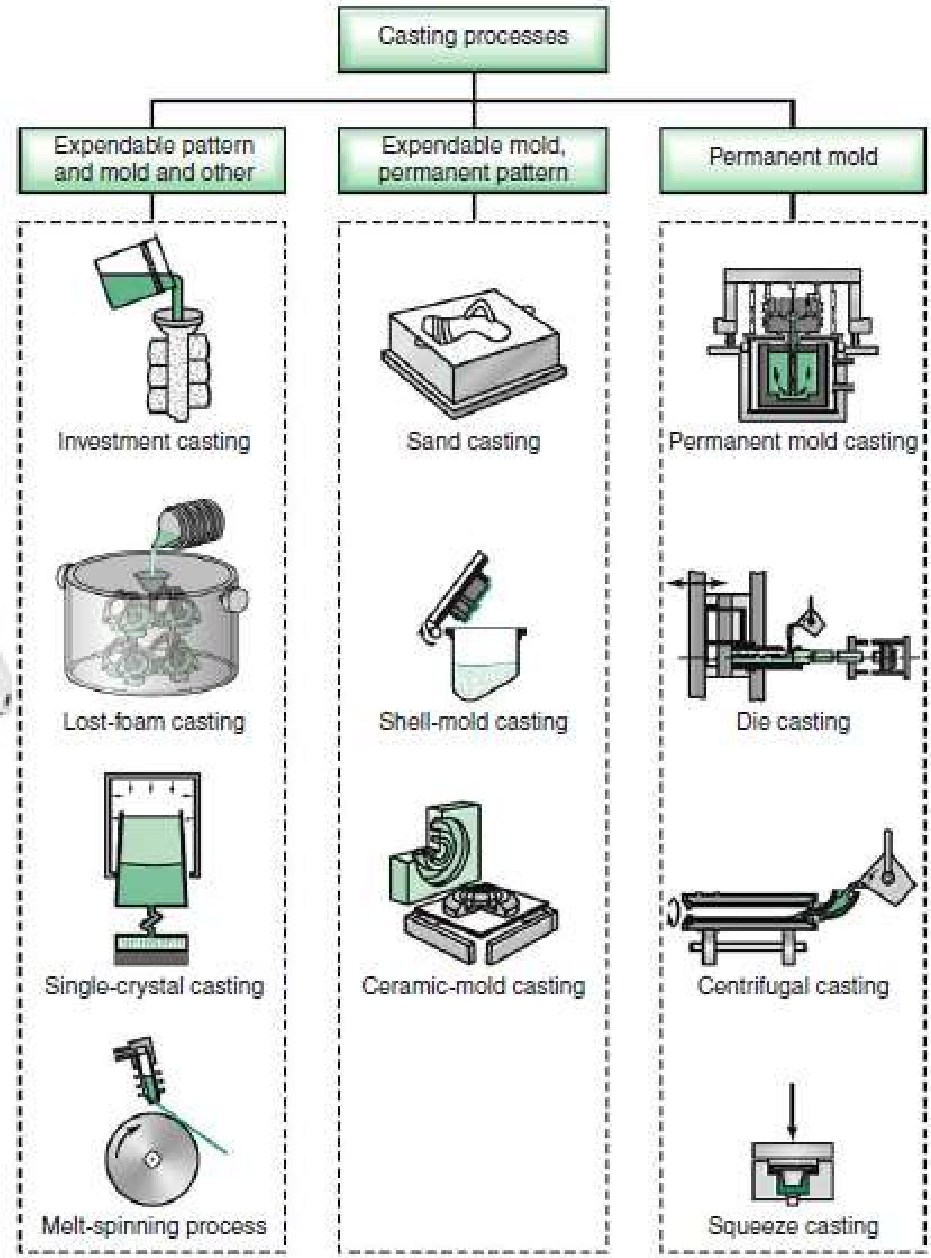
Casting Processes

(a) Melting of metal in a furnace,
(b) Flow of molten metal into a mold cavity,
(c) Solidification and cooling of metal in mold,



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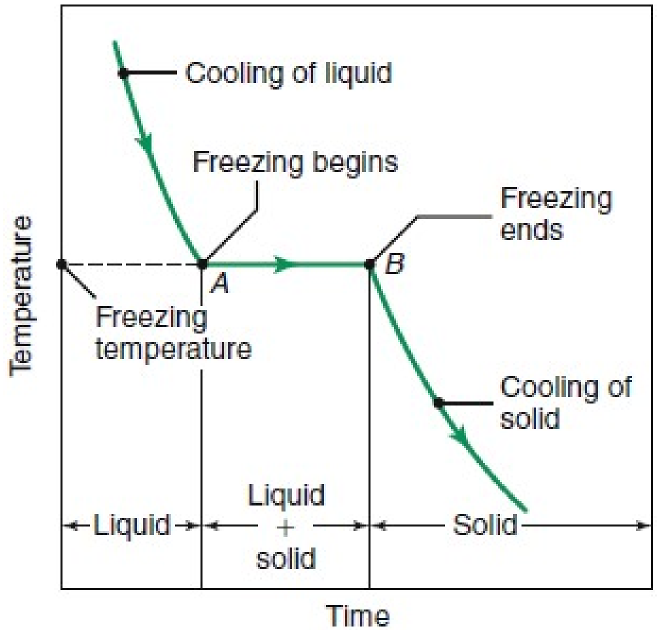
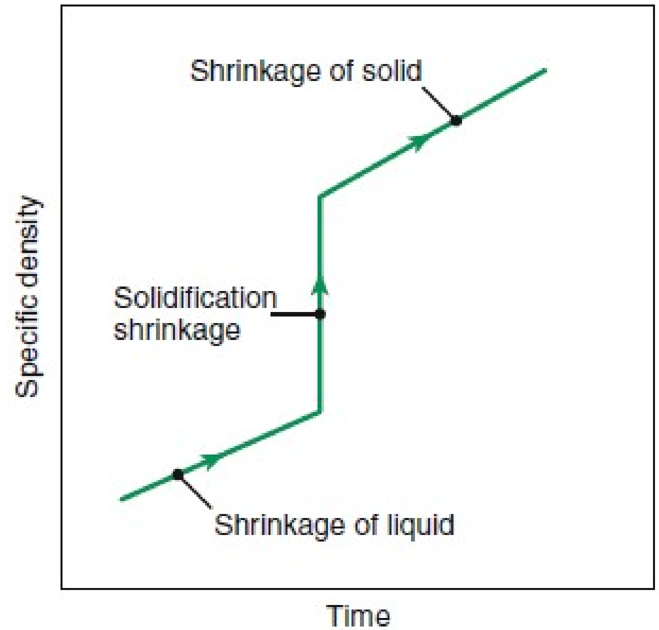
Casting Processes – Solidification – Pure Metal





(a) Pure metal solidifies at a fixed temp. (e.g. Al – 660 C; Fe – 1537 C; W – 3410 C)

(b) At freezing temperature, latent heat of fusion is given off,

(c) Solidification front (solid – liquid interface) moves through the molten metal from the mold wall towards the center,

(d) Once solidified, the cast is taken out of mold.

(e) Metal also shrinks as it solidifies and cools to room temperature.

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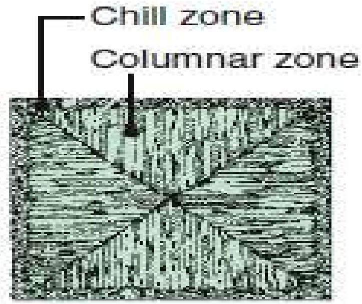
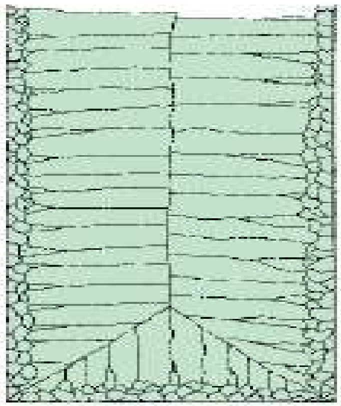
Solidification Structure – Pure Metal

Mold wall is much cooler – so. molten metal cools rapidly and produces a solidified skin of fine equiaxed zone,



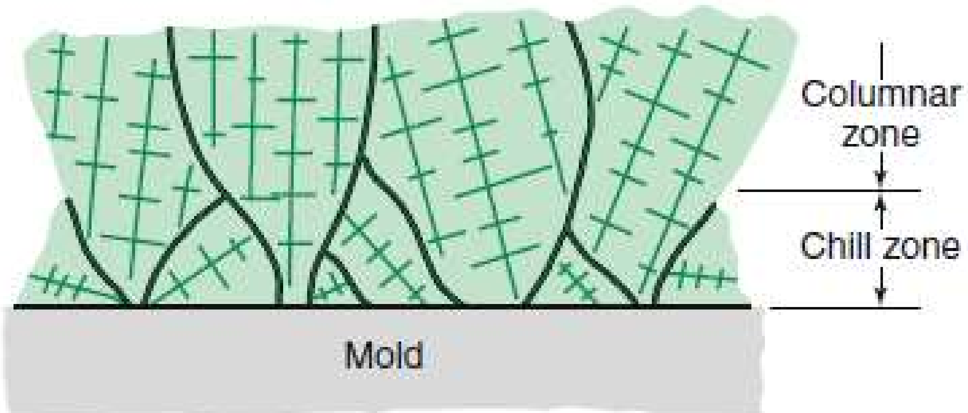
Grains grow in a direction opposite to that of the heat transfer through the mold – **columnar grains**,



Grains with favorable orientation grow as **columnar grains** but those with different orientation are blocked

As temperature gradient reduces away from mold wall, grains are equiazed and coarse,

This is **homogeneous nucleation** – i.e. grains (crystals) grow upon themselves,



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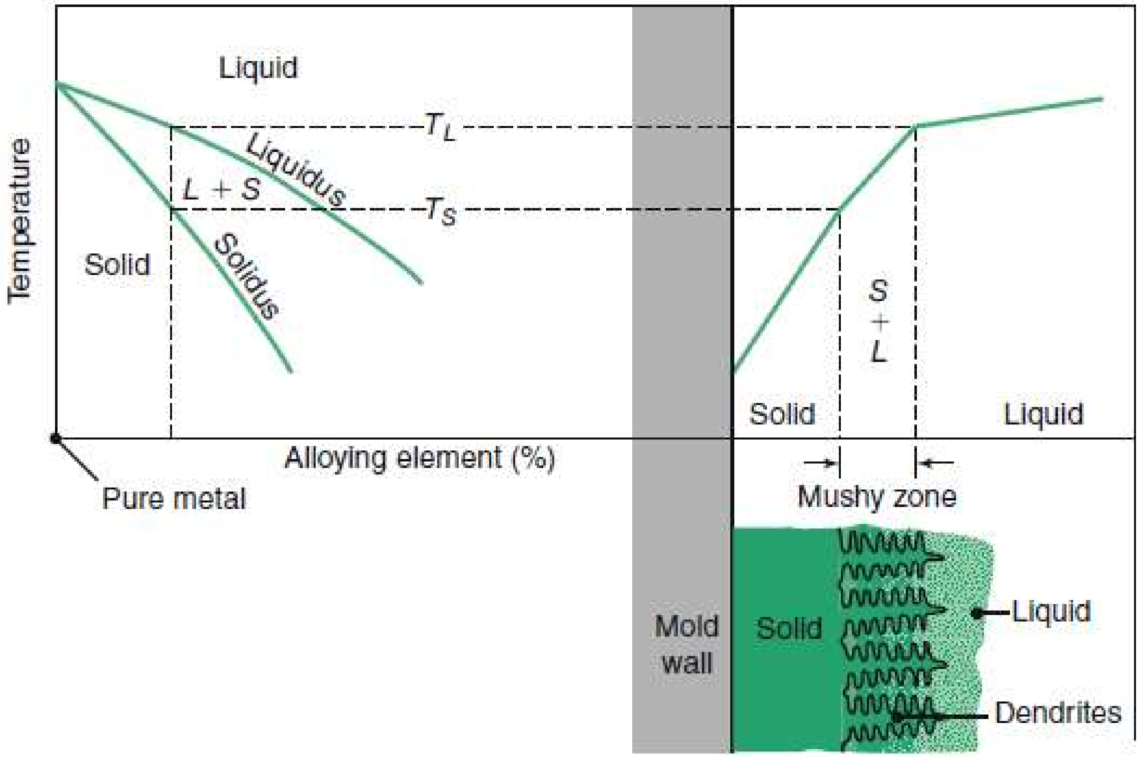
Solidification Structure – Alloys



Solidification in alloys begins when temperature drops below T_L, and is complete when it reaches T_S.

Between (T_L and T_S), the alloy remains in a mushy state consisting of **columnar dendrites**.

Dendritic Structure is bad as the dendrite arms entrap eutectic liquid.

Dendritic Structure also contribute to several other detrimental factors such as compositional variation, segregation and microporosity in a cast part.

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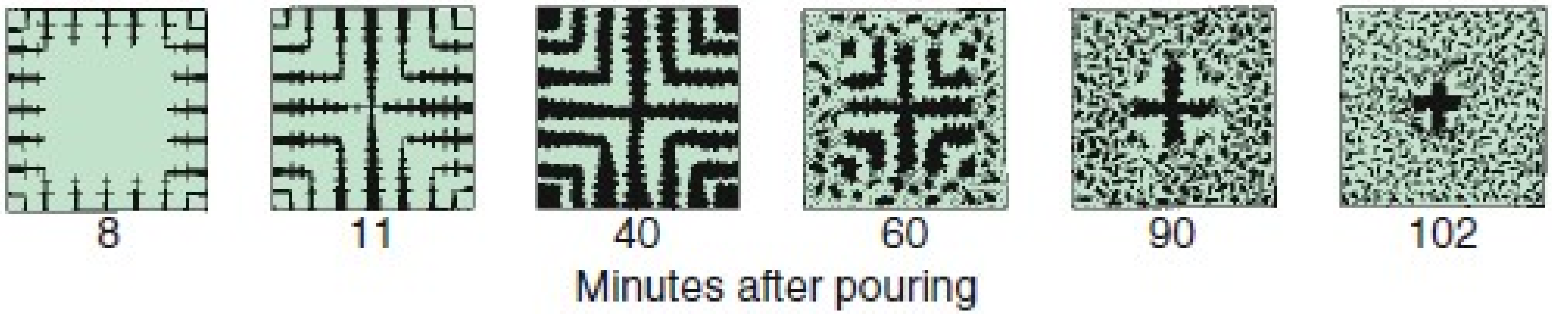
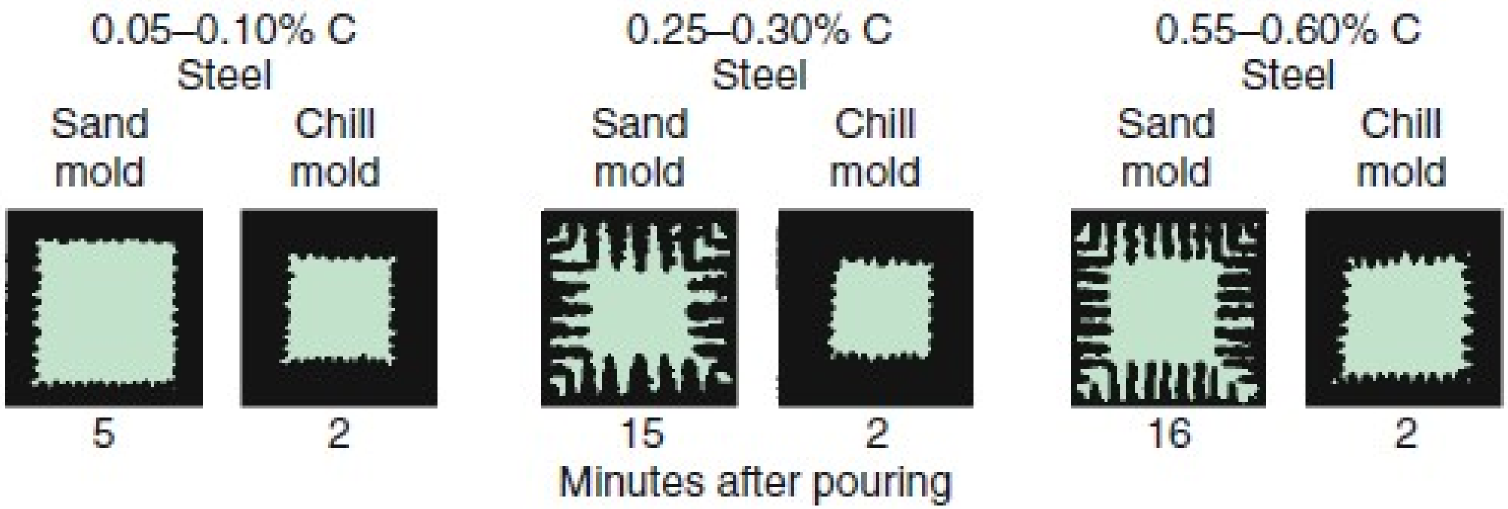
Solidification Structure – Alloys



Solidification pattern for gray cast iron in a 180 mm square cast – takes almost 2 hrs for complete solidification – however, dendrites reach each other after even 11 s.



Heat transfer conditions of mold walls and chemical composition of alloys can influence the solidification structure and final property of the cast significantly.

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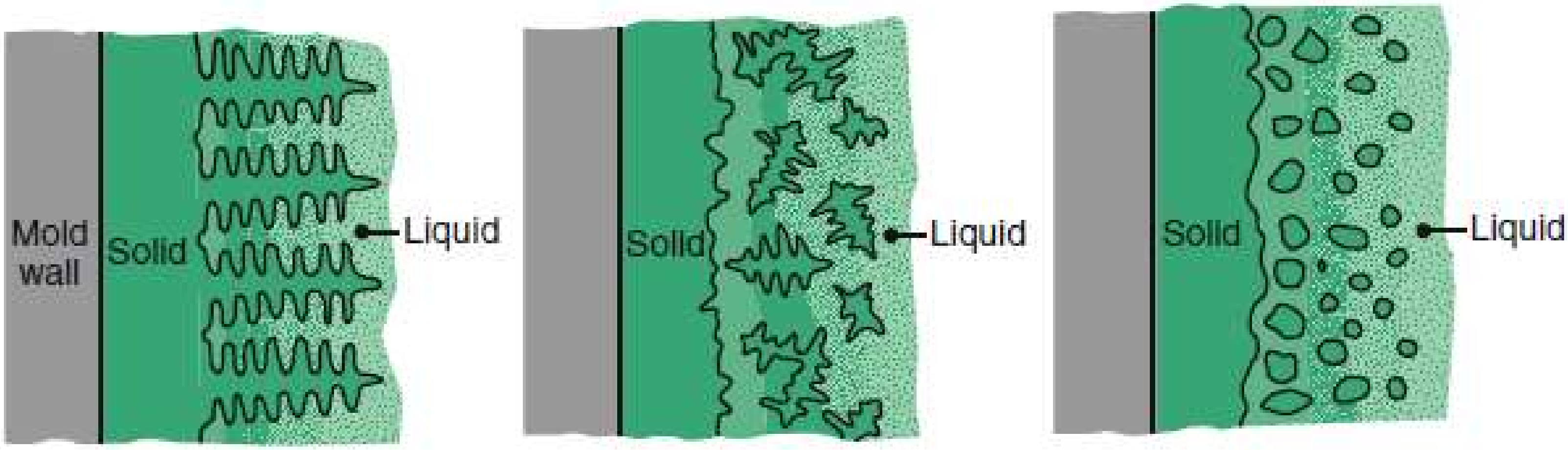
Solidification Structure and Property – Alloys



Morphology of dendrites and **Concentration** of alloys can vary widely in different regions of the cast resulting in variation in properties within the cast.

A very slow cooling can allow dendrites to form uniform composition. But, a little fast cooling, which usually happen in reality, form **cored dendrites** (surface has higher concentration of alloying elements than the core - **microsegregation**).

Marosegregation is another challenge. This refers to compositional difference thru' the cast. For example, low melting point constituents in the solidified alloy are driven towards the center (**normal segregation**).

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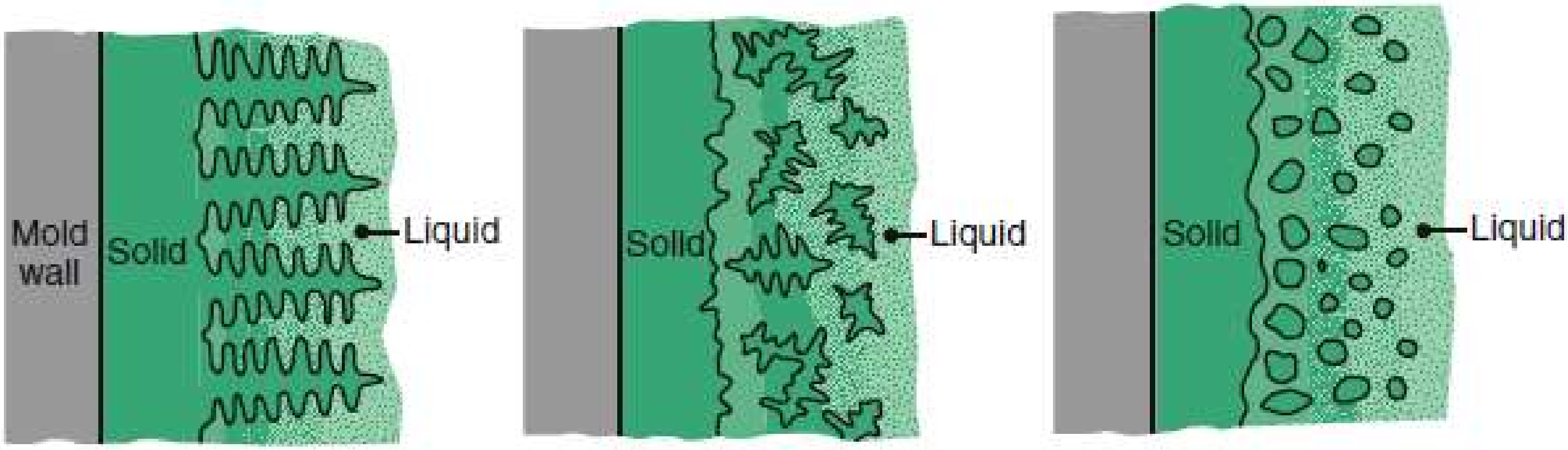
Solidification Structure and Property – Alloys



The structure in the middle can be influenced by increasing convection in the liquid. A bit of convection can help separation of dendrite arms and transition from columnar to equiaxed (**CTE**) structure.

Dendrite arms can also be broken in the early stages of solidification (rheocasting, semisolid processing, etc.) by agitation or mechanical vibration producing equiaxed non-dendritic structure (**top – right**).

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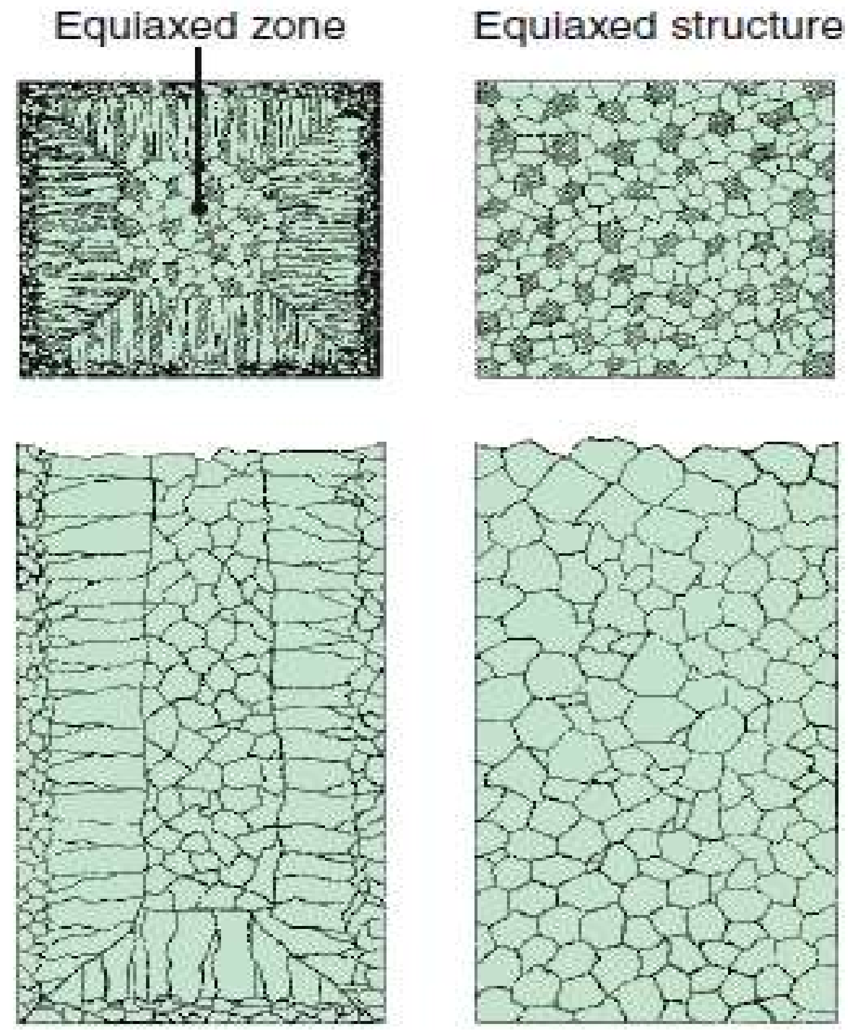
Solidification Structure – Solid Solution Alloys

A typical cast structure of a solid-solution alloy with an inner zone of equiaxed grains.

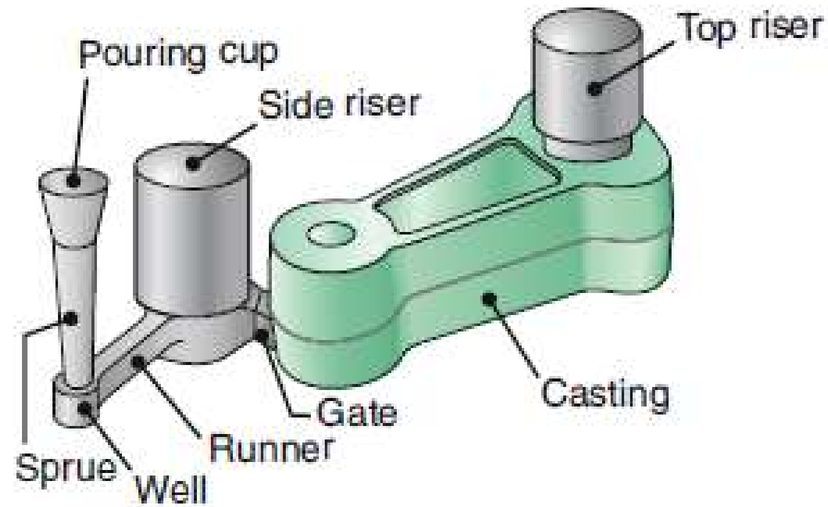
The inner zone can be extended all through the cast by adding an inoculant (nucleating agent) to the alloy. The inoculant induces nucleation of the grains through out the liquid – this is called **heterogeneous nucleation.**

Another form of segregation of alloys is due to gravity, which allows higher density inclusions and compounds to sink and lighter elements to float on the surface. This is referred to as the gravity segregation.



Flow of Molten Metal

Molten metal is poured through a pouring basin and it then flows through the gating system (sprue, runner and gates) to mold cavity.



Risers or feeders act as reservoirs of molten metal, which will be supplied (if required) to prevent porosity due to shrinkage during solidification.

Risers or feeders act as reservoirs of molten metal, which will be supplied (if required) to prevent porosity due to shrinkage during solidification.

As molten metal enters into the actual mold, it must be handled carefully to avoid formation of oxides. It should not cool before reaching to the mold cavity, and do not entrap any gas.

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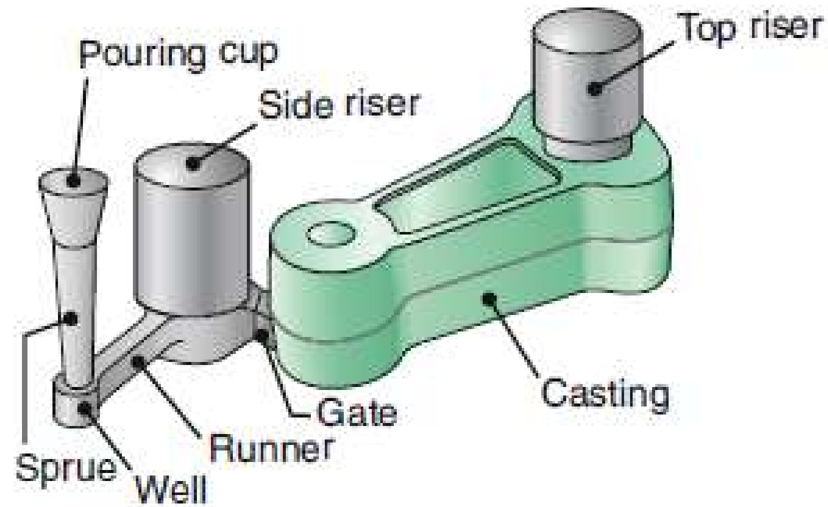
Flow of Molten Metal

$$h + \frac{p}{\rho g} + \frac{v^2}{2g} = \text{constant},$$



h is elevation above a certain level, *p* is pressure at that elevation, *v* is the velocity of the liquid at that elevation, ρ is density of liquid (assuming that it is incompressible) and *g* is the gravitational constant.

$$h_1 + \frac{p_1}{\rho g} + \frac{v_1^2}{2g} = h_2 + \frac{p_2}{\rho g} + \frac{v_2^2}{2g} + f,$$

f is the friction loss.

$$Q = A_1 v_1 = A_2 v_2,$$

Continuity of Mass: *For incompressible fluids and in a system with impermeable walls, the rate of flow is constant*

Q is volume rate of flow, A is cross-sectional area of liquid stream and v is the average velocity of the liquid in that cross-section.

A constant permeability of mold wall is very important. Otherwise, some liquid will escape through the mold wall and flow rate will decrease as the liquid stream will move thru' the mold.

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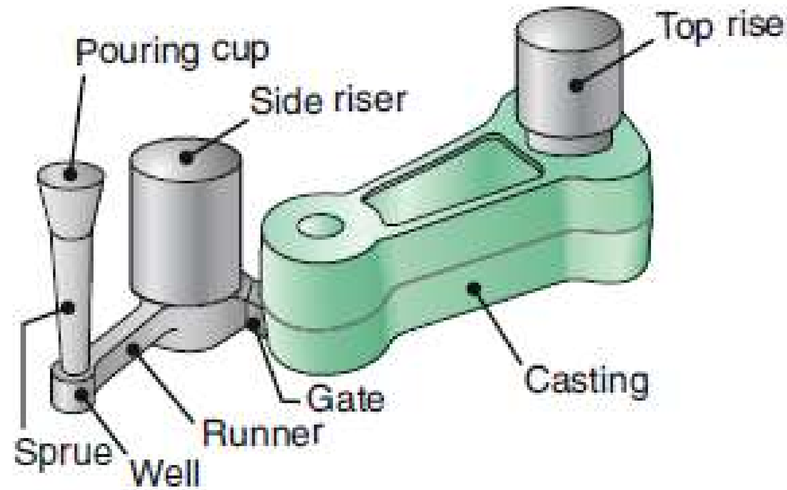
Flow of Molten Metal – Sprue Design

For a free falling liquid (such as water from a faucet), the cross-section area of the stream decreases as the liquid gains velocity downward.



So, if we design a sprue with constant cross-section, regions can develop where liquid loses contact with sprue wall. As a result, **ASPIRATION** (**a process whereby air is sucked in or entrapped in the liquid**) may take place.

A tapered sprue is an alternative and its specific shape can be determined as

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

Assuming no frictional loss encountered by the liquid stream.

Flow of Molten Metal – Solidification Time

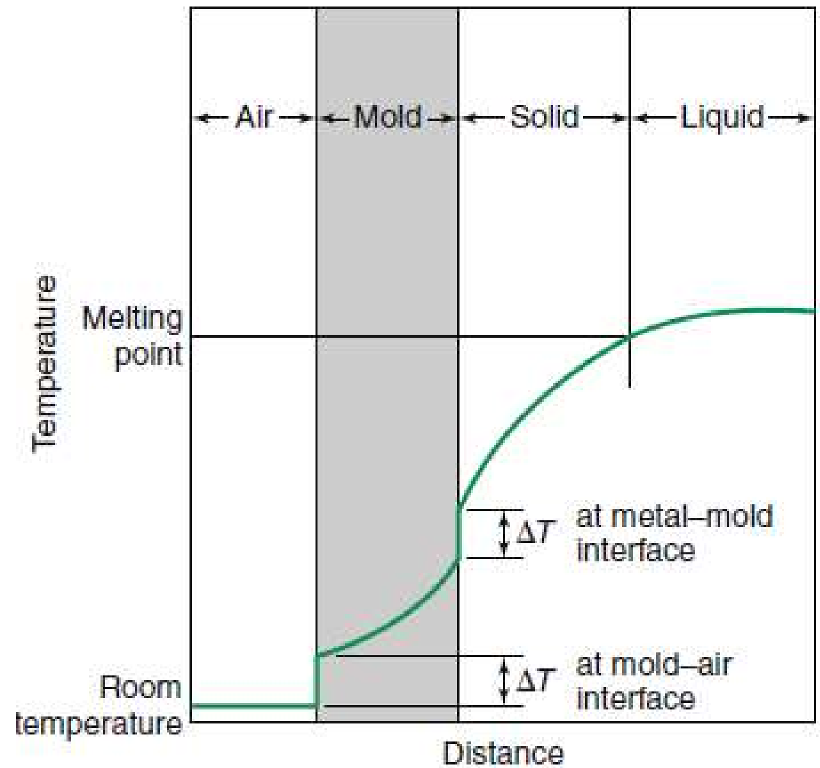
Heat transfer from pouring to solidification to cooling to room temperature is very important.

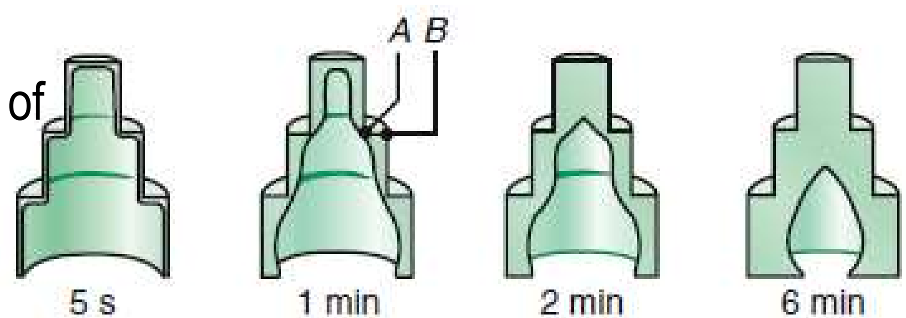
Heat from the liquid metal is given off thru' the mold wall and to the surrounding air. The temperature drop at the air-mold and mold-metal interfaces is caused by the presence of the boundary layers and imperfect contact at these interfaces.

During the early stages, a thin skin begins to form at the relatively cool mold walls. As time passes, the thickness of the ski increases. **With a flat mold wall, this thickness is almost proportional to the square root of time.**

The solidification time is a function of the volume of a casting and its surface area (*Chvorinov's rule*).

$$\text{Solidification time} = C\left(\frac{\text{Volume}}{\text{Surface area}}\right)^n$$





Typical slush casting with molten metal being poured out after the indicated times.

Flow of Molten Metal – Solidification Time

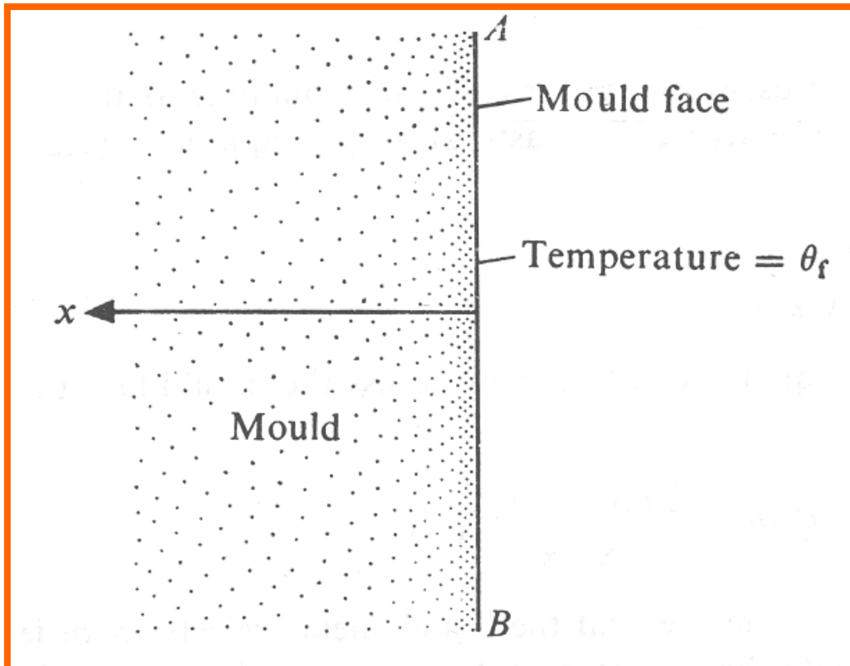
$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t}$$

$$T_x(t) = T_0 + (T_f - T_0)\left[1 - \operatorname{erf}\frac{x}{2\sqrt{\alpha t}}\right]; \quad \operatorname{erf}(z) = \frac{2}{\sqrt{\pi}}\int_0^z e^{-x^2}dx$$

$$\dot{Q} = -kA\left.\frac{\partial T}{\partial x}\right|_{x=0} = \frac{kA(T_f - T_0)}{\sqrt{\pi\alpha t}}$$

$$Q_{t_0} = \int_0^{t_0}\dot{Q}\,dt = \frac{2kA(T_f - T_0)}{\sqrt{\pi\alpha}}\sqrt{t_0}$$

$$Q_R = \rho_m V[L + C_m(T_p - T_f)]$$



$$t_s = \gamma\left(\frac{V}{A}\right)^2 \quad \text{where} \quad \gamma = \left(\frac{\rho_m\sqrt{\pi\alpha}\,[L + C_m(T_p - T_f)]}{2k(T_f - T_0)}\right)$$

Chvorinov's rule

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Flow of Molten Metal – Filling of Mold Cavity

Instantaneous Filling

Pressure Die Casting, Centrifugal Casting, Injection Molding

Slow Filling

Sand Casting, Investment Casting, Shell Molding, Gravity Die Casting

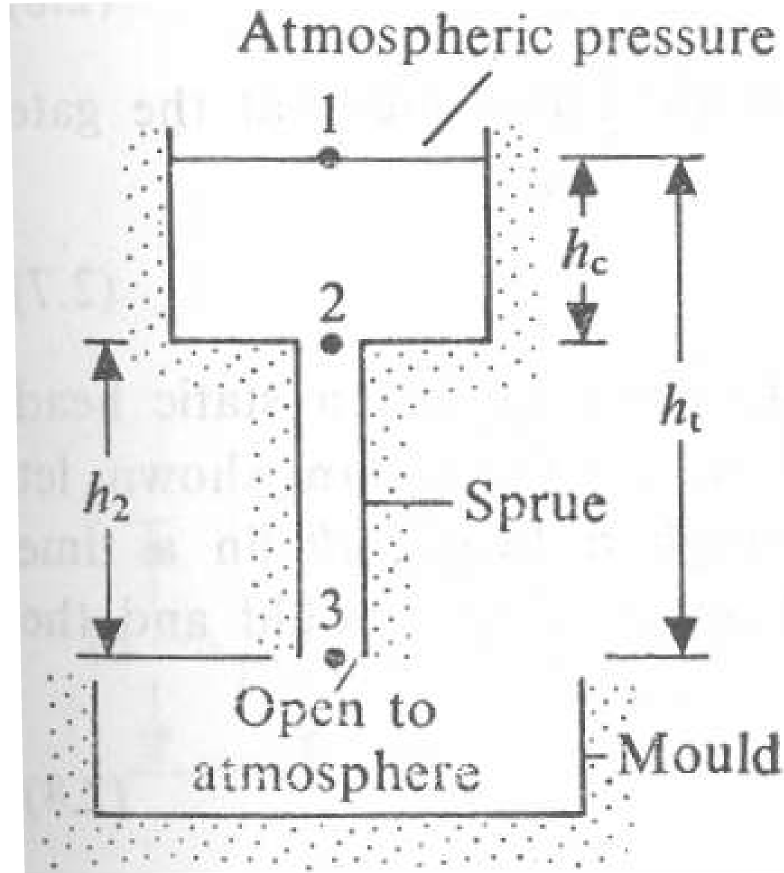
Sand Casting

Top Gating, Bottom Gating, Horizontal Gating

Time to fill a Mold Cavity – Sand Mold

Energy Balance

$$\frac{v_3^2}{2}+\frac{p_3}{\rho_m}+g\cdot 0=\frac{v_1^2}{2}+\frac{p_1}{\rho_m}+gh_t$$



Time to fill, t_f

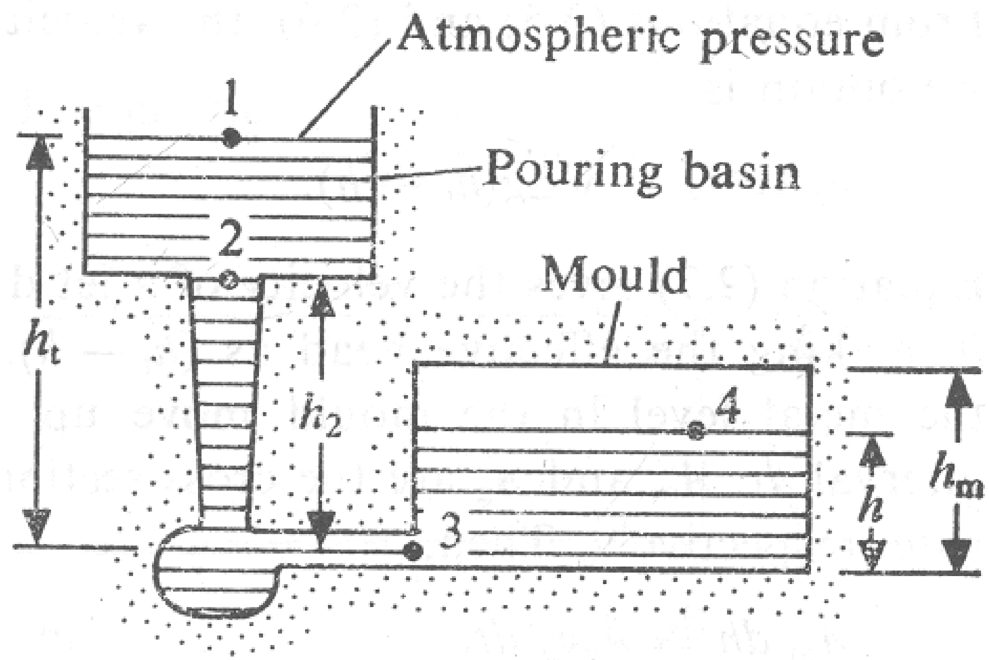
$$t_f=\frac{V}{A_g v_3}$$

Time to fill a Mold Cavity – Sand Mold (Bottom Gating)

Energy Balance

$$\frac{v_3^2}{2} + \frac{p_3}{\rho_m} + g \cdot 0 = \frac{v_1^2}{2} + \frac{p_1}{\rho_m} + gh_t$$

$$\frac{v_4^2}{2} + \frac{p_4}{\rho_m} + gh = \frac{v_3^2}{2} + \frac{p_3}{\rho_m} + g \cdot 0$$



$$\Rightarrow \quad \boxed{v_g = v_3 = \sqrt{2g(h_t - h)}}$$

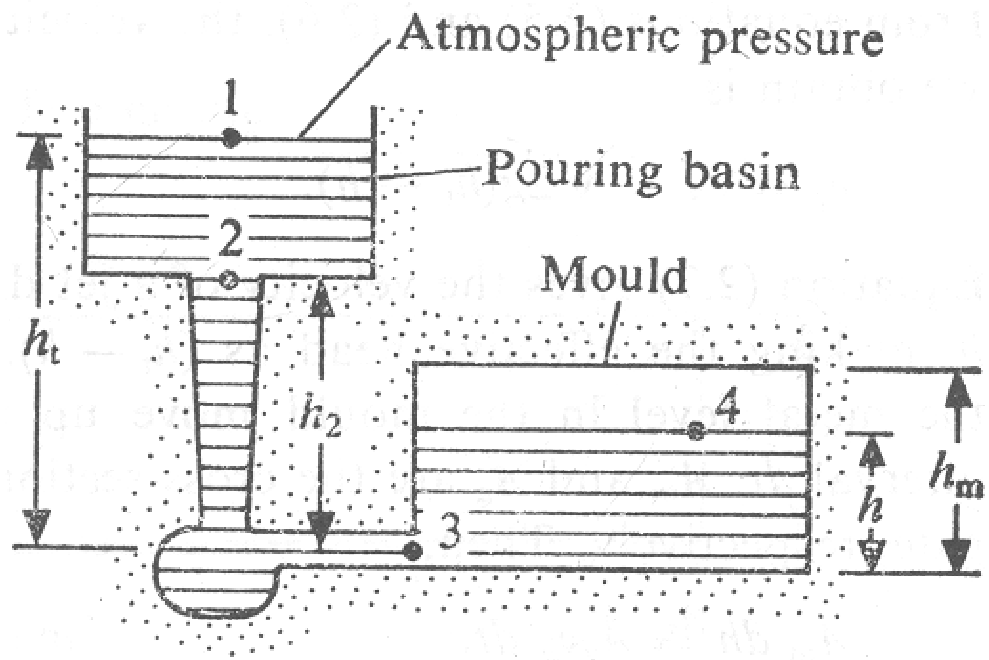
Time to fill a Mold Cavity – Sand Mold (Bottom Gating)

Mass conservation

$$A_m dh = A_g v_g dt$$

$$\Downarrow$$

$$\frac{1}{\sqrt{2g}} \frac{dh}{\sqrt{h_t - h}} = \frac{A_g}{A_m} dt$$



Time to Fill, t_f

$$\Rightarrow \quad \frac{1}{\sqrt{2g}} \int_0^{h_m} \frac{dh}{\sqrt{h_t - h}} = \frac{A_g}{A_m} \int_0^{t_f} dt$$

$$t_f = \frac{A_m}{A_g} \frac{1}{\sqrt{2g}} 2\left(\sqrt{h_t} - \sqrt{(h_t - h_m)}\right)$$

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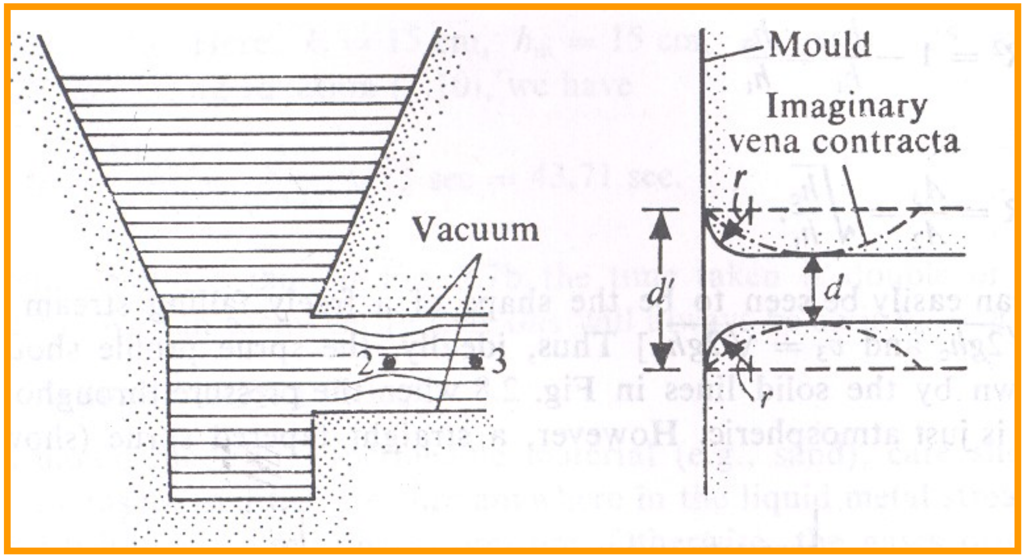
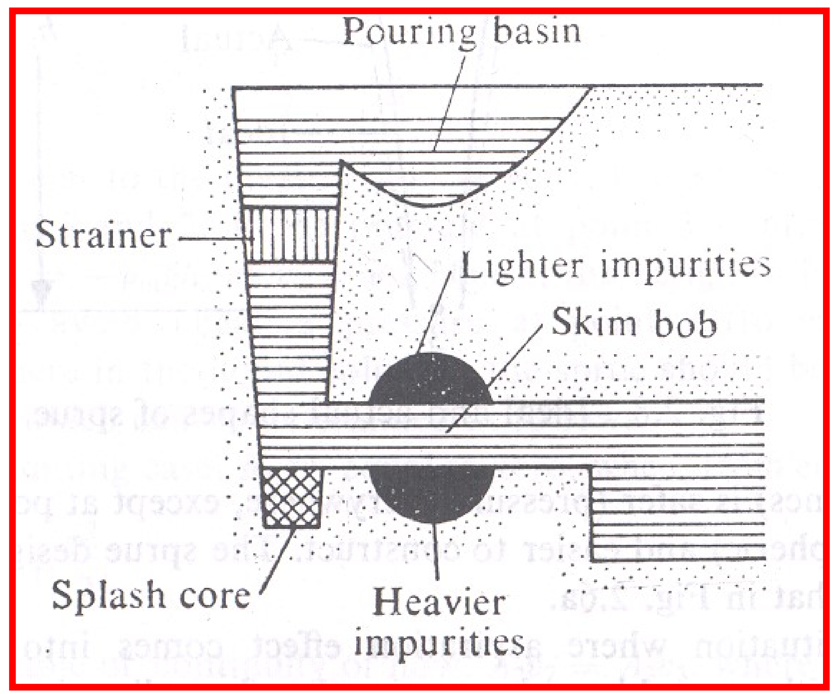
Gating Design is very important





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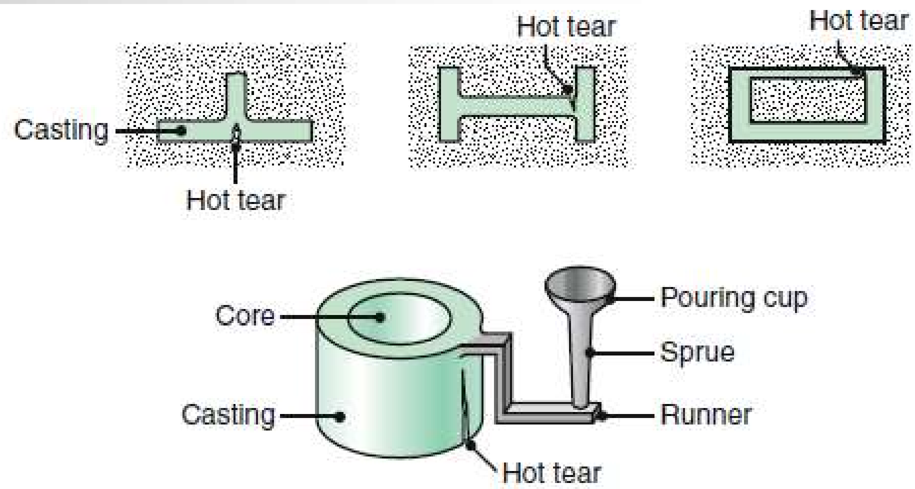
Common defects in Casting

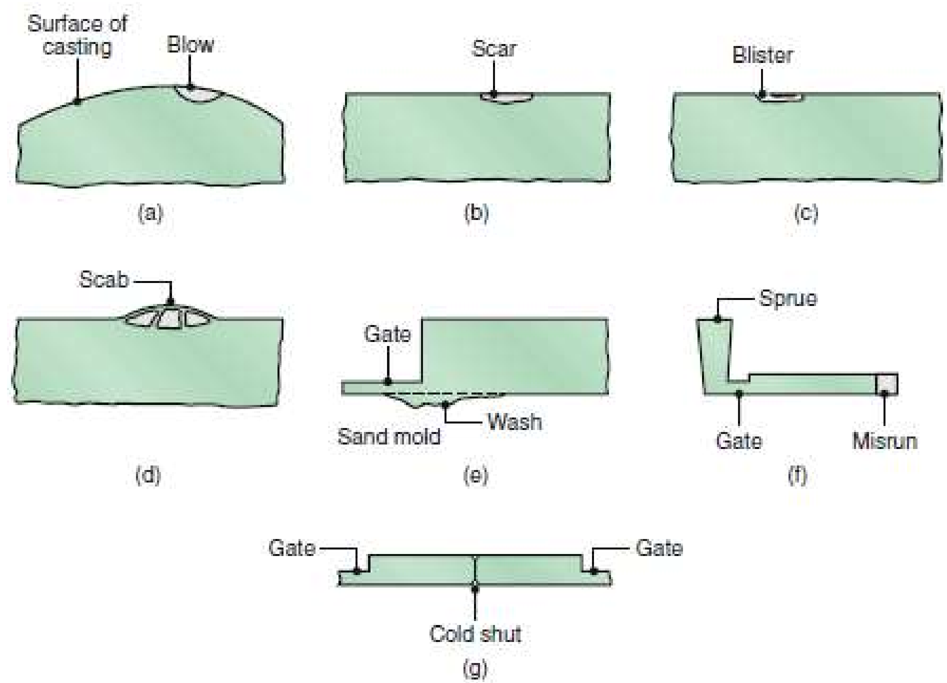
Metallic Projections – consisting of fins, flash, or projections such as swells & rough surfaces.

Cavities – rounded or rough internal or exposed cavities including blowholes, pinholes and shrinkage cavities.

Discontinuities – cracks, cold or hot tearing, and cold shuts. If solidifying metal is constrained from free shrinkage, cracking and tearing may occur. **Cold shut** is an interface that lacks complete fusion because of meeting of two liquid streams from different gates.

Defective surface – surface folds, laps, scars, adhering sand layers and oxide scale.





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Common defects in Casting

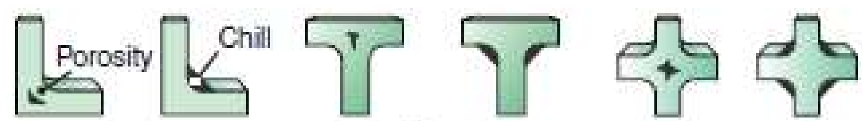
Incomplete casting – misrun due to premature solidification and insufficient volume of metal poured, and runout due to loss of metal from the mold after pouring.

Incorrect dimension or shape – due to improper shrinkage allowance, pattern-mounting error, irregular contraction, deformed pattern, warped casting….. .

Inclusions – generally nonmetallic and forms during melting, solidification and molding. These are harmful as they arc as stress raisers and reduce the impact strength and ductility of the casting.

Porosity – can form due to shrinkage, or dissolved gases or both. Microporosity can develop when liquid metal soldifies and shrinks between dendrtes and between dendrite branches.

(a)



(b)

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Casting Processes - Classifications

Casting processes are generally categorized as **permanent mold** and **expendable mold** processes. **Expendable mold** processes are further categorized as **permanent mold** and **expendable pattern** processes..

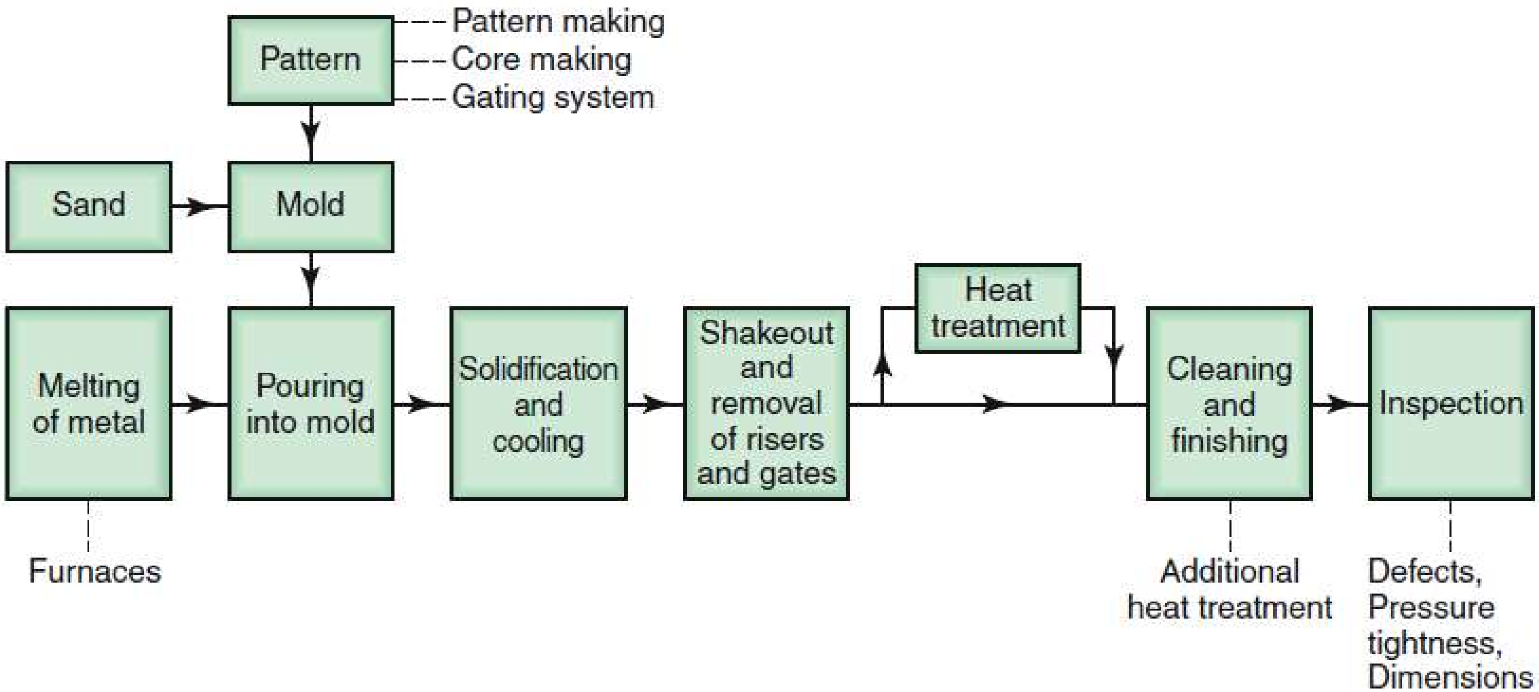
Expendable molds: made of sand, plaster, ceramics, and similar refractory materials. These are mixed with various binders for improved properties. A typical sand mold consists of 90% sand, 7% clay, and 3% water.

In **sand and shell casting**, the mold is produced from a pattern, which can be reused - so, **expendable-mold, permanent-pattern processes**.

But, **investment casting** consumes a pattern for each mold produced - so, **expendable-mold, expendable pattern** process.

Permanent mold :: made of metals that maintain their strength at high temperatures. These are made for repeated use with a facility for easy removal of cast.

Expendable Mold Permanent Pattern Casting



Naturally bonded (bank sand) and **synthetic (lake sand)** - two types of sand are generally used. **Synthetic sand** is used as its composition can be controlled more accurately.

Sand particles should be **fine**, **rounded** and **uniformly distributed** to form a smooth mold surface. Fine grained sand enhances mold strength but lowers mold permeability. The mold also should have good **collapsibility** to allow the casting to shrink while cooling and, thus, to avoid defects in the casting, such as hot tearing and cracking.

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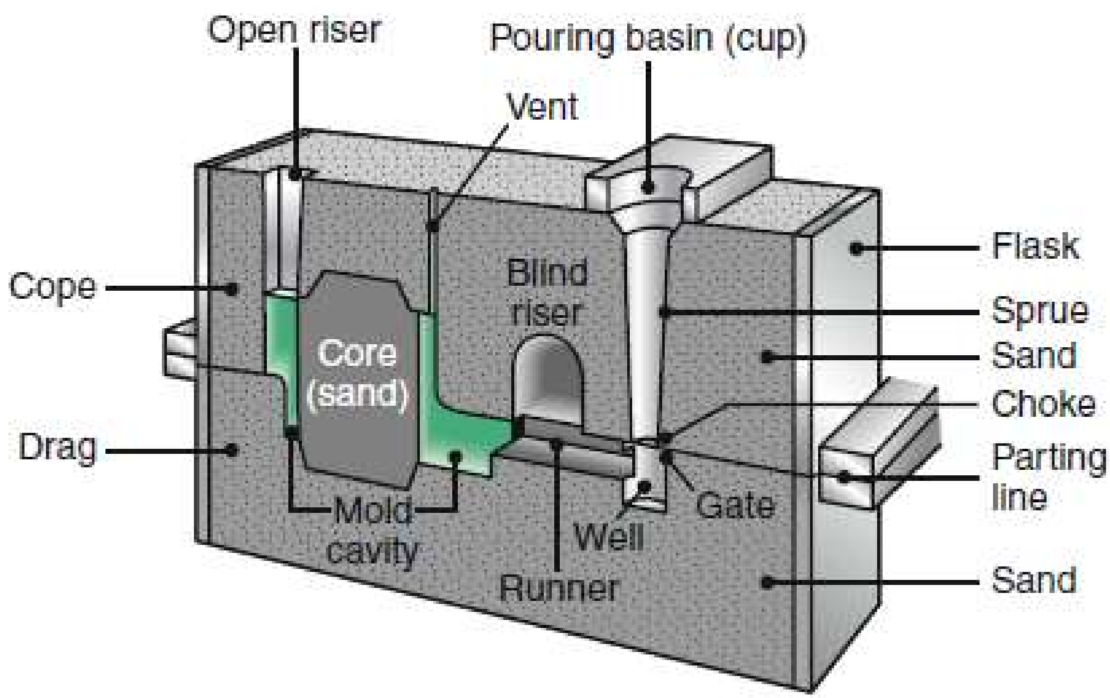
Types of Sand Mold

Green Sand, **Cold-Box** and **No-bake** – three basic types of sand molds are common. The most common mold material is **Green Molding Sand,** which is **a mixture oft sand, clay and water.** The word "green" refers to the fact that the sand in the mold is moist or damp while molten metal is being poured in it.

In **cold-box mold** process, various organic and inorganic binders are blended into the sane to bond the grains chemically for greater strength. Such molds produce more dimensionally accurate parts. In the **no-bake mold**, a synthetic liquid resin is mixed with the sand and the sand hardens at room temperature.



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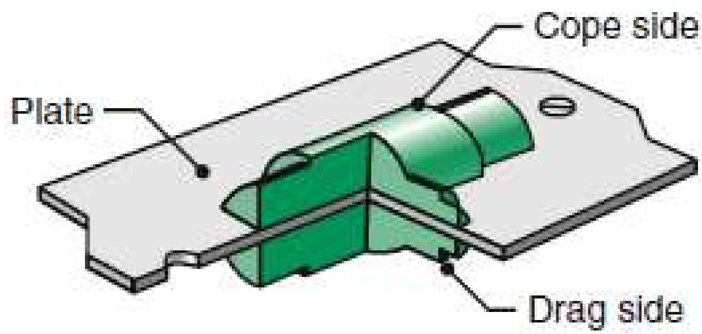
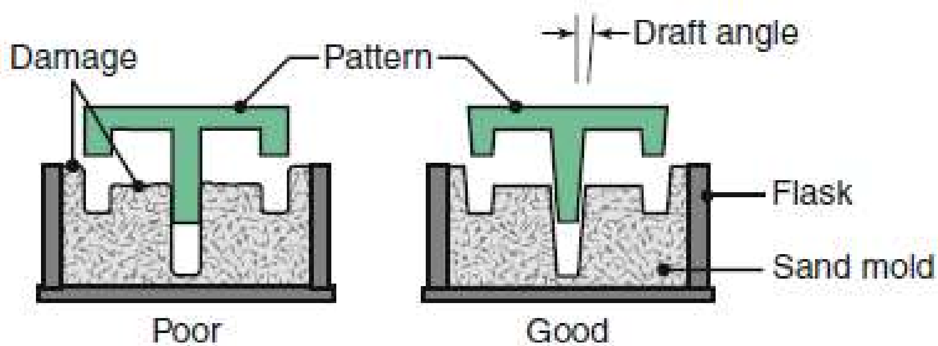
Types of Patterns



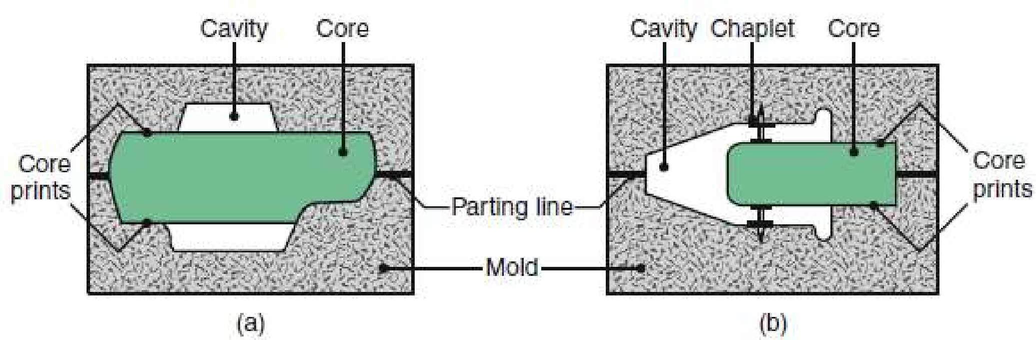
Match plate Pattern

Different types of patterns are used such as – **One Piece** pattern, **Split** patterns and **Match Plate** patterns.

Patterns must include shrinkage & machining allowance.



Patterns must provide a draft for their easy removal from the mold.



Sand Cores and **Core Prints** and **Chaplets** to support the cores.

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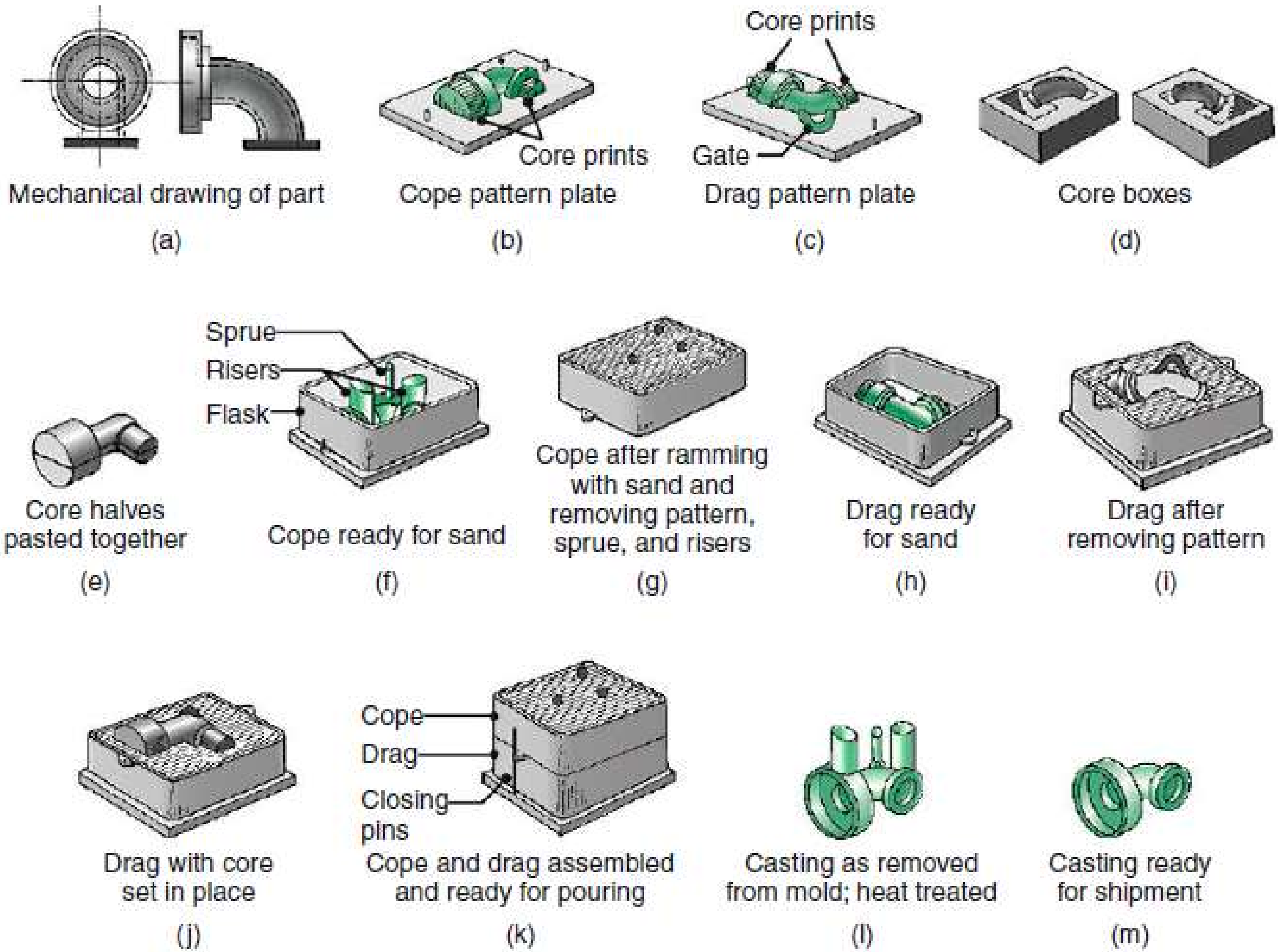
Sequence of Operations – Sand Casting



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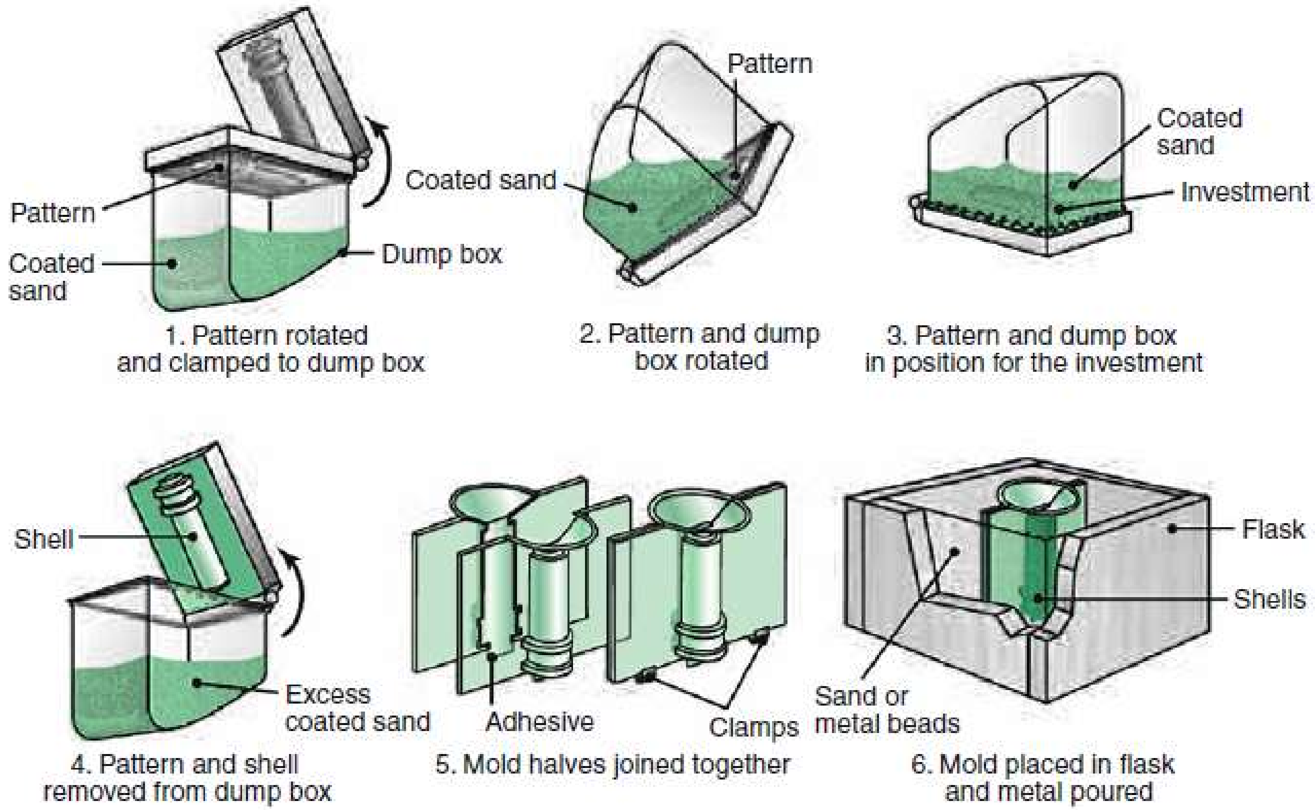
Shell Molding Process



A heated (175 to 370 C) metallic pattern (steel or aluminium) is coated with a parting agent (such as silicone) and placed in a box containing a fine sand mixed with 2.5 to 4% thermosetting resin. The box is rotated or the sand mixture is blown over the pattern to form the coating. The assembly is then overn-heated to complete the curing of the resin.

Shell sand has much lower permeability. Decomposition of resin yields lots of gas and it is a challenge..

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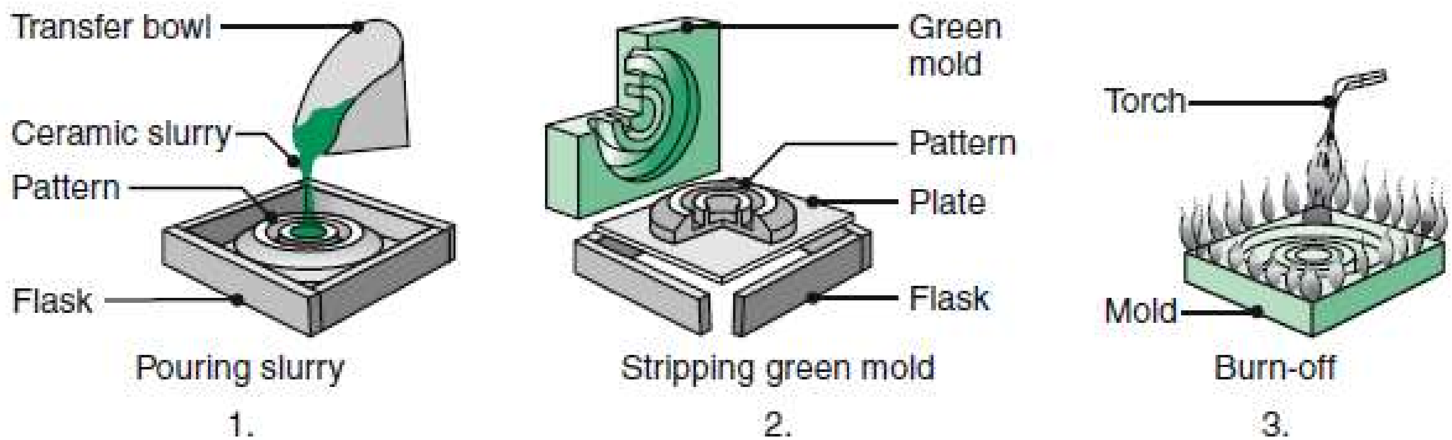
Plaster-mold and Ceramic-mold

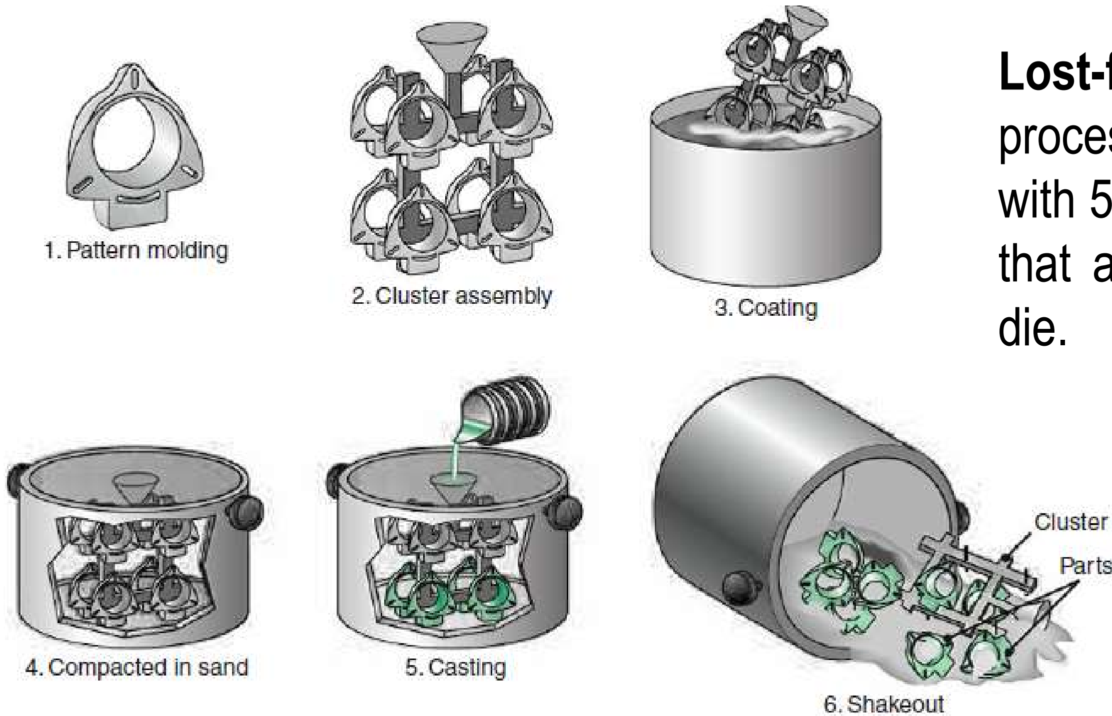
In the **plaster-molding process**, the mold is made of plaster of paris (gypsum or calcium sulfate) with the addition of talc and silica flour to improve strength and to control the time required for the plaster to set. These components are mixed with water, and the resulting slurry is poured over the pattern.

After the plaster sets (usually within 15 minutes), it is removed, and the mold is dried at a temperature range of 120 to 260 C. The mold halves are assembled to form the mold cavity and are preheated to about 120 C The molten metal is then poured into the mold. A metallic or thermoset polymer pattern is used.



The ceramic-mold casting process (also called cope-and-drag investment casting) is similar to the plaster-mold process, except that it uses refractory mold materials suitable for high-temperature applications. The slurry is a mixture of fine-grained zircon ($ZrSiO_4$) aluminum oxide, and fused silica, which are mixed with bonding agents and poured over the pattern, which is placed in a flask.

Expendable-mold Expendable-Pattern Casting



Lost-foam or **evaporative-pattern** casting process involves use of polystyrene beads with 5 to 8% pentane (volatile hydrocarbon) that are placed in a preheated aluminium die.

As the die is heated, polystyrene expands and takes the shape of the die cavity. Additional heat is supplied to fuse and bond the beads together. Die is then opened and polystyrene pattern is removed.

The pattern is coated with a water-based refractory slurry, dried, and placed in a flask. The flask is then filled with loose, fine sand, which surrounds and supports the pattern.

The sand is compacted periodically, without removing the polystyrene pattern; then the molten metal is poured into the mold. The molten metal vaporizes the pattern and fills the mold cavity, completely replacing the space previously occupied by the polystyrene. Any degradation products from the polystyrene are vented into the surrounding sand..

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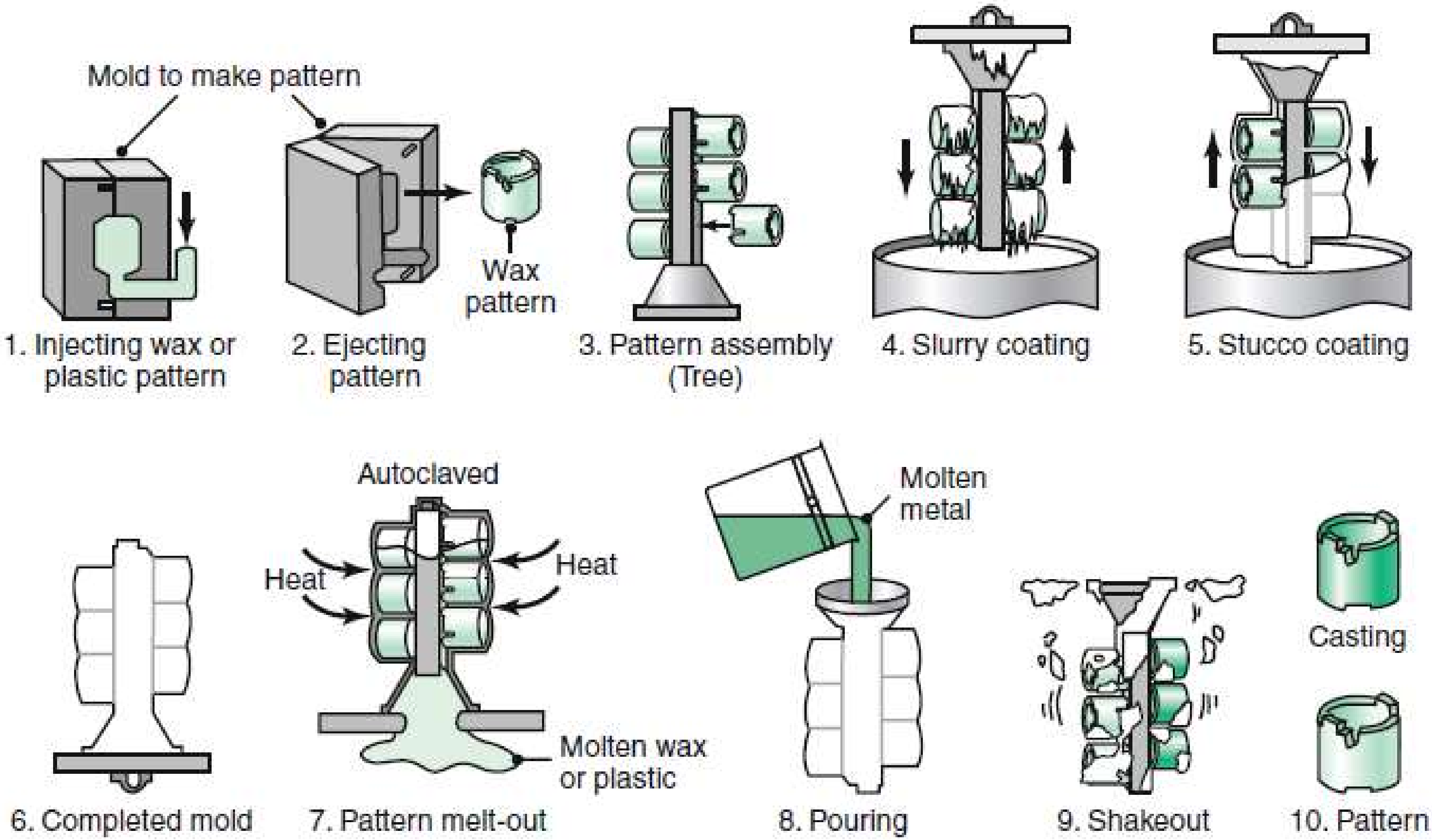
Investment Casting



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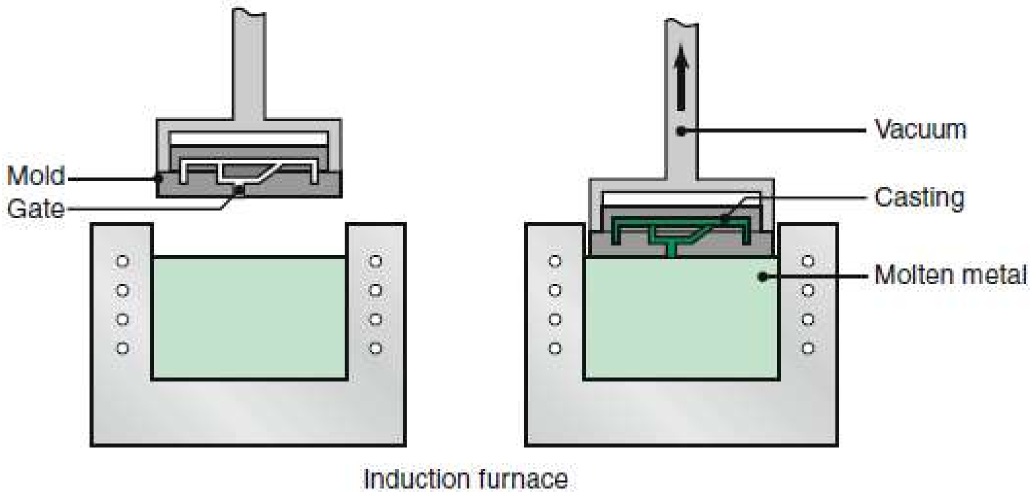
Permanent Mold Casting – Vacuum Casting



Vacuum-casting process, or countergravity low pressure (CL) process is an alternative to investment, shell-mold, and green-sand casting and is suitable particularly for thin-walled (~ 0.75 mm) complex shapes with uniform properties. Typical parts made are superalloy gas-turbine components with walls as thin as 0.5 mm..

A mixture of fine sand and urethane is molded over metal dies and cured with amine vapor. The mold is then held with a robot arm and immersed partially into molten metal held in an induction furnace. The metal is melted in air (CLA process) or in a vacuum (CLV process).

The vacuum reduces the air pressure inside the mold to about two-thirds of atmospheric pressure, thus drawing the molten metal into the mold cavities through a gate in the bottom of the mold. The metal in the furnace is usually at a temperature of 55 C above the liquidus temperature of the alloy. Consequently, it begins to solidify within a very short time. After the mold is filled, it is withdrawn from the molten metal.