Some Facts

- First casting: 5000-3000 BC
- Bronze, iron age, light metal age?
- Versatility
  - Many types of metals
  - Rapid production
  - Wide range of shapes and sizes
  - Complex parts as an integral unit

Example – Sand Casting
Casting Process Physics and Constraints

- Phase Change
  - Density
  - Solubility
  - Diffusion rates
- High melting temperature
  - Chemical activity
  - High latent heat
  - Handling

Analysis of Casting Processes

- Fluid mechanics for mold filling
- Heat transfer for solidification
- Thermodynamics, mass transfer and heat transfer for nucleation and growth
- Materials behavior for structure-property relationships
Mold Filling

- Bernoulli’s equation
  \[ h + \frac{P}{\rho g} + \frac{v^2}{2g} = \text{const.} \]
  \[ v \approx \sqrt{2gh} \approx 1.5 \text{ m/s} \]
- Reynold’s number
  \[ \text{Re} = \frac{vD\rho}{\mu} \approx 5 \times 10^4 \]
- Turbulence
- Injection Molding: Re \( \sim 10^4 \)

Cooling for Sand Mold

- Bernoulli’s equation
- Reynold’s number
- Turbulence
- Injection Molding: Re \( \sim 10^4 \)

Conductivity / Diffusivity

- Conductivity (W/mK)
  - Cu \( \sim 400 \), Al \( \sim 200 \)
  - Sand \( \sim 0.5 \), PMMA
- Sand Casting
  - \( \alpha_{\text{sand}} < \alpha_{\text{metal}} \)
- Die Casting
  - \( \alpha_{\text{tool metal}} \approx \alpha_{\text{metal}} \)
- Injection Molding
  - \( \alpha_{\text{tool metal}} > \alpha_{\text{polymer}} \)

Solidification Time: Sand Casting

- Transient 1-D heat transfer
  \[ \frac{\partial T}{\partial t} = \frac{1}{\alpha} \frac{\partial^2 T}{\partial x^2} \]
- Solution
  \[ T - T_M = \text{erf} \left( \frac{-x}{2\sqrt{\alpha t}} \right) \]
- Solidification time
  \[ t_s = C \left( \frac{V}{A} \right)^2 \]
  Chvorinov’s rule
Solidification Time: Die Casting

- Transient 1-D heat transfer
  \[ mC_P \frac{dT}{dt} = -Ah(T - T_m) \]

Solution

\[ t = \frac{mC_P}{Ah} \ln \left( \frac{T_{mol} + \Delta T - T_m}{T_{mol} - T_m} \right) \]

- Solidification time
  \[ t_s = C \left( \frac{V}{A} \right)^{\frac{1}{2}} \]

Comparison: Sand Mold vs Metal Mold

- Sand Mold
  Sand casting
  \[ t_s \sim \frac{V}{A} \]

- Metal Mold
  Die casting
  \[ t_s \sim \frac{V}{A} \]

Microstructure Formation

Schematic illustration of three basic types of cast structures
(a) Columnar dendritic (b) equiaxed dendritic (c) equiaxed nondendritic

Formation of Dendrites

Temperature

Alloying element

Mushy zone

Dendrites
Constitutional Supercooling

- SOLID
- LIQUID
- Solute enriched layer in front of liquid-solid interface
- Constitutionally supercooled region
- Liquid composition distance, \( x^* \)
- Temperature distance, \( T^* \)
- Actual temperature liquids

Green Sand Casting

- Mechanical drawing of part
- Core boxes
- Core halves pasted together
- Cope pattern plate
- Drag pattern plate
- Cope ready for sand
- Drag ready for sand
- Cope after ramming with sand and removing pattern, sprue, and risers
- Drag after ramming
- Drag with core set in place
- Cope and drag assembled ready for pouring
- Casting as removed from mold, sand treated
- Casting ready for shipment

Green Sand Mold

- Dimensional, thermal, and chemical stability at high T
- Size and shape
- Wettability by molten metal
- Compatibility with binder system
- Availability and consistency

Pattern Design Considerations (DFM)

- Shrinkage allowance
- Machining allowance
- Distortion allowance
- Parting line
- Draft angle
Typical Shrinkage Allowance

<table>
<thead>
<tr>
<th>Metal or alloy</th>
<th>Shrinkage allowances mm / m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloy</td>
<td>13</td>
</tr>
<tr>
<td>Aluminum bronze</td>
<td>21</td>
</tr>
<tr>
<td>Yellow brass (thick sections)</td>
<td>13</td>
</tr>
<tr>
<td>Yellow brass (thin sections)</td>
<td>13</td>
</tr>
<tr>
<td>Gray cast iron (a)</td>
<td>8 - 13</td>
</tr>
<tr>
<td>White cast iron</td>
<td>21</td>
</tr>
<tr>
<td>Tin bronze</td>
<td>16</td>
</tr>
<tr>
<td>Gun metal</td>
<td>11 - 16</td>
</tr>
<tr>
<td>Lead</td>
<td>26</td>
</tr>
<tr>
<td>Magnesium</td>
<td>26</td>
</tr>
<tr>
<td>Magnesium alloys (25%)</td>
<td>16</td>
</tr>
<tr>
<td>Manganese bronze</td>
<td>21</td>
</tr>
<tr>
<td>Copper-nickel</td>
<td>21</td>
</tr>
<tr>
<td>Nickel</td>
<td>21</td>
</tr>
<tr>
<td>Phosphor bronze</td>
<td>11 - 16</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>16 - 21</td>
</tr>
<tr>
<td>Chromium steel</td>
<td>21</td>
</tr>
<tr>
<td>Manganese steel</td>
<td>26</td>
</tr>
<tr>
<td>Tin</td>
<td>21</td>
</tr>
<tr>
<td>Zinc</td>
<td>26</td>
</tr>
</tbody>
</table>

Typical Pattern Machining Allowance

<table>
<thead>
<tr>
<th>Pattern size, mm</th>
<th>Allowances, mm</th>
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<tbody>
<tr>
<td></td>
<td>Bore</td>
</tr>
<tr>
<td>For cast irons</td>
<td></td>
</tr>
<tr>
<td>Up to 152</td>
<td>3.2</td>
</tr>
<tr>
<td>152 - 305</td>
<td>3.2</td>
</tr>
<tr>
<td>305 - 510</td>
<td>4.8</td>
</tr>
<tr>
<td>510 - 915</td>
<td>6.4</td>
</tr>
<tr>
<td>915 - 1524</td>
<td>7.9</td>
</tr>
<tr>
<td>For cast steels</td>
<td></td>
</tr>
<tr>
<td>Up to 152</td>
<td>3.2</td>
</tr>
<tr>
<td>152 - 305</td>
<td>6.4</td>
</tr>
<tr>
<td>305 - 510</td>
<td>6.4</td>
</tr>
<tr>
<td>510 - 915</td>
<td>7.1</td>
</tr>
<tr>
<td>915 - 1524</td>
<td>7.9</td>
</tr>
<tr>
<td>For nonferrous alloys</td>
<td></td>
</tr>
<tr>
<td>Up to 76</td>
<td>1.6</td>
</tr>
<tr>
<td>76 - 152</td>
<td>1.6</td>
</tr>
<tr>
<td>152 - 305</td>
<td>2.4</td>
</tr>
<tr>
<td>305 - 510</td>
<td>3.2</td>
</tr>
<tr>
<td>510 - 915</td>
<td>3.2</td>
</tr>
<tr>
<td>915 - 1524</td>
<td>4.0</td>
</tr>
</tbody>
</table>

Gating System: Sprue, Runner, and Gate

- Rapid mold filling
- Minimizing turbulence
- Avoiding erosion
- Removing inclusions
- Controlled flow and thermal conditions
- Minimizing scrap and secondary operations

Riser: Location and Size

- Casting shrinkage
- Directional solidification
- Scrap and secondary operation
Progressive Solidification in Riser

- Progressive solidification:
  - Intermediate rate
  - Slow rate
  - Fast rate

- Temperature gradient rising toward riser
- Directional solidification

Draft in Pattern

Investment Casting

- Injection wax or plastic patterns
- Ejecting pattern
- Wax pattern
- Pattern assembly (Tree)
- Slurry coating
- Stucco coating
- Compressed mold
- Pattern meltout

- Autoclaved
- Heat

Investment Casting (cont.)

- Pouring
- Heat
- Casting
- Pattern
- Shakeout
- Finished product
Advantages of Investment Casting

- Intricate geometry
- Close dimensional tolerance
- Superior surface finish
- High-melting point alloys

Advantages of Die Casting

- High production rates
- Closer dimensional tolerances
- Superior surface finish
- Improved mechanical properties

Die Casting

Lost Foam Casting
Lost Foam Casting

- Receive raw polystyrene beads
- Expand beads
- Mold component pattern, including gating system
- Join patterns (if multipiece)
- Coat pattern assembly
- Dry assembly
- Invest assembly in flask with backlip medium
- Vibrate to compact medium
- Pour
- Shakeout castings
- Clean castings assembly
- Inspect castings
- Ship castings

Advantages of Lost Foam Casting

- No parting line
- No cores
- One-piece flask
- Freedom of design
- Minimum handling of sand
- Ease of cleaning and secondary operation

Semi-solid Casting

- Punch
- Die
- Induction furnace

Advantages of Semi-solid Casting
Casting Process Comparison

### Cost - Casting

- **Sand casting**
  - Tooling and equipment costs are low
  - Direct labor costs are high
  - Material utilization is low
  - Finishing costs can be high
- **Investment casting**
  - Tooling costs are moderate depending on the complexity
  - Equipment costs are low
  - Direct labor costs are high
  - Material costs are low
- **Die casting**
  - Tooling and equipment costs are high
  - Direct labor costs are low to moderate
  - Material utilization is high

### Quality - Casting

- **Sand casting**
  - Tolerance (0.7~2 mm) and defects are affected by shrinkage
  - Material property is inherently poor
  - Generally have a rough grainy surface
- **Investment casting**
  - Tolerance (0.08~0.2 mm)
  - Mechanical property and microstructure depends on the method
  - Good to excellent surface detail possible due to fine slurry
- **Die casting**
  - Tolerance (0.02~0.6 mm)
  - Good mechanical property and microstructure due to high pressure
  - Excellent surface detail

### Rate - Casting

- **Sand casting**
  - Development time is 2~10 weeks
  - Production rate is depending on the cooling time: $t \sim (V/A)^2$
- **Investment casting**
  - Development time is 5~16 weeks depending on the complexity
  - Production rate is depending on the cooling time: $t \sim (V/A)^2$
- **Die casting**
  - Development time is 12~20 weeks
  - Production rate is depending on the cooling time: $t \sim (V/A)^1$

---

<table>
<thead>
<tr>
<th>Process</th>
<th>Die</th>
<th>Equipment</th>
<th>Labor</th>
<th>Production rate (Pc/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sand</td>
<td>L</td>
<td>L</td>
<td>L-M</td>
<td>&lt;20</td>
</tr>
<tr>
<td>Shell-mold</td>
<td>L-M</td>
<td>M-H</td>
<td>L-M</td>
<td>&lt;50</td>
</tr>
<tr>
<td>Plaster</td>
<td>L-M</td>
<td>M</td>
<td>M-H</td>
<td>&lt;10</td>
</tr>
<tr>
<td>Investment</td>
<td>M-H</td>
<td>L-M</td>
<td>H</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>Permanent</td>
<td>M</td>
<td>M</td>
<td>L-M</td>
<td>&lt;60</td>
</tr>
<tr>
<td>Die</td>
<td>H</td>
<td>H</td>
<td>L-M</td>
<td>&lt;200</td>
</tr>
<tr>
<td>Centrifugal</td>
<td>M</td>
<td>H</td>
<td>L-M</td>
<td>&lt;50</td>
</tr>
</tbody>
</table>

*L, low; M, medium; H, high.*
Flexibility - Casting

- Sand casting
  - High degree of shape complexity (limited by pattern)

- Investment casting
  - Ceramic and wax cores allow complex internal configuration but costs increase significantly

- Die casting
  - Low due to high die modification costs

New Developments in Casting

- Computer-aided design
- Rapid (free-form) pattern making