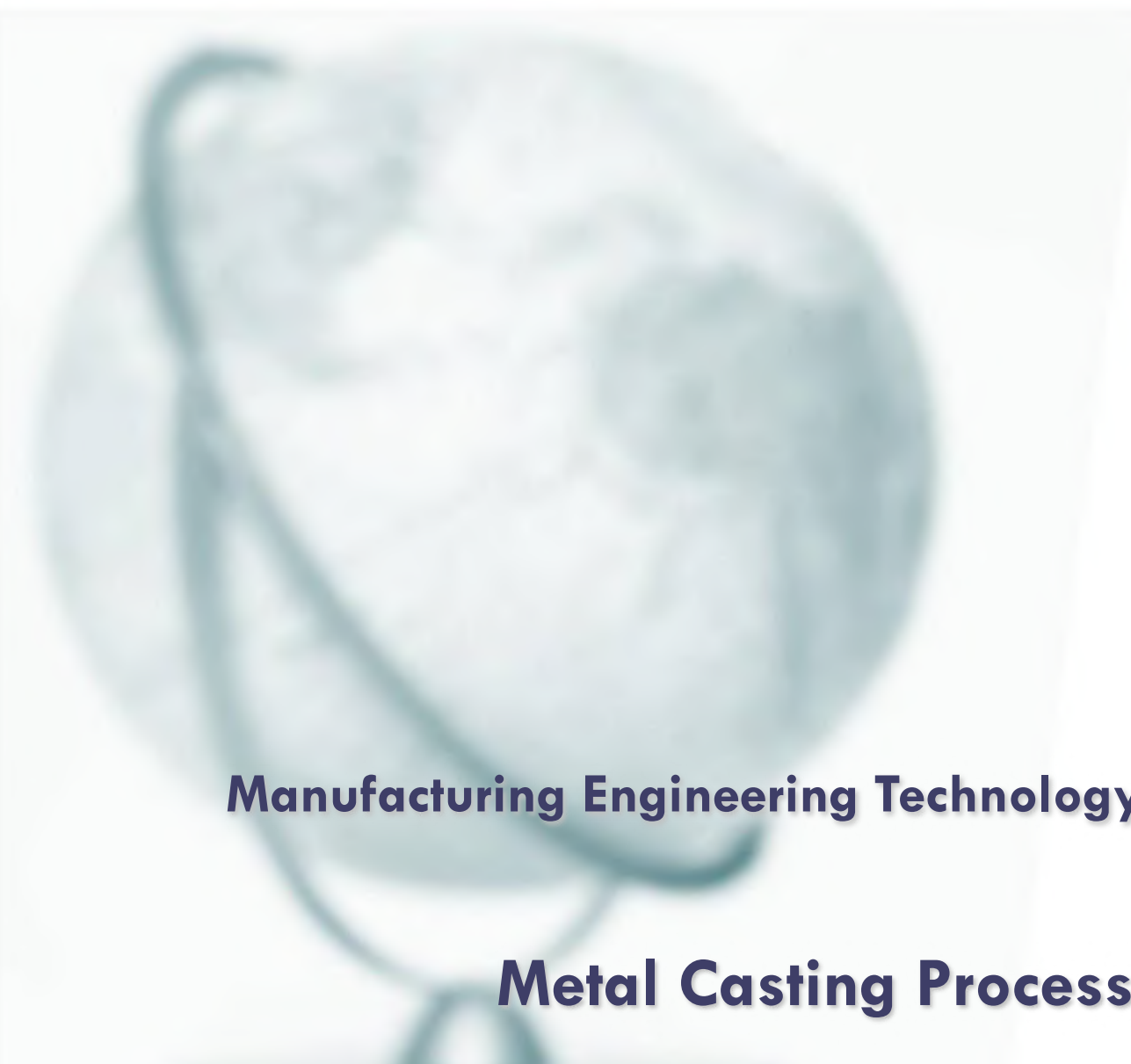




**Manufacturing Engineering Technology in SI Units, 6<sup>th</sup> Edition**

**Chapter 11:  
Metal Casting Processes and Equipment**

# Chapter Outline

- Introduction
- Expendable-mold, Permanent-pattern Casting Processes
- Expendable-mold, Expendable-pattern Casting Processes
- Permanent-mold Casting Processes
- Casting Techniques for Single-crystal Components
- Rapid Solidification
- Inspection of Castings
- Melting Practice and Furnaces
- Foundries and Foundry Automation

# Introduction

- Various casting processes developed over time to meet specific design requirements

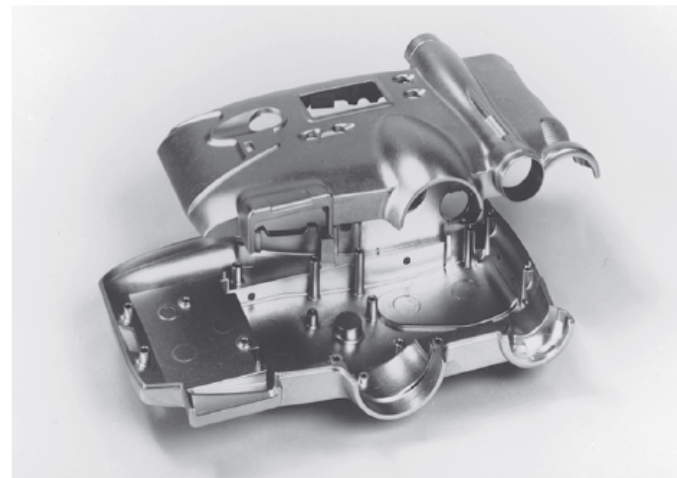
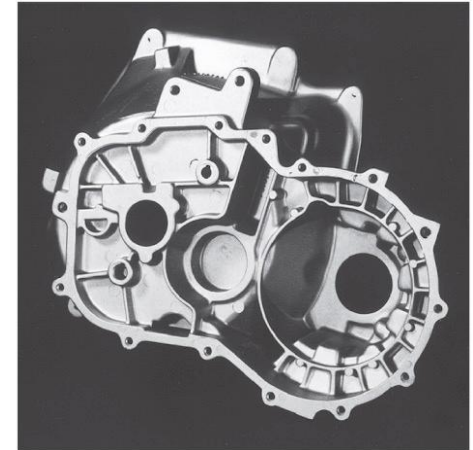
**Summary of Casting Processes**

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



# Introduction

- Molding categories:
  1. **Expendable molds**
  2. **Permanent molds**
  3. **Composite molds**



# Introduction

- General characteristics of sand casting and casting processes are summarized

| General Characteristics of Casting Processes              |                                       |        |                     |                              |            |                |                                |             |
|-----------------------------------------------------------|---------------------------------------|--------|---------------------|------------------------------|------------|----------------|--------------------------------|-------------|
|                                                           | Sand                                  | Shell  | Evaporative pattern | Plaster                      | Investment | Permanent mold | Die                            | Centrifugal |
| Typical materials cast                                    | All                                   | All    | All                 | Nonferrous<br>Al, Mg, Zn, Cu | All        | All            | Nonferrous<br>(Al, Mg, Zn, Cu) | All         |
| Weight (kg):                                              |                                       |        |                     |                              |            |                |                                |             |
| Minimum                                                   | 0.01                                  | 0.01   | 0.01                | 0.01                         | 0.001      | 0.1            | <0.01                          | 0.01        |
| Maximum                                                   | No limit                              | 100+   | 100+                | 50+                          | 100+       | 300            | 50                             | 5000+       |
| Typical surface finish ( $R_a$ in $\mu\text{m}$ )         | 5–25                                  | 1–3    | 5–25                | 1–2                          | 0.3–2      | 2–6            | 1–2                            | 2–10        |
| Porosity <sup>1</sup>                                     | 3–5                                   | 4–5    | 3–5                 | 4–5                          | 5          | 2–3            | 1–3                            | 1–2         |
| Shape complexity <sup>1</sup>                             | 1–2                                   | 2–3    | 1–2                 | 1–2                          | 1          | 2–3            | 3–4                            | 3–4         |
| Dimensional accuracy <sup>1</sup>                         | 3                                     | 2      | 3                   | 2                            | 1          | 1              | 1                              | 3           |
| Section thickness (mm):                                   |                                       |        |                     |                              |            |                |                                |             |
| Minimum                                                   | 3                                     | 2      | 2                   | 1                            | 1          | 2              | 0.5                            | 2           |
| Maximum                                                   | No limit                              | —      | —                   | —                            | 75         | 50             | 12                             | 100         |
| Typical dimensional tolerance (mm)                        | 1.6–4 mm<br>(0.25 mm for small parts) | ±0.003 |                     | +0.005 – 0.010               | +0.005     | ±0.015         | ±0.001 – 0.005                 | 0.015       |
| Equipment                                                 | 3–5                                   | 3      | 2–3                 | 3–5                          | 3–5        | 2              | 1                              | 1           |
| Pattern/die                                               | 3–5                                   | 2–3    | 2–3                 | 3–5                          | 2–3        | 2              | 1                              | 1           |
| Labor                                                     | 1–3                                   | 3      | 3                   | 1–2                          | 1–2        | 3              | 5                              | 5           |
| Typical lead time <sup>2</sup>                            | Days                                  | Weeks  | Weeks               | Days                         | Weeks      | Weeks          | Weeks to months                | Months      |
| Typical production rate <sup>2</sup><br>(parts/mold-hour) | 1–20                                  | 5–50   | 1–20                | 1–10                         | 1–1000     | 5–50           | 2–200                          | 1–1000      |
| Minimum quantity <sup>2</sup>                             | 1                                     | 100    | 500                 | 10                           | 10         | 1000           | 10,000                         | 10–10,000   |

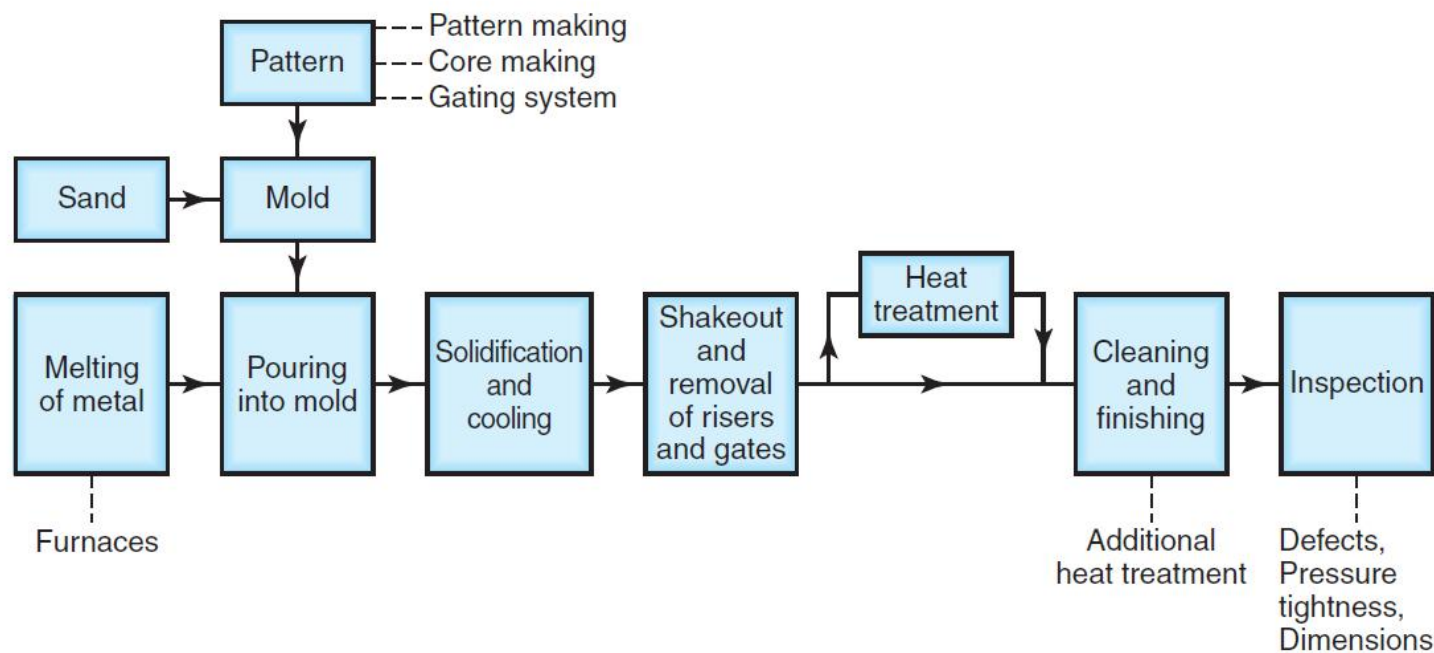
Notes: 1. Relative rating, from 1 (best) to 5 (worst). For example, die casting has relatively low porosity, mid to low shape complexity, high dimensional accuracy, high equipment and die costs, and low labor costs. These ratings are only general; significant variations can occur, depending on the manufacturing methods used.

2. Approximate values without the use of rapid prototyping technologies. Minimum quantity is 1 when applying rapid prototyping.

Source: Data taken from J.A. Schey, *Introduction to Manufacturing Processes*, 3d ed., McGraw-Hill, 2000.

# Expendable-mold, Permanent-pattern Casting Processes: Sand Casting

- Most prevalent form of casting
- Application for machine bases, large turbine impellers, propellers, plumbing fixtures



# Expendable-mold, Permanent-pattern Casting Processes: Sand Casting

## Sand

- Sand-casting operations use silica sand as the mold material
- Sand is inexpensive and suitable high melting point process
- 2 types of sand: **naturally bonded** (*bank sand*) and **synthetic** (*lake sand*)
- Fine grained sand enhances mold strength and lower mold *permeability*

# Expendable-mold, Permanent-pattern Casting Processes: Sand Casting

## Types of Sand Molds

3 basic types:

1. **Green-sand mold**

Sand in the mold is moist or damp while the metal is being poured into it

2. **Cold-box mold**

Organic and inorganic *binders* are blended into the sand to bond the grains chemically

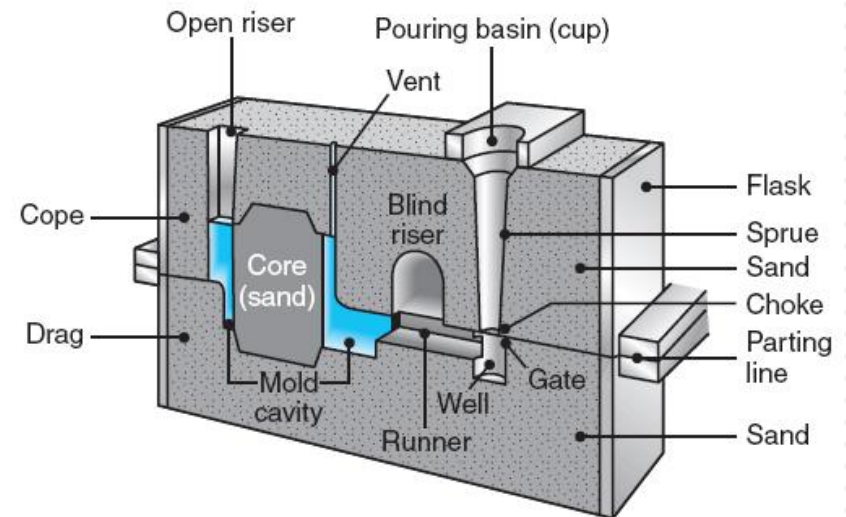
3. **No-bake mold**

Synthetic liquid resin is mixed with the sand and allow to hardens at room temperature

# Expendable-mold, Permanent-pattern Casting Processes: Sand Casting

## Major features of molds in sand casting

- ❑ **Flask**
- ❑ **Cope** on top and a **drag** on the bottom
- ❑ **Pouring basin / Pouring cup**
- ❑ **Sprue**
- ❑ **Runner system, gates**
- ❑ **Risers**
- ❑ **Cores**
- ❑ **Vents**



# Expendable-mold, Permanent-pattern Casting Processes: Sand Casting

## Pattern

- *Patterns* are used to mold the sand mixture into the shape of the casting
- Selection of a pattern material depends on the
  1. Size and shape of the casting
  2. Dimensional accuracy
  3. Quantity of castings required
  4. Molding process

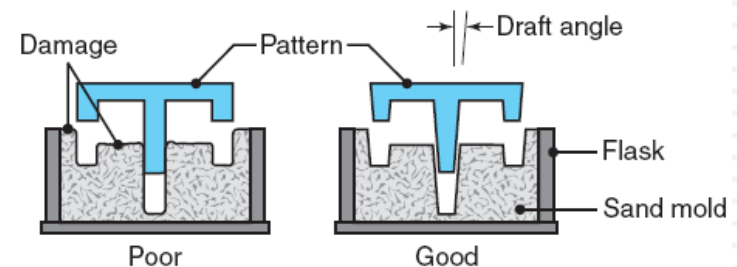
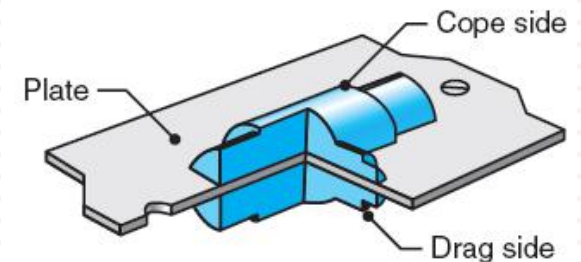
# Expendable-mold, Permanent-pattern Casting Processes: Sand Casting

## Pattern

### □ Match-plate patterns

2 patterns are constructed by securing each half of one or more split patterns to the opposite sides of a single plate

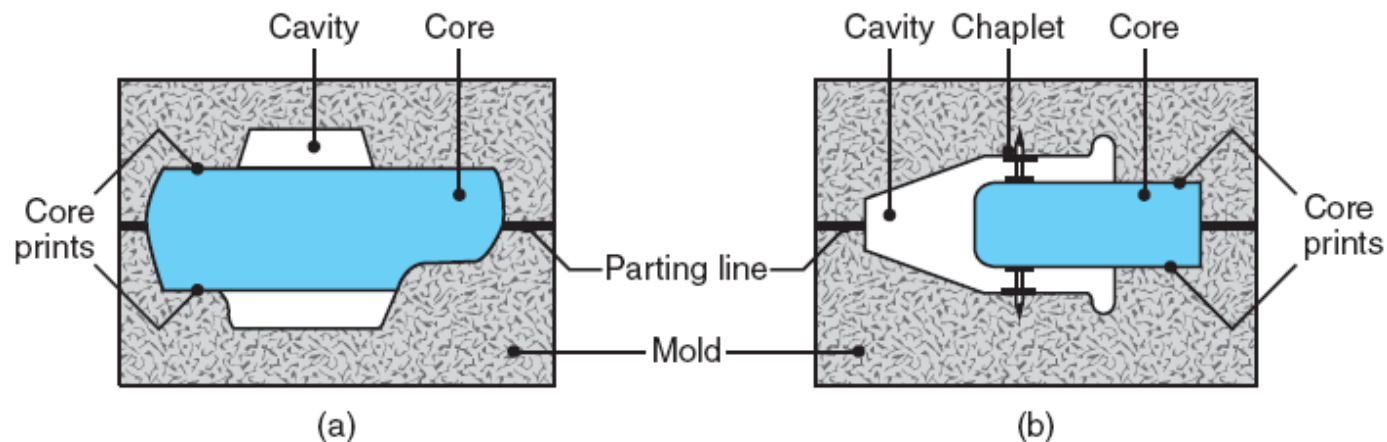
- Pattern design should provide for **metal shrinkage** to allow the pattern to be easily removed



# Expendable-mold, Permanent-pattern Casting Processes: Sand Casting

# Cores

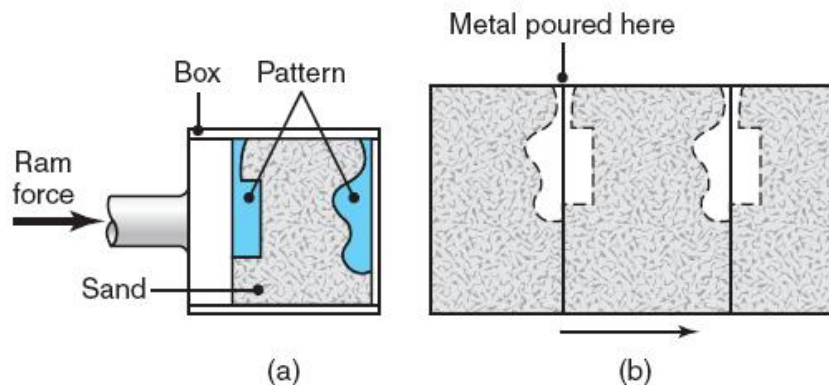
- Cores are placed in the mold cavity to form the interior surfaces of the casting
- It is removed from the finished part during shakeout and further processing



# Expendable-mold, Permanent-pattern Casting Processes: Sand Casting

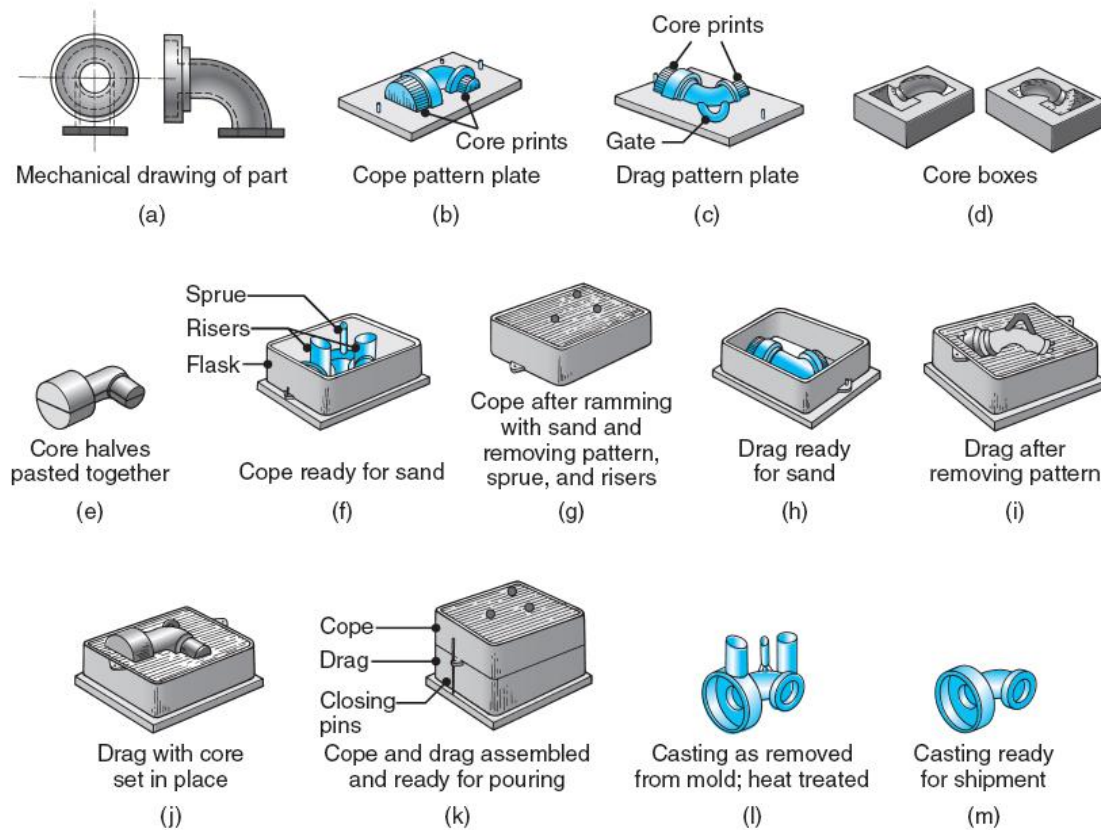
## Sand-molding Machines

- In **vertical flaskless molding**, the halves of the pattern form a vertical chamber wall against which sand is blown and compacted



# Expendable-mold, Permanent-pattern Casting Processes: Sand Casting

## The Sand-casting Operation



# Expendable-mold, Permanent-pattern Casting Processes: Sand Casting

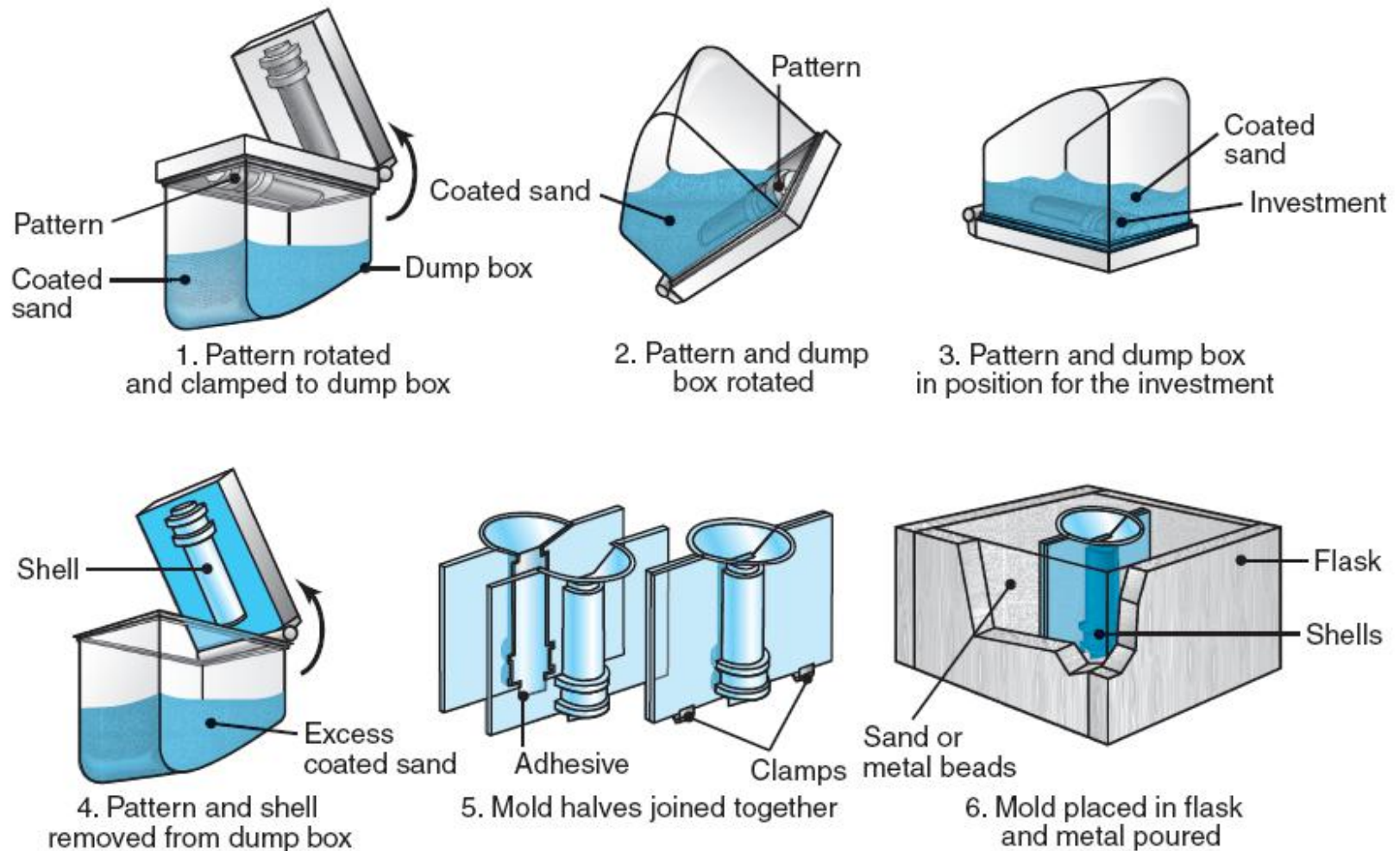
## The Sand-casting Operation

- *Finishing operations* may involve machining, straightening, or forging with dies (sizing) to obtain final dimensions
- *Inspection* is carried out to ensure that the casting meets all design and quality-control requirements

# Expendable-mold, Permanent-pattern Casting Processes: Shell Molding

- *Shell molding* can produce many types of castings with close dimensional tolerances and a good surface finish at low cost
- Applications include small mechanical parts requiring high precision such as gear housings
- Shell sand has lower permeability than sand used for green-sand molding
- Complex shapes can be produced with less labor since it can be automated easily

# Expendable-mold, Permanent-pattern Casting Processes: Shell Molding



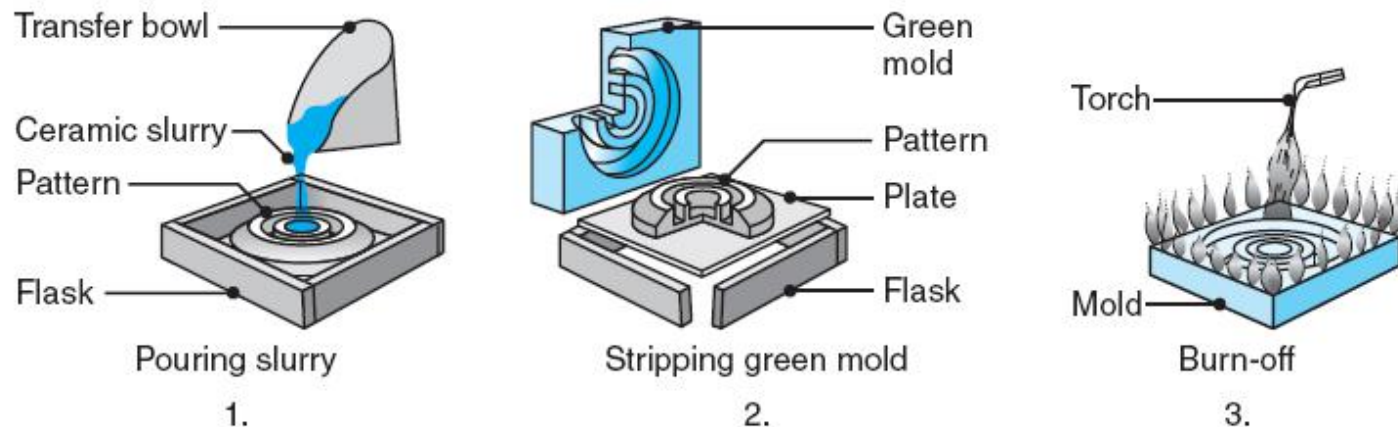
# Expendable-mold, Permanent-pattern Casting Processes:

## Plaster-mold Casting

- **Precision casting** produce high dimensional accuracy and good surface finish products
- Typical parts made are lock components, gears, valves, fittings, tooling, and ornaments
- In *plaster-molding* process, the mold is made of plaster of paris with the addition of talc and silica flour to improve strength

# Expendable-mold, Permanent-pattern Casting Processes: Ceramic-mold Casting

- *Ceramic-mold casting* process is similar to the plaster-mold process but uses refractory mold materials suitable for high-temperature applications



# Expendable-mold, Expendable-pattern Casting Processes: Evaporative-pattern Casting (Lost-foam Process)

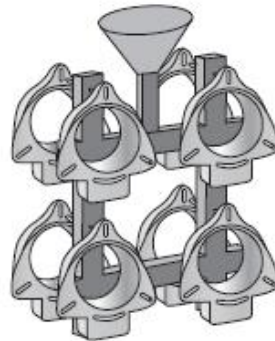
- *Evaporative-pattern casting* process uses a polystyrene pattern, which evaporates upon contact with molten metal to form a cavity for the casting
- Used for ferrous and nonferrous metals which is applicable to automotive industry
- The advantages are:
  1. Simple
  2. Inexpensive flasks and polystyrene
  3. Minimal finishing and cleaning operations
  4. Process can be automated



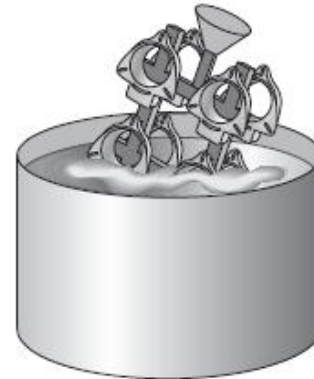
# Expendable-mold, Expendable-pattern Casting Processes: Evaporative-pattern Casting (Lost-foam Process)



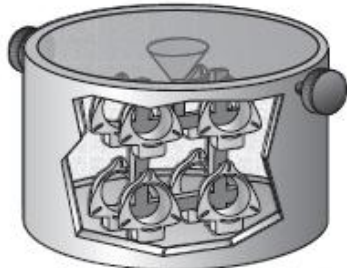
1. Pattern molding



2. Cluster assembly



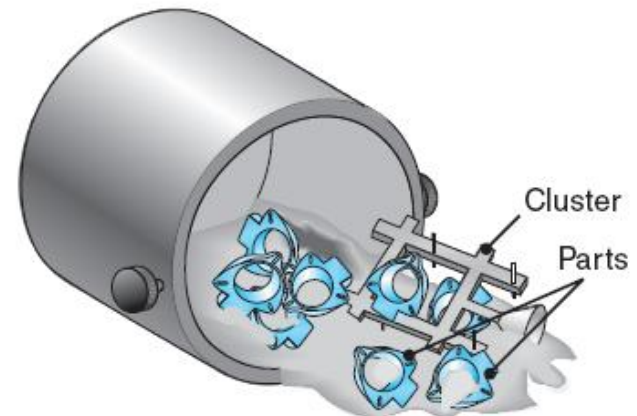
3. Coating



4. Compacted in sand



5. Casting



6. Shakeout

# Expendable-mold, Expendable-pattern Casting Processes: Evaporative-pattern Casting (Lost-foam Process)

## CASE STUDY 11.1

### Lost-foam Casting of Engine Blocks

- a) Metal is poured into a mold for lost-foam casting of a 60-hp, three-cylinder marine engine
- b) Finished engine block



(a)

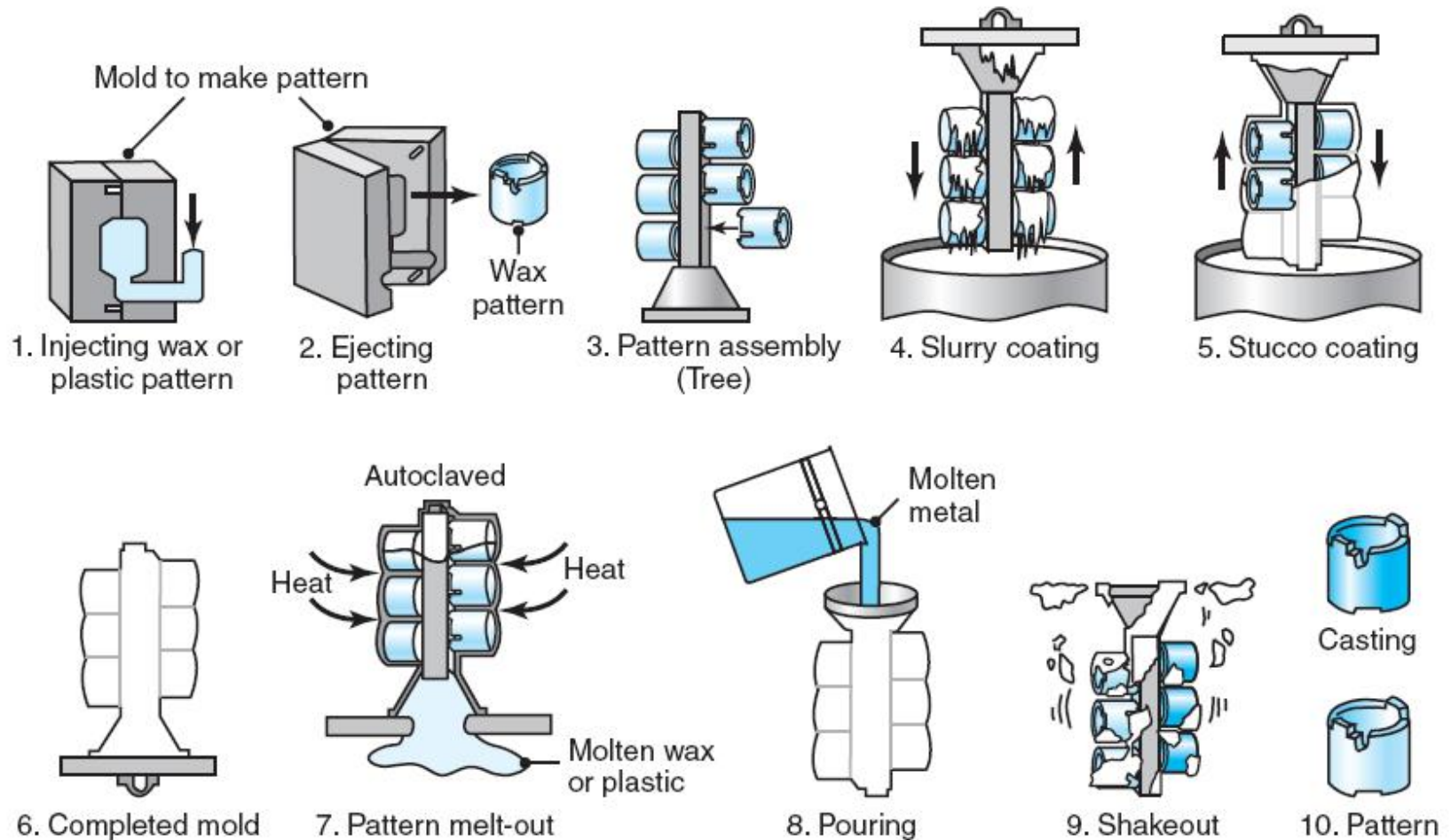


(b)

# Expendable-mold, Expendable-pattern Casting Processes: Investment Casting

- Also called **lost-wax process**
- Used to make office equipment, and mechanical components such as gears
- Pattern is invested (surrounded) with the refractory material
- Mold is heated up to drive off the water of crystallization and to burn off any residual wax
- Process is capable of producing intricate shapes from ferrous and nonferrous metals and alloys

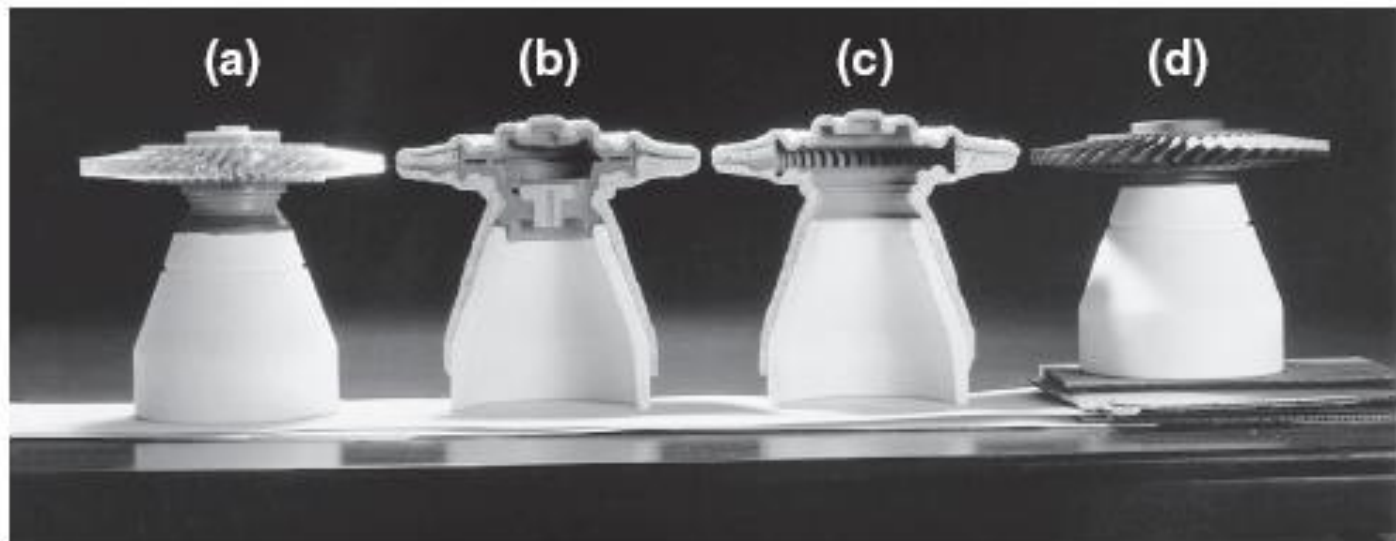
# Expendable-mold, Expendable-pattern Casting Processes: Investment Casting



# Expendable-mold, Expendable-pattern Casting Processes: Investment Casting

## Ceramic-shell Investment Casting

- Process is economical and is used for the precision casting of steels and high-temperature alloys

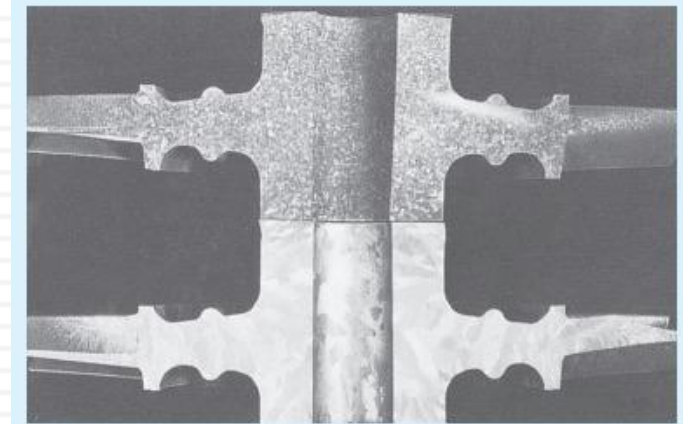


# Expendable-mold, Expendable-pattern Casting Processes: Investment Casting

## EXAMPLE 11.1

### Investment-cast Superalloy Components for Gas Turbines

- Figure shows a cross section and microstructure of two rotors:
  1. (Top) Investment cast
  2. (Bottom) Conventionally cast

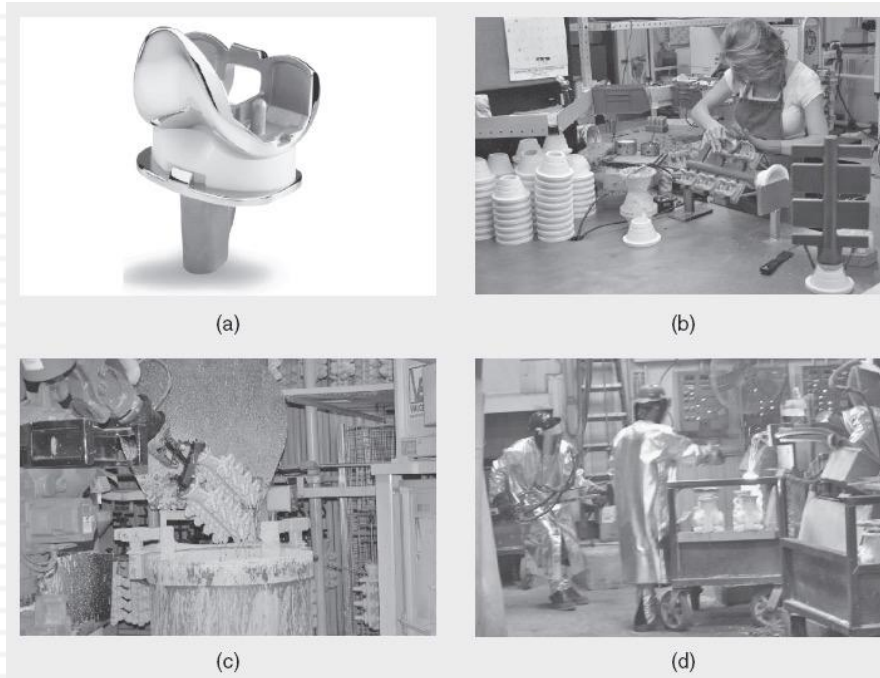


# Expendable-mold, Expendable-pattern Casting Processes: Investment Casting

## CASE STUDY 11.2

### Investment Casting of Total Knee Replacements

- Manufacture of total knee replacements

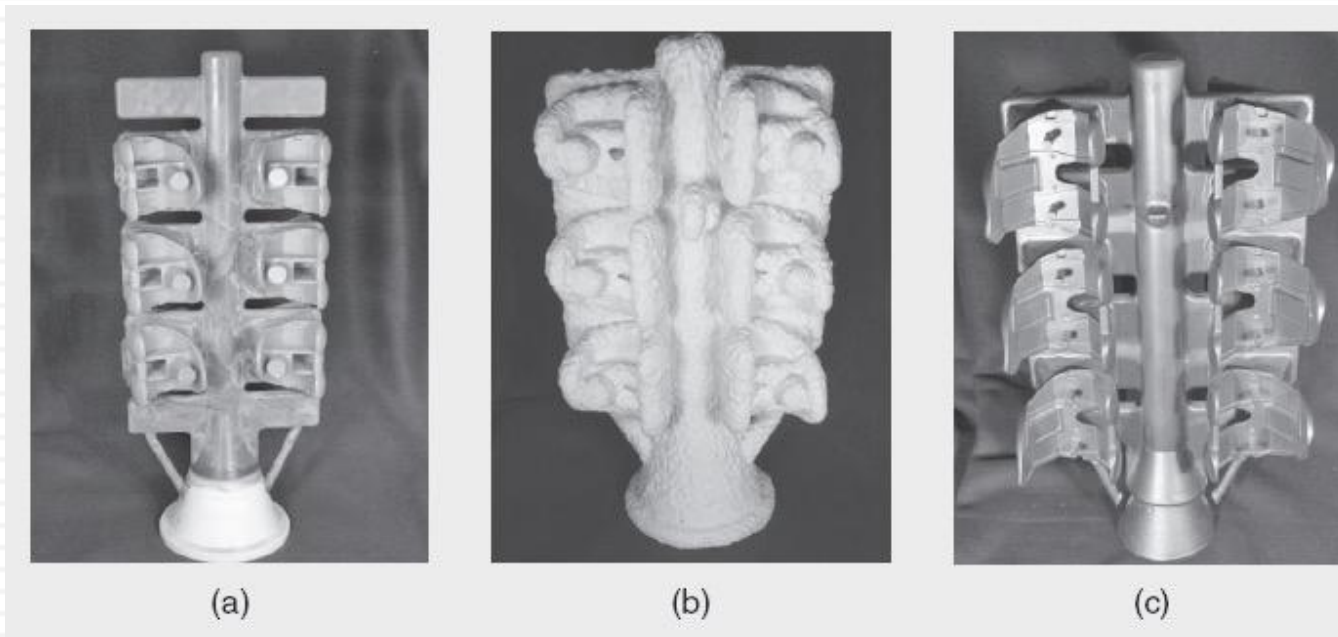


# Expendable-mold, Expendable-pattern Casting Processes: Investment Casting

## CASE STUDY 11.2

### Investment Casting of Total Knee Replacements

- Progression of the tree



# Permanent-mold Casting Processes:

## Permanent-mold Casting

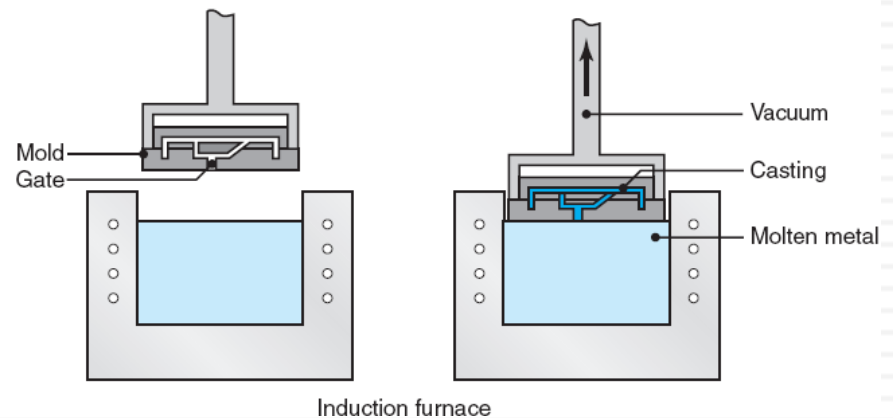
- 2 halves of a mold are made from materials with high resistance to erosion and thermal fatigue
- In order to increase the life of permanent molds, the surfaces of the mold cavity are coated with a refractory slurry or sprayed with graphite
- Equipment costs is high but labor costs are kept low through automation
- Not economical for small production runs



# Permanent-mold Casting Processes:

## Vacuum Casting

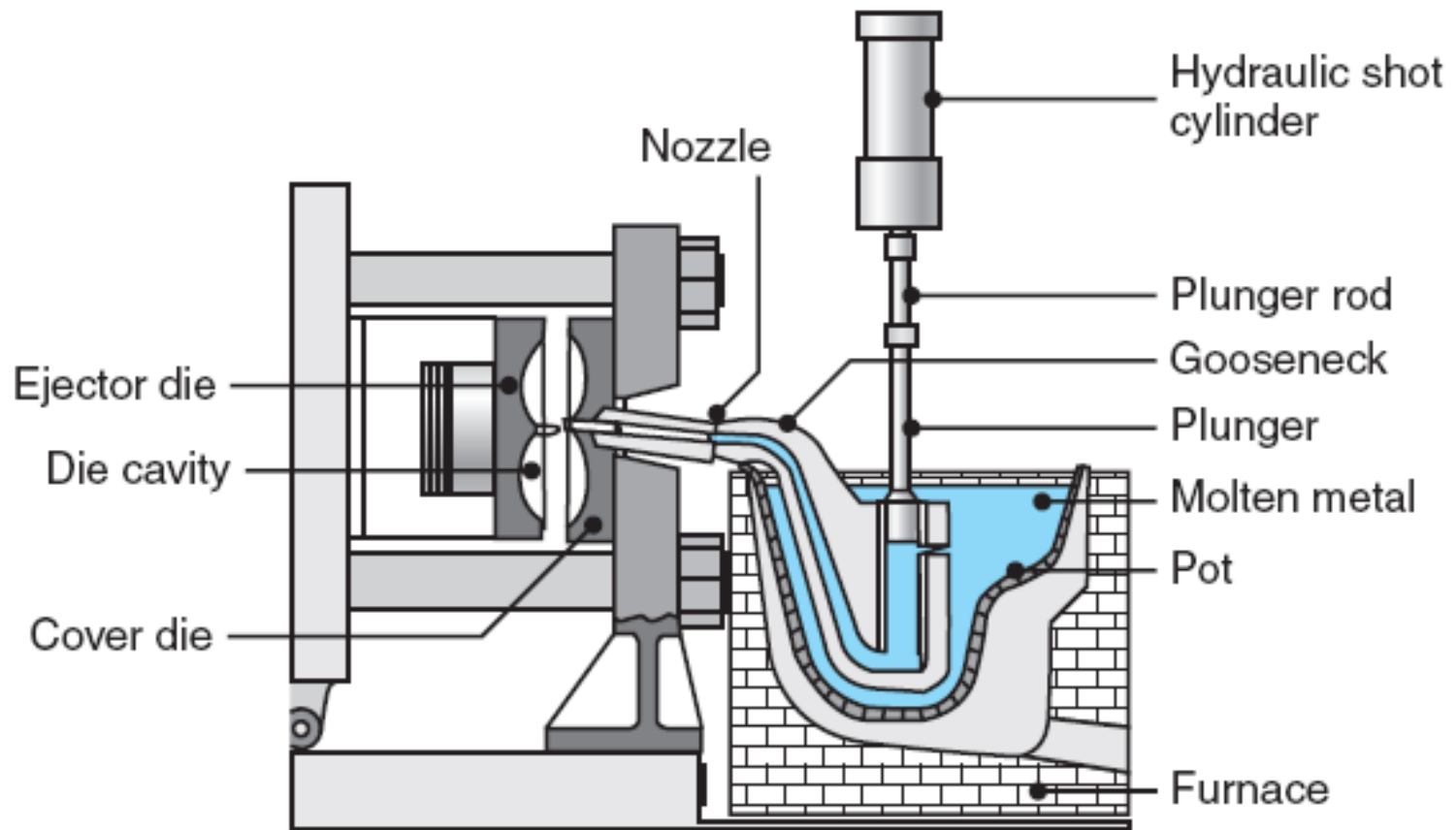
- Vacuum casting is an alternative to other casting and is suitable for thin-walled complex shapes with uniform properties
- A mixture of fine sand and urethane is molded over metal dies and cured with amine vapor
- Automated and production costs are similar green-sand casting



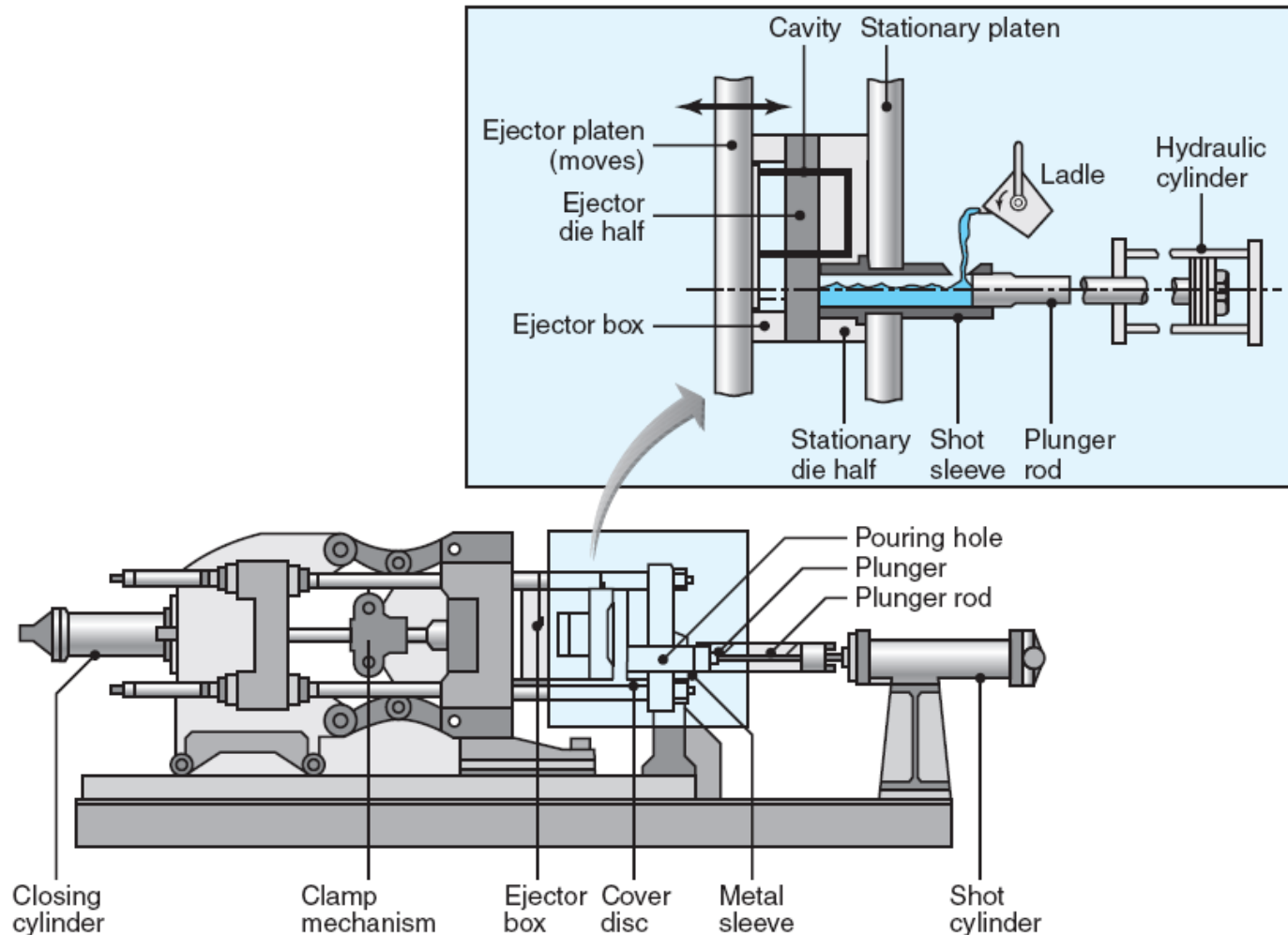
# Permanent-mold Casting Processes: Die Casting

- *Die-casting* process is a further example of permanent-mold casting
- 2 basic types of die-casting machines:
  1. **Hot-chamber process** use a piston to forces a certain volume of metal into the die cavity through a gooseneck and nozzle
  2. **Cold-chamber process** is where molten metal is poured into the injection cylinder (*shot chamber*)

# Permanent-mold Casting Processes: Die Casting (*Hot Chamber*)



# Permanent-mold Casting Processes: Die Casting (Cold Chamber)



# Permanent-mold Casting Processes: Die Casting

## Process Capabilities and Machine Selection

- Die casting is able to produce strong and high-quality parts with complex shapes
- Also produces good dimensional accuracy and surface details
- Strength-to-weight ratio of die-cast parts increases with decreasing wall thickness

# Permanent-mold Casting Processes: Die Casting

## Process Capabilities and Machine Selection

Properties and Typical Applications of Some Common Die-casting Alloys

| Alloy                          | Ultimate tensile strength (MPa) | Yield strength (MPa) | Elongation in 50 mm (%) | Applications                                                                      |
|--------------------------------|---------------------------------|----------------------|-------------------------|-----------------------------------------------------------------------------------|
| Aluminum 380 (3.5 Cu–8.5 Si)   | 320                             | 160                  | 2.5                     | Appliances, automotive components, electrical motor frames and housings           |
| 13 (12 Si)                     | 300                             | 150                  | 2.5                     | Complex shapes with thin walls, parts requiring strength at elevated temperatures |
| Brass 858 (60 Cu)              | 380                             | 200                  | 15                      | Plumbing fixtures, lock hardware, bushings, ornamental castings                   |
| Magnesium AZ91 B (9 Al–0.7 Zn) | 230                             | 160                  | 3                       | Power tools, automotive parts, sporting goods                                     |
| Zinc No. 3 (4 Al)              | 280                             | —                    | 10                      | Automotive parts, office equipment, household utensils, building hardware, toys   |
| No. 5 (4 Al–1 Cu)              | 320                             | —                    | 7                       | Appliances, automotive parts, building hardware, business equipment               |

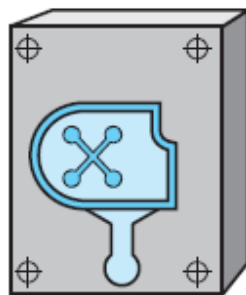
Source: American Die Casting Institute.

# Permanent-mold Casting Processes: Die Casting

## Process Capabilities and Machine Selection

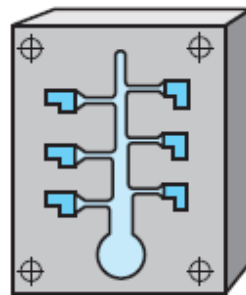
□ Die-casting dies can be

1. *Single cavity*
2. *Multiple cavity* (several identical cavities)
3. *Combination cavity* (several different cavities)
4. *Unit dies*



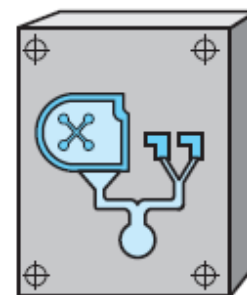
Single-cavity die

(a)



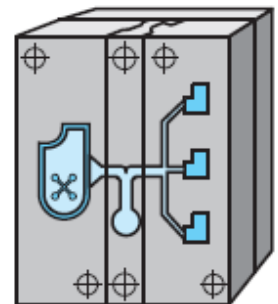
Multiple-cavity die

(b)



Combination die

(c)



Unit die

(d)

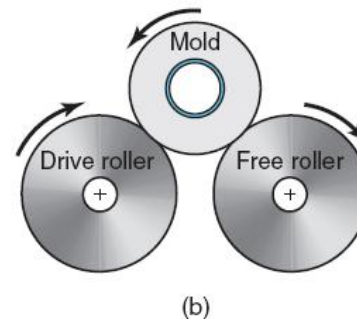
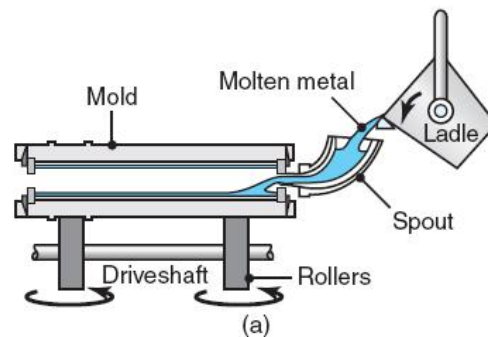
# Permanent-mold Casting Processes:

## Centrifugal Casting

- *Centrifugal-casting* process utilizes inertial forces to distribute the molten metal into the mold cavities

### True Centrifugal Casting

- Cylindrical parts (such as pipes, gun barrels) are produced by the technique

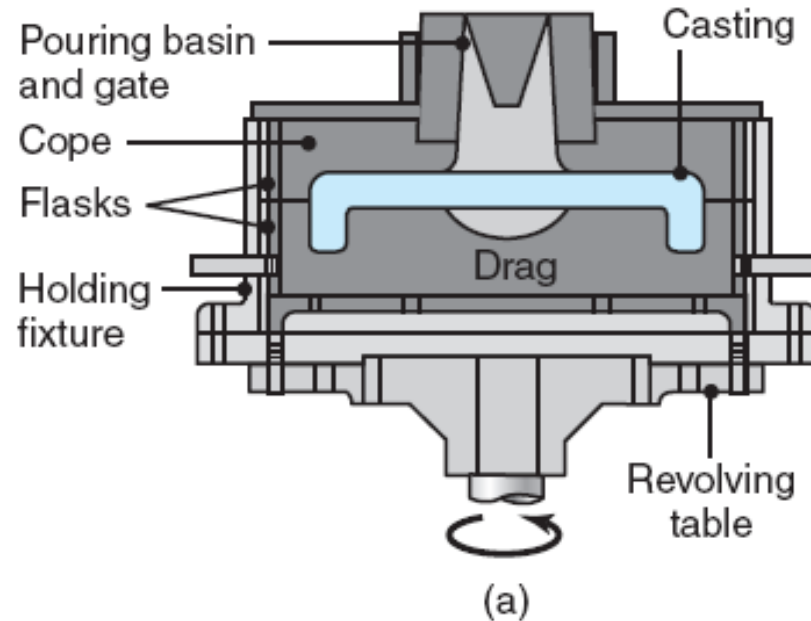


# Permanent-mold Casting Processes:

## Centrifugal Casting

### Semicentrifugal Casting

- Used to cast parts with rotational symmetry, such as a wheel with spokes.

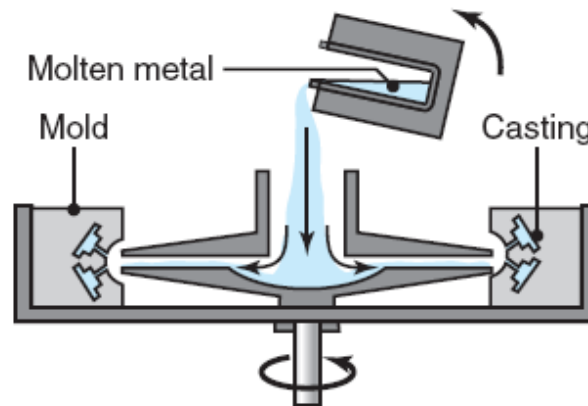


# Permanent-mold Casting Processes:

## Centrifugal Casting

### Centrifuging

- Mold cavities of any shape are placed at a certain distance from the axis of rotation
- Properties of the castings can vary by distance from the axis of rotation, as in true centrifugal casting

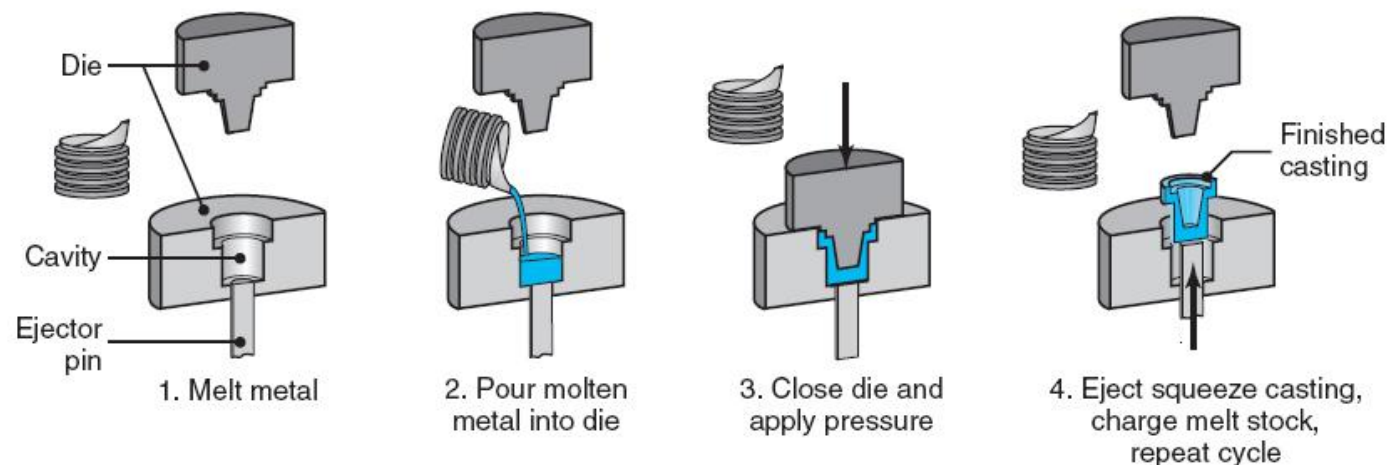


# Permanent-mold Casting Processes:

## Squeeze Casting and Semisolid-metal Forming

### Squeeze Casting

- Involves the solidification of molten metal under high pressure
- Products made are automotive components and mortar bodies



# Permanent-mold Casting Processes: Composite-mold Casting Operations

- *Composite molds* are made of two or more different materials
- Used for casting complex shapes such as impellers for turbines
- Composite molds
  1. Increase the strength of the mold
  2. Improve the dimensional accuracy and surface finish
  3. Help reduce overall costs and processing time

# Casting Techniques for Single-crystal Components

## Conventional Casting of Turbine Blades

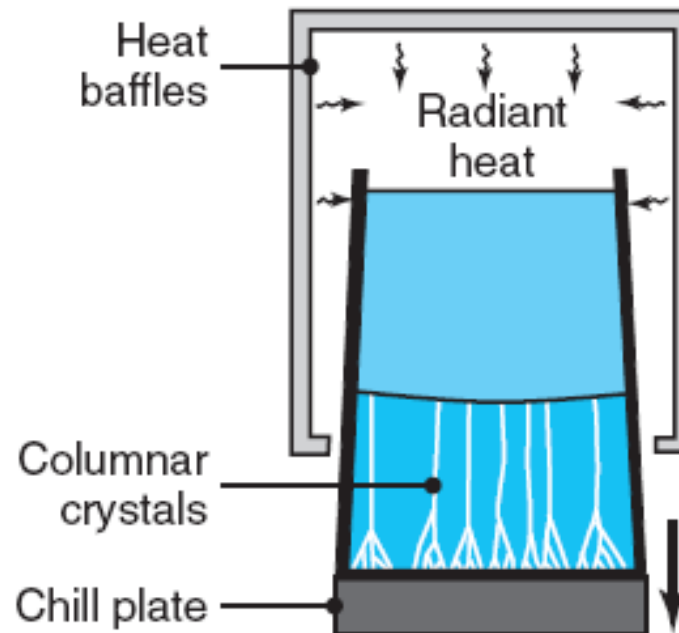
- ❑ Uses a ceramic mold
- ❑ Molten metal is poured into the mold and solidify at the ceramic walls
- ❑ Grain structure developed is polycrystalline
- ❑ Grain boundaries cause structure to creep and cracking along the boundaries



# Casting Techniques for Single-crystal Components

## Directionally Solidified Blades

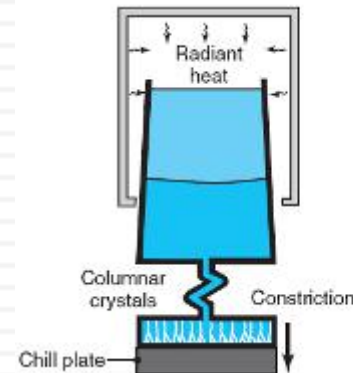
- ❑ Ceramic mold is preheated by radiant heating
- ❑ Metal is poured into the mold and allow crystals to grow



# Casting Techniques for Single-crystal Components

## Single-crystal Blades

- The mold has a constriction in the shape of a corkscrew or helix
- Only the most favourably oriented crystals are able to grow through the helix
- Blades are more expensive, lack of grain boundaries has resistant to creep and thermal shock
- Longer and more reliable service life



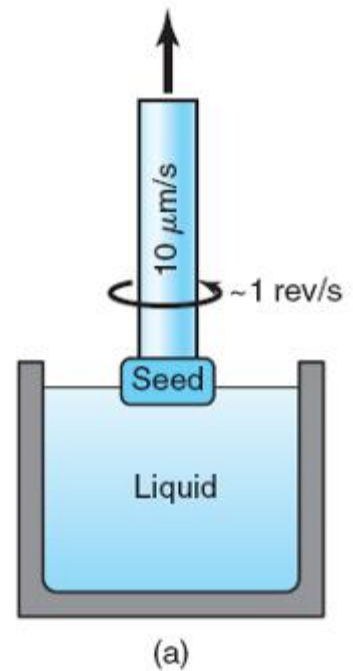
# Casting Techniques for Single-crystal Components

## Single-crystal Growing

□ 2 basic methods of crystal growing:

1. **Czochralski (CZ) process**

- a seed crystal is dipped into the molten metal and then pulled out slowly while being rotated
- liquid metal solidify on the seed and crystal structure of the seed is continued throughout

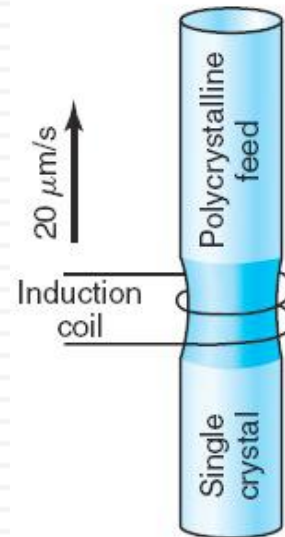


# Casting Techniques for Single-crystal Components

## Single-crystal Growing

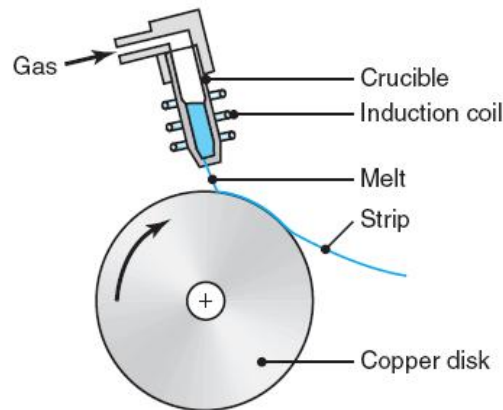
### 2. Floating-zone method

- a rod of polycrystalline silicon resting on a single crystal
- induction coil heats these two pieces while the coil moves slowly upward
- single crystal grows upward while maintaining its orientation



# Rapid Solidification

- Technique for making *amorphous alloys* involves cooling the molten metal at high rates
- Thus does not have sufficient time to crystallize
- For **melt spinning**, the alloy is melted by induction in a ceramic crucible and propelled under high gas pressure against a rotating copper disk



# Inspection of Castings

- ❑ Control of all casting stages is essential to maintaining good quality
- ❑ Castings can be inspected *visually* or *optically* for surface defects
- ❑ In *destructive* testing, specimens are determined for the presence, location, and distribution of porosity and defects
- ❑ *Pressure tightness* of cast components is determined by sealing the openings in the casting and pressurizing it with water, oil, or air



# Melting Practice and Furnaces

- ❑ Melting practice has a direct bearing on the quality of castings
- ❑ Fluxes are inorganic compounds that refine the molten metal by removing dissolved gases and various impurities
- ❑ Added manually or injected automatically into the molten metal

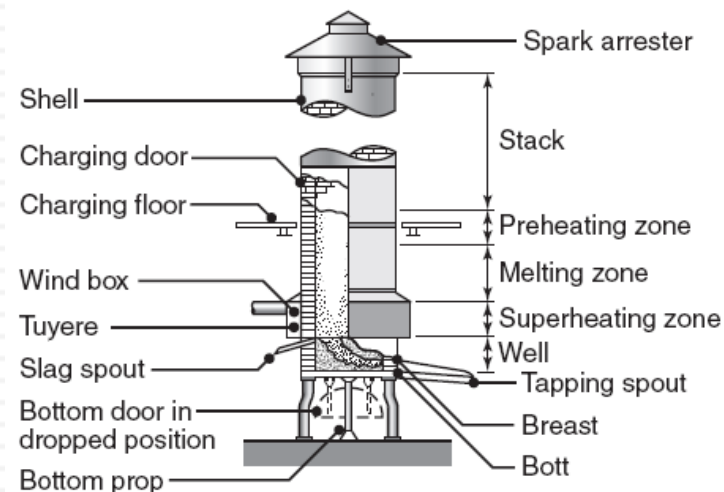
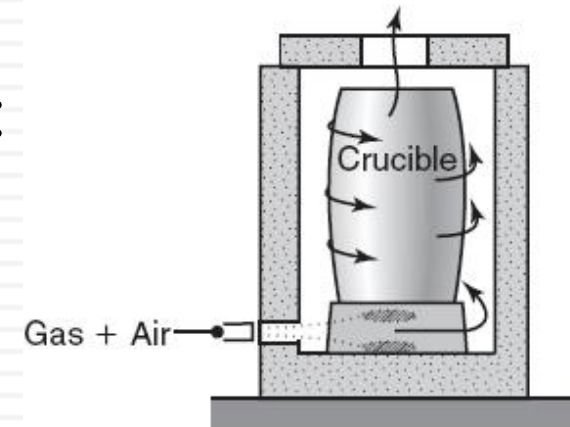


# Melting Practice and Furnaces

## Melting Furnaces

□ Commonly used melting furnaces:

1. **Electric-arc furnaces**
2. **Induction furnaces**
3. **Crucible furnaces**
4. **Cupolas**
5. **Levitation melting**



# Foundries and Foundry Automation

- ❑ Casting operations usually are carried out in foundries
- ❑ Modern foundries have automated and computer-integrated facilities for all aspects of their operations
- ❑ Automation minimizes labor, reduces the possibility of human error, increases the production rate and attains higher quality level

