2.008

Metal Casting

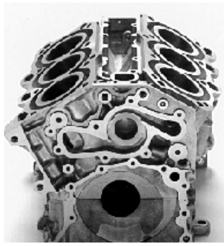
Outline

- Introduction
- Process Constraints
- Green Sand Casting
- Other Processes

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



Example – Die Casting

Example – Investment 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

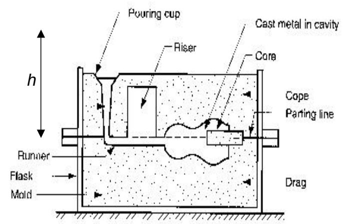
$$h + \frac{P}{\rho g} + \frac{v^2}{2g} = const.$$

$$v \cong \sqrt{2gh} \approx 1.5\,\mathrm{m/s}$$

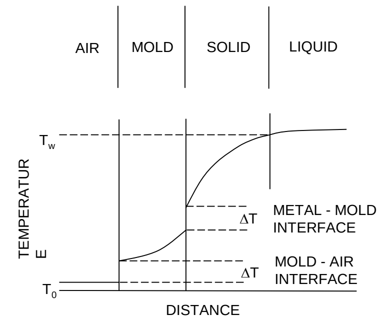
- Reynold's number

$$\mathrm{Re} = \frac{vD\rho}{\mu} \approx 5 \times 10^4$$

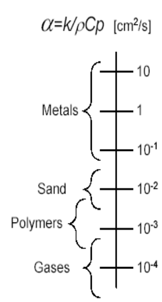
  - Turbulence
  - Injection Molding : Re ~ 10^{-4}



Cooling for Sand Mold

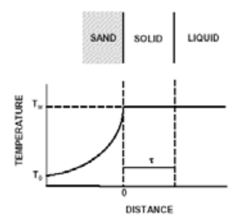


Conductivity / Diffusivity



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

Solidification Time : Sand Casting



- Transient 1-D heat transfer

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

Solution

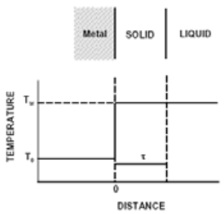
$$\frac{T - T_M}{T_o - T_M} = erf\,\frac{-x}{2\sqrt{\alpha_s t}}$$

- Solidification time

$$t_s = C\left(\frac{V}{A}\right)^2$$

Chvorinov's rule

Solidification Time : Die Casting



- Transient 1-D heat transfer

$$mC_p \frac{\partial T}{\partial t} = -Ah(T - T_o)$$

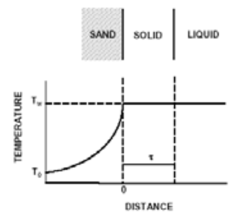
Solution

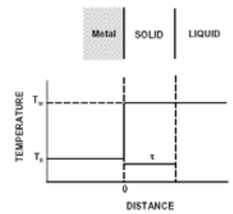
$$t = \frac{mC_p}{Ah} \ln\left(\frac{T_{inject} + \Delta T_{sp} - T_{mold}}{T_{eject} - T_{mold}} \right)$$

- Solidification time

$$t_s = C\left(\frac{V}{A}\right)^1$$

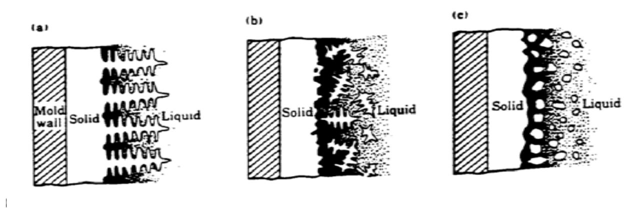
Comparison: Sand Mold vs Metal Mold





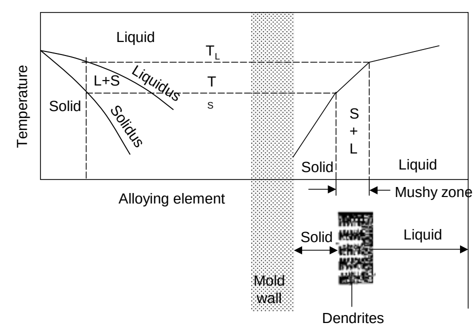
Sand Mold	Metal Mold
Sand casting	Die casting
$t_s \sim (V/A)^2$	$t_s \sim (V/A)^1$

Microstructure Formation

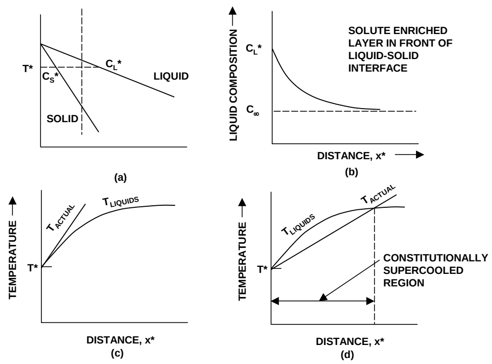


Schematic illustration of three basic types of cast structures
(a) Columnar dendritic (b) equiaxed dendritic (c) equiaxed nondendritic

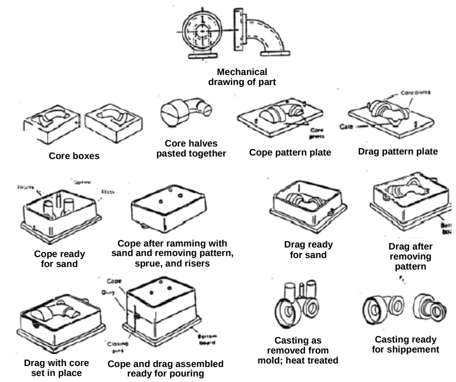
Formation of Dendrites



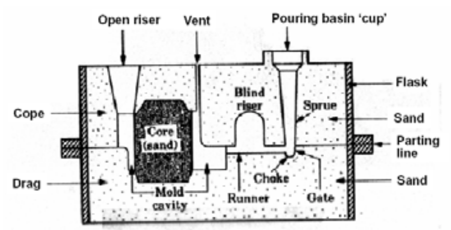
Constitutional Supercooling



Green Sand Casting



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

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

Typical Pattern Machining Allowance

	Allowances, mm		
Pattern size, mm	Bore	Surface	Cope side
For cast irons			
Up to 152	3.2	2.4	4.8
152 - 305	3.2	3.2	6.4
305 - 510	4.8	4.0	6.4
510 - 915	6.4	4.8	6.4
915 - 1524	7.9	4.8	7.9
For cast steels			
Up to 152	3.2	3.2	6.4
152 - 305	6.4	4.8	6.4
305 - 510	6.4	6.4	7.9
510 - 915	7.1	6.4	9.6
915 - 1524	7.9	6.4	12.7
For nonferrous alloys			
Up to 76	1.6	1.6	1.6
76 - 152	2.4	1.6	2.4
152 - 305	2.4	1.6	3.2
305 - 510	3.2	2.4	3.2
510 - 915	3.2	3.2	4.0
915 - 1524	4.0	3.2	4.8

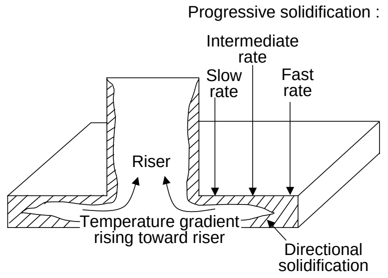
Gating System: Sprue, Runner, and Gate

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

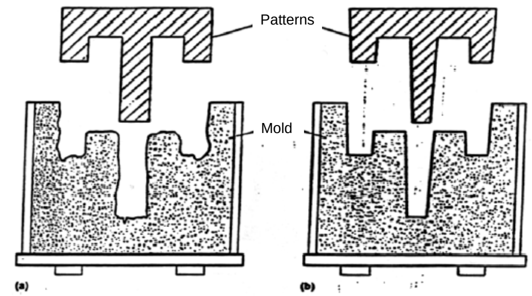
Riser: Location and Size

- Casting shrinkage
- Directional solidification
- Scrap and secondary operation

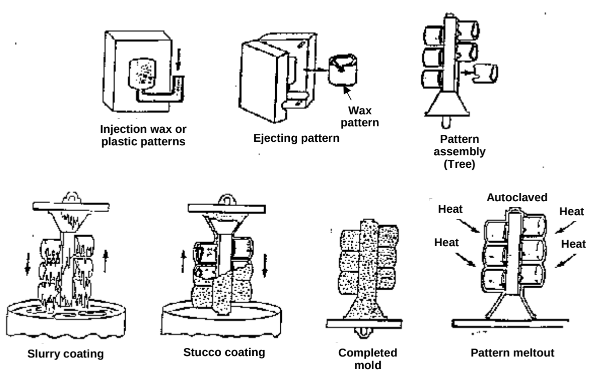
Progressive Solidification in Riser



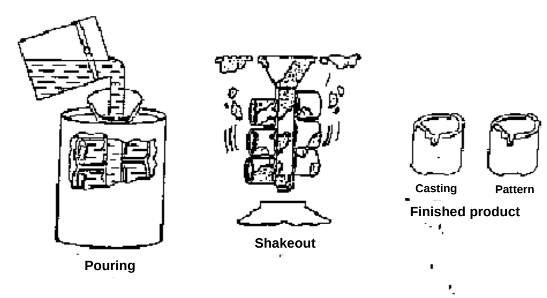
Draft in Pattern



Investment Casting



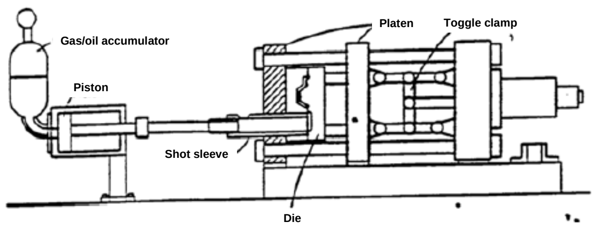
Investment Casting (cont.)



Advantages of Investment Casting

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

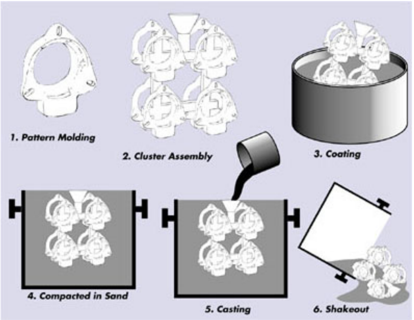
Die Casting



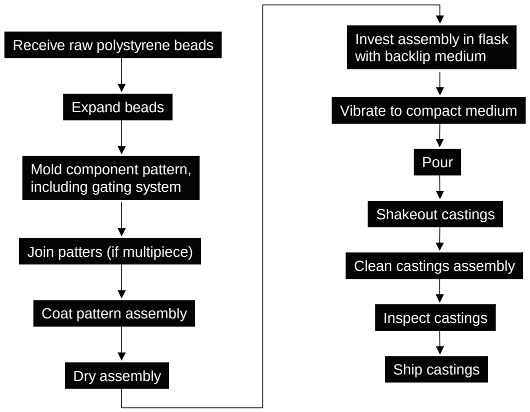
Advantages of Die Casting

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

Lost Foam Casting



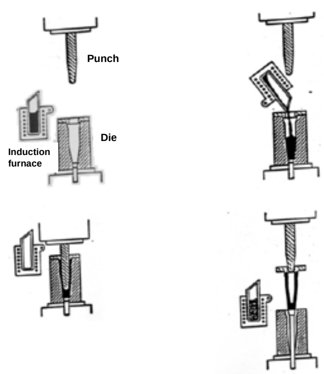
Lost Foam Casting



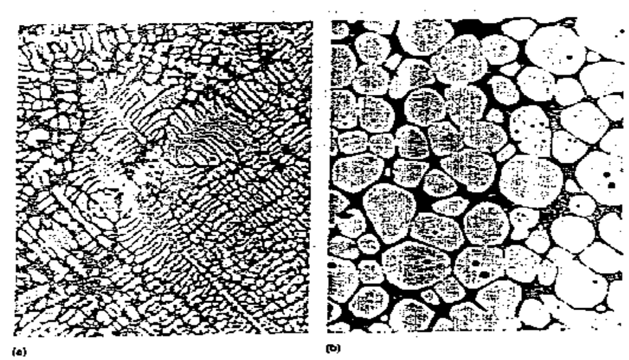
Advantages of Lost Foam Casting

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

Semi-solid Casting



Advantages of Semi-solid Casting



Casting Process Comparison

Process	Cost * Die	Cost * Equipment	Cost * Labor	Production rate (Pc/hr)
Sand	L	L	L–M	<20
Shell-mold	L–M	M-H	L–M	<50
Plaster	L–M	M	M–H	<10
Investment	M–H	L-M	H	<1000
Permanent mold	M	M	L–M	<60
Die	H	H	L–M	<200
Centrifugal	M	H	L–M	<50

* L, low; M, medium; H, high.

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 : $t \sim (V/A)^1$

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