Casting Defects and Design Issues

ver. 2
Overview

• Processes
• Analysis
• Defects
• Design rules
• Economics
Issues in Casting

• Shrinkage
• Porosity
• Piping
• Microstructure
Shrinkage

- Can amount to 5-10% by volume
- Gray cast iron expands upon solidification due to phase changes
- Need to design part and mold to take this amount into consideration
Shrinkage

<table>
<thead>
<tr>
<th>Metal or alloy</th>
<th>Volumetric solidification contraction (%)</th>
<th>Metal or alloy</th>
<th>Volumetric solidification contraction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>6.6</td>
<td>70%Cu–30%Zn</td>
<td>4.5</td>
</tr>
<tr>
<td>Al–4.5%Cu</td>
<td>6.3</td>
<td>90%Cu–10%Al</td>
<td>4</td>
</tr>
<tr>
<td>Al–12%Si</td>
<td>3.8</td>
<td>Gray iron</td>
<td>Expansion to 2.5</td>
</tr>
<tr>
<td>Carbon steel</td>
<td>2.5–3</td>
<td>Magnesium</td>
<td>4.2</td>
</tr>
<tr>
<td>1% carbon steel</td>
<td>4</td>
<td>White iron</td>
<td>4–5.5</td>
</tr>
<tr>
<td>Copper</td>
<td>4.9</td>
<td>Zinc</td>
<td>6.5</td>
</tr>
</tbody>
</table>

*Source: After R. A. Flinn.*
Casting Defects

(a) Surface of casting
(b) Scar
(c) Blister
(d) Scab
(e) Gate
(f) Sprue
(g) Cold shut
Defects - Hot Tears

[Diagram showing examples of hot tears in casting processes, with labels for casting, hot tear, core, pouring cup, sprue, and runner.]
Steam Engine Flywheels
Car Rims

Stamped

Cast
Casting Defects - Porosity
Porosity

• Types
  – due to gases – smooth bubbles
  – due to shrinkage – rough voids

• Not a problem for ingots
  – parts that will be deformation processed
  – as long as it is not exposed to air (corrosion)
  – can be healed
Porosity due to Gases

• Smooth bubbles
  – result from entrapped gases
  – solubility in liquid is high, in solid is low, so gas is rejected during cooling

• Sievert’s law

  \[ S = kp_g^{0.5} \]

  – \( S \) = solubility
  – \( k \) = constant
  – \( p_g \) = partial pressure of gas over melt
Remedies for Gas Bubbles

• Control atmosphere
  – vacuum
  – gases with less solubility
• Proper venting to let gases out
• Proper design of runners and gates to avoid turbulence
Remedies for Gas Bubbles

• Add metallic elements to react with gases
  – killed steels - highly deoxidized (Al, Si)
    • high shrinkage due to gas removal - piping
  – semi-killed steels - less deoxidized
    • less piping, porosity
  – rimmed steels - little deoxidization
    • blow holes in ring at rim (sometimes break through)
    • little piping because gas doesn’t escape
Porosity due to Shrinkage

- Rough bubbles - voids
- Stages
  - cooling liquid
  - rejects latent heat at melting point
    - alloys become slushy - liquid and solid co-exist
  - cooling solid
Differential Cooling

- Transition between thicker and thinner sections can lead to porosity
Porosity / Shrinkage Solutions

• Risers allow molten metal to flow into mold to make up for shrinkage

• Design flow so no part freezes early
  – large channels

• “Flexible” molds
  – allow metal to shrink, not hold metal
Porosity / Shrinkage Solutions

- Heating or cooling certain areas to maintain uniform cooling (thermit or chills)
- Uniform part thickness
  - leads to uniform cooling, less residual stress
Chills

(a) Sand Casting Chill Sand

(b) L Clip Porosity L Clip Chill T Clip T Clip T Clip T Clip

(c) Casting Boss Chill
Pipe Defect

• Due to shrinkage giving rise to a funnel-like cavity

• Solutions
  – insulate top (glass wool)
  – heat top (exothermic mixture - thermit)
Microstructure

(a) Chill zone
   Columnar zone
(b) Equiaxed zone
(c) Equiaxed structure
Grains on Willie B’s head
Microstructure - Dendrites

- Finer structure at walls
- Grains / dendrites grow to center
Microstructure - Dendrites
Microstructure

• Post-treatment may be necessary to get desired properties - grain structure
  – annealing
  – tempering
  – cold working
Design Rules Summary

- Uniform wall thickness
- Flat parting lines
- Gradual thickness transitions
- Draft for removal
  - tapers: 0.5 to 2 degrees
- Surface of mold gives surface of part
Sand Casting Rules
Economics Example - Optical Bench
Requirements

• Casting of Al-Si alloy

• Number
  – one-off
  – preliminary run (100)
  – production run (10,000)

• High precision required
  – machining required
  – pick cheapest casting method
Alternative Processes

- Sand casting
- Low pressure casting
- Permanent mold casting
- Die casting
Cost Equation

\[ C = C_m + \frac{C_c}{n} + \frac{C_L}{\dot{n}} \]

- \( C = \text{cost/part} \)
- \( C_m = \text{material cost} \)
- \( C_c = \text{capital cost} \)
- \( C_L = \text{labor cost} \)
- \( n = \text{number produced} \)
- \( \dot{n} = \text{production rate} \)
## Process Costs

<table>
<thead>
<tr>
<th>Process</th>
<th>Sand Casting</th>
<th>Low Pressure</th>
<th>Permanent Mold</th>
<th>Die Casting</th>
</tr>
</thead>
<tbody>
<tr>
<td>Material, $C_m$ ($)</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Labor, $C_L$ ($/hr$)</td>
<td>20</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Capital, $C_C$ ($)</td>
<td>0.9</td>
<td>4.4</td>
<td>700</td>
<td>3000</td>
</tr>
<tr>
<td>Rate, $n$ (#/hr)</td>
<td>6.25</td>
<td>22</td>
<td>10</td>
<td>50</td>
</tr>
</tbody>
</table>
Process Economics

![Graph showing process economics with lines for DIE, PERMANENT MOULD, LOW PRESSURE, SAND, and number of components on a log scale.]
Process Selection

- Probably pick low pressure casting, as a preliminary run of 100 is assured.
- If production run is needed, die casting will probably be used.

- The tough part is getting the process cost data.
## Production of Aluminum Auto Parts

<table>
<thead>
<tr>
<th>Main Characteristic</th>
<th>Casting Gravity(^A)</th>
<th>Low-Pressure Die Casting(^B)</th>
<th>High-Pressure Die Casting (Pores Free)(^C)</th>
<th>Squeeze Casting(^D)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pouring/Filling Method</td>
<td>Ladle</td>
<td>Air pressure through stalk</td>
<td>High-speed and high-pressure injection by hydraulic piston</td>
<td>Relatively low-speed and high-pressure injection</td>
</tr>
<tr>
<td>Filling Time (s)</td>
<td>10-30</td>
<td>10-30</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Operating Pressure (atm.)</td>
<td>1</td>
<td>1+(0.2-0.5)</td>
<td>100-500</td>
<td>500-1,000</td>
</tr>
<tr>
<td>Cycle Time (min.)</td>
<td>5-10</td>
<td>5-10</td>
<td>1-2</td>
<td>2</td>
</tr>
<tr>
<td>Die/Mold Temperature</td>
<td>High</td>
<td>High</td>
<td>Low</td>
<td>Low-medium</td>
</tr>
<tr>
<td>Dimensional Accuracy</td>
<td>+</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Design Availability</td>
<td>+++</td>
<td>++</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Productivity</td>
<td>+</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Quality</td>
<td>+</td>
<td>++</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Cost</td>
<td>+</td>
<td>+</td>
<td>+++</td>
<td>+++</td>
</tr>
<tr>
<td>Machining Required</td>
<td>Many</td>
<td>Many</td>
<td>Few</td>
<td>Few</td>
</tr>
<tr>
<td>Main Parts (other than wheels)</td>
<td>Intake manifold, cylinder block and head, piston</td>
<td>Cylinder block, cylinder head, suspension, member</td>
<td>Cylinder block, oil pan, cylinder head cover, transaxle case</td>
<td>Piston, disk-brake caliper, power steering toe control hub, knuckle</td>
</tr>
</tbody>
</table>
Advantages of Casting

- Near- or net-shape
- Less scrap
- Intricate shapes
- Large hollow shapes
- No limit to size
Disadvantages of Casting

• Shrinkage, porosity, cracks

• No strain hardening
  – can be brittle

• Tooling can be expensive
  – part shape depends on tool (mold)

• Microstructure can be difficult to control
  – non-uniform cooling
  – faster on outside produces finer grain structure there
Summary

- Defects
- Design rules
- Economics