

Metal Casting

Casting is a process in which molten [metal](#) flows by gravity or other force into a mold where it solidifies in the shape of the mold cavity – the geometry of the mold cavity determines the shape of the cast part.

Capabilities and Advantages:

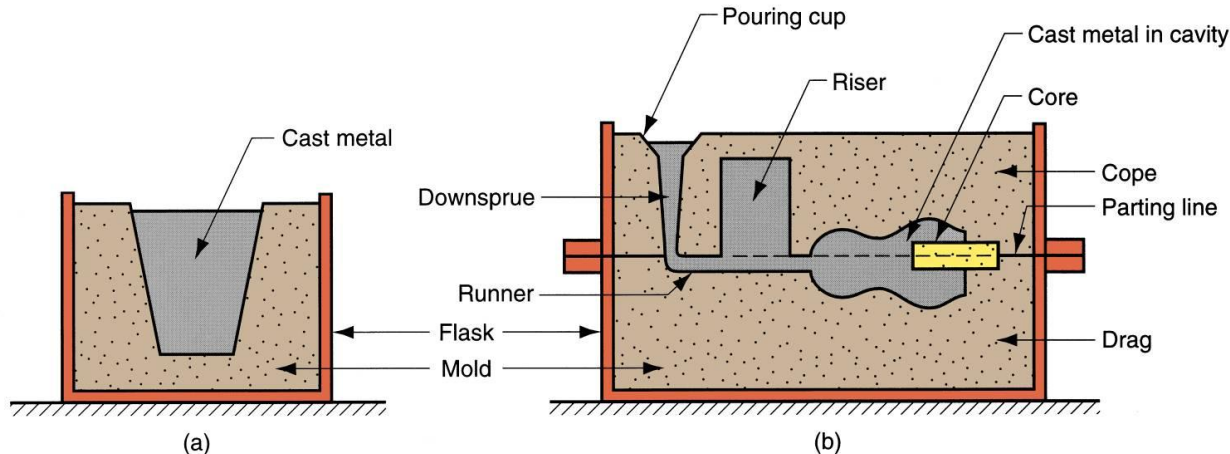
- Complex part geometries – external and internal.
- Net shape manufacturing (some) – no machining is required to achieve close tolerances on certain part features.
- Small to very large parts – parts weighing a few ounces to over 100 tons.
- Mass production (some).

Disadvantages:

- Limitations on mechanical properties.
- [Porosity](#).
- Poor dimensional accuracy and surface finish (some).
- Safety hazards to operators.
- Environmental problems.

Casting Molds:

- Mold materials: sand, plaster, ceramics, and metal.
- The size and shape of the mold cavity must be designed slightly oversized to allow for **shrinkage** that occurs in the metal during solidification and cooling.
- **Open Mold:** simply a container in the shape of the desired part.
- **Closed Mold:** the mold geometry is more complex and requires a gating system (passageway) leading into the cavity.
 - External surface of the cast part – mold cavity; Internal surfaces – core.
 - The gating system: pouring cup, downsprue (sprue), and runner.
 - The **riser** is a reservoir in the mold that serves as a source of liquid metal for the casting to **compensate** for shrinkage during solidification.



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Expendable Mold Casting Processes:

- The mold in which the molten metal solidifies must be destroyed in order to remove the casting (e.g., sand casting). These molds are made out of sand, plaster, and similar materials, whose form is maintained by using binders of various kinds.
- The mold cavity is formed by means of a **pattern**, which is made of wood, metal, plastic, etc., and has the shape of the part to be cast (oversized).

Permanent Mold Casting Processes:

- A permanent mold is one that can be used over and over to produce casting parts (e.g., die casting). The mold is often made of metal that can withstand the high temperature of the casting operation.

Complex Casting Geometry vs. High Production Rate

Removal of Air and Gases:

- Natural porosity (sand molds).
- Small vent holes in the mold or the parting line (permanent metal molds).

Heating:

1. Heat to raise the temperature of the casting metal to the melting point.
2. Heat of fusion (from solid to liquid).
3. Heat to raise the molten metal to the desired temperature for pouring.

$$H = m [C_s(T_m - T_0) + H_f + C_l(T_p - T_m)]$$

Complexities:

- $C_s \equiv C_s(T)$, change of phase (most casting metals are alloys)
- $T_m \neq \text{const.}$ (alloys)
- Heat loss to the environment

Pouring:

Bernoulli's Equation: $\frac{P}{\rho} + \frac{v^2}{2} + gz + F = \text{const.}$

Continuity Equation: $Q = vA = \text{const.}$

→ The sprue should be **tapered!**

Mold Filling Time (min.): $MFT = \frac{V}{Q}$

Pouring Temperature: temperature of the molten metal as introduced into the mold.

High pouring temperature aggravates:

- Oxide formation.
- Gas porosity.
- Penetration of liquid metal into the interstitial spaces between the grains of sand comprising the mold (embedded sand on the casting surface).

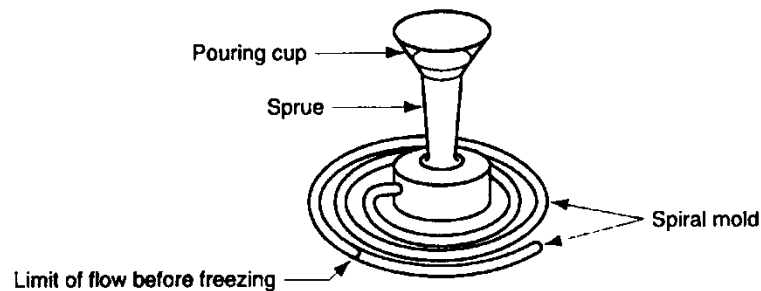
Pouring Rate: volumetric rate at which the molten metal is poured into the mold.

Turbulence – agitated and irregular flow of liquid metal.

- Accelerates the formation of metal oxides.
- Aggravates mold erosion and wear.

Fluidity (vs. viscosity):

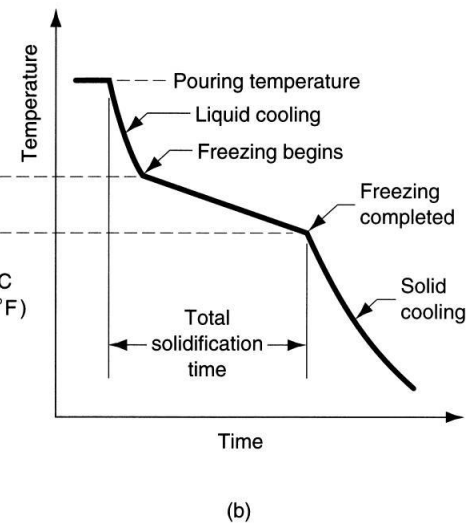
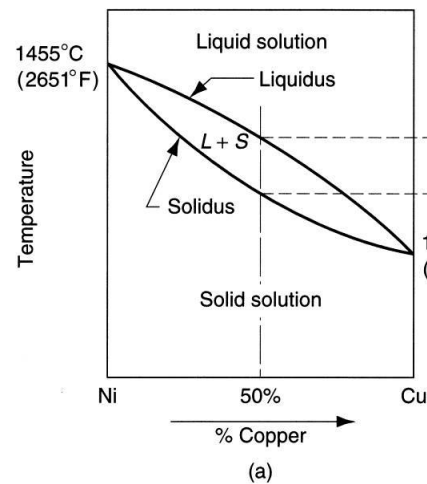
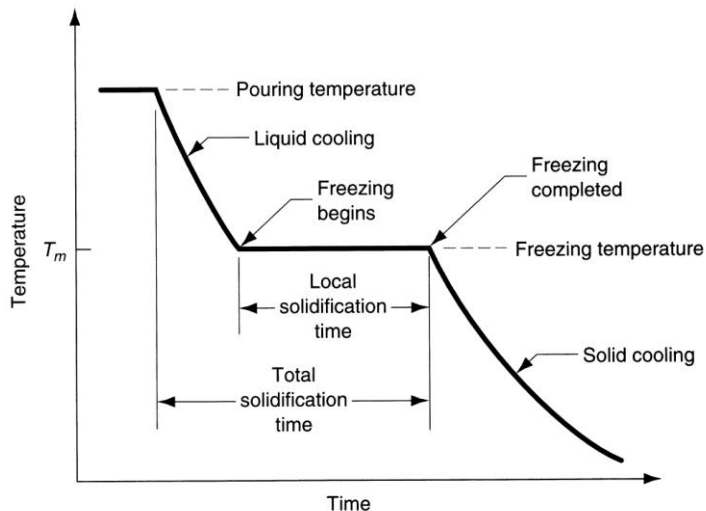
- A measure of the capability of a liquid metal to flow into and fill the mold before solidification.
- Spiral mold test:



Solidification and Cooling:

Solidification involves the transformation of the molten metal back into the solid state.

- A pure metal solidifies at a **constant** temperature (freezing point or melting point).
- Most alloys freeze over a temperature **range** rather than at a single temperature.



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Metallic Grain Formation and Growth:

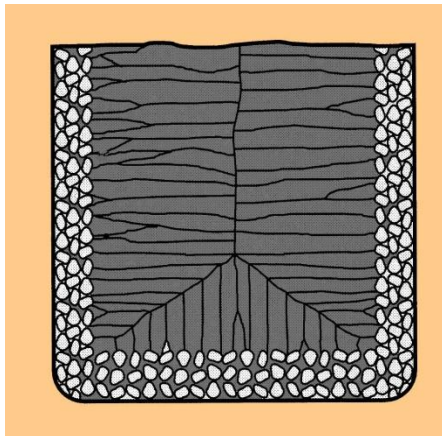
Because of the chilling action of the mold wall (large temperature gradient), a thin skin of solid metal is initially formed at the interface immediately after pouring.

The rate at which freezing proceeds depends on:

- Heat transfer into the mold.
- Thermal properties of the metal.

Pure Metals:

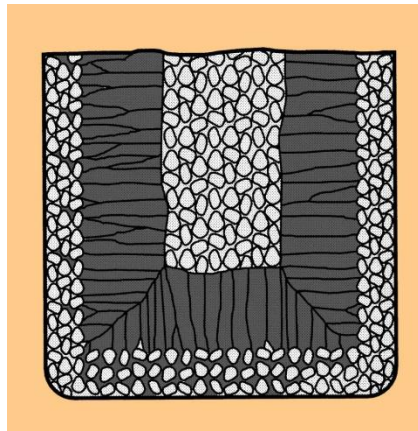
- Randomly oriented grains of small size near the mold wall (due to rapid cooling action at the mold wall).
- Large and columnar grains oriented toward the center of the casting (due to dendritic growth of treelike structures in a direction away from the heat transfer).



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Alloys (most):

- Fine and randomly oriented grains near the mold wall.
- Dendrites that grow away from the walls.
- Formation of the **mushy zone** during solidification (both liquid and solid metal coexist).
- **Segregation** of alloying components (composition imbalance):
 - microscopic level (within a single grain)
 - macroscopic level (throughout the casting)



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Eutectic Alloys:

- A **particular composition** in an alloy system for which the solidus and liquidus are at the same temperature.
- Casting eutectic alloys: aluminum-silicon (11.6% Si) and cast iron (4.3% C).

Solidification Time:

Chvorinov's Rule (an empirical relationship)

Total Solidification Time: $TST = C_m \left(\frac{V}{A} \right)^n$ $n \approx 2$ C_m : the mold constant

The mold constant is a function of the following:

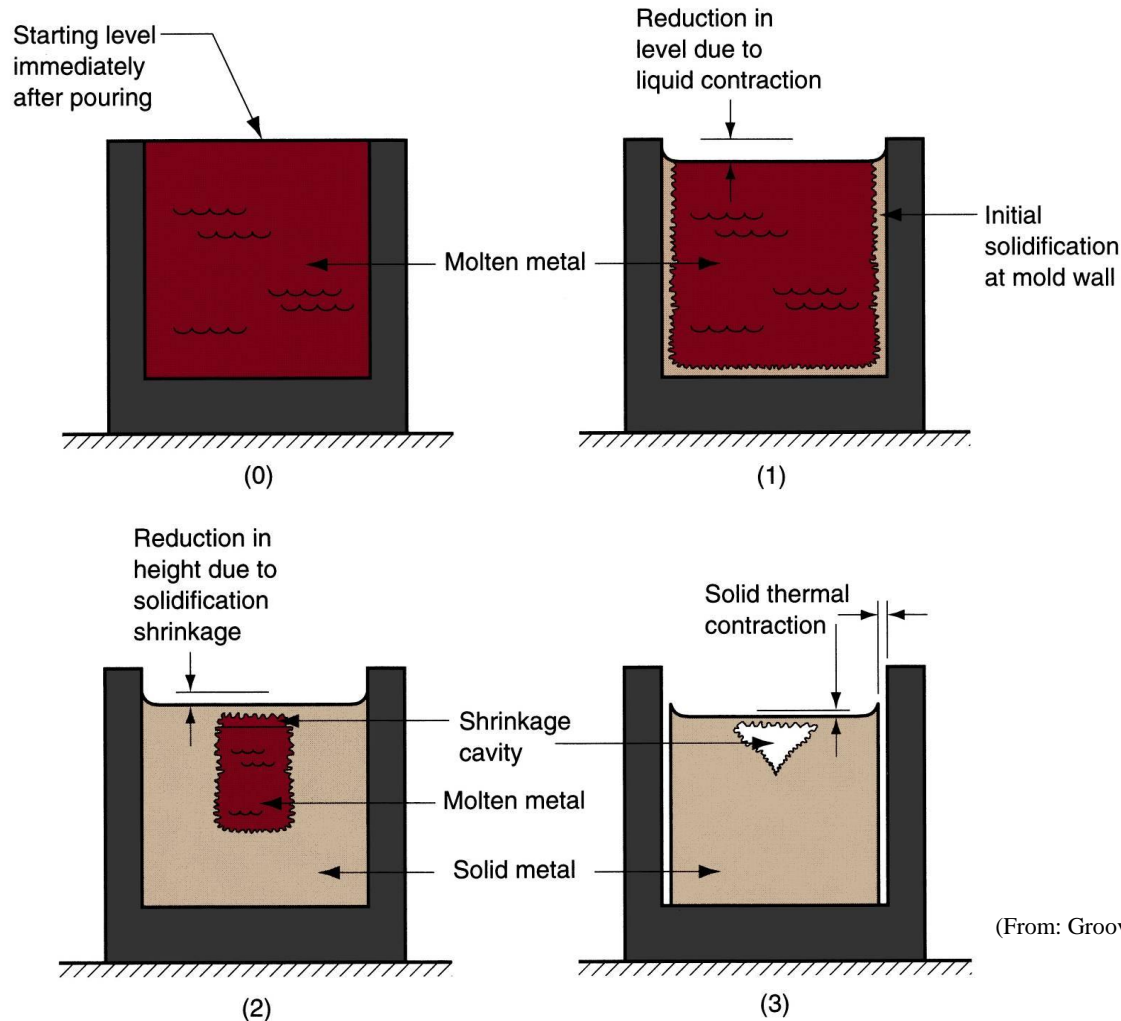
1. Mold material (thermal conductivity and specific heat).
2. Thermal properties of the cast metal (thermal conductivity, specific heat, and heat of fusion).
3. Pouring temperature.

Riser Design:

- TST for the riser must exceed the TST for the main casting; i.e., the riser must remain molten until after the casting solidifies.
- Keep volume of metal in the riser to a minimum → maximize the riser V/A ratio.
- Side Riser vs. Top Riser
- Open Riser vs. Blind Riser

Shrinkage:

1. Liquid contraction during cooling prior to solidification.
2. Solidification Shrinkage – contraction during the phase change from liquid to solid.
3. Thermal contraction of the solidified casting during cooling to room temperature.



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Directional Solidification:

To minimize the damaging effects of shrinkage, it is desirable:

- To first freeze the regions of the casting most distant from the liquid metal supply;
- To progress the solidification from these remote regions **toward the riser(s)**; and
- To avoid premature solidification in sections of the mold nearest the riser(s).

The desired directional solidification is achieved by observing Chvorinov's rule in:

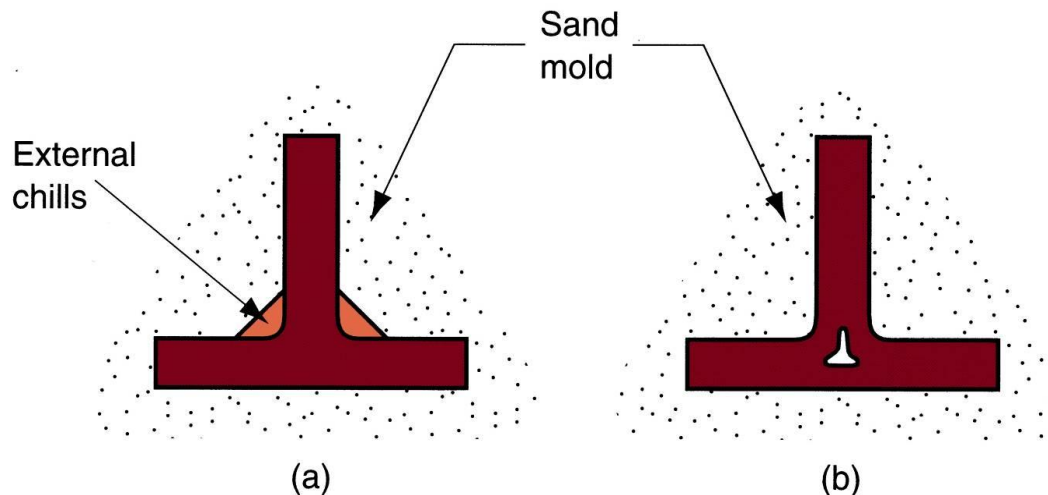
- Design of the casting part.
- Orientation of the casting within the mold (identify casting sections with lower V/A ratios).
- Design of the riser system.

Passageway (between the riser and the main cavity) **Design:**

- Minimize the volume in the connection (to reduce wasted metal).
- Provide sufficient cross-sectional area to delay the onset of freezing.
- Make the passageway short in length.

Chills:

- Internal or external heat sinks that cause rapid freezing in certain regions of the casting (another way to encourage directional solidification).
- Chills are used to encourage rapid freezing in those sections of the casting that are difficult to feed with liquid metal (to encourage solidification while the connection to liquid metal is still open).
- **Internal Chills** – small metal parts placed inside the cavity before pouring so that the molten metal will solidify first around these parts.
- **External Chills** – metal inserts in the walls of the mold cavity that can remove heat from the molten metal more rapidly than the surrounding sand to promote solidification.



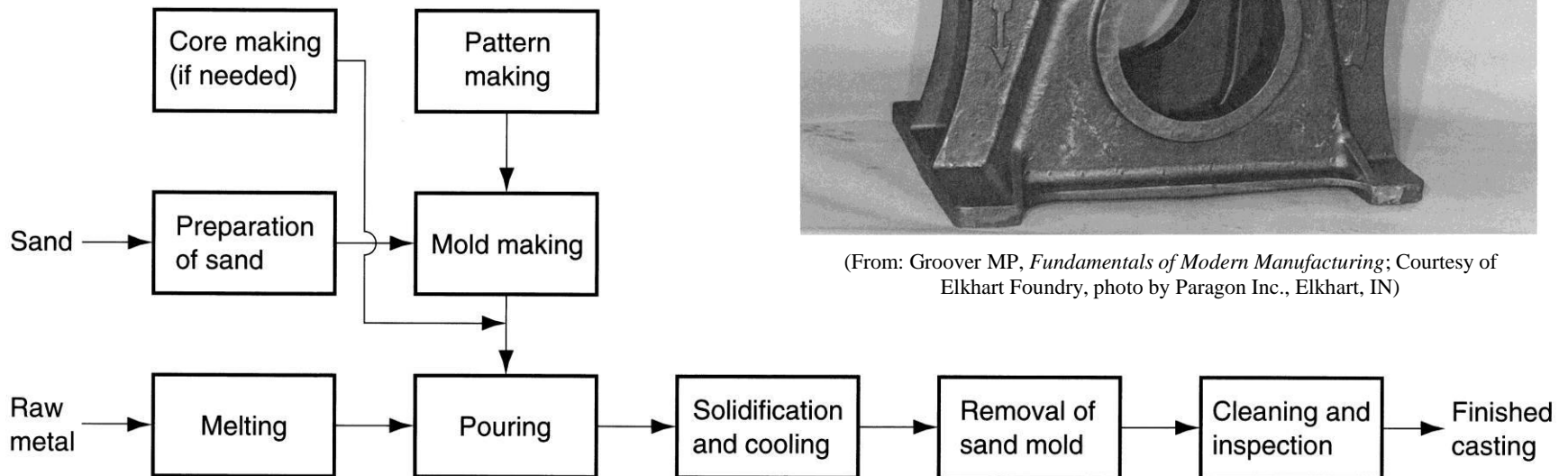
(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Sand Casting:

- Used for metals with high melting temperatures (steels, nickel, titanium, etc.).
- Part size: small to very large.
- Production quantity: one to millions.



(From: Groover MP, *Fundamentals of Modern Manufacturing*; Courtesy of Elkhart Foundry, photo by Paragon Inc., Elkhart, IN)



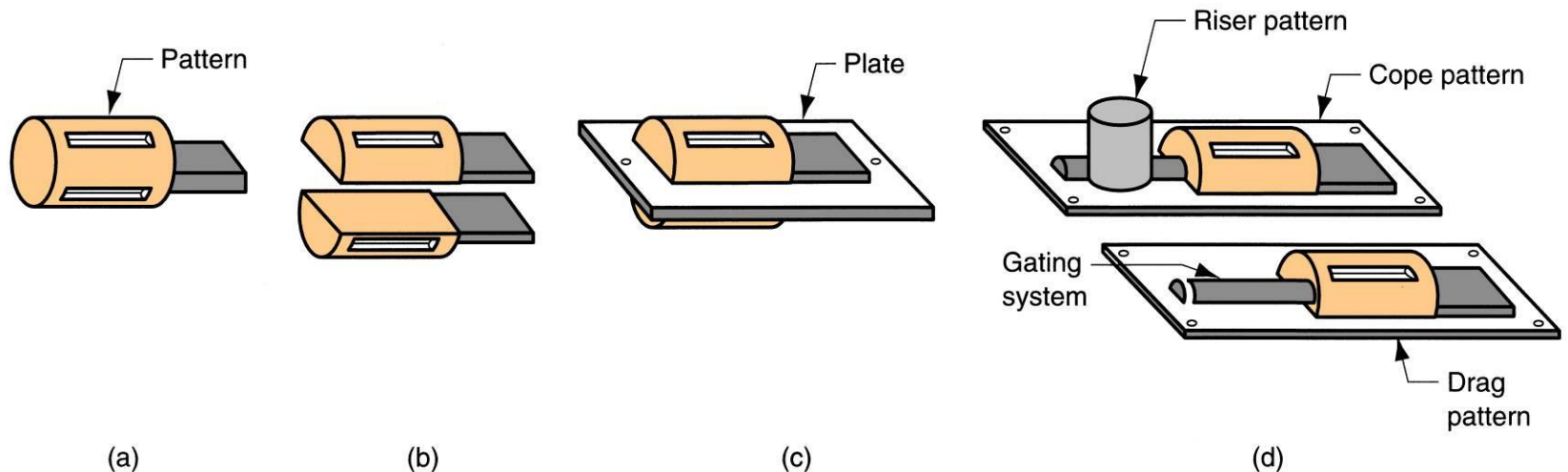
(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Patterns:

A full-sized model of the part, enlarged to account for shrinkage and machining allowances in the final casting.

Pattern Materials: wood (most common), plastics, and metals.

- Solid patterns: very low production quantities (skilled foundry workers needed).
- Split patterns: moderate production quantities (pre-determined parting line).
- Match-plate patterns and Cope-and-drag patterns: higher production quantities (accurate mold alignment is achieved using [locating holes](#)).

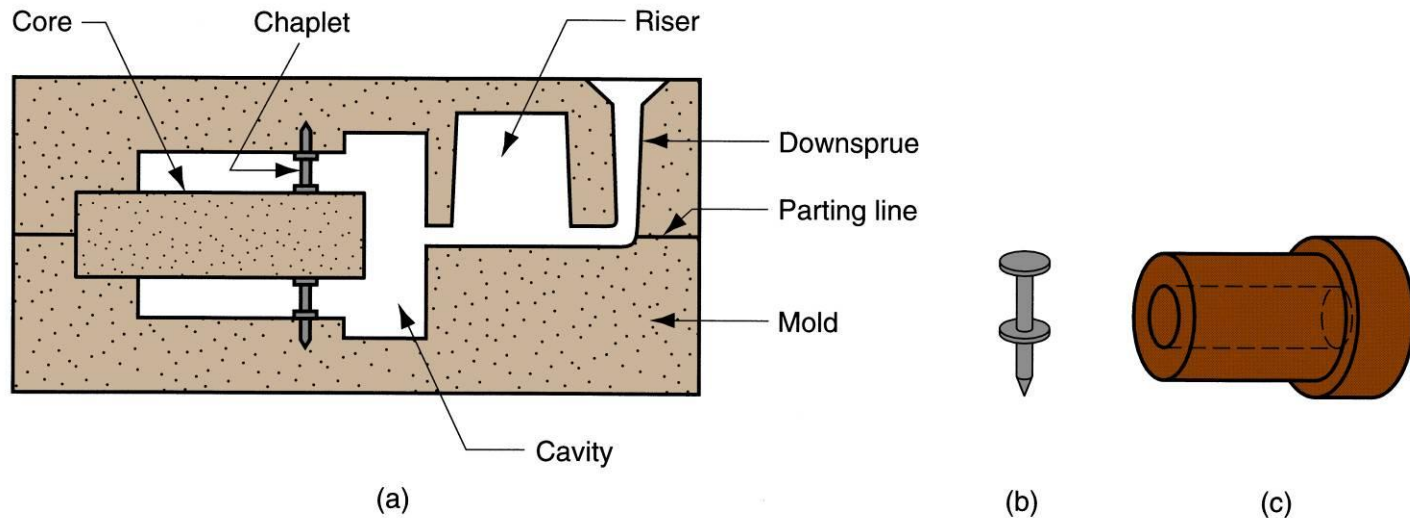


Cores:

Pattern → external shape of the cast part

Core → internal surfaces

- A core is a full-scale model of the interior surfaces of the part (taking into account the shrinkage and machining allowances). It is usually made of sand and inserted into the mold cavity prior to pouring.
- **Chaplets** – support the core to hold it in position in the mold cavity during pouring (against, e.g., the buoyancy force). They are made of a metal with a higher melting temperature than the casting metal.



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Foundry Sands:

Silica (SiO_2) or silica mixed with other minerals.

Important Features:

- Refractory properties – the capacity to stand high temperature without melting or otherwise degrading.
- Grain size (small vs. large).
- Distribution of grain size in the mixture.
- Shape of the individual grains (irregular vs. round).

Binders:

- Water and Clay (e.g., 90% sand, 3% water, and 7% clay in volume)
- Organic Resins
- Inorganic Binders

Additives – to enhance the mixture properties such as strength, permeability, etc.

The Packing Process:

- Hand ramming
- Packing machines

Sand Mold Quality Indicators:

- Strength – the ability to maintain shape and resist erosion.
- Permeability – the ability of the mold to allow hot air and gases from the casting operation to pass through the voids in the sand.
- Thermal Stability – the ability of the sand at the surface of the mold cavity to resist cracking and buckling upon contact with the molten metal.
- Collapsibility – the ability of the mold to give way and allow the casting to shrink after it solidifies without cracking the casting.
- Reusability.

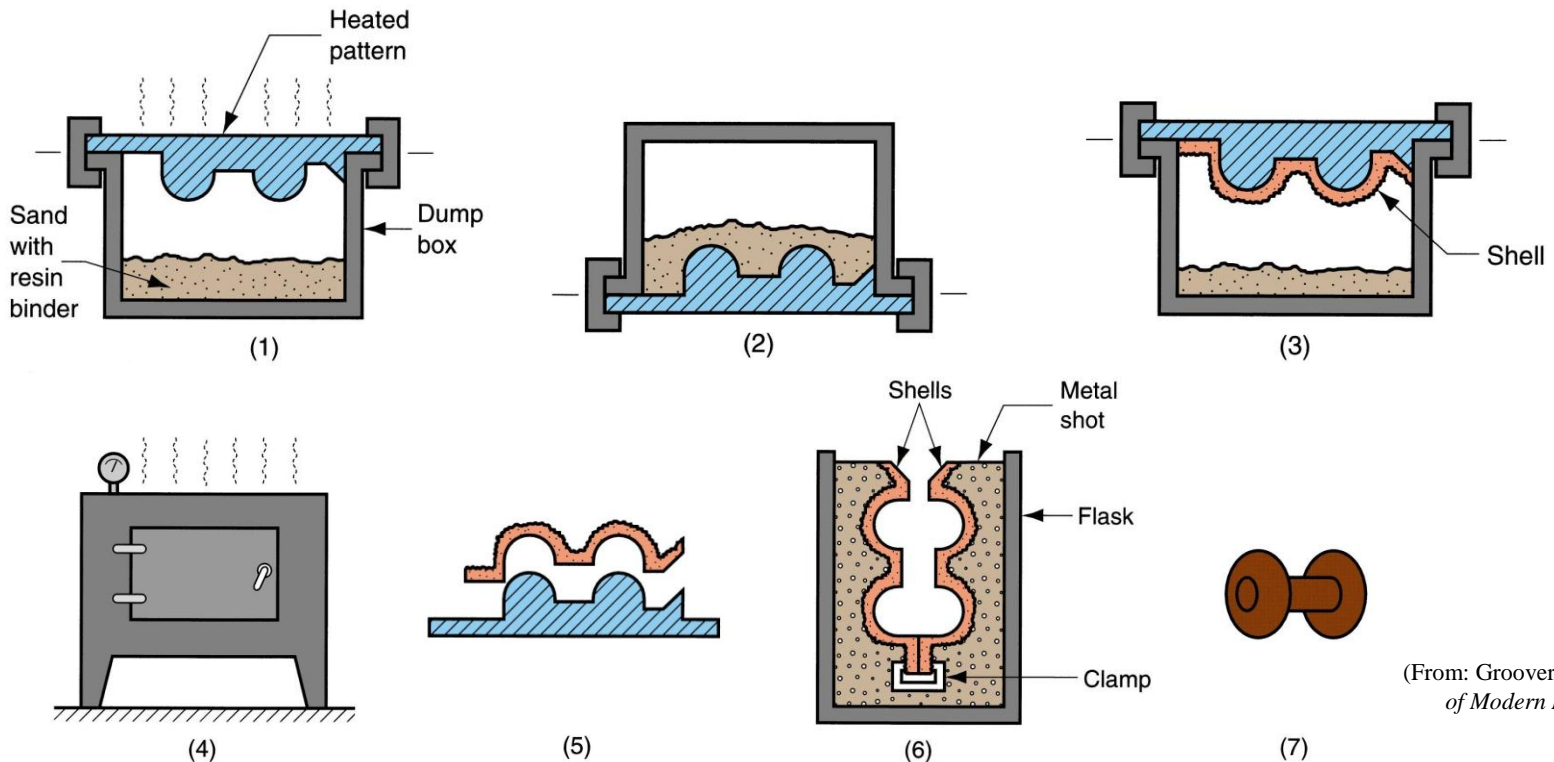
Sand Mold Classifications:

- Greensand molds – mixture of sand, clay, and water (most widely used).
- Dry-sand molds – organic binders (rather than clay) and oven baking.
 - better dimensional control (stronger mold and harder cavity surface)
 - more expensive (reduced production rate)
- Skin-dried molds – drying the surface of green sand molds to a depth of 0.5 to 1 in.
- Chemically bonded molds.
Gaining popularity due to good dimensional control in high production applications.

Shell Molding:

A casting process in which the mold is a thin shell (typically 3/8 in.) made of sand held together by a thermosetting resin binder.

- Smoother surface of the mold cavity (pouring and casting quality).
- Good dimensional accuracy (0.010 in.).
- Sufficient collapsibility.
- Can be mechanized for mass production.
- Economical for large quantities (more expensive metal patterns).

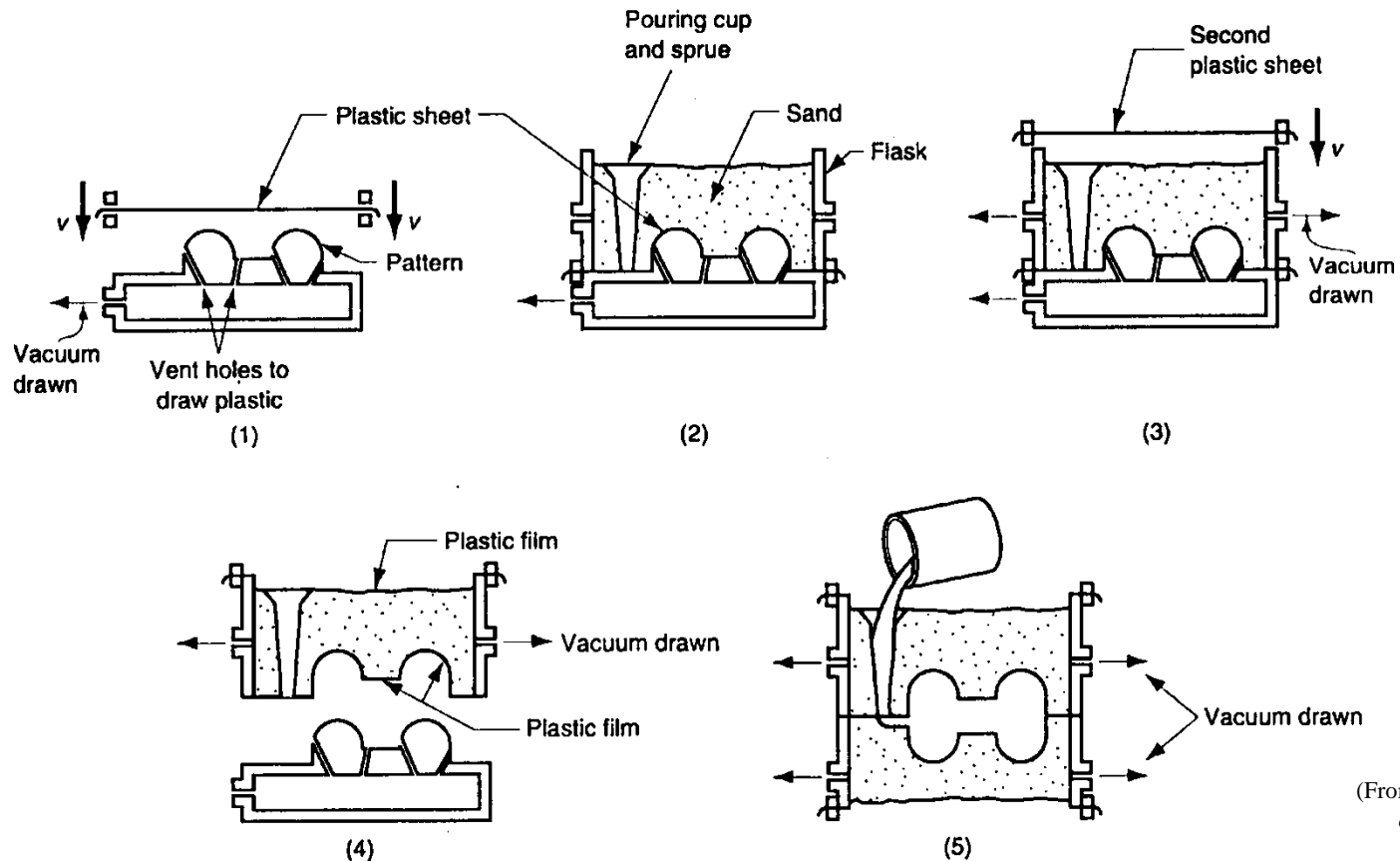


(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Vacuum Molding:

Uses a sand mold held together by vacuum rather than by a chemical binder.

- Easy recovery and reuse of sand (no binders are used).
- No moisture-related defects (no water is used).
- Relatively slow and not readily adaptable to mechanization.



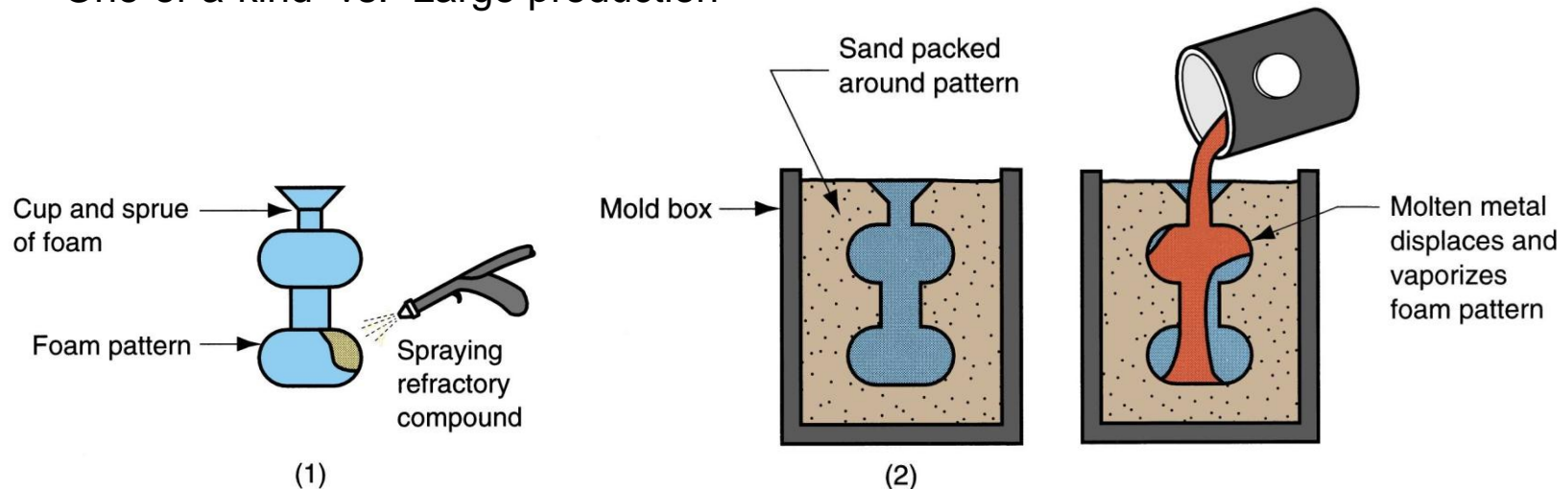
(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Expanded Polystyrene Casting Process:

Uses a mold of sand packed around a polystyrene foam pattern that **vaporizes** when the molten metal is poured into the mold.

- The polystyrene foam pattern does not need to be removed from the mold – simplifies and expedites mold making.
- The pattern includes the sprue, riser(s), gating system, and cores (if needed).
- Considerations of **draft** and **parting lines** can be ignored (the mold does not have to be opened into cope and drag sections).
- A new pattern is needed for every casting.
- Economic justification – depends on the cost of producing the patterns.

One-of-a-kind vs. Large production

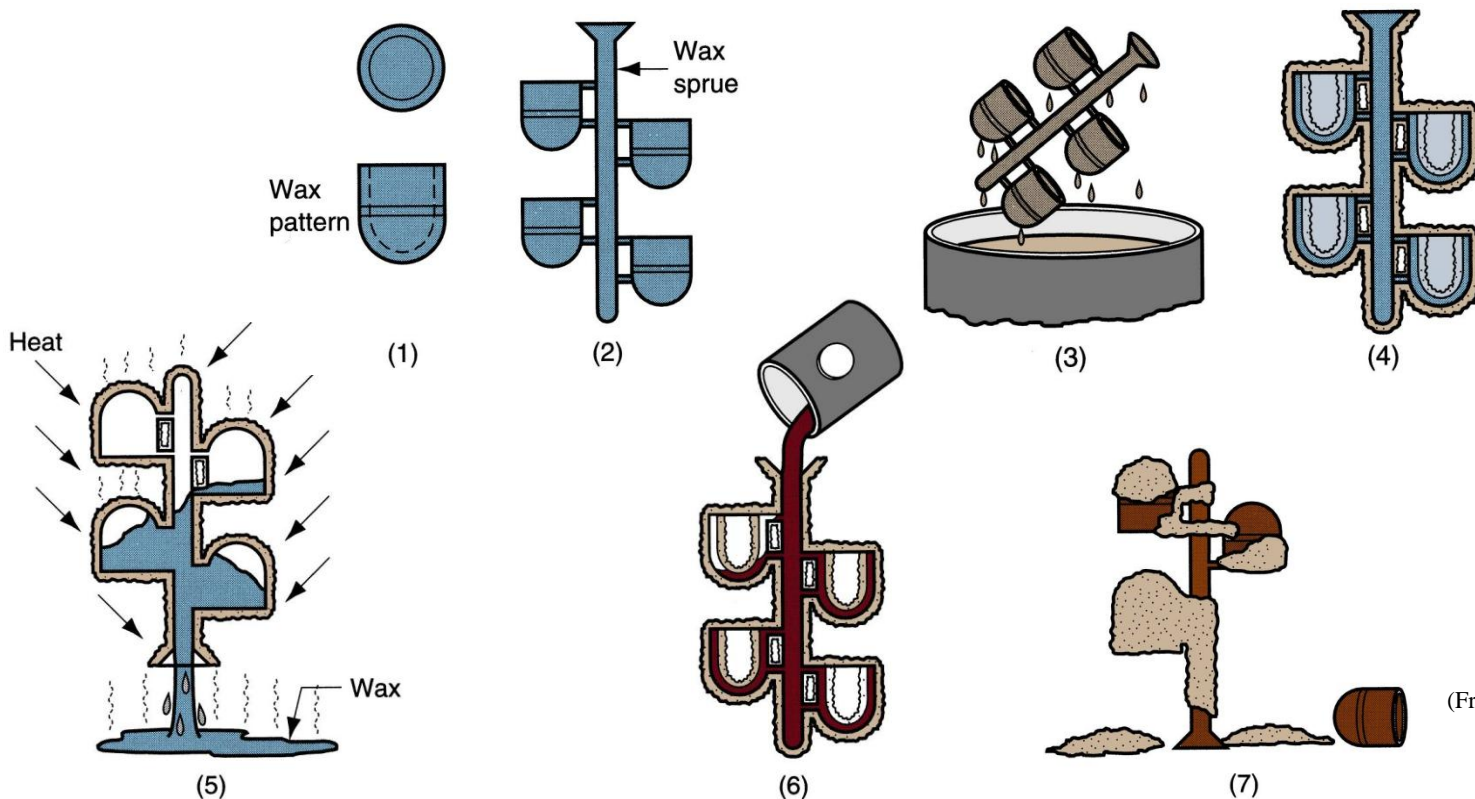


(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Investment Casting (lost-wax process):

A pattern made of wax is coated with a refractory material to make the mold, after which the wax is melted away prior to pouring the molten metal.

- Capable of casting parts of high accuracy (± 0.003 in.), great complexity, and intricate details – a relatively expensive but **precision** casting process.
- A separate pattern must be made for every casting (a molding operation).
- Refractory materials – very **fine** grained silica or others mixed with plaster.

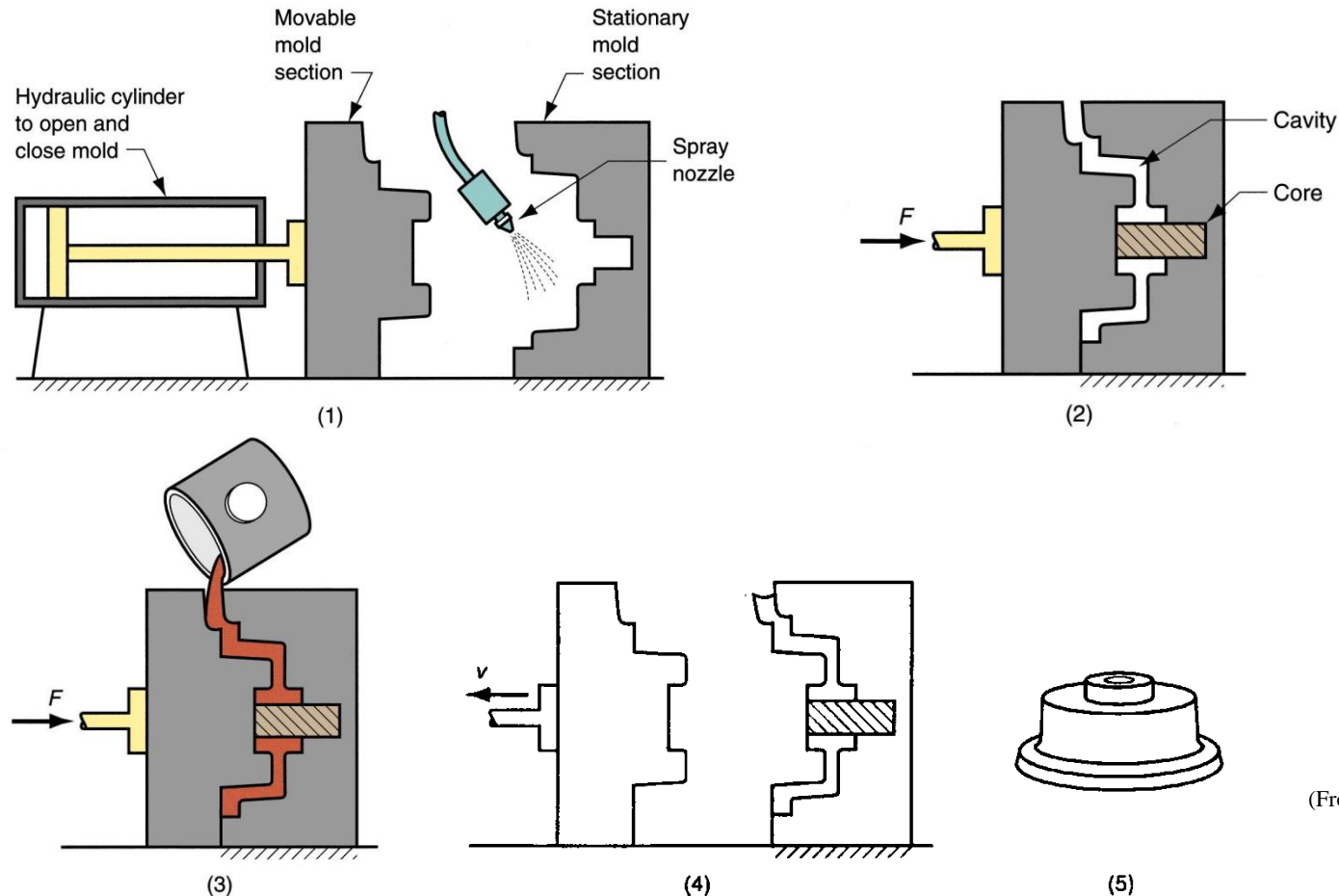


(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Basic Permanent Mold Casting:

Uses a metal mold constructed of two sections that are designed for easy, precise opening and closing.

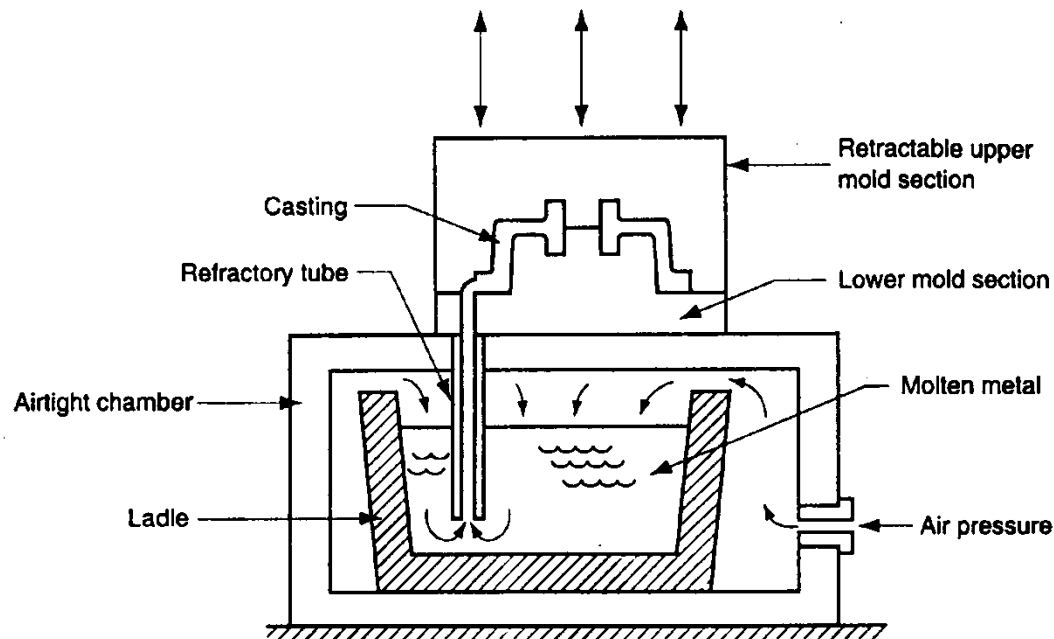
- Mold materials: steel or cast iron
- Casting materials: aluminum, magnesium, copper-based alloys, etc.



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

- Mold preheating – aids metal flow through the gating system and into the cavity.
- Spraying – facilitates heat dissipation and lubricates the mold surface for easier separation of the cast part.
- After pouring, as soon as the metal solidifies, the mold is opened and the casting is removed – to prevent cracks from developing in the casting.
- Metal cores vs. Sand cores (semi-permanent mold casting)
- Good surface finish, close dimensional control, and stronger castings (finer grains).
- Expense of the mold (substantial) – best suited for high volume production.

Low-Pressure Casting:



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

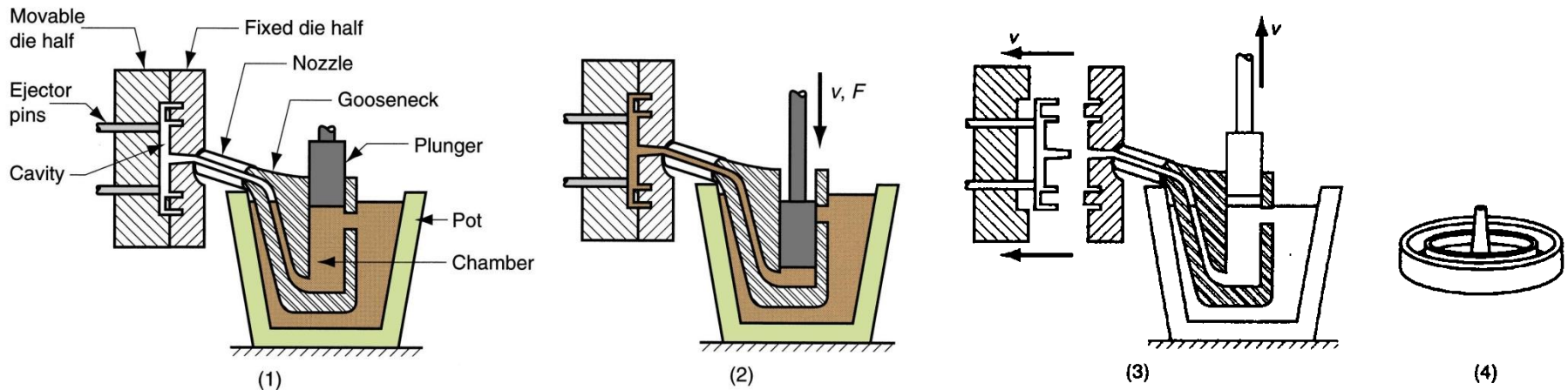
Die Casting:

A permanent mold casting process in which the molten metal is **injected** into the mold cavity under high pressure (1,000 to 50,000 lb/in²).

- The pressure is maintained during solidification.
- Venting holes must be built into the dies to evacuate the air and gases in the cavity.
- Flash formation – common in die casting (due to the high pressure).
- Thin sections are possible (down to about 0.020 in.).
- High production rates – economical for large production quantities.

Hot-Chamber Die Casting:

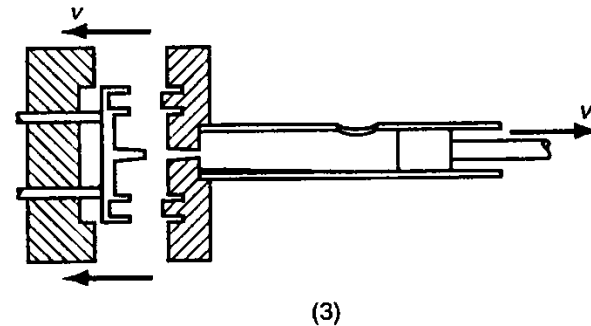
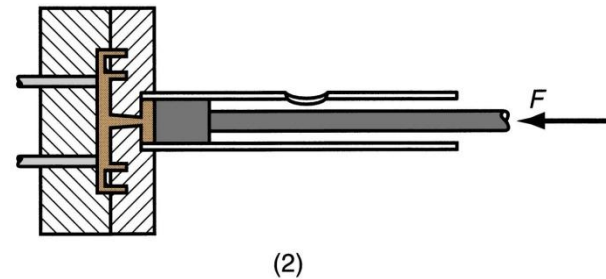
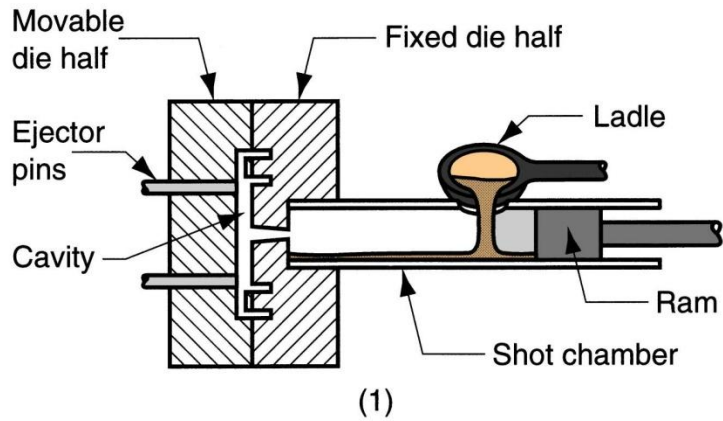
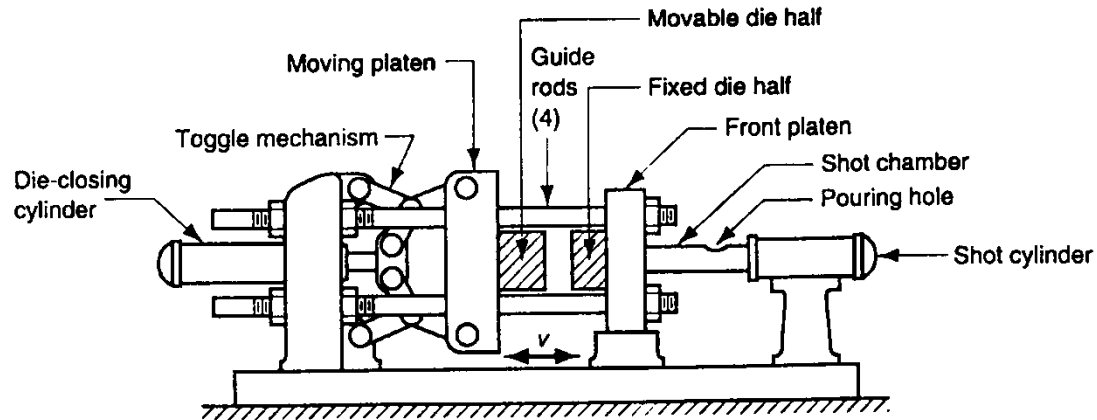
- Applications limited to low melting point metals that do not chemically attack the plunger and other mechanical components – zinc, tin, lead, etc.



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Cold-Chamber Die Casting:

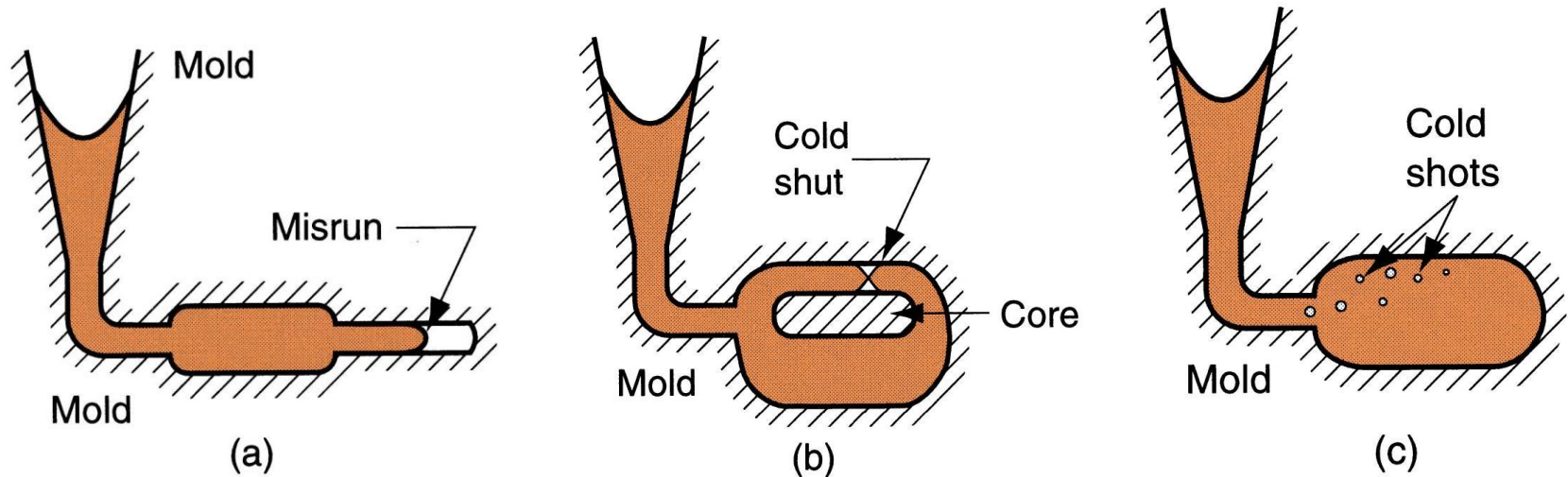
- Casting materials: aluminum, brass, and magnesium alloys



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Common Casting Defects:

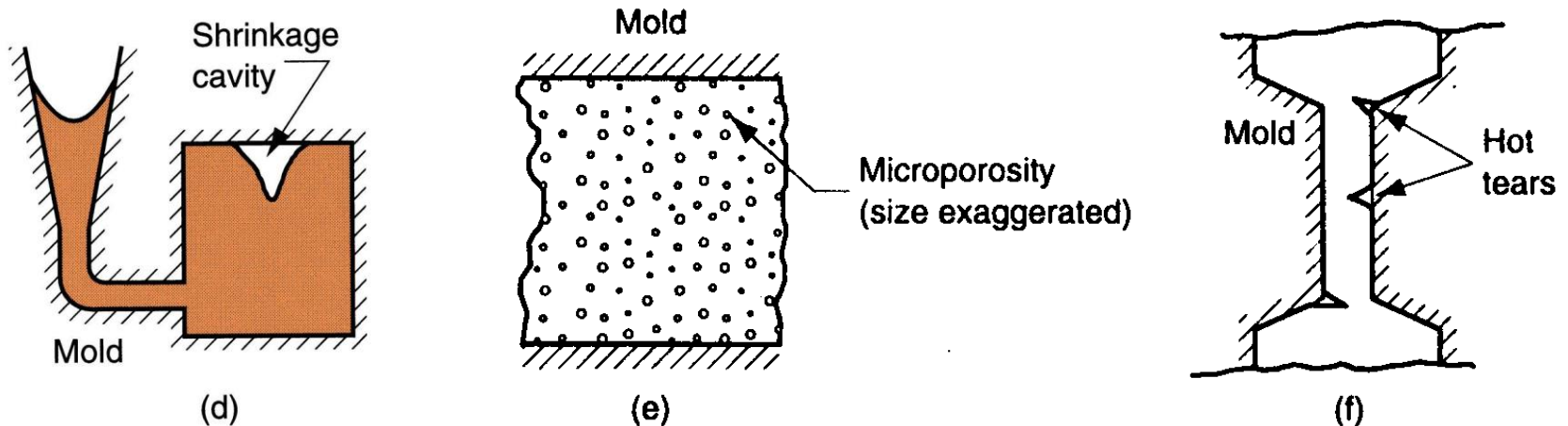
- **Misrun** – a casting that has solidified before completely filling the mold cavity (insufficient fluidity and/or inappropriate mold design).
- **Cold Shut** – occurs when two portions of the metal flow together, but there is a lack of fusion between them due to premature freezing.
- **Cold Shots** – when splattering occurs during pouring, solid globules of metal are formed that become entrapped in the casting.



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

- **Shrinkage Cavity** – a depression in the surface or an internal void in the casting caused by solidification shrinkage.
- **Microporosity** (usually for alloys) – a network of small voids distributed throughout the casting caused by localized solidification shrinkage of the final molten metal in the dendritic structure.
- **Hot Tearing** (Hot Cracking) – occurs when the casting is restrained from contraction by an unyielding mold during the final stages of solidification or early stages of cooling after solidification.

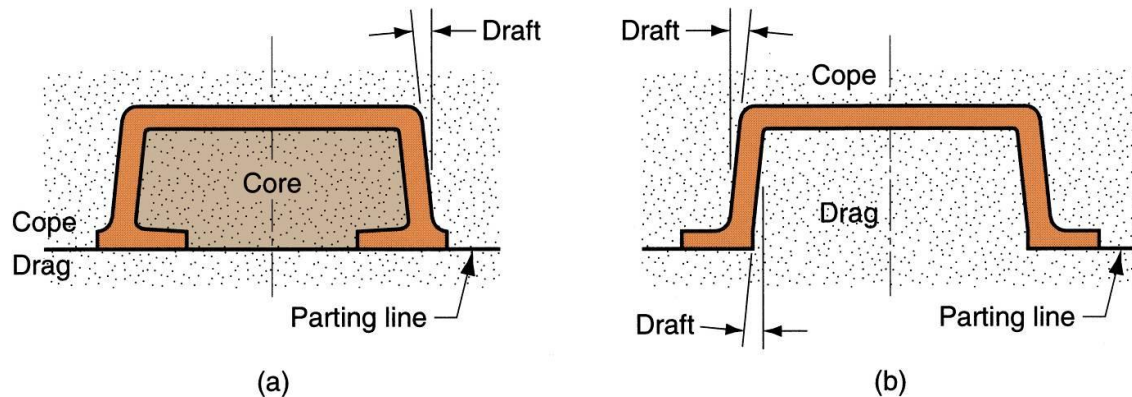
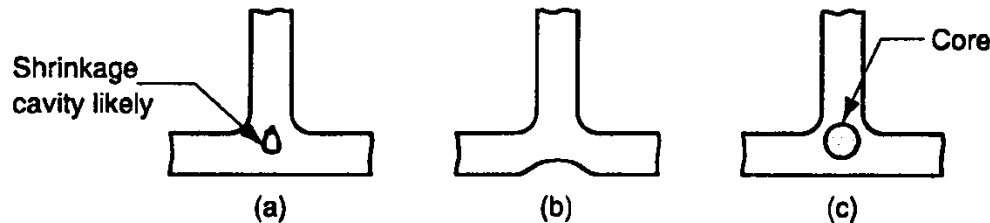
Expendable mold processes vs. Permanent mold processes



(From: Groover MP, *Fundamentals of Modern Manufacturing*)

Product Design Considerations:

- Geometric simplicity – avoid unnecessary complexities.
- Corners – avoid sharp corners and angles (use generous fillets).
- Section thicknesses – uniform to avoid shrinkage cavities.
- Draft – for part sections that project into the mold.
 - Expendable mold casting – 1° , Permanent mold casting – 2° to 3° .
- Reduce the use of cores.
- Dimensional tolerances and surface finish considerations.



(From: Groover MP, *Fundamentals of Modern Manufacturing*)