FUNDAMENTALS OF METAL CASTING

0. Phase Diagram
1. Overview
2. Heating & Pouring
3. Solidification and Cooling

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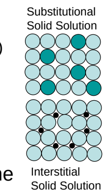
0. Alloys and Phase Diagram

- Pure Metals
- Alloys
  - Solid solutions
    - Substitutional Solid Solution (Zn/Cn and Cu/Ni)
      - Atomic radii is similar
      - Lattice type is the same
    - Interstitial Solid Solution
      - Smaller atoms are interstitially located among bigger atoms
      - Lattice type usually does not change
  - Intermediate Phases – The solubility of one element in another element is limited.
    - Metallic compounds (Fe_3C)
    - Intermetallic compounds(Mg_2Pb)



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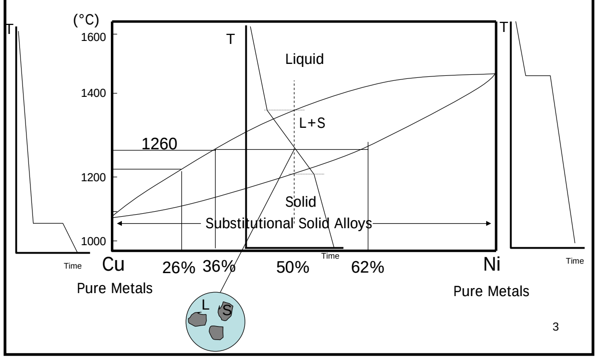
Cu-Ni Phase Diagram



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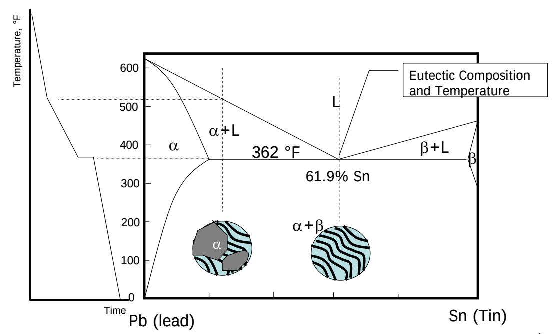
Pb-Sn Phase Diagram



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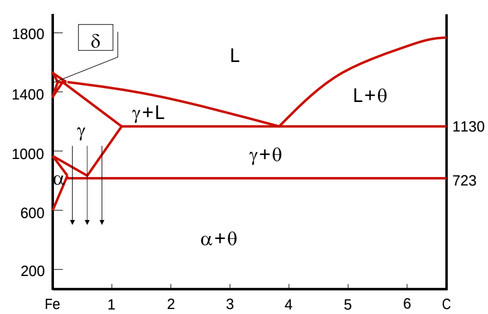
Fe-C Phase Diagram



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Introduction

- Dated back 6000 years
- Ingot vs. Shape casting
- Polymers and ceramics are cast as well.
- Issues in casting
  - Flow
  - Heat Transfer
  - Selection of Mold Materials
  - Solidification- Nucleation and Growth
- Depending on how we control solidification, these events influence the size, shape, uniformity and chemical composition of the grains.

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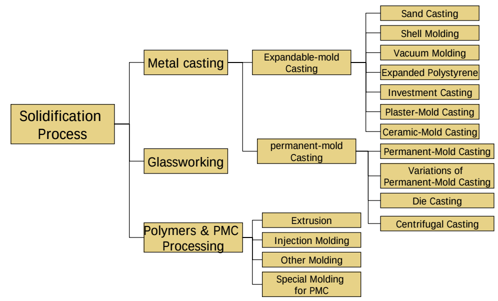
Introduction

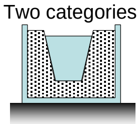
- Casting (process) – melt the metal, pour into a mold by gravity or other force and solidify.
- Casting (Part)
- Advantages
  - Complex geometries – external and internal
  - Can be net-shaped or near net-shaped
  - Can produce very large parts
  - Any metals
  - Can be mass-produced
  - Size variety – big and small
- Disadvantages
  - Limitation in mechanical properties, porosity,
  - Dimensional accuracy, surface finish
  - Safety Hazard
  - Environmental problems

Classification

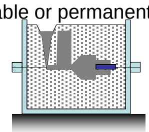


1. Overview

- A Foundry is a casting factory which equipped for making molds, melting and handling molten metal, performing the casting process, and cleaning the finished casting
  - Foundrymen are workers.
- Open Molds – Simple parts
- Closed Molds – Complex parts.
  - A passageway - the gating system leading into the cavity
- Two categories -Expandable or permanent molds.



(a) open mold



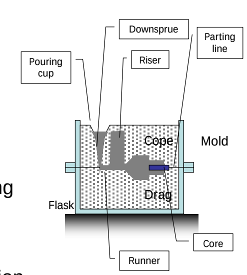
(b) closed mold

Two Main Categories

1. *Expendable mold processes* –A *mold* after process must be destroyed in order to remove casting
   - Mold materials: sand, plaster and similar materials + binders
   - More intricate geometries
2. *Permanent mold processes* – A *mold* can be used many times to produce many castings
   - Mold: made of metal and, less commonly, a ceramic refractory material
   - Part shapes are limited
   - Permanent mold processes are more economic in high production operations

Basic features of Molds

- Sand Casting Molds
  - Mold: cope (upper half) & drag (bottom half)
  - Flask - containment
  - Parting line
  - Pattern – the mold cavity
  - The gating system – pouring cup, (down)sprue, runner
  - Riser – a source of liquid metal to compensate for shrinkage during solidification



Casting Processes

- Forming the Mold Cavity
  - Mold cavity is formed by packing sand around a pattern.
  - The pattern usually oversized for shrinkage is removed.
  - Sand for the mold is moist and contains a binder to maintain shape
- Cores in the Mold Cavity
  - The mold cavity - the external surfaces of the cast part
  - A *core*, placed inside the mold cavity to define the interior geometry of part. In sand casting, cores are made of sand.
- Gating System - Channel through which molten metal flows into cavity
  - A downsprue, through which metal enters a runner
  - At top of downsprue, a pouring cup to minimize splash and turbulence
- Riser - Liquid metal reservoir to compensate for shrinkage during solidification
  - The riser must be designed to freeze after the main casting solidify.

2. Heating & Pouring

- Sufficient to melt and raise the molten metal to a right state
- Total Heat Energy required:
  $H=\rho V[C_s(T_m-T_o)+H_f+C_l(T_p-T_m)]$
  where ρ=density, V=volume, C_s=specific heat for solid
  C_l=specific heat for liquid, T_m=melting temperature
  T_o=starting temperature, T_p=pouring temperature
- Factors affecting 'pouring'
  - Pouring temperature (vs. melting temp.)
  - Pouring rate
    - Too slow, metal freezes
    - Too high, turbulence
  - Turbulence
    - Accelerate the formation of oxides
    - Mold erosion
    - Voids?

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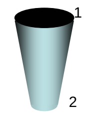
Pouring Analysis

- Bernoulli's theorem at any two points in a flowing liquid $h_1+\frac{P_1}{\rho}+\frac{v_1^2}{2g}=h_2+\frac{P_2}{\rho}+\frac{v_2^2}{2g}$
  - h=head, P=pressure, ρ=density, v=flow velocity, g=gravity, F=friction loss
  - Assuming no frictional loss and same pressure
    $$h_1+\frac{v_1^2}{2g}=h_2+\frac{v_2^2}{2g}$$
  - Assuming point 2 is reference (h_2=0) and v_1=0,
    $$\boxed{h_1=\frac{v_2^2}{2g}; \qquad v_2=\sqrt{2gh_1}}$$



- Continuity law $Q=v_1A_1=v_2A_2$
- Mold fill time (MFT) $MFT=\frac{V}{Q}$

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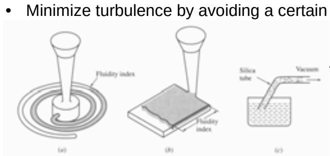
Fluidity

- Fluidity: A measure of the capability of a metal to flow into and fill the mold before freezing. (Inverse of viscosity)
- Factors affecting fluidity - Pouring temperature, Metal composition, Viscosity, Heat transfer to the surroundings, Heat of fusion and Solidification
- Higher Re, greater tendency for turbulence flow
  - Turbulence and laminar flow
    Reynold's number: Re=vDr/h
  Re ranges 2,000(laminar) to 20,000 (mixture of laminar-turbulence)
  greater than 20,000 turbulence resulting in air entrainment and dross (scum) formation
- Minimize turbulence by avoiding a certain range in flow direction



Pure metals: good fluidity
Alloys: not as good

Tests for fluidity [Schey, 2000]

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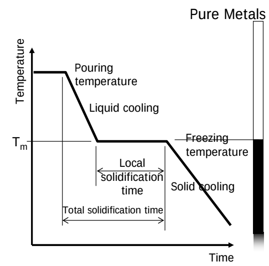
3. Solidification(Pure Metals)

Transformation of molten metal into solid state
- Solidification differs depending on a pure element or an alloy
- For Pure Metal
  - Super(Under)cooling
  - Solidification occurs at a constant temperature and supercooled Temperature
  - Actual freezing during the local solidification time



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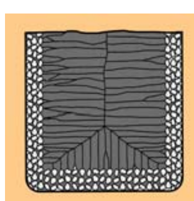
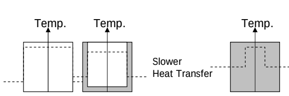
Solidification of Pure Metals

- A thin skin of solid metal is formed at the cold mold wall immediately after pouring
- Skin thickness increases to form a shell around the molten metal as solidification progresses
- Rate of freezing depends on heat transfer into mold, as well as thermal properties of the metal



Randomly oriented grains of small size near the mold wall, and large columnar grains oriented toward the center of the casting (Dendritic growth)



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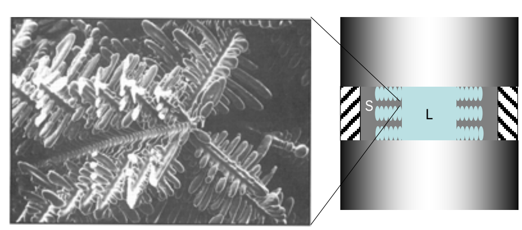
Dendrite Growth



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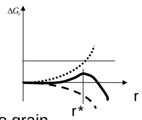
Solidification of Alloy

- Most Alloys freeze over a temperature range, not at a single temperature.

$$\Delta G_r = \frac{4}{3}\pi r^3 \Delta G_v + 4\pi r^2 \gamma$$

- Nucleation
  - Energy involved in homogeneous nucleation
  - Total free energy change:

  where ΔG_v =volume free energy
  r = radius of embryo
  γ = specific surface free energy



- Chemical compositional gradiency within a single grain
- Chemical compositional gradiency throughout the casting – ingot segregation
- Eutectic Alloys – Solidification occurs at a single temperature

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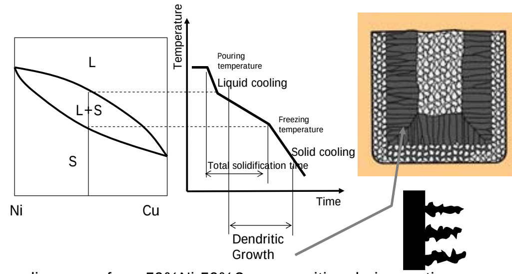
Solidification of Alloys



cooling curve for a 50%Ni-50%Cu composition during casting

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Solidification Time

- Chvorinov's Empirical relationship: Solidification time as a function of the size and shape

$$TST = C_m\left(\frac{V}{A}\right)^n$$

V=volume A=surface area and n=2

C_m=experimentally determined value that depends on mold material, thermal properties of casting metal, and pouring temperature relative to melting point

- A casting with a higher volume-to-surface area ratio solidifies more slowly than one with a lower ratio
- Used in riser design: the solidification time of the riser must be equal to the solidification time of the cast part.

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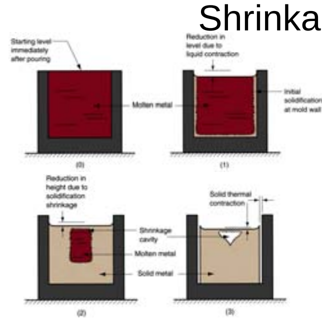
pattern shrinkage allowance

Shrinkage



Simplification

Metal	Volume Contraction	
	Solidification	Thermal Contraction
Aluminum	7%	5.6%
Al alloys	7	5
Gray cast iron	1.8	3
Gray Cast Iron with High C	0	3
Low C Cast Steel	3	7.2
Copper	4.5	7.5
Bronze	5.5	6

- Exception: cast iron with high C content because of graphitization during final stages causes expansion that counteracts volumetric decrease associated with phase change

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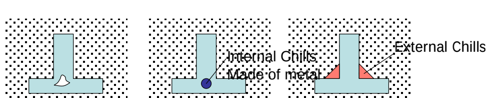
Directional Solidification

- To minimize the damage during casting, the region most distant from the liquid metal supply needs to freeze first and the solidification needs to procede toward the riser.
- Based on Chvorinov's rule, the section with lower V/A ratio should freeze first.
- Use 'Chills': Internal and External chills which encourage rapid cooling.



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METAL CASTING PROCESSES

1. Sand Casting
2. Other Expandable Mold Casting Processes
3. Permanent Mold Casting Processes
4. Foundry practice
5. Casting Quality
6. Metals for Casting
7. Product Design Consideration

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Introduction

- Casting of Ingot and **Shape casting**
- Major Classification
  - Expandable Mold
    - A new mold is required for each new casting
    - Production rate is limited except Sand casting
    - Sand Casting, Shell Molding, Vacuum Molding, Expandable Polystyrene, Investment Casting, Plaster Molding, Ceramic Mold Casting
  - Permanent Mold
    - Mold is made of durable materials
    - Ideal for a product with a high production rate

1. Sand Casting

- Most widely used casting process.
- Parts ranging in size from small to very large
- Production quantities from one to millions
- Sand mold is used.
- Patterns and Cores
  - Solid, Split, Match-plate and Cope-and-drag Patterns
  - Cores – achieve the internal surface of the part
- Molds
  - Sand with a mixture of water and bonding clay
  - Typical mix: 90% sand, 3% water, and 7% clay
  - to enhance strength and/or permeability

Molds

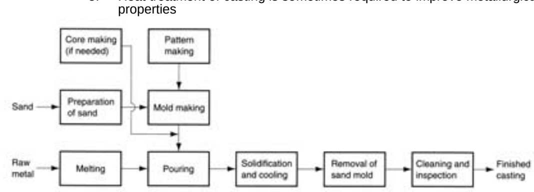
- Sand – Refractory for high temperature
- Size and shape of **sand**
  - Small grain size -> better surface finish
  - Large grain size -> to allow escape of gases during pouring
  - Irregular grain shapes -> strengthen molds due to interlocking but to reduce permeability
- Types
  - *Green-sand molds* - mixture of sand, clay, and water; "Green" means mold contains moisture at time of pouring
  - *Dry-sand mold* - organic binders rather than clay and mold is baked to improve strength
  - *Skin-dried mold* - drying mold cavity surface of a green-sand mold to a depth of 10 to 25 mm, using torches or heating lamps

Steps in Sand Casting

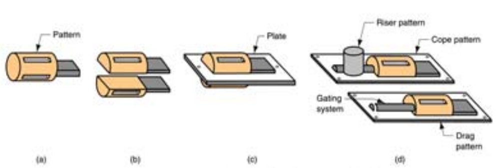
The *cavity* in the sand mold is formed by packing sand around a pattern, separating the mold into two halves

- The mold must also contain gating and riser system
- For internal cavity, a *core* must be included in mold
- A new sand mold must be made for each part

1. Pour molten metal into sand mold
2. Allow metal to solidify
3. Break up the mold to remove casting
4. Clean and inspect casting
5. Heat treatment of casting is sometimes required to improve metallurgical properties

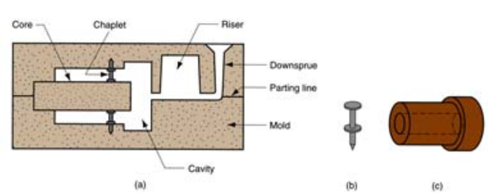


Types of patterns used in sand casting:



(a) solid pattern
(b) split pattern
(c) match-plate pattern
(d) cope and drag pattern

Internal Cavity with Core



(a) Core held in place in the mold cavity by chaplets

(b) possible chaplet design

(c) casting with internal cavity

Desirable Mold Properties and Characteristics

- Strength - to maintain shape and resist erosion
- Permeability - to allow hot air and gases to pass through voids in sand
- Thermal stability - to resist cracking on contact with molten metal
- Collapsibility - ability to give way and allow casting to shrink without cracking the casting
- Reusability - can sand from broken mold be reused to make other molds?

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2. Other Expendable Mold Casting

- Shell Molding
- Vacuum Molding
- Expanded Polystyrene Process
- Investment casting
- Plaster and Ceramic Mold casting

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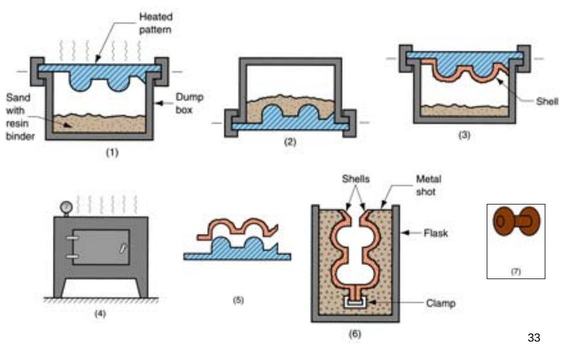
Steps in shell-molding



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Shell Molding

- Advantages:
  - Smoother cavity surface permits easier flow of molten metal and better surface finish on casting
  - Good dimensional accuracy
  - Machining often not required
  - Mold collapsibility usually avoids cracks in casting
  - Can be mechanized for mass production
- Disadvantages:
  - More expensive metal pattern
  - Difficult to justify for small quantities

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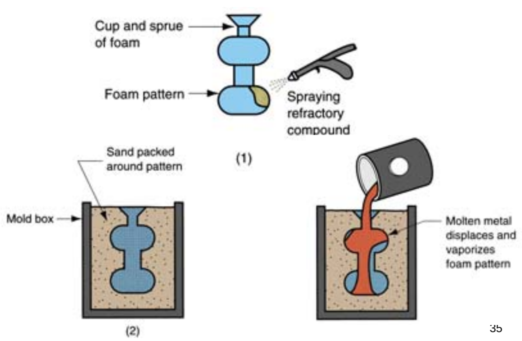
Expanded Polystyrene Casting



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Expanded Polystyrene Casting

- Advantages:
  - Pattern need not be removed from the mold
  - Simplifies and expedites mold-making, since two mold halves (cope and drag) are not required as in a conventional green-sand mold
  - Automated Mass production of castings for automobile engines
- Disadvantages:
  - A new pattern is needed for every casting
  - Economic justification of the process is highly dependent on cost of producing patterns

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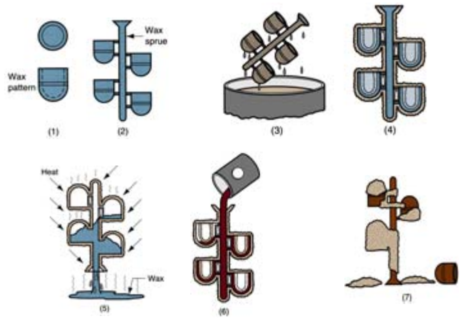
Investment Casting



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Investment Casting

- Advantages:
  - Parts of great complexity and intricacy can be cast
  - Close dimensional control and good surface finish
  - Wax can usually be recovered for reuse
  - Additional machining is not normally required - this is a net shape process
- Disadvantages
  - Many processing steps are required
  - Relatively expensive process

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Plaster Molding

- Similar to sand casting except mold is made of plaster of Paris (gypsum - $CaSO_4$-$2H_2O$)
- Plaster and water mixture is poured over plastic or metal pattern to make a mold
- Advantages:
  - Good dimensional accuracy and surface finish
  - Capability to make thin cross-sections in casting
- Disadvantages:
  - Moisture in plaster mold causes problems:
    - *Mold must be baked to remove moisture*
    - *Mold strength is lost when is over-baked, yet moisture content can cause defects in product*
  - Plaster molds cannot stand high temperatures

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3. Permanent Mold Casting

- Basic Permanent Mold Process
  - Uses a metal mold constructed of two sections designed for easy, precise opening and closing
  - Molds for lower melting point alloys: steel or cast iron and Molds for steel: refractory material, due to the very high pouring temperatures
- Variations
  - Slush Casting
  - Low-pressure Casting
  - Vacuum Permanent Mold Casting
- Die Casting
- Centrifugal Casting

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Permanent Mold Casting Process

- Metals - Al, Mg, Copper alloy and Cast Iron
- Basic Steps
  - Preheated Mold (metals to flow)
  - Coatings are sprayed
  - Pour and solidify
  - Mold is open and casting is removed
- Advantage - Good surface finish and dimensional control and Fine grain due to rapid solidification.
- Disadvantage - Simple geometric part, expensive mold.
- Example - automobile piston, pump bodies castings for aircraft and missiles.

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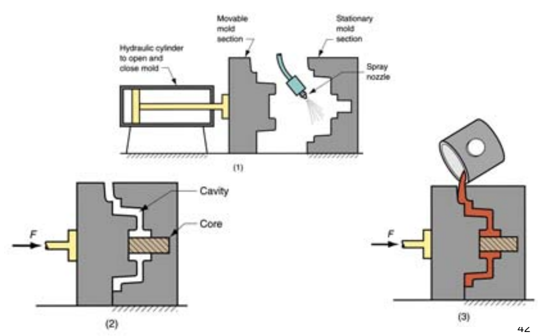
Basic Permanent Mold Process



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Permanent Mold Casting

- Advantages:
  - Good dimensional control and surface finish
  - More rapid solidification caused by the cold metal mold results in a finer grain structure, so stronger castings are produced
- Limitations:
  - Generally limited to metals of lower melting point
  - Simple part geometries compared to sand casting because of the need to open the mold
  - High cost of mold
- Due to high mold cost, process is best suited to automated high volume production

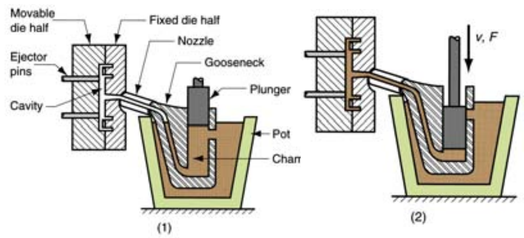
Die Casting

- The molten metal is injected into mold cavity (die) under **high pressure** (7-350MPa). Pressure maintained during solidification.
- Hot Chamber (Pressure of 7 to 35MPa)
  - The injection system is submerged under the molten metals (low melting point metals such as lead, zinc, tin and magnesium)
- Cold Chamber (Pressure of 14 to 140MPa)
  - External melting container (in addition aluminum, brass and magnesium)

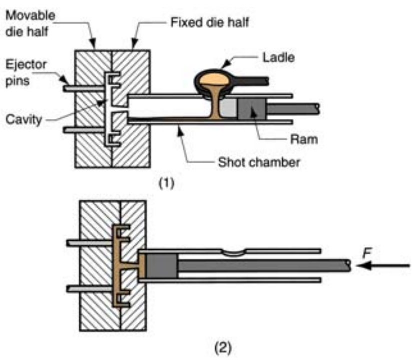
Die Casting

- Molds are made of tool steel, mold steel, maraging steel, tungsten and molybdenum.
- Single or multiple cavity
- Lubricants and Ejector pins to free the parts
- Venting holes and passageways in die
- Formation of flash that needs to be trimmed
- Advantages
  - High production, Economical, close tolerance, good surface finish, thin sections, rapid cooling

Hot-Chamber Die Casting



Cold Chamber Die Casting

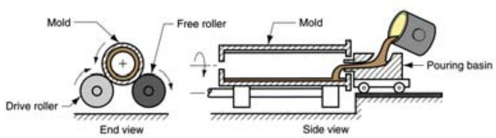


Die Casting

- Advantages:
  - Economical for large production quantities
  - Good dimensional accuracy and surface finish
  - Thin sections are possible
  - Rapid cooling provides small grain size and good strength to casting
- Disadvantages:
  - Generally limited to metals with low metal points
  - Part geometry must allow removal from die cavity

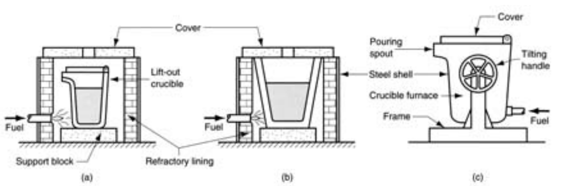
Centrifugal casting

- True centrifugal casting
- Semicentrifugal casting
- Centrifuge casting

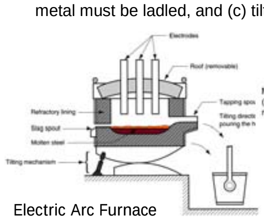


4. Foundry Practice

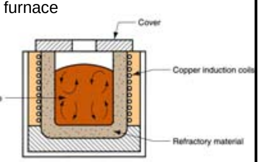
- Furnace
  - Cupolas (Fig. 11.18)
  - Direct Fuel-fired furnace
  - Crucible Furnace (Fig. 11.19)
  - Electric-arc Furnace
  - Induction Furnace
- Pouring with ladle
- Solidification – watch for oxidation
- Trimming, surface cleaning, repair and heat treat, inspection



Three types : (a) lift-out crucible, (b) stationary pot, from which molten metal must be ladled, and (c) tilting-pot furnace



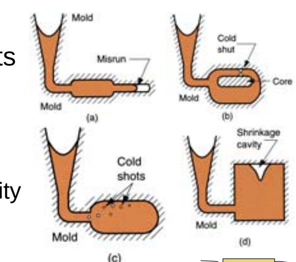
Electric Arc Furnace

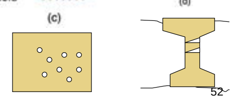


Induction furnace

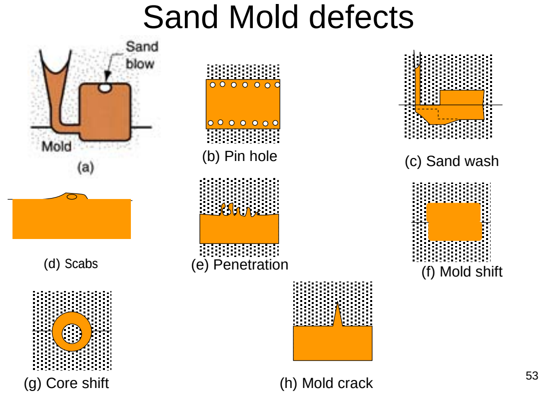
5. Casting Quality

- Casting defects
  a) Misruns
  b) Cold shut
  c) Cold shots
  d) Shrinkage cavity
  e) Microporosity
  f) Hot Tearing





Sand Mold defects



6. Metals for Casting

- Ferrous casting alloys: cast iron
  - Gray Cast Iron, Nodular iron, White Cast Iron, Malleable Iron, Alloy cast iron
- Ferrous casting alloys: Steels
  - Melting temperature is higher that casting alloys. Thus they are more reactive.
  - Less Fluidity
  - Higher strength, Tougher
  - Isotropy and weldable
- Nonferrous casting alloys
  - Aluminum, Magnesium, Copper, Tin-based, Zinc, Nickel and Titanium Alloys

7. Product Design Considerations

- Geometric simplicity
- Corners
- Section thicknesses – Hot spot
- Draft (Fig. 11.25)
- Use of Cores
- Dimensional tolerances and surface finish
- Machining allowance
- Tolerance and Surface Roughness for Various Casting Processes
  - See Table 11.2

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