Chapter 11

11.1 Introduction

Various casting processes have been developed over the time, each with its own characteristics and applications to meet specific engineering and service requirements. (Table 11.1).

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

A large variety of parts and components are made by casting, such as engine blocks, crankshafts, automotive components and power-trains (Fig. 11.1), agricultural and railroad equipment, pipes and plumbing fixtures, power tools, gun barrels, frying pans, office equipment, and very large components for hydraulic turbines.

Figure 11.1 (a) Typical gray-iron castings used in automobiles, including the transmission valve body (left) and the hub rotor with disk-brake cylinder (front). (b) A cast transmission housing. (c) The Polaroid PDC-2000 digital camera with a AZ191D die-cast high-purity magnesium case. (d) A two-piece Polaroid camera case made by the hot-chamber die-casting process.
The major categories of casting processes are as follows:

1. **Expendable molds**
   - Typically made of sand, plaster, ceramics, and similar materials. Generally mixed with various binders, or bonding agents.
   - A typical sand mold consists of 90% sand, 7% clay, and 3% water.
   - These materials are refractory (withstand high temperature of molten metal).
   - After the casting has solidified, the mold in these processes is broken up to remove the casting.

2. **Permanent molds,**
   - Made of metals that maintain their strength at high temperatures.
   - They are used repeatedly. Designed so casting can be removed easily and mold can be used again.
   - Better heat conductor than expandable nonmetallic molds; hence, solidifying casting is subjected to a higher rate of cooling, which affects the microstructure and the grain size.

3. **Composite molds**
   - Made of two or more different materials (such as sand, graphite, and metal) combining the advantages of each material.
   - Molds have a permanent and an expendable portion and are used in various casting processes to improve mold strength, control the cooling rates, and optimize the overall economics of the process.

The general characteristics of sand casting and other casting processes are given in Table 11.2 (see next page).

- Almost all commercially used metals can be cast.
- The surface finish obtained is largely a function of mold material.
- Sand castings generally have rough, grainy surface.
- Dimensional tolerances generally are not as good as those in machining and other net-shape processes.
- However, **intricate** shapes can be made by casting, such as cast-iron engine blocks and very large propellers for ocean liners.
### TABLE 11.2

**General Characteristics of Casting Processes**

<table>
<thead>
<tr>
<th></th>
<th>Sand</th>
<th>Shell</th>
<th>Evaporative pattern</th>
<th>Plaster</th>
<th>Investment</th>
<th>Permanent mold</th>
<th>Die</th>
<th>Centrifugal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical materials cast</td>
<td>All</td>
<td>All</td>
<td>All</td>
<td>Nonferrous (Al, Mg, Zn, Cu)</td>
<td>All</td>
<td>All</td>
<td>Nonferrous (Al, Mg, Zn, Cu)</td>
<td>All</td>
</tr>
<tr>
<td>Weight (kg):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>minimum</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.01</td>
<td>0.001</td>
<td>0.1</td>
<td></td>
<td>6.001</td>
</tr>
<tr>
<td>maximum</td>
<td>No limit</td>
<td>100+</td>
<td>100+</td>
<td>50+</td>
<td>100+</td>
<td>300</td>
<td></td>
<td>50</td>
</tr>
<tr>
<td>Typ. surface finish (Rv in μm)</td>
<td>5-25</td>
<td>1-3</td>
<td>5-25</td>
<td>1-2</td>
<td>0.3-2</td>
<td>2-6</td>
<td></td>
<td>1-2</td>
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<tr>
<td>Porosity¹</td>
<td>3-5</td>
<td>4-5</td>
<td>3-5</td>
<td>4-5</td>
<td>5</td>
<td>2-3</td>
<td></td>
<td>1-3</td>
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<tr>
<td>Shape complexity¹</td>
<td>1-2</td>
<td>2-3</td>
<td>1-2</td>
<td>1-2</td>
<td>1</td>
<td>2-3</td>
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<td>3-4</td>
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<tr>
<td>Dimensional accuracy¹</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td></td>
<td>1</td>
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<tr>
<td>Section thickness (mm):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td></td>
<td>0.5</td>
</tr>
<tr>
<td>Maximum</td>
<td>No limit</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>75</td>
<td>50</td>
<td></td>
<td>12</td>
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<tr>
<td>Typ. dimensional tolerance (mm/mm)</td>
<td>1.6-4 mm</td>
<td>±0.003</td>
<td>±0.005-0.010</td>
<td>±0.005</td>
<td>±0.015</td>
<td>±0.001-0.005</td>
<td></td>
<td>0.015</td>
</tr>
<tr>
<td>Cost¹² (for small parts)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Equipment</td>
<td>3-5</td>
<td>3</td>
<td>2-3</td>
<td>3-5</td>
<td>3-5</td>
<td>2</td>
<td></td>
<td>1</td>
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<tr>
<td>Patternmaking</td>
<td>3-5</td>
<td>2-3</td>
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<td>3-5</td>
<td>2-3</td>
<td>2</td>
<td></td>
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</tr>
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<td>Labor</td>
<td>1-3</td>
<td>3</td>
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<td>1-2</td>
<td>1-2</td>
<td>3</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>Typical lead time²</td>
<td>Days</td>
<td>Weeks</td>
<td>Weeks</td>
<td>Days</td>
<td>Weeks</td>
<td>Weeks-months</td>
<td></td>
<td>Months</td>
</tr>
<tr>
<td>Typical production rate²</td>
<td>1-20</td>
<td>5-50</td>
<td>1-20</td>
<td>1-10</td>
<td>1-1000</td>
<td>5-50</td>
<td></td>
<td>2-200</td>
</tr>
<tr>
<td>(parts/mold-hour)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum quantity²</td>
<td>1</td>
<td>100</td>
<td>500</td>
<td>10</td>
<td>10</td>
<td>1000</td>
<td></td>
<td>10,000</td>
</tr>
</tbody>
</table>

**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.

11.2 Expendable-Mold Casting Processes

- The major types of expendable-mold casting are (see tables 11.1 & 11.2):
  a) Sand,
  b) Shell mold,
  c) Plaster mold,
  d) Ceramic mold,
  e) Evaporative pattern, and
  f) Investment casting.

11.2.1 Sand Casting

- Casting metals using sand molds has been used for millennia.
- Sand casting is still the most prevalent form of casting; in the United States alone, about 15 million tons of metal are cast by this method each year.
- Typical applications of sand casting include machine bases, large turbine impellers, propellers, plumbing fixtures, and numerous components for agricultural and railroad equipment.
- **Sand casting consists of:**
  a) Placing a pattern having the shape of the desired casting in sand to make an imprint (mold cavity),
  b) Incorporating a gating system,
  c) Removing the pattern and filling the resulting cavity with molten metal,
  d) Allowing the metal to cool until it solidifies,
  e) Breaking away the sand mold,
  f) Removing the casting. (see Fig 11.2).

![Figure 11.2 Outline of production steps in a typical sand-casting operation.](image)
### 11.2.1.A Sands
- Most sand casting operations use silica sand (SiO2).
- Sand is inexpensive and has high melting point (~ 1710°C).
- There are two general types of sand: **naturally bonded** (bank sand) and **synthetic** (lake sand). Because its composition can be controlled more accurately, synthetic sand is **preferred** by most foundries.
- For proper functioning, mold sand must be clean and preferably new.
- Several factors affect the selection of sand for molds:
  - Sand having fine, round grains can be closely packed and forms a smooth mold surface.
  - Although fine-grained sand enhances mold strength, the fine grains also lower mold permeability.
  - Good permeability of molds (and cores) allows gases and steam evolved during casting to escape easily.
  - The mold should have good collapsibility “to allow for the casting to shrink while cooling” thus, to avoid defects in the casting, such as hot tearing and cracking.

**Mulling machines** are used to uniformly and thoroughly mull (mix) sand with additives:
- Clay (bentonite) is used as a cohesive agent to bond sand particles, giving the sand strength.
- Zircon (ZrSiO₄), olivine (Mg₂SiO₄), and iron silicate (Fe₂SiO₄) sands are often used in steel foundries for their low thermal expansion.
- Chromite (FeCr₂O₄) is used for its high heat-transfer characteristics.

### 11.2.1.B Types of Sand Molds
- Three basic types of sand molds: green-sand, cold-box, and no-bake molds.

1. **Green molding sand**:
   - Most common and it is a mixture of sand, clay, and water.
   - “Green” – sand in the mold is moist or damp while the metal is being poured into it.
   - Least expensive method of making molds and the sand is recycled easily for next use.
   - In the skin-dried method, the mold surfaces are dried, either by storing the mold in air or by using torches.

2. **Cold-box mold process**:
   - Various organic and inorganic binders are blended into the sand to bond the grains chemically for greater strength.
   - These molds are dimensionally more accurate than green-sand molds but are more expensive.

3. **No-bake mold process**:
   - Here, a synthetic liquid resin is mixed with the sand; the mixture hardens at room temperature.
   - Because bonding of mold in this and in the cold-box process takes place without heat, they are called Cold-setting processes.

- If sand molds are oven dried (baked) prior to pouring the molten metal, they are stronger than green-sand molds and impart better dimensional accuracy and surface finish to the casting. However, this method has drawbacks: **a)** distortion of the mold is greater; **b)** the castings are more susceptible to hot treating because of the lower collapsibility of the mold; and **c)** the production rate is slower because of the drying time required.
The major features of sand molds are described next (Fig. 11.3):

1. The **flask** which supports the mold itself. Two-piece molds consist of a **cope** on top and a **drag** on the bottom; the seam between them is the **parting line**.
2. A **pouring basin** (or cup), into which the molten metal is poured.
3. A **sprue**, through which the molten metal flows downward.
4. The **runner system**, which has channels that carry the molten metal from the sprue to the mold cavity. **Gates** are the inlet of the mold cavity.
5. **Risers**, which supply additional metal to the casting as it shrinks during solidification (blind riser and an open riser).
6. **Cores**, which are inserts made from sand. They are placed in the mold to form hollow region or otherwise define the interior surface of the casting.
7. **Vents**, which are placed in molds to carry off gases produced when the molten metal comes into contact with the sand in the mold and core. Vents also exhaust air from the mold cavity as the molten metal flows into the mold.
11.2.1.C Patterns

- Patterns are used to *mold the sand mixture into the shape of casting*.
- They may be made of wood, plastic, or metal (see table below).
- Because patterns are used repeatedly to make molds, the strength and durability of the materials selected must reflect the number of castings that the mold will produce.
- Patterns are usually coated with a *parting agent* to facilitate their removal from the molds.

<table>
<thead>
<tr>
<th>TABLE 11.3</th>
<th>Pattern Material Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic</td>
<td>Wood</td>
</tr>
<tr>
<td>Machinability</td>
<td>E</td>
</tr>
<tr>
<td>Wear resistance</td>
<td>P</td>
</tr>
<tr>
<td>Strength</td>
<td>F</td>
</tr>
<tr>
<td>Weightb</td>
<td>E</td>
</tr>
<tr>
<td>Repairability</td>
<td>E</td>
</tr>
</tbody>
</table>

| Resistance to: | 
| Corrosionc | E | E | P | E | P |
| Swellingc | P | E | E | E | E |

*E, Excellent; G, good; F, fair; P, poor.*

bAs a factor in operator fatigue.
cBy water.


- Patterns can be designed with a variety of features to fit specific applications and economic requirements:

1. **One-piece patterns:**
   - Also called loose or solid patterns.
   - Used for *simpler* shapes and low-quantity production.
   - Are generally made of wood and are inexpensive.

2. **Split patterns:**
   - Two-piece patterns made such that each part forms a portion of the cavity for the casting. In this way casting with *complicated* shapes can be produced.
3. **Match-plate patterns:**

- Two-piece patterns are constructed by securing each half of one or more split patterns to the opposite sides of a single plate (Fig. 11.4).
- The gating system can be mounted on the drag side of the pattern.

![Figure 11.4 A typical metal match-plate pattern used in sand casting.](image)

- Pattern design should provide for *metal shrinkage, ease of removal* from the sand by means of a taper or draft (Fig. 11.5), and proper metal flow in the mold cavity.

![Figure 11.5 Taper on patterns for ease of removal from the sand mold](image)

**11.2.1.D Cores**

- Cores are placed in the mold cavity to form the interior surfaces of the casting and are removed from the finished part during shakeout and further processing.
- Like molds, cores must possess strength, permeability, ability to withstand heat, and collapsibility; hence, cores are made of sand aggregates.
- The core is anchored by core prints, which are recesses added to the pattern to support the core and provide vents for the escape of gases (Fig. 11.6).
- To keep the cores from shifting, metal supports (*chaplets*) may be used to anchor the core in place.
The oldest known method of molding (still used) is to compact the sand by hand hammering (taping) or ramming it around the pattern.

For most operations, however, the sand mixture is compacted around the pattern by molding machines.

Vertical flaskless molding:
- The halves of the pattern form a vertical chamber wall against which sand is blown and compacted (Fig. 11.10).
- Then, the mold halves are packed horizontally, with the parting line oriented vertically and moved along a pouring conveyor.
- This operation is simple and eliminates the need to handle flasks, allowing for very high production rates.
In Impact Molding
- The sand is compacted by controlled explosion or instantaneous release of compressed gases.
- This method produces molds with uniform strength and good permeability.

In Vacuum Molding (V process)
- The pattern is covered tightly by a thin sheet of plastic.
- A flask is placed over the coated pattern and is filled with dry, binderless sand.
- A second sheet of plastic is then placed on top of the sand, and a vacuum action compacts the sand so that the pattern can be withdrawn. Both halves of the mold are made this way and assembled.
- During pouring, the mold remains under a vacuum but the casting cavity does not.
- When the metal has solidified, the vacuum is turned off and the sand falls away, releasing the casting.
- Vacuum molding produces casting with high-quality detail and dimensional accuracy.
- It is especially well suited for large, relatively flat castings.

11.2.1.E The Sand-Casting Operation
- After the mold has been shaped and the cores have been placed in position, the two halves (cope and drag) are closed, clamped, and weighted down to prevent separation of mold sections.
- A complete sequence of operations for sand casting is shown in Fig. 11.8.
Figure 11.8  Schematic illustration of the sequence of operations for sand casting.

- **(a)** A mechanical drawing of the part is used to generate a design for the pattern. Considerations such as part **shrinkage** and **draft** must be built into the drawing.
- **(b-c)** Patterns have been mounted on plates equipped with pins for **alignment**. Note the presence of **core prints** designed to hold the core in place.
- **(d-e)** Core boxes produce core halves, which are pasted together. The cores will be used to produce the hollow area of the part shown in (a).
- **(f)** The cope half of the mold is assembled by securing the cope pattern plate to the flask with aligning pins and attaching **inserts to form the sprue and risers**.
- **(g)** The flask is rammed with sand and the **plate and inserts are removed**.
- **(h)** The drag half is produced in a similar manner with the pattern inserted. A bottom board is placed below the drag and aligned with pins.
- **(i)** The pattern, flask, and bottom board are inverted; and the pattern is withdrawn, leaving the appropriate imprint.
- **(j)** The core is set in place within the drag cavity.
- **(k)** The mold is closed by placing the **cope on top of the drag** and securing the assembly with pins. The flasks then are subjected to pressure to counteract buoyant forces in the liquid, which might lift the cope.
- **(l)** After the metal solidifies, the casting is removed from the mold.
- **(m)** The sprue and risers are cut off and recycled, and the casting is cleaned, inspected, and heat treated (when necessary).

- Note that after solidification:
  - Casting is shaken out of its mold and oxide layers adhering to the casting are removed by vibration (using a shaker) or by sand blasting.
  - Castings also are cleaned by blasting with steel shot or grit (shot blasting).
  - The risers and gates are cut off by **oxyfuel-gas cutting, sawing, shearing, and abrasive wheels**; or they are trimmed in dies.
  - Gates and risers on steel castings also may be removed with carbon-arc or torches.
  - Castings may be cleaned further by electrochemical means or by pickling with chemicals to remove surface oxides.
  - The casting subsequently may be heat treated to improve certain properties required for its intended service use (specially steel castings).
  - Finishing operations may involve machining, straightening, or forging with dies (sizing) to obtain final dimensions.
  - Inspection is an important final step to ensure that the casting meets all design and quality-control requirements.

### 11.2.1.G Rammed-Graphite Molding

- Rammed graphite is used to make molds **for casting reactive metals**, such as **titanium and zirconium**. Sand cannot be used because these metals react vigorously with silica.
  - **The molds are packed like sand molds, air dried, baked at 175°F, fired at 870°F, and then stored under controlled humidity and temperature.**
  - Casting procedures are similar to those for sand molds.
11.2.2 Shell Molding

- Shell molding first was developed in the 1940’s and has grown significantly.
- It can produce many types of castings with close dimensional tolerance and a good surface finish at low cost.
- Shell-molding applications include small mechanical parts requiring high precision, such as gear housings, cylinder heads, connecting rods, and high-precision molding cores.

In this process (see Figure 11.9)

1. A mounted pattern made of a ferrous metal or aluminum is heated to 175° C – 370° C.
2. Coated with a parting agent such as silicone.
3. Clamped to a box or chamber that contains fine sand, mixed with 2.5% to 4% thermosetting resin binder (such as phenol-formaldehyde) that coats the sand particles.
4. The box is either rotated upside down or the sand mixture is blown over the pattern, to coat the pattern.
5. The assembly is then placed in an oven for a short period of time to complete the curing of the resin.
6. The shell hardens around the pattern and is removed from the pattern using built-in ejector pins.
7. Two half-shells are made in this manner and are bonded or clamped together to form a mold.

Figure 11.9 The shell-molding process, also called dump-box technique.
- The thickness of the shell can be determined accurately by controlling the time that the pattern is in contact with the mold.
- The shells are light and thin (usually 5-10 mm), and consequently their thermal characteristics are different from those for thicker mold.
- Shell sand has a much lower permeability than sand used for green-sand molding, because finer sand is used for shell casting.
- The decomposition of the shell-sand binder produces a high volume of gas; unless the molds are properly vented, trapped air and gas can cause serious problems in shell molding of ferrous castings.
- The high quality of the finished casting can reduce cleaning, machining, and other finishing costs significantly.
- Complex shapes can be produced with less labor, and the process can be automated fairly easily.

### 11.2.3 Plaster-Mold Casting
- It is known as precision casting because of the high dimensional accuracy and good surface finish obtained (as well as ceramic-mold and investment casting).
- Typical parts made are lock components, gears, valves, fittings, tooling, and ornaments.
- In this process:
  a) The mold is made of plaster of paris (gypsum or calcium sulfate) with the addition of talc and silica flour to improve strength and to control the time required for the plaster to set.
  b) These components are mixed with water, and the resulting slurry is poured over the pattern.
  c) After the plaster sets (usually within 15 minutes) it is removed, and the mold is dried at a temperature range of 120° C to 260° C to remove the moisture.
  d) The mold halves are assembled to form the mold cavity and are preheated to about 120° C. The molten is then poured into the mold.
  e) Because plasters molds have very low permeability, gases evolved during solidification of the metal cannot escape. Consequently, the molten metal is poured either in vacuum or under pressure.
  f) Mold permeability can be increased by the Antioch process, in which molds dehydrated in an autoclave (pressurized oven) for 6-12 hours and then dehydrated in air for 14 hours.
  g) Foamed plaster containing trapped air bubbles is another method used to increase permeability of the mold.
- Patterns here are generally made of materials such as aluminum alloys, thermosetting plastics, brass, or zinc alloys.
- Since there is a limit to the maximum temperature that the plaster mold can withstand (about 1200° C), plaster-mold casting is used only for aluminum, magnesium, zinc, and some copper-based alloys.
- The castings have a good surface finish with fine details.
- Molds have lower thermal conductivity than others, the castings cool slowly, and thus, a more uniform grain structure is obtained with less warpage.
- Wall thickness of the cast parts can be 1 – 2.5 mm.
11.2.4 Ceramic-Mold Casting

- Also called cope-and-drag investment casting. It is similar to the plaster-mold process with the exception that it uses refractory materials suitable for high-temperature applications.
- Typical parts made are impellers, cutters for machining operations, dies for metalworking, and molds for making plastic and rubber components. Can cast up to 700 kg parts.
- The slurry is a mixture of fine-grained zircon, aluminum oxide, and fused silica, which are mixed with bonding agent and poured over the pattern (Fig. 11.10), which has been placed in a flask.

![Figure 11.10 Sequence of operations in making a ceramic mold.](image)

- The pattern may be made of wood or metal.
- After setting, the molds (ceramic facings) are removed, dried, burned off to remove volatile matter, and baked.
- The molds are compacted firmly and used as an all-ceramic mold.
- The high temperature resistance of the refractory molding materials allows these molds to be used for casting ferrous and high-temperature alloys, stainless steels and tool steels.
- Although the process is somewhat expensive, the castings have good dimensional accuracy and surface finish over a wide range of sizes and intricate shapes.

11.2.5 Evaporative-pattern casting (lost-foam process)

- Sometimes referred to as expendable mold-expendable pattern processes.
- It is unique in that a mold and a pattern must be produced for every casting.
- Typical applications are cylinder heads, engine blocks, crankshafts, brake components, and machine bases (see table 11.2).
- This process has become one of the more important casting processes for ferrous and nonferrous metals, particularly for the automotive industry.
- This process uses a polystyrene pattern, which evaporates upon contact with molten metal to form a cavity for the casting (lost-foam casting). In this process:
  a) Raw expendable polystyrene (EPS) beads, containing 5% to 8% pentane (a volatile hydrocarbon), are placed in a preheated die which is usually made of aluminum.
  b) The polystyrene expands and takes the shape of the die cavity. Additional heat is applied to fuse and bond the beads together.
  c) The die is then cooled and opened, and the polystyrene pattern is removed.
  d) The pattern is coated with water-based refractory slurry, dried, and placed in a flask.
  e) The flask then is filled with loose fine sand, which surrounds and supports the pattern (Fig. 11.11) and may be dried or mixed with bonding agents to give it additional strength.
  f) The sand is periodically compacted by various means.
g) Without removing the polystyrene pattern, the molten metal is poured into the mold. This action immediately vaporizes the pattern and fills the mold cavity, completely replacing the space previously occupied by the polystyrene pattern. The heat degrades the polystyrene, and the degradation products are vented into the surrounding sand.

Figure 11.15 Schematic illustration of the expendable pattern casting process, also known as lost foam or evaporative casting.

Notes:
- The flow velocity of the molten metal in the mold depends on the rate of degradation of the polymer. Studies have shown that the flow the molten metal is basically laminar, with Reynolds number in the range 400 to 3000.
- The velocity of the molten metal at the metal-polymer pattern front is estimated to be in the range of 0.1 m/s – 1.0 m/s.
- The velocity can be controlled by producing patterns with cavities or hollow sections. Thus, the velocity will increase as the molten metal crosses these hollow regions, similar to pouring the metal into an empty cavity.
- The molten metal cools faster than it would if it were poured directly into an empty cavity. Consequently, fluidity is less than in sand casting.

The evaporative-pattern process has a number of advantages over other casting methods:
1. The process is relatively simple because there are no parting lines, cores, or riser systems, hence it has design flexibility.
2. Inexpensive flasks are sufficient for the process.
3. Polystyrene is inexpensive and can be easily processed into patterns having complex shapes, various sizes, and fine surface detail.
4. The casting requires minimum finishing and cleaning operation.
5. The process can be automated and is economical for long production runs.

In a modification of the evaporative-pattern process, a polystyrene pattern is surrounded by a ceramic shell. The pattern is burned out prior pouring the molten metal into the mold. Its principal advantage over investment casting (see next section) is that carbon pickup into the metal is entirely avoided.
11.2.6 Investment Casting (lost-wax process)

- It was first used during the period from 4000-3000 B.C.
- Typical parts made are components for office equipment as well as mechanical components, such as gears, valves, and ratchets. Parts up to 1.5 m in diameter and weighing up to 1140 kg (see table 11.2).
- The sequence involved in investment casting are shown in Fig. 11.13:
  a) The pattern is made by injecting molten wax or plastic (such as polystyrene) into a metal die in the shape of the pattern.
  b) The pattern is then dipped into a slurry of refractory material such as very fine silica and binders, including water, ethyl silicate, and acids.
  c) After this initial coating has dried, the pattern is coated repeatedly to increase its thickness for better strength.
  d) The one-piece mold is dried in air and heated to a temp. of 90° C–175° C, while held in an inverted position for about 12 hours to melt out the wax.
  e) The mold is then fired to 650° C–1050° C for about 4 hours, to drive off the water of crystallization and burn off any residual wax.
  f) After the metal has been poured and has solidified, the mold is broken up and the casting is removed.
- A number of patterns can be joined to make one mold, called a tree, significantly increasing the production rate.
- The process is suitable for casting high-melting-point alloys with good surface finish and close dimensional tolerances; few or no finishing operations.

Figure 11.13  Schematic illustration of investment casting (lost-wax) process. Castings by this method can be made with very fine detail and from a variety of metals
**Ceramic-shell Investment Casting:**
- Uses the same type of wax or plastic pattern, which is dipped first in ethyl silicate gel and subsequently into a fluidized bed of fine-grained fused silica or zircon flour.
- The pattern is then dipped into coarser-grained silica to build up additional coatings and proper thickness so that the pattern can withstand the thermal shock of pouring.
- The rest of the procedure is similar to investment casting.
- The sequence of operations involved in making a turbine disk by this method is shown in Fig. 11.14.

![Ceramic-shell Investment Casting](image)

Figure 11.14 Investment casting of an integrally cast rotor for a gas turbine. (a) Wax pattern assembly. (b) Ceramic shell around wax pattern. (c) Wax is melted out and the mold is filled, under a vacuum, with molten superalloy. (d) The cast rotor, produced to net or near-net shape.

See Example 11.1

### 11.3 Permanent-Mold Casting Processes

#### 11.3.1 Permanent-Mold Casting
- Permanent mold casting is also called **hard-mold** casting.
- **Two halves** of a mold are made from materials such as cast iron, steel, bronze, graphite, or refractory metal alloys.
- Typical parts made are automotive pistons, cylinder heads, connecting rods, gear blanks for appliance, and kitchenware (see table 11.2).
- The mold cavity and gating system are machined into the mold and, thus, become an integral part of it.
- To produce castings with internal cavities, cores made of metal, or sand aggregate are placed in the mold prior to casting. Typical core materials are oil-bonded or resin-bonded sand, plaster, graphite, gray iron, low-carbon steel, and hot-work die steel.
- To increase the life of permanent molds, the surfaces of the mold cavity are usually coated with refractory slurry (such as sodium silicate and clay) or sprayed with graphite every few castings. These coatings also serve as parting agents and as thermal barriers, controlling the rate of cooling of the casting. Mechanical ejectors may be needed for removal of complex castings.
- The molds are clamped together by mechanical means and heated to about 150°C – 200°C to facilitate metal flow and reduce thermal damage to the dies due to high-temperature gradients.
- Molten metal then is poured through the gating system.
- After solidification, the molds are opened and the casting is removed.
- **Cooling** the mold may include water or using fins.
- This process is used mostly for aluminum, magnesium, copper alloys, and gray iron because of their generally lower melting points.
Steels can also be cast using graphite or heat-resistant metal molds. This process produces castings with good surface finish, close dimensional tolerances, uniform and good mechanical properties, and at high production rates.

11.3.2 Vacuum Casting

- Vacuum casting or counter-gravity low-pressure (CL) process is shown in Fig. 11.16.
- It is suitable for thin-walled (0.75 mm) complex shapes with uniform properties.
- Typical parts made are gas-turbine components from superalloys. Carbon, low- and high-alloy steel, and stainless steel parts weighing as much as 70 kg have been vacuum cast.
- In this process:
  a) A mixture of fine sand and urethane is molded over metal dies and cured with amine vapor.
  b) The mold then is held with a robot arm and immersed partially into the molten metal contained in an induction furnace.
  c) The metal may be melted in air (CLA process) or in vacuum (CLV process).
  d) The vacuum reduces the air pressure inside the mold to about 2/3 of atmospheric pressure, thus drawing the molten metal into the mold cavities through a gate in the bottom of the mold.
  e) The metal is solidified within a very short time.
  f) After the mold is filled, it is pulled out of the molten metal.

Figure 11.16 Schematic illustration of the vacuum-casting process. Note that the mold has a bottom gate. (a) Before and (b) after immersion of the mold into the molten metal.

11.3.3 Slush Casting

- Hollow castings with thin walls can be made by permanent-mold casting using the principle that a solidified skin develops first in a casting (See Fig. 10.11) and this skin becomes thicker with time.
- It used for small production runs and generally is used for making ornamental and decorative objects such as lamp bases and stem, and toys from low-melting metals such as zink, tin, and lead alloy.
- In this process:
  a) The molten metal is poured into the metal mold.
  b) After the desired thickness of the solidified skin is obtained, the mold is inverted (or slung) and the remaining liquid metal is poured out.
  c) The mold halves then are opened and the casting is removed.
- This process is very similar to making hollow chocolate shapes, eggs, and so on.
11.3.4 Pressure Casting
- Also called pressure pouring or low-pressure casting.
- Generally used for high-quality casting; such as steel railroad-car wheels
- In this process:
  a) The molten metal is forced upward by gas pressure into graphite or metal mold.
  b) The pressure is maintained until the metal has solidified completely in the mold.
  c) The molten metal also may be forced upward by a vacuum, which also removes dissolved gases and produces a casting with lower porosity.

11.3.5 Die Casting
- Another permanent casting developed in early 1900s.
- Typical parts made by die-casting are motor housing, engine blocks, business-machine and appliance components, hand tools, and toys.
- Cast parts weigh from 90 g to about 25 kg (see table 11.2).
- The cost of die is somewhat high, but labor costs are generally low, because the process is now semi- or fully automated.
- It is economical for large production runs.
- In this process the molten metal is forced into the die cavity at pressures ranging from 0.7 – 700MPa.
- There are two basic types of die-casting machines: hot-chamber and cold-chamber.

A. Hot-Chamber Process:
- The hot chamber process (Fig. 11.17) involves the use of a piston, which traps a certain volume of molten metal and forces it into the die cavity through a gooseneck and nozzle.
- Pressures range up to 35 MPa but with an average of about 15 MPa.
- The metal is held under pressure until it solidifies in the die.
- To improve die life and to aid in rapid metal cooling (thereby reducing cycle time), dies are usually cooled by circulating water or oil through various passageways in the die block.
- Low-melting-point alloys such as: zinc, magnesium, tin, and lead are commonly cast using this process.

![Figure 11.17 Schematic illustration of the hot-chamber die-casting process.](image)
B. Cold-Chamber Process

- In the cold chamber process (Fig. 11.18), molten metal is poured into the injection cylinder (shot chamber).
- The shot chamber is not heated, hence the term cold chamber. The metal is forced into the die cavity at pressures usually ranging from 20 to 70 MPa, although they may be as high as 150 MPa.
- The machines may be horizontal (Figs. 11.24a and b) or vertical, in which case the shot chamber is vertical.
- High melting-point alloys of aluminum, magnesium, and copper are normally cast using this method, although other metals (including ferrous metals) can also be cast.

![Figure 11.18 Schematic illustration of the cold-chamber die-casting process. These machines are large compared to the size of the casting, because high forces are required to keep the two halves of the dies closed under pressure.](image)

Process Capabilities and Machine Selection:

- Die casting has the capability for rapid production of strong, high-quality parts with complex shapes, specially with aluminum, brass, magnesium, and zinc (see table 11.3)
- It produces good dimensional accuracy and surface details (net-shape forming).
- Because the molten metal chills rapidly at the die walls, the casting has a fine-grained, hard skin with high strength. Consequently, the strength-to-weight ratio of die-cast parts increase with decreasing wall thickness.
- Because of the high pressures involved, walls as thin as 0.38 mm are produced. However, ejector marks remain, as may small amounts of fish (thin material squeezed out between the dies) at the die parting line.
- Because of the high pressures involves, dies have a tendency to part unless clamped together tightly.
Die-casting machines are rated according to the clamping force needed to keep the dies closed. Commercially available machines range from about 25 to 3000 tons.

Other factors involved in the selection of die-casting machines are die size, piston stroke, shot pressure and cost.

Die casting dies (Fig. 11.19) may be single cavity, multiple cavity (with several identical cavities), combination cavity (with several different cavities), or unit dies (simple small dies that can be combined in two or more units in a master holding die).

Typically, the ratio of die-weight to part-weight is 1000 to 1.

Dies are usually made of hot-work die steels or mold steels.

Die wear increases with the temperature of the molten metal.
When die materials are selected and properly maintained, dies may last more than half a million shots before any significant die wear takes place.

Die design includes draft to allow the removal of the casting.

Components such as pins, shafts, and threaded fasteners can be die cast integrally. Called insert molding.

Lubricants (parting agents) often are applied as thin coatings on die surfaces. The usually are water-based lubricants with graphite.

### 11.3.6 Centrifugal Casting:

- As the name implies, the centrifugal-casting process utilizes the inertial forces caused by rotation to distribute the molten metal into the mold cavities.
- First suggested in the early 1800s.
- There are three types of centrifugal casting: True centrifugal, semi-centrifugal, and centrifuging casting.

#### A. True centrifugal Casting

- In true centrifugal casting, hollow cylindrical parts (such as pipes, gun barrels, bushings, bearing rings, and streetlamp posts) are produced. See Fig. 11.20.
- In this technique the molten metal is poured into a rotating mold. The axis of rotation is usually horizontal but can be vertical for short work-pieces.
- Molds are made of steel, iron, or graphite, and may be coated with a refractory lining to increase mold life.
- The mold surfaces can be shaped so that pipes with various external designs can be cast.
- Cylindrical parts ranging from 13 mm to 3 m in diameter and 16 m long can be cast centrifugally, with wall thicknesses ranging from 6 mm to 125 mm.
- Castings with good quality, dimensional accuracy, and external surface detail are obtained by this process (see table 11.2).

![Schematic illustration of the centrifugal-casting process](image)

Figure 11.20 (a) Schematic illustration of the centrifugal-casting process. Pipes, cylinder liners, and similarly shaped parts can be cast with this process. (b) Side view of the machine.

#### B. Semi-centrifugal casting.

- This method is used to cast parts with rotational symmetry such as a wheel with spokes.
- See example 11.21a.
C. **Centrifuging (centrifuge casting)**
- Mold cavities of any shape are placed at a certain distance from the axis of rotation.
- The molten metal is poured from the center and is forced into the mold by centrifugal forces; see Fig. 11.21b.

![Centrifuging (centrifuge casting)](image1)

**Figure 11.21** (a) Schematic illustration of the semicentrifugal casting process. Wheels with spokes can be cast by this process. (b) Schematic illustration of casting by centrifuging. The molds are placed at the periphery of the machine, and the molten metal is forced into the molds by centrifugal force.

11.3.7 **Squeeze casting and semisolid metal forming**
- Two casting processes that basically are combinations of casting and forging (chapter 14).

A. **Squeeze casting**
- Developed in the 1860’s, squeeze casting (liquid-metal forging) process involves the solidification of molten metal under high pressure (Fig. 11.22).
- Typical products made are automotive components and mortar bodies (short-barreled cannon).
- The machinery includes a **die, punch, and ejector pin**.
- With rapid heat transfer, fine microstructure with good mechanical properties obtained.
- Complex parts can be made to near-net shape with fine surface detail from both ferrous and nonferrous alloys.

![Squeeze casting](image2)

**Figure 11.22** Sequence of operations in the squeeze-casting process. This process combines the advantages of casting and forging.
B. Semisolid-metal forming
- Also called mushy state processing (see Fig 10.4) was developed in 1970 and put into commercial production by 1981.
- When it enters the die, the metal (consisting from liquid and solid components) is stirred so that all of the dendrites are crushed into fine solids, and when cooled in the die, it develops into a fine-grained structure.
- The alloy exhibits thixotropic behavior (process is called thixoforming), meaning its viscosity decreases when agitated.
- Thixotropic behavior has been utilized in developing technologies that combine casting and forging of parts using cast billets that are forged when 30 to 40% liquid.
- Parts made include control arms, brackets, and steering components.
- The advantages of semisolid metal forming over die casting are: (a) the structure developed are homogeneous, with uniform properties and high strength, (b) both thin and thick parts can be made, (c) casting as well as wrought alloys can be used, and (d) parts subsequently can be heat treated. However, material and overall costs are high than those for die casting.

11.3.8 Composite mold casting operations
- Composite molds are made of two or more different materials and are used in shell molding and other casting processes.
- They are generally employed in casting complex shapes, such as impellers for turbines.
- Composite molds increase the strength of the mold, improve the dimensional accuracy and surface finish of casting, and can help reduce overall costs and processing time.
- Molding materials commonly used are shells, plaster, sand with binder, metal, and graphite.
- Composite molds may also include cores and chills to control the rate of solidification in critical areas of castings.

11.4 Casting Techniques for Single-Crystal Components (not covered)

11.5 Rapid solidification (amorphous alloys)
- The technique for making amorphous alloys (known as metallic glasses) involves cooling the molten metal at rates as high as $10^6$ K/s. So no sufficient time to crystallize.
- This process is called rapid solidification.
- Rapid solidification results in a significant extension of solid solubility, grain refinement, and reduced micro segregation, among other effects.

![Figure 11.25](image-url) (a) Schematic illustration of melt-spinning to produce thin strips of amorphous metal. (b) Photograph of nickel-alloy production through melt-spinning.
In melting spinning, the alloy is melted by induction in a ceramic crucible. It is then propelled under high gas pressure at very high speed against a rotating copper disk (chill block), which chills the alloy rapidly (splat cooling).

11.6 Inspection of castings
- Castings can be inspected visually or optically for surface defects.
- Subsurface and internal defects are investigated using various nondestructive techniques (section 36.10).
- In destructive testing (section 36.11), test specimens are removed from various sections of a casting to test for strength, ductility, and other mechanical properties, and to determine the presence and location of porosity and any other defects.
- Pressure tightness of cast components (valves, pumps, and pipes) is usually determined by sealing the openings in the casting and pressurizing it with water, oil, or air.
- For extreme leak tightness requirements, pressurized helium or specially scented gases with detectors (sniffers) are used. Unacceptable or defective casting is remelted for reprocessing.

11.7 Melting Practice and Furnaces
- Furnaces are charged with melting stock, consisting of metal, alloying elements, and various other materials (such as flux and slag-forming constituents).
- Fluxes are inorganic compounds that refine the molten metal by removing dissolved gases and various impurities. They may be added manually or can be injected automatically into the molten metal.
- Fluxes have several functions, depending on the metal.

Melting Furnaces commonly used in foundries
a. Electric Arc Furnaces (Fig 5.2 a & b)
  - High rate of melting (and thus a high production rate),
  - Much less pollution than other types of furnaces,
  - The ability to hold the molten metal (at constant temperature for a period of time) for alloying purposes.

b. Induction Furnaces (Fig.5.2c). Two basic types.
  1. The coreless induction furnace:
     - Consists of a crucible completely surrounded with a water-cooled copper coil through which high frequency current passes.
Because there is a strong electromagnetic stirring action during induction heating, this type of furnace has excellent mixing characteristics for alloying and adding new charge of metal.

2. Core or channel furnace:

- Uses low frequency (as low as 60 Hz) and has a coil that surrounds only a small portion of the unit.
- Commonly used in nonferrous foundries and is particularly suitable for superheating (above normal casting temp. to improve fluidity), holding, and duplexing (using two furnaces to, for instance, melt the metal in one furnace and transfer it to another).

3. Crucible furnaces (Fig. 11.26a):

- Heated with various fuels such as commercial gases, fuel oil, and fusel fuel, as well as electricity. They may be stationary, tilting, or movable.

4. Cupolas (Fig. 11.26b):

- Refractory-lined vertical steel vessels charged with alternating layers of metal, coke, and flux. Cupolas operate continuously, have high melting rates, and produce large amounts of molten metal. However, increasingly are being replaced by induction furnaces.

Furnace selection:

a. Economic considerations.
b. Composition and melting point of the alloy to be cast as well as the ease of controlling its chemistry.
c. Control of the furnace atmosphere to avoid contamination of the metal.
d. Capacity and rate of melting required.
e. Environmental consideration.
f. Power supply and its availability and cost of fuels.
g. Ease of superheating the metal.
h. Type of charge material that can be used.
11.8 Foundries and Foundry Automation

- Modern foundries have automated and computer-integrated facilities for all aspects of their operations.
- As outlined in Fig. 11.2, foundry operations involve two separate groups of activities:
  1. The first group is pattern and mold making. Computer-aided design and manufacturing and rapid prototyping techniques are now used to minimize trial and error and, thus, improve efficiency. A variety of automated machinery is used to minimize labor cost, which can be significant in the production of castings.
  2. The second group of activities is melting the metal, controlling their composition and impurities, and pouring them into molds.
- The rest of operations, such as pouring into molds carried along conveyors, shakeout, cleaning, heat treatment, and inspection, are also automated.
- Automation minimizes labor, reduces the possibility of human error, increase the production rate, and attains higher quality levels.
- Industrial robots are now used extensively in foundry operations, such as cleaning, riser cutting, mold venting, mold spraying, pouring, sorting, and inspection.
- Automated storage and retrieval systems for cores and patterns using automated guided vehicles are used.