Casting

2.810

Prof. Timothy Gutowski
Casting since about 4000 BC…

Ancient Greece; bronze statue casting circa 450BC

Iron works in early Europe, e.g. cast iron cannons from England circa 1543
Outline

• Sand Casting, Investment Casting, Die Casting
• Basics and countermeasures
• Phase Change, Shrinkage
• Heat Transfer
• Pattern Design
• Variations & Developments
• Environmental Issues
Casting

Readings:
1. Kalpakjian, Chapters 10, 11, 12
2. Booothroyd, “Design for Die Casting”
3. Flemings “Heat Flow in Solidification”

Note: a good heat transfer reference can be found by Prof John Lienhard online http://web.mit.edu/lienhard/www/ahtt.html
Casting Methods

- **Sand Casting**
  High Temperature Alloy, Complex Geometry, Rough Surface Finish

- **Investment Casting**
  High Temperature Alloy, Complex Geometry, Moderately Smooth Surface Finish

- **Die Casting**
  High Temperature Alloy, Moderate Geometry, Smooth Surface
Sand Casting

(a) Mechanical drawing of part
(b) Cope pattern plate
(c) Core prints
(d) Core boxes
(e) Core halves pasted together
(f) Flask
(g) Sprue
(h) Cope ready for sand
(i) Cope after ramming with sand and removing pattern, sprue, and risers
(j) Drag ready for sand
(k) Drag after removing pattern
(l) Cope and drag assembled ready for pouring
(m) Casting as removed from mold; heat treated
(n) Casting ready for shipment
Sand Casting

Description: Tempered sand is packed into wood or metal pattern halves, removed form the pattern, and assembled with or without cores, and metal is poured into resultant cavities. Various core materials can be used. Molds are broken to remove castings. Specialized binders now in use can improve tolerances and surface finish.

Metals: Most castable metals.

Size Range: Limitation depends on foundry capabilities. Ounces to many tons.

Tolerances:
Non-Ferrous $\pm \frac{1}{32}$" to 6"
Add $\pm .003$" to 3", $\pm 3/64$" from 3" to 6".
Across parting line add $\pm .020$" to $\pm .090$" depending on size.
(Assumes metal patterns)

Surface Finish:
Non-Ferrous: 150-350 RMS
Ferrous: 300-700 RMS

Minimum Draft Requirements:
1° to 5°
Cores: 1° to 1 1/2°

Normal Minimum Section Thickness:
Non-Ferrous: 1/8" - 1/4"
Ferrous: 1/4" - 3/8"

Ordering Quantities: All quantities

Normal Lead Time:
Samples: 2-10 weeks
Production 2-4 weeks A.S.A.
Sand Casting Mold Features

Vents, which are placed in molds to carry off gases produced when the molten metal comes into contact with the sand in the molds and core. They also exhaust air from the mold cavity as the molten metal flows into the mold.

FIGURE 10.7  Schematic illustration of a typical riser-gated casting. Risers serve as reservoirs, supplying molten metal to the casting as it shrinks during solidification. See also Fig. 11.4. Source: American Foundrymen’s Society.

FIGURE 11.4  Schematic illustration of a sand mold, showing various features.
See Video from Mass Foundry
Production sand casting

FIGURE 11.8
(a) Schematic illustration of a jolt-type mold-making machine. (b) Schematic illustration of a mold-making machine which combines jolting and squeezing.
The **investment-casting process**, also called the **lost-wax process**, was first used during the period 4000-3500 B.C. The pattern is made of wax or a plastic such as polystyrene. The sequences involved in investment casting are shown in Figure 11.18. The pattern is made by injecting molten wax or plastic into a metal die in the shape of the object.
Description: Metal mold makes wax or plastic replica. There are sprued, then surrounded with investment material, baked out, and metal is poured in the resultant cavity. Molds are broken to remove the castings.

Metals: Most castable metals.

Size Range: fraction of an ounce to 150 lbs..

Tolerances:
- ± .003” to 1/4”
- ± .004” to 1/2”
- ± .005” per inch to 3”
- ± .003” for each additional inch

Surface Finish: 63-125RMS

Minimum Draft Requirements: None

Normal Minimum Section Thickness:
- .030” (Small Areas)
- .060” (Large Areas)

Ordering Quantities:
- Aluminum: usually under 1,000
- Other metals: all quantities

Normal Lead Time:
- Samples: 5-16 weeks (depending on complexity)
- Production 4-12 weeks A.S.A. (depending on subsequent operations)

Talbot Associates Inc.
Die Casting – Cold-Chamber Casting

Cycle in cold-chamber casting: (1) with die closed and ram withdrawn, molten metal is poured into the chamber; (2) ram forces metal to flow into die, maintaining pressure during the cooling and solidification; and (3) ram is withdrawn, die is opened, and part is ejected. Used for higher temperature metals eg Aluminum, Copper and alloys.
Die Casting – Hot-Chamber Casting

Cycle in hot-chamber casting:
(1) with die closed and plunger withdrawn, molten metal flows into the chamber;
(2) plunger forces metal in chamber to flow into die, maintaining pressure during cooling and solidification; and
(3) plunger is withdrawn, die is opened, and solidified part is ejected. Finished part is shown in (4).
Die Casting

Description: Molten metal is injected, under pressure, into hardened steel dies, often water cooled. Dies are opened, and castings are ejected.

Metals: Aluminum, Zinc, Magnesium, and limited Brass.

Size Range: Not normally over 2 feet square. Some foundries capable of larger sizes.

Tolerances:
- Al and Mg $\pm .002"$/in.
- Zinc $\pm .0015"$/in.
- Brass $\pm .001"$/in.
- Add $\pm .001"$ to $\pm .015"$ across parting line depending on size

Surface Finish: 32-63RMS

Minimum Draft Requirements:
- Al & Mg: 1° to 3°
- Zinc: 1/2° to 2°
- Brass: 2° to 5°

Normal Minimum Section Thickness:
- Al & Mg: .03" Small Parts: .06" Medium Parts
- Zinc: .03" Small Parts: .045" Medium Parts
- Brass: .025" Small Parts: .040" Medium Parts

Ordering Quantities:
- Usually 2,500 and up.

Normal Lead Time:
- Samples: 12-20 weeks
- Production: ASAP after approval.
High Melt Temperature

- Chemical Activity
- High Latent Heat
- Handling
- Off-gassing

3000° C
- Tungsten Carbide, WC
- Silicon Carbide, SiC
- Cubic Zirconia, ZrO₂
- Molybdenum

2000° C
- Alumina Al₂O₃
- Platinum, Pt
- Titanium, Ti
- Iron, Plain Carbon Steels, low alloy, stainless
- Nickel, Ni
- Nickel Alloys
- Silicon, Si

1000° C
- Copper, Cu, Bronze, Brass
- Aluminum
- Magnesium
- Zinc, Zn
- PTFE (Teflon)
- Tin, Sn
- HDPE

0° C
- Nylon
- Acetal

Mold Filling

Bernoulli’s Equation:
\[ h + \frac{p}{pg} + \frac{v^2}{2g} = \text{Const.} \]

Reynold’s Number:
\[ \text{Re} = \frac{\nu DP}{\mu} \]

- Short filling times
- Potential Turbulence

(see p. 273 ... Kalpakjian)
Mold Filling Example (order of magnitude)

from Bernoulli's Eq'n, the inlet velocity can be estimated as:

\[ \dot{V} = \sqrt{2gh} \]

\[ = \sqrt{2 \times 10 \text{ m/s}^2 \times 10^{-1} \text{ m}} = 1.4 \text{ m/s} \]
Mold Filling Example (2 of 2)

Calculate Reynold's Number:

\[ \text{Re} = \frac{v \cdot D \cdot \rho}{\mu} = 1.4 \frac{m}{s} \times \frac{5 \text{ cm}}{1.5 \text{ cm}} \times \frac{3.8 \text{ g}}{\text{cm}^3} \]

\[ = \frac{10^{-3} \frac{N}{m^2} \cdot s}{(1 \text{ kg/m} \cdot s)} = 21,000 \text{ turbulence!} \]

Air entrainment, reaction with air-oxides, "dross"... BAD!

Runner system design (Sprue, Runner, Gate,...) + Filters
Phase Change & Shrinkage
Solidification of a binary alloy

FIGURE 12.5 (a) Phase diagram for a copper–nickel alloy system and (b) associated cooling curve for a 50% Ni–50% Cu composition during casting.
Composition change during solidification

FIGURE 7.2  Phase diagram for the copper–nickel alloy system.
Solidification

FIGURE 10.5  Schematic illustration of three basic types of cast structures: (a) columnar dendritic; (b) equiaxed dendritic; and (c) equiaxed nondendritic. Source: D. Apelian.
Cast structures

Schematic illustration of three cast structures solidified in a square mold: (a) pure metals; (b) solid solution alloys; and (c) structure obtained by using nucleating agents. Source: G. W. Form, J. F. Wallace, and A. Cibula
Pop quiz; If you top fill the mold below, what will the part look like after solidification?
Can you explain these features?
Heat Transfer – Sand Casting

\[ t_s \approx \left( \frac{V}{A} \right)^2 \]

**FIGURE 1-6**
Approximate temperature profile in solidification of a pure metal poured at its melting point against a flat, smooth mold wall.
Heat Transfer – Die Casting

\[ t_S \approx \left( \frac{V}{A} \right)^{1} \]

FIGURE 1-9
Temperature profile during solidification against a large flat mold wall with mold-metal interface resistance controlling.
Steady State Conduction Heat Transfer

Figure 1

\[ q = -k \frac{T_1 - T_2}{\Delta x} \]

Fourier’s Law
Steady State Conduction Heat Transfer

Figure 2

In steady-state, \( q_A = q_B = q_c = q_D = q \), hence for each layer (large \( \Delta T_i \) implies a large \( \Delta R_i \) and vice versa). Since \( \Delta T = \sum \Delta T_i \Rightarrow \text{Equivalent} = \frac{\Delta T}{\sum \frac{1}{R_i}} \)

i.e. \( q = \Delta T / \text{Eqv} \)

Hence, referring to Eq. 2: \( \text{Eqv} \approx R_e \Rightarrow q \approx \frac{\Delta T}{R_e} \)
Thermal Conductivity “k” of Various Materials for Parts and Molds (W/m °K)

<table>
<thead>
<tr>
<th>Material</th>
<th>k (W/m °K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>394</td>
</tr>
<tr>
<td>Aluminum</td>
<td>222</td>
</tr>
<tr>
<td>Iron</td>
<td>29</td>
</tr>
<tr>
<td>Sand</td>
<td>0.61</td>
</tr>
<tr>
<td>PMMA</td>
<td>0.20</td>
</tr>
<tr>
<td>PVC</td>
<td>0.16</td>
</tr>
</tbody>
</table>

\[ q = -k \frac{dT}{dx} \]
Film Coefficients $W/m^2^\circ K$

- Typical die casting: 5,000
- Natural convection: 1 - 10
- Flowing air: 10 - 50

\[ q = -h(\Delta T) \]
Transient Heat Transfer

\[ q \rightarrow \boxed{\text{ }} \rightarrow q + dq \]

\[ \rho C_p \frac{\partial T}{\partial t} = k \frac{\partial^2 T}{\partial x^2} \]

\[ k \neq k(x) \]

\[ \alpha = \frac{k}{\rho C_p} \]
Sand Casting (see Flemings)

Define new variable

\[ \zeta = \frac{x}{\sqrt{\alpha t}} \]

Use

\[ \theta = \frac{T - T_M}{T_o - T_M} \]

Diagram:
- To (sand)
- Tm (liquid metal)
- t
Sand Casting (see Flemings)

Ordinary differential eq'v

\[ \frac{d^2 \theta}{d\zeta^2} = -\frac{\zeta}{2} \frac{d\theta}{d\zeta} \]

i.c. \( \theta = 1 \) at \( \zeta = \infty \)

b.c. \( \theta = 0 \) at \( \zeta = 0 \)

\[ \theta = \text{erf}\left(-\frac{\zeta}{2}\right) \]
Solidification Time

Heat required to solidify to distance "s"

\[ = A \cdot s \cdot \rho \cdot H \]

Rate eq'n (per unit area)

\[ \rho H \frac{ds}{dt} = -\dot{q} = k \left( \frac{\partial T}{\partial x} \right)_{x=0} \]

Use Flemings result here
Solidification Time (cont.)

this leads to

\[
s = \frac{2}{\sqrt{\pi}} \left( \frac{T_M - T_o}{\rho_M H_M} \right) \sqrt{K_s \rho_s C_p s} t
\]

let \( s = \frac{V}{A} \)

\[
t = C \left( \frac{V}{A} \right)^2
\]

Chvorinov's rule
Cooling Time; thin slab

\[ \text{Cooling Time} = f \left( \frac{V}{A} \right) \]

\[ \frac{V}{A} = \frac{L \times h \times 1}{2 \times L \times 1} = \frac{h}{2} \]
Cooling time; intersection

\[
\frac{V}{A} = \frac{h}{2} \left[ 1 + \frac{1}{2} \left( \frac{1}{\frac{L}{h} - 1} \right) \right]
\]
Pattern Design suggestions

Figure 7.2.24 Identifying hot spots in castings by using outward projecting arrows of length half the casting thickness. Where arrows overlap, hot spots may develop. (Courtesy of Meehanite Metal Corp.)

Figure 7.2.25 Examples of relative cooling times. (Courtesy of Meehanite Metal Corp.)

Figure 7.2.26 Fillet all sharp angles. (Courtesy of Meehanite Metal Corp.)
More Pattern Design Suggestions

Figure 7.2.01 Design for bolting or bearing bosses. (Courtesy of Mechanic Metal Corp.)

Figure 7.2.02 More interference details. (Courtesy of Mechanic Metal Corp.)

Figure 7.2.03 Shrink fit. (Courtesy of Mechanic Metal Corp.)

Figure 7.2.04 Hardened section cannot be lost. (Courtesy of Mechanic Metal Corp.)

Figure 7.2.05 Light section at top prevents fatigue. (Courtesy of Mechanic Metal Corp.)

Figure 7.2.06 Correct position of the groove. (Courtesy of Mechanic Metal Corp.)

Figure 7.2.07 Avoid abrupt section changes. (Courtesy of Mechanic Metal Corp.)
And more...

Figure 7.2.32
Omit outside bosses and the need for cores.
(Courtesy of Meehanite Metal Corp.)

Figure 7.2.35
Avoid using ribs which meet at acute angles.
(Courtesy of Meehanite Metal Corp.)
Die Casting
Solidification Time

Time to form solid part

\[ \dot{q} = -hA(T_M - T_o) = \rho_M H_M A \frac{ds}{dt} \]

\[ t = \frac{\rho_M H_M V}{h(T_M - T_o) A} \]

Also need to cool casting to below \( T_M \)
to eject \( \rightarrow T_{eject} \)
and will inject at \( T_{inject} > T_M \).
Time to cool part to the ejection temperature. (lumped parameter model)

\[ mC_p \frac{dT}{dt} = -Ah(T - T_o) \]

let \( \theta = T - T_o \)

\[ \int_{\theta_i}^{\theta_f} \left( \frac{d\theta}{\theta} \right) = -\int_{t_i}^{t_f} \frac{Ah}{mC_p} \, dt \]

\[ \Delta \theta_i = T_i + \Delta T_{sp} - T_{mold} \]

\[ \Delta T_{sp} = \frac{H}{C_p} \]

\[ \Delta \theta_f = T_{eject} - T_{mold} \]

Integration yields...

\[ t = \frac{-mC_p}{Ah} \ln \frac{\Delta \theta_f}{\Delta \theta_i} \]

Or for thin sheets of thickness “w”,

\[ t = \frac{wpC_p}{2h} \ln \left( \frac{T_{inject} + \Delta T_{sp} - T_{mold}}{T_{eject} - T_{mold}} \right) \]

“sp” means superheat
Pattern Design Issues (Alum)

- Shrinkage Allowance .013/1
- Machining Allowance 1/16”
- Minimum thickness 3/16”
- Parting Line
- Draft Angle 3 to 5%
- Uniform Thickness
Pattern Design

Table 12.1
Normal Shrinkage Allowance for Some Metals Cast in Sand Molds

<table>
<thead>
<tr>
<th>Metal</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray cast iron</td>
<td>0.83 – 1.3</td>
</tr>
<tr>
<td>White cast iron</td>
<td>2.1</td>
</tr>
<tr>
<td>Malleable cast iron</td>
<td>0.78 – 1.0</td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td>1.3</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>1.3</td>
</tr>
<tr>
<td>Yellow brass</td>
<td>1.3 – 1.6</td>
</tr>
<tr>
<td>Phosphor bronze</td>
<td>1.0 – 1.6</td>
</tr>
<tr>
<td>Aluminum bronze</td>
<td>2.1</td>
</tr>
<tr>
<td>High-manganese steel</td>
<td>2.6</td>
</tr>
</tbody>
</table>

FIGURE 12.5 Redesign of a casting by making the parting line straight to avoid defects. Source: Steel Casting Handbook, 5th ed. Steel Founders’ Society of America, 1980. Used with permission.

FIGURE 11.7 Taper on patterns for ease of removal from the sand mold.
Variations and Developments

• Continuous casting
• Lost foam molding
• 3D Printing of Investment tooling
• Direct printing with metal droplets
• Uniform metal spray
Steel from the electric or basic oxygen furnace is tapped into a ladle and taken to the continuous casting machine. The ladle is raised onto a turret that rotates the ladle into the casting position above the tundish. Referring to Figure 2, liquid steel flows out of the ladle (1) into the tundish (2), and then into a water-cooled copper mold (3). Solidification begins in the mold, and continues through the First Zone (4) and Strand Guide (5). In this configuration, the strand is straightened (6), torch-cut (8), then discharged (12) for intermediate storage or hot charged for finished rolling.
3D Printing of Investment cast tooling
Shell and part (Turbine blade)
Microcasting of droplets

CMU

MIT
Environmental Issues

• Energy
• Materials
• Emission

• Off-gassing see AFS webpage on green sand emissions;
  http://www.afsinc.org/environmental.html
Process Material Flow

Metals Flow
- Melting
- Pouring
- Cooling
- Shakeout
- Trim
- Product Finishing
- Product & Waste

Sand+ Flow
- Mixing
- Mold Formation
- Sand Cooling
- Sand Processing (AO Treatment)
- Losses

Recycling

A. Jones
Sand casting; boundaries

S. Dalquist
Sand casting; energy profile

- National statistics
- Averages 6 to 12 MJ/kg (at the factory) of saleable cast metal
- Melting largest component

S. Dalquist
Nat’l statistics Vs model

- pour Vs part size ~ 2 to 3
- thermal energy
  \[ \Delta H = mC_p \Delta T + m \Delta H_f \Rightarrow 0.95 \text{ (aluminum), 1.3 MJ/kg (cast iron)} \]
- furnace efficiency, 0.6<\(\eta\)<0.8
- melt energy
  \[ \approx 3 \text{ to 6 (model) Vs 2.9 to 6.7 (statistics)} \]
## Casting Energy Example

<table>
<thead>
<tr>
<th>Stage</th>
<th>MJ/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mold preparation</td>
<td>3.0</td>
</tr>
<tr>
<td>Metal preparation</td>
<td>5.8</td>
</tr>
<tr>
<td>Casting</td>
<td>0.7</td>
</tr>
<tr>
<td>Finishing</td>
<td>1.2</td>
</tr>
<tr>
<td>Total at foundry</td>
<td>10.7</td>
</tr>
<tr>
<td>Electricity losses</td>
<td>6.0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>16.7</strong></td>
</tr>
</tbody>
</table>

Metals & sand used in Casting

- Iron accounts for 3/4 of US sand cast metals
  - Similar distribution in the UK
  - Share of aluminum expected to increase with lightweighting of automotive parts
- Sand used to castings out—about 5.5:1 by mass
- Sand lost about 0.5:1 in US; 0.25:1 in UK

Improving sand casting

\[ \eta_{II} = \frac{C_p \Delta T + \Delta h}{15 \frac{MJ}{kg}} \approx \frac{1}{15} \approx 7\% \]

- reduce pour size
- improve furnace efficiency
- use waste heat
- use fuel Vs electricity
Aggregate TRI data (toxic releases)

kg released per tonne cast

- Zinc compounds
- Manganese compounds
- Methyl alcohol
- Tin (metal or dust)
- Toluene
- Chromium compounds
- Xylene (mixed isomers)
- Phenol
- Copper
- Toluene
- Ammonia
- Lead
- Naphthalene
- Benzene
- Cyanide
- Lead compounds
- Certain glycol ethers
- Barium
- Nickel
- Formaldehyde
- Ethylene glycol
- Dichloroethane
- Styrene
- N-methyl-2-pyrrolidone
- Copper compounds
- Thionyl chloride
- Barium compounds
- Tetrachloroethylene
- Tetrahydrofuran
- Methyl ethyl ketone
- Cresol (mixed isomers)
- Dispersants
- N-butyl alcohol
- Sulfonic acid
- Nitrate compounds

Legend:
- Land disposal
- Point air
- Fugitive air
Sandcasting Emissions Factors

- Emissions factors are useful because it is often too time consuming or expensive to monitor emissions from individual sources.
- They are the best way to estimate emissions if you do not have test data.

<table>
<thead>
<tr>
<th>Iron Melting Furnace Emissions Factors (kg/Mg of iron produced)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Process</td>
</tr>
<tr>
<td>Cupola</td>
</tr>
<tr>
<td>Uncontrolled</td>
</tr>
<tr>
<td>Baghouse</td>
</tr>
<tr>
<td>Electric Induction</td>
</tr>
<tr>
<td>Uncontrolled</td>
</tr>
<tr>
<td>Baghouse</td>
</tr>
</tbody>
</table>

* S = % of sulfur in the coke. Assumes 30% conversion of sulfur into SO₂.
Source: EPA AP-42 Series 12.10 Iron Foundries

<table>
<thead>
<tr>
<th>Pouring, Cooling Shakeout Organic HAP Emissions Factors for Cored Greensand Molds (lbs/ton of iron produced)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Loading</td>
</tr>
<tr>
<td>-------------------------------------</td>
</tr>
<tr>
<td>AFS heavily cored</td>
</tr>
<tr>
<td>AFS average core</td>
</tr>
<tr>
<td>EPA average core</td>
</tr>
</tbody>
</table>

Source: AFS Organic HAP Emissions Factors for Iron Foundries
www.afsinc.org/pdfs/OrganicHAPemissionfactors.pdf
## TRI Emissions Data – 2003

**XYZ Foundry (270,000 tons poured)**

<table>
<thead>
<tr>
<th>Chemical</th>
<th>Total Air Emissions (lbs)</th>
<th>Surface Water Discharge (lbs)</th>
<th>Total on-site Release (lbs)</th>
<th>Total transfers off site for waste Management (lbs)</th>
<th>Total waste Managed (lbs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>COPPER</td>
<td>69</td>
<td>9</td>
<td>78</td>
<td>74,701</td>
<td>74,778</td>
</tr>
<tr>
<td>DIISOCYANATES</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>LEAD</td>
<td>127</td>
<td>40</td>
<td>167</td>
<td>39,525</td>
<td>39,692</td>
</tr>
<tr>
<td>MANGANESE</td>
<td>274</td>
<td>48</td>
<td>322</td>
<td>768,387</td>
<td>768,709</td>
</tr>
<tr>
<td>MERCURY</td>
<td>14.35</td>
<td>0</td>
<td>14.35</td>
<td>0.25</td>
<td>14.6</td>
</tr>
<tr>
<td>PHENOL</td>
<td>6,640</td>
<td>5</td>
<td>6,645</td>
<td>835</td>
<td>7,484</td>
</tr>
<tr>
<td>ZINC (FUME OR DUST)</td>
<td>74</td>
<td>0</td>
<td>74</td>
<td>262,117</td>
<td>262,191</td>
</tr>
<tr>
<td><strong>TOTALS</strong></td>
<td></td>
<td></td>
<td><strong>7,300</strong></td>
<td><strong>1,145,585</strong></td>
<td><strong>1,152,889</strong></td>
</tr>
</tbody>
</table>
Readings

• G. Boothroyd et al., "Design for Die Casting"
• Flemings, "Solidification Process"
• Kalpakjian Ch 10-12, Skim Sec 30.9, 30.10,
• Skim Ch 32 (Ch 10-12, Skim Ch 29, 30)
• Dalquist, S… "Life Cycle Analysis of Conventional Manufacturing Techniques: Sand Casting,"