ME 4563

Introduction to Manufacturing Processes

College of Engineering
Arkansas State University

Metal Casting Process

Casting – Overview

- The conversion of raw materials into useful shapes using phase transformations
- Is one of the <u>first steps</u> in converting raw materials into useful products
- Applicable to most materials
  - Metals & alloys
  - Ceramics
  - Plastics
  - Glass
- Also includes mixtures
  - Ceramic slips and slurries

Casting – Overview

- Advantages
  - Complex geometries
  - Can be "net shaped"
  - Can produce very large parts
  - Any metals
  - Can be mass-produced
  - No size limits (realistic limits)
  - Close tolerances (some processes
  - High surface finish (some processes)
  - Less scrap

Casting – Overview

- Disadvantages
  - Limitation in mechanical properties, dimensional accuracy and surface finish
  - Shrinkage, porosity, cracks
  - Tooling can be expensive
    – part shape depends on tool (mold)
  - Can be brittle
  - Microstructure can be difficult to control
    – non-uniform cooling
    – faster on outside produces finer grain structure
  - Some Safety Hazard

Casting Process

The Casting Process essentially involves the following steps:

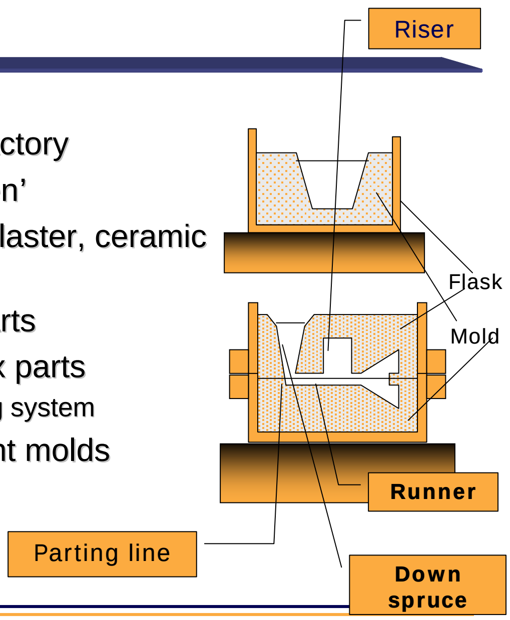
- making a mold patterned after the component to be manufactured
- pouring molten metal into the mold
- allowing it to cool
- and removing the metal from the mold

Types of Casting

- Molten materials which solidify on cooling
  - Metals, ceramics, glasses
- Liquids which solidify by reacting with chemical activators/hardeners or moisture
  - Plastics
- Slurries which solidify by the extraction of the suspending medium (usually water)
  - Ceramics

Casting

- A Foundry is a casting factory
- Workers are 'Foundrymen'
- Mold Materials – sand, plaster, ceramic and metals
- Open Molds – Simple parts
- Closed Molds – Complex parts
  - A passageway - the gating system
- Expandable or permanent molds



Metal Casting - Origins

- **3200 B.C.** A copper frog, the oldest known casting in existence, is cast in Mesopotamia.
- **2000 B.C.** Iron is discovered.
- **800-700 B.C.** First Chinese production of cast iron.
- **645 B.C.** Earliest known sand molding (Chinese).
- **233 B.C.** Cast iron plowshares are poured in China.
- **500 A.D.** Cast crucible steel is first produced in India, but the process is lost until 1750, when Benjamin Huntsman reinvents it in England.

Metal Casting - Origins

Middle Ages to 1800

- **1642** Saugus Iron Works, America's first iron foundry (and second industrial plant), is established near Lynn, Massachusetts. The first American iron casting, the Saugus pot, is poured there.
- **1709** Englishman Abraham Darby creates the first true foundry flask for sand and loam molding.
- **1730** Abraham Darby is the first to use coke as fuel in his melting furnace in Coalbrookdale, England.
- **1794** First use of the cupola in iron founding. Invented by John Wilkinson of England, the original had metal-cladding and utilized a steam engine to provide the air blast.

Summary of Casting Processes

TABLE 11.1

Process	Advantages	Limitations
Sand	Almost any metal cast; no limit to size, shape or weight; low tooling cost.	Some finishing required; somewhat coarse finish; wide tolerances.
Shell mold	Good dimensional accuracy and surface finish; high production rate.	Part size limited; expensive patterns and equipment required.
Expendable pattern	Most metals cast with no limit to size; complex shapes	Patterns have low strength and can be costly for low quantities
Plaster mold	Intricate shapes; good dimensional accu- racy and finish; low porosity.	Limited to nonferrous metals; limited size and volume of production; mold making time relatively long.
Ceramic mold	Intricate shapes; close tolerance parts; good surface finish.	Limited size.
Investment	Intricate shapes; excellent surface finish and accuracy; almost any metal cast.	Part size limited; expensive patterns, molds, and labor.
Permanent mold	Good surface finish and dimensional accuracy; low porosity; high production rate.	High mold cost; limited shape and intricacy; not suitable for high-melting-point metals.
Die	Excellent dimensional accuracy and surface finish; high production rate.	Die cost is high; part size limited; usually limited to nonferrous metals; long lead time.
Centrifugal	Large cylindrical parts with good quality; high production rate.	Equipment is expensive; part shape limited.

General Characteristics of Casting Processes

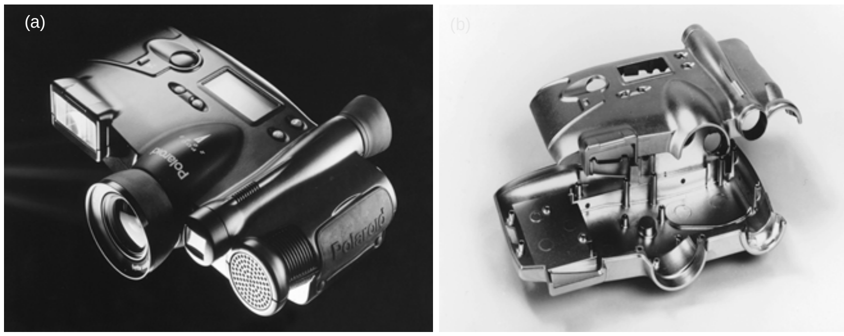
TABLE 11.2

Process	Typical materials cast	Weight (kg) Minimum	Weight (kg) Maximum	Typical surface finish (μm, R_a)	Porosity*	Shape complexity*	Dimensional accuracy*	Section thickness (mm) Minimum	Section thickness (mm) Maximum
Sand	All	0.05	No limit	5-25	4	1-2	3	3	No limit
Shell	All	0.05	100+	1-3	4	2-3	2	2	--
Expendable mold pattern	All	0.05	No limit	5-20	4	1	2	2	No limit
Plaster mold	Nonferrous (Al, Mg, Zn, Cu)	0.05	50+	1-2	3	1-2	2	1	--
Investment	All (High melting pt.)	0.005	100+	1-3	3	1	1	1	75
Permanent mold	All	0.5	300	2-3	2-3	3-4	1	2	50
Die	Nonferrous (Al, Mg, Zn, Cu)	<0.05	50	1-2	1-2	3-4	1	0.5	12
Centrifugal	All	--	5000+	2-10	1-2	3-4	3	2	100

*Relative rating: 1 best, 5 worst.

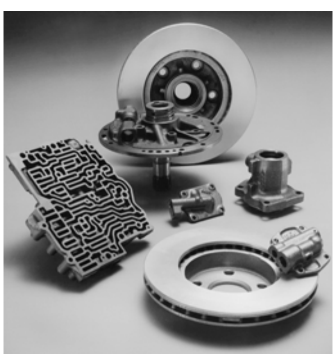
Note: These ratings are only general; significant variations can occur, depending on the methods used.

Die-Casting Examples



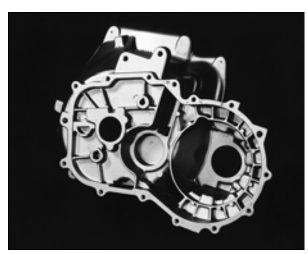
(a) The Polaroid PDC-2000 digital camera with a AZ91D die-cast, high purity magnesium case. (b) Two-piece Polaroid camera case made by the hot-chamber die casting process. *Source*: Courtesy of Polaroid Corporation and Chicago White Metal Casting, Inc.

Casting Examples



Typical gray-iron castings used in automobiles, including transmission valve body (left) and hub rotor with disk-brake cylinder (front).

Source: Courtesy of Central Foundry Division of General Motors Corporation.



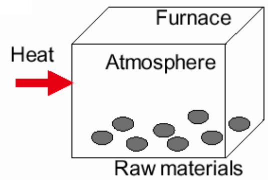
A cast transmission housing.

Casting – What is Involved ?

- Analysis
- Defects
- Processes
- Economics

Casting Analysis – Fluid Flow

Casting Steps - Melting



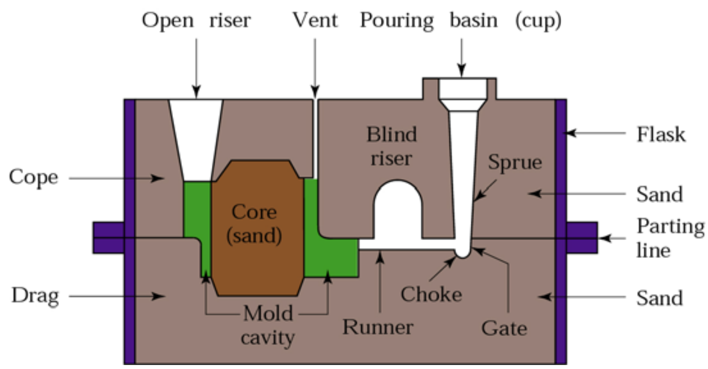
- Raw material (charge)
  - scrap, alloying materials
- Atmosphere
  - Air (oxygen), vacuum, inert gas (argon)
- Heating
  - External - electric, gas, oil
  - Internal - induction, mix fuel with charge
    - steel making in blast furnace -mix coke with steel
- Furnace material - refractory
  - high melting point metals, ceramics

Casting Steps

quick route from raw material to finished product

- Melt metals
- Pour / force liquid into hollow cavity (mold)
- Cool / Solidify
- Remove
- Finish

Sand Mold Features



Schematic illustration of a sand mold, showing various features.

Practical Fluid Flow

- Pouring basin
  - where the molten metal enters the mold
- Gating system
  - connects the pouring basin to the rest of the mold through
    - Sprue connects the pouring basin to the runners
    - Runners carry the molten metal to the mold
- Risers
  - act as reservoirs to supply molten material as it solidifies and shrinks

Metal Casting

Major Factors Involved in Casting

- mould cavity
- molten metal
- escape of air /gas
- shrinking
- mould removal
- finishing

Metal Casting

So where is the problem ???

- the flow of molten metal into a cavity
- the solidification and cooling of the metal in the mold
- the defects that can be formed in the cast part
- the influence of the type of mold material
- etc.

Casting - Molten Material

- Factors affecting solidification characteristics from the molten state
  - Fluidity -
    - Flow of molten material into the cavity

Fluidity

- Fluidity: A measure of the capability of a metal to flow into and fill the mold before freezing
- Gives an idea of the distance the metal flows before cooling
- Provides a measure of viscosity
- Fluidity is dependent on:
  - Characteristics of the molten metal
  - Casting parameters

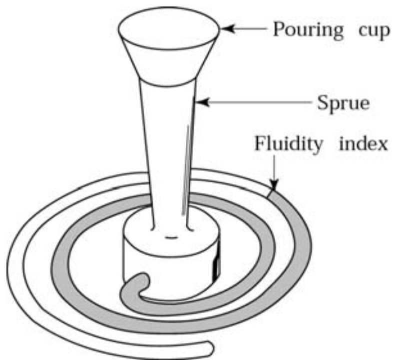
Fluidity

- Molten Metal Factors affecting fluidity
  - Viscosity
  - Pouring temperature
  - Metal composition (pure metals – good fluidity; alloys – not as good)
  - Surface tension (due to film formation; e.g., Al – s.t. triples due to oxide film)
  - Rate of solidification

Fluidity

- Casting Parameters affecting fluidity
  - Mold design – dimensions of risers, sprue, etc., influence fluidity
  - Mold material and its surface – thermal conductivity, roughness
    - Heating mold improves fluidity
  - Rate of pouring (slow rate increases fluidity due to local cooling)
  - Heat transfer (affects viscosity and hence fluidity)
  - Degree of superheat (is the temp above the melting point of the metal/alloy; increases fluidity by delaying solidification)
  - All the characteristics are "bundled" into one term – called Castability

Fluidity Test



A test method for fluidity using a spiral mold.

The *fluidity index* is the length of the solidified metal in the spiral passage.

The greater the length of the solidified metal, the greater is its fluidity.

Casting Steps – Fluid Flow

- Reynold's number
- Bernoulli's equation
- Continuity

Casting Steps – Fluid Flow

Reynold's Number - Re

Reynolds number for a flow through a pipe is proportional to (inertial force) / (viscous force)

$$\mathrm{Re} = \frac{\rho V d}{\mu} = \frac{(\text{density}) * (\text{velocity}) * (\text{diameter})}{(\text{viscosity})}$$

Casting Steps – Fluid Flow

Critical Reynold's Number - Re

- Re < 2,000 – laminar flow; always preferred
- Re ~ 2,000
  - laminar to turbulent transition
  - eddies begin to form
- Re > 20,000
  - very turbulent
- Can cause air entrapment and dross (oxide) formation – results in defects in castings
- Controlled through gate and runner design

Casting Steps – Fluid Flow

Critical Reynold's Number - Re

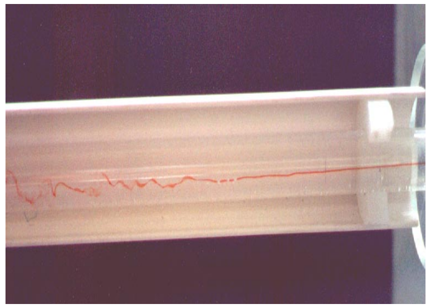


Photo shows dye stream transitioning from laminar flow to turbulent flow

Casting Steps – Fluid Flow

Reynold's Number – An Example

How fast would a stream of honey 1 in. in diameter need to be to be turbulent?

- Density (ρ) = 1.43 g/cm 3 (at 20^o C)
- Viscosity (μ) = 189 poise (at 20.6^o C)

$$\mathrm{Re} = \frac{\rho V d}{\mu}$$

$$= \frac{1430 * V * 0.0254}{18.9}$$

Casting Steps – Fluid Flow

Reynold's Number – An Example

So, for turbulent flow transition,

$$Re = 2{,}000 = 1{,}430 * V * 0.0254/18.9$$

which gives:

$$V = 1{,}040 \text{ m/s (Mach 3.1)}$$

(This ignores shear thinning)

Flow - Pouring

- 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?

Bernoulli's Theorem

$$h + \frac{p}{\rho g} + \frac{v^2}{2g} = \text{constant}$$

- Where:
  ‘h’ is the elevation above a reference plane
  ‘p’ is the pressure at that elevation
  ‘v’ is the velocity of the liquid at that elevation
  ‘ρ’ is the density of the liquid and
  ‘g’ is the gravitational constant

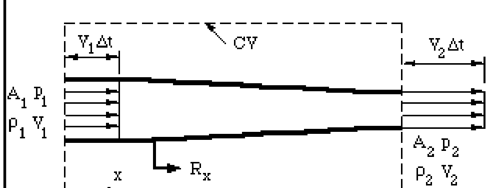
  - For zero velocity, pressure is proportional to height and density
  - For a constant height, Velocity is proportional to the square root of pressure

Pouring Analysis

- Bernoulli’s theorem: at any two points in a flowing liquid

$$h_1 + \frac{P_1}{\rho g} + \frac{v_1^2}{2g} = h_2 + \frac{P_2}{\rho g} + \frac{v_2^2}{2g}$$

  - h = head, P = pressure, ρ = density, v = flow velocity, g = gravity, F = frictional losses



- points 1 and 2 lie on a streamline
- the fluid has constant density
- the flow is steady, and
- there is no friction

Pouring Analysis

$$h_1 + \frac{P_1}{\rho g} + \frac{v_1^2}{2g} = h_2 + \frac{P_2}{\rho g} + \frac{v_2^2}{2g}$$

- 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, and $v_1 = 0$,

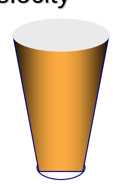
$$h_1 = \frac{v_2^2}{2g}; \qquad v = \sqrt{2gh}$$

Pouring Analysis

- For an incompressible liquid:

  A.v = constant, the flow rate

  where A is the cross-section area and v is the flow velocity



- Continuity law
  - Volumetric flow; $Q = v_1 A_1 = v_2 A_2$

- Mold fill time (MFT) = Time required to fill the cavity of volume V

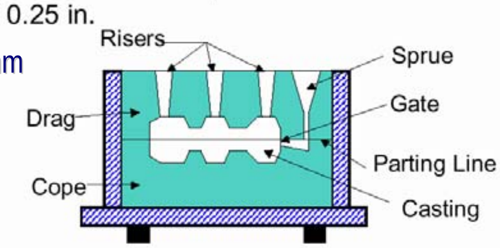
$$MFT = \frac{V}{Q}$$

Pouring Analysis

Consider an Example ...

- You are pouring liquid iron into a mold.
- The mold has a sprue height of 2 inches.
- The bottom of the sprue has a diameter of 0.25 in.

0.25in = approx 6mm

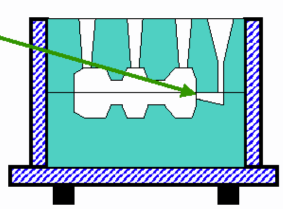


Pouring Analysis

Consider an Example ...

• You wish to pour the metal so that you do not entrap air

- What should the diameter of the gate (d_{gate}) at the bottom of the mold be?



Pouring Analysis

Example …

- We need to use:

– Reynold's number

values below 20,000 are OK in casting

– Bernoulli's equation

– Continuity

Pouring Analysis

Example …

Material – Iron …

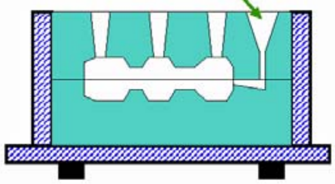
- Iron data:
  - density (ρ) = 7860 kg/m^3
  - viscosity at pouring temp (μ) = 2.25 cp = 2.25 x 10^{-3} N*s/m^2
- h_0 = 2 in. = 0.051 m
- h_1 = 0 m
- g = 9.8 m/s^2
- $A_1 = \pi r^2 = 3.14 * 0.0032^2 =$ 3.22 x 10^{-5} m^2

Pouring Analysis

Example …

- Now we need to determine the velocity at the bottom of the sprue (v_1) using Bernoulli's equation.

- We can assume that the velocity at the top of the mold (v_o) is zero, if there is a pouring basin, which is typical.



- Ignore friction effects (f=0).
- Assume the mold is open to atmospheric pressure ($P_0=P_1=P_{atm}$).

Pouring Analysis

Example …

- Substituting into Bernoulli's equation:

$$P_o + \frac{\rho v_o^2}{2} + \rho g h_o = P_1 + \frac{\rho v_1^2}{2} + \rho g h_1 + f$$

$$P_{atm} + \frac{7860 * 0^2}{2} + 7860 * 9.8 * 0.051 =$$

$$P_{atm} + \frac{7860 * v_1^2}{2} + 7860 * 9.8 * 0 + 0$$

Pouring Analysis

Example …

- And solving:

  $v_1 = 1$ m/s

- Checking Reynolds number

  Re = 7860*1*0.0032/2.25x10^{-3}
  =11,179 < 20,000

- Now using continuity:

$A_1 v_1 = A_{gate} v_{gate} =$

$3.22 \times 10^{-5} * 1 = A_{gate} v_{gate}$

and $A_{gate} = \pi r_{gate}^2$

Pouring Analysis

Example …

- Now, Reynold's number < 20,000

$$Re = \frac{\rho V d}{\mu} = \frac{7860 * v_{gate} * d_{gate}}{2.25 * 10^{-3}} = 20{,}000$$

- Solving gives:

  $v_{gate} * d_{gate} = 5.72 \times 10^{-3}$ m^2/s

Pouring Analysis

- Combining the following equations:
- $3.22 \times 10^{-5} * 1 = A_{gate} v_{gate}$
- $A_{gate} = \pi r_{gate}^2$
- $v_{gate} * d_{gate} = 5.72 \times 10^{-3}$ m²/s

- And solving gives:

d_{gate} = 3.6 mm = 0.14 in.

(We were given that the sprue is 6mm in diameter – so this gate dia seems reasonable)

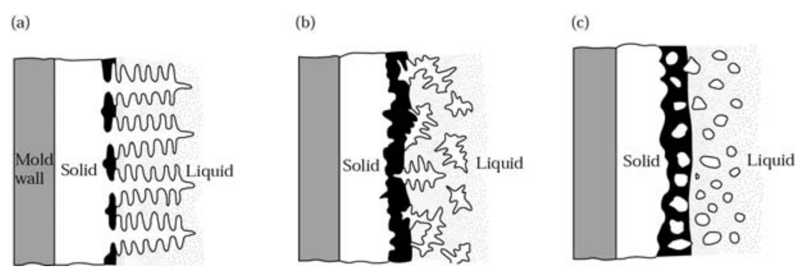
Cast Structures

One of the parameters in judging the Quality of a Casting is its grain structure

Structure-Property Relationships

- Slow cooling - uniform composition
- Normal cooling - Microsegregation and Macro segregation
- Microsegregation
  - Segregation of alloying elements within the grains or dendrites
  - Dendrites are the columnar grains that typically grow from the mold surface
  - Dendrite surface has higher concentration of alloying elements than core
- Macrosegregation
  - Segregation of alloying elements across the casting itself

Cast Structures

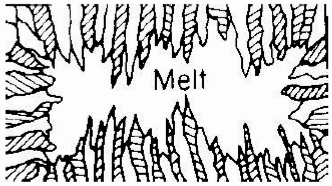


Schematic illustration of three basic types of cast structures: (a) columnar dendritic; (b) equiaxed dendritic; and (c) equiaxed nondendritic.

Source: D. Apelian.

Cast Structures

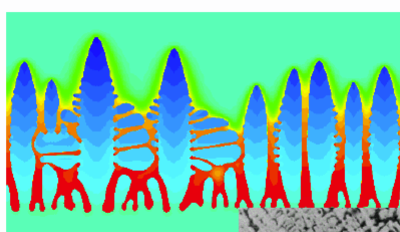
Microstructure - Dendrites

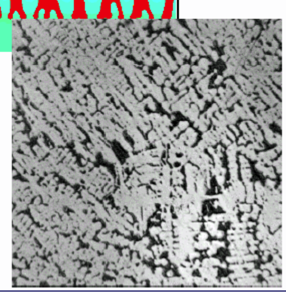


- Finer structure at walls
- Grains / dendrites grow to center

Cast Structures

Microstructure - Dendrites





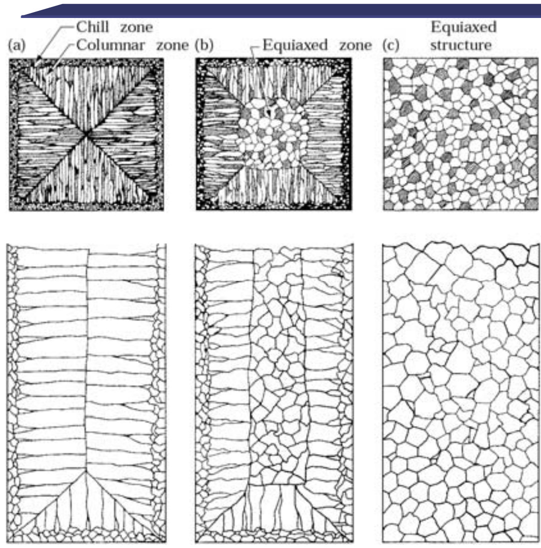
Structure-Property

- Macrosegregration
  - Normal
    - Lower melting constituents driven away from the mold wall
      - higher concentration at center
  - Inverse
    - melt enters the cavities among the dendrites formed at the surface
  - Gravity
    - Heavy elements sink to the bottom
- Macrosegregation gives rise to poor microstructures
- Essentially, Macrosegregation is NOT GOOD

Avoidance of Macrosegregation

- Use
  - Nucleation agents
  - Create more grains by mechanical means
    - Rheocasting - stir the metal while it is in the mushy zone
    - Vibration
    - Electromagnetic stirring

Cast Structures of Metals



Schematic illustration of three cast structures of metals 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, J. L. Walker, and A. Cibula.

Cast Structures

After the Casting Process

Microstructure

- Post-treatment may be necessary to get desired properties - grain structure
  - annealing
  - tempering
  - cold working

Influence of Grain Size on Microstructure

DECREASE in

- Grain size
- Microporosity

LEADS to
INCREASE in
Strength and Ductility
REDUCED
Cracking Tendency

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Casting - Molten Material

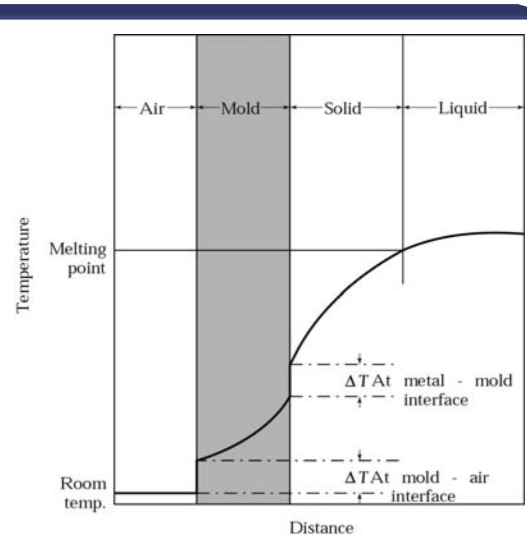
- Factors affecting solidification characteristics from the molten state
  - Fluidity -
    - Flow of molten material into the cavity
  - Heat transfer
    - During solidification and cooling

Heat Transfer

- Very complex phenomenon
  - **All three mechanisms involved**
- Very simple process
  - A cold mold extracts heat from the melt causing it to solidify
- Critical to the design of a mold
- Can compute a relative time for solidification
  - is proportional to the square of the ratio of the volume and surface area
    - A sphere will have a much longer solidification time than a complex shape of the same volume

Temperature Distribution

Temperature distribution at the interface of the mold wall and the liquid metal during solidification of metals in casting.



Cooling Rate – how does it affect ?

- Rate of cooling critical for the structure of the material and hence its properties
  - Slow cooling (~10^{2} °K/s) gives large grain sizes
  - Fast cooling (~10^{4} °K/s) gives small grain sizes
  - Very fast cooling rates (>10^{6} °K/s)produce amorphous materials (no proper form)
- Implications:-
  - Should design casting to be thin and not massive
  - Require "chills" to control cooling rate

Casting - Molten Material

- Factors affecting solidification characteristics from the molten state
  - Fluidity -
    - Flow of molten material into the cavity
  - Heat transfer
    - During solidification and cooling
  - Solidification

Importance of Solidification for Metals

- Microstructure of the product depends upon how the metal Solidifies
- Following parameters may be affected:
  - Grain size (coarse, fine)
  - Grain distribution
  - Grain morphology (structure)
  - Grain boundaries
  - Grain composition (metal or alloy)
  - Porosity content

How does Solidification Affect ?

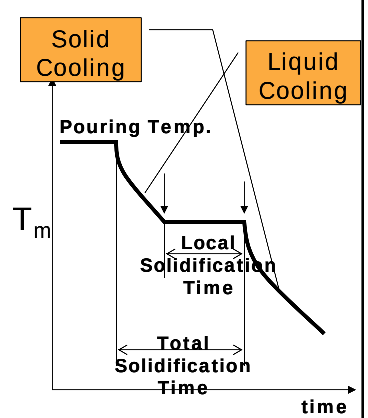
- Where the type of material becomes important
  - Molten metal solidification events depend on the type of material
    - Pure metals
    - Alloy
  - Plastics
    - Not as critical as for metals
  - Semiconductors
    - Specialty crystal growing
    - Single crystal so no microstructures
  - Glass
    - No microstructure

Solidification of Pure Metals

- Solidification occurs from the mold walls to the center in a plane front
- Composition and cooling rates of the melt affect the size and shape of grains in the solidifying alloy
  - This in turn affects the properties of the casting
  - Grains tend to be equiaxed and grow outward from the mold wall in a columnar structure (no particular axis of orientation)
- Solidification time is a function of the volume of the casting and its surface area
- Nucleation agents can cause a more equiaxed structure (more uniform grains and size distribution)

Solidification (Pure Metals)

- Solidification of pure metals takes place at constant temperature
- Solidification of alloys take place over a range of temperatures
- Phase diagrams are important tools for identifying the solidification point or points – especially for critical metals



Cooling Curve

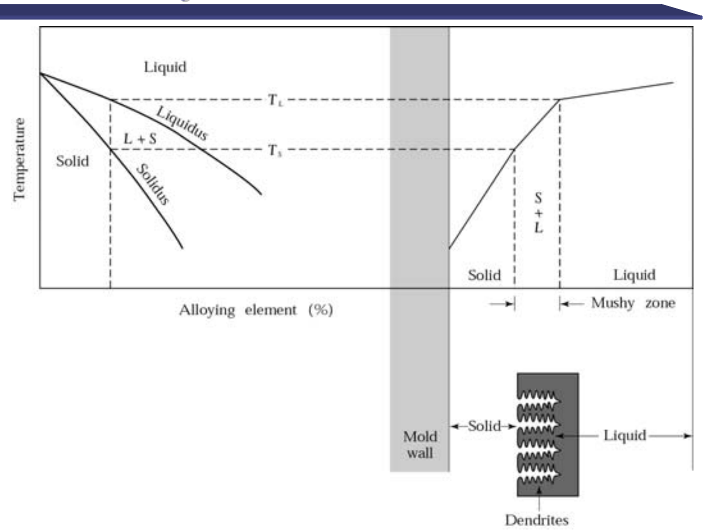
Solidification of Alloys

- Most Alloys freeze over a temperature range, not at a single temperature. Also is dependent on
  - Chemical compositional gradiency within a single grain
  - Chemical compositional gradiency throughout the casting – ingot segregation
- Eutectic Alloys – Solidification occurs at a single temperature

Eutectic Mixture - A solid solution consisting of two or more substances and having the lowest freezing point of any possible mixture of these components. The minimum freezing point for a set of components is called the **eutectic point**. Low-melting-point alloys are usually eutectic mixtures

Alloy Solidification

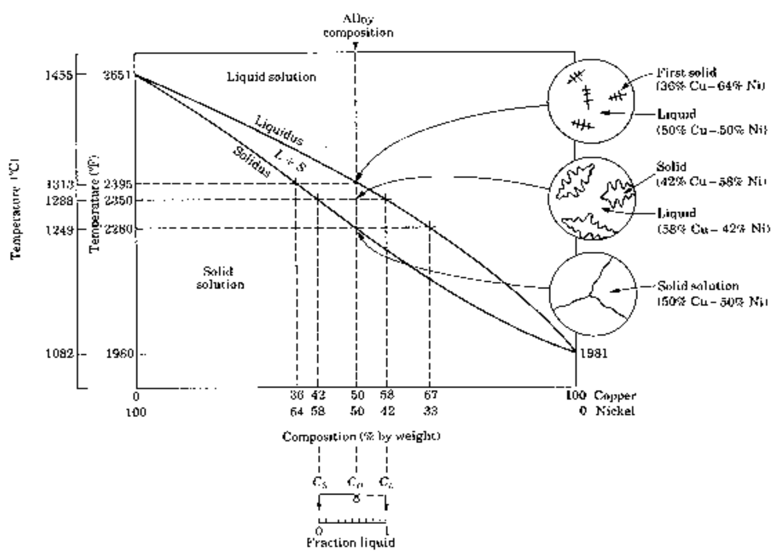
Schematic illustration of alloy solidification and temperature distribution in the solidifying metal. Note the formation of dendrites in the mushy zone.



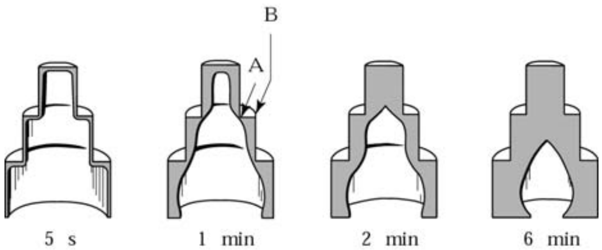
Solidification of Alloys

- Alloys with liquidus and solidus temperatures have a physical “mushy zone”
- “Mushy zone” - solid particles and liquid co-existing
- Solid particles tend to be dendritic (tree form) in nature and grow from the mold wall
- Microstructure highly dependent on cooling rate
- Freezing range ($T_L - T_S$) is the difference between the liquidus and solidus temperatures
- Ferrous alloys tend to have small freezing ranges
- Aluminum and magnesium alloys tend to have wide freezing ranges

Cu-Ni Phase Diagram



Solidification Time



Solidified skin on a steel casting. The remaining molten metal is poured out at the times indicated in the figure. Hollow ornamental and decorative objects are made by a process called slush casting, which is based on this principle. *Source*: H. F. Taylor, J. Wulff, and M. C. Flemings.

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 n = 2
C_m = experimentally determined value

- Used to estimate cooling time

Solidification Time

- Used in riser design: the solidification time of the riser must be equal to the solidification time of the cast part
- Constant 'C_m' is a function of the mold material, cast material and heat transfer coefficients

Heat Transfer

Comparison of Shapes with Same Volume

Shape	Area	Volume	(V/A)	$(V/A)^2$
cube	6	1	0.167	0.028
cylinder	5.54	1	0.181	0.033
sphere	4.84	1	0.207	0.043

Use for riser design

$$\left(\frac{V}{A}\right)_{riser} > \left(\frac{V}{A}\right)_{casting}$$

- else casting freezes before riser
  - leads to shrinkage or porosity

Heat Transfer

Solidification time

• Assumptions

– no thermal resistance at mold-metal interface

– no temperature gradients in metal

– mold is semi-infinite medium with uniform properties

Heat Transfer

Solidification time

$$t = \left[\frac{\pi}{4} \left(\frac{\rho_c \Delta H_f}{T_m - T_0} \right)^2 \frac{1}{k_m \rho_m c_m} \right] \left(\frac{V}{A} \right)^2$$

- Subscripts
  - c = casting
  - m = mold
- ΔH_f = latent heat of solidification
- T_m = metal melting temperature
- T_0 = initial mold temperature
- k_m = thermal conductivity of metal

Heat Transfer

Example …

- You are die casting a magnesium part with dimensions of 10 cm by 10 cm by 0.25 cm. The initial iron mold is at 25°C.
- Determine the time for the part to solidify if the metal is poured at its melting point.
- Determine the time for the part to solidify if the metal is poured at 50°C above its melting point, so as to alleviate the potential problem of short shots.

Heat Transfer

Example …

Material	Specific heat (J/g-°C)	Density (g/cm^3)	Thermal conductivity (W/m-°C)
Iron (solid)	0.7	7.9	73
Magnesium (solid)	1.07		
	Melting point (°C)	Latent heat of solidificaiton (J/g)	Specific heat (J/g-°C)
Magnesium (liquid)	650	384	1.38

Heat Transfer

Example …

- Solidification is a phase change that occurs at the melting point
- Solidification time:

$$t = \left[\frac{\pi}{4} \left(\frac{\rho_c \Delta H_f}{T_m - T_0} \right)^2 \frac{1}{k_m \rho_m c_m} \right] \left(\frac{V}{A} \right)^2$$

Heat Transfer

Example …

- the parameters:
  - ΔH_f = 384 J/g = 384 kJ/kg
  - ρ_c = 1.7 g/cm^3 = 1700 kg/m^3
  - T_m = 650^{o}C
  - T_o = 25^{o}C
  - k_m = 73 W/m-^{o}C
  - ρ_m = 7.9 g/cm^3 = 7900 kg/m^3
  - c_m = 0.70 J/g-^{o}C = 0.70 kJ/kg-^{o}C

Heat Transfer

Example …

- V = 0.1 x 0.1 X0.0025 = 2.5 x 10^{-5} m^3
- A = 2 x (0.1 x 0.1) + 4 X (0.1 x 0.0025) = 0.021 m^2
- $(V/A)^2$ = 1.42 x 10^{-6} m^2

- So

$$t = \left[\frac{\pi}{4} \left(\frac{1700 \times 384 \times 10^3}{650 - 25} \right)^2 \frac{1}{73 \times 7900 \times 0.70} \right] \left(1.42 \times 10^{-6}\right)$$

- t = 3.01 s

Heat Transfer

Example …

- Now, we have to take into account cooling the liquid from (650 + 50)°C to 650°C
- So, the latent heat of solidification (ΔH_f) will be increased by $c_p \Delta T$

- For liquid magnesium
  - c_p = 1.38 J/g-°C
  - ΔT = 50°C
- So

  $\Delta H = \Delta H_f + c_p \Delta T$

  = 384 + 1.38 x 50 = 453 J/g

Heat Transfer

Example …

- So

$$t = \left[\frac{\pi}{4}\left(\frac{1700 \times 453 \times 10^3}{700 - 25}\right)^2 \frac{1}{73 \times 7900 \times 0.70}\right]\left(1.42 \times 10^{-6}\right)$$

t = 3.6 s (a bit slower)

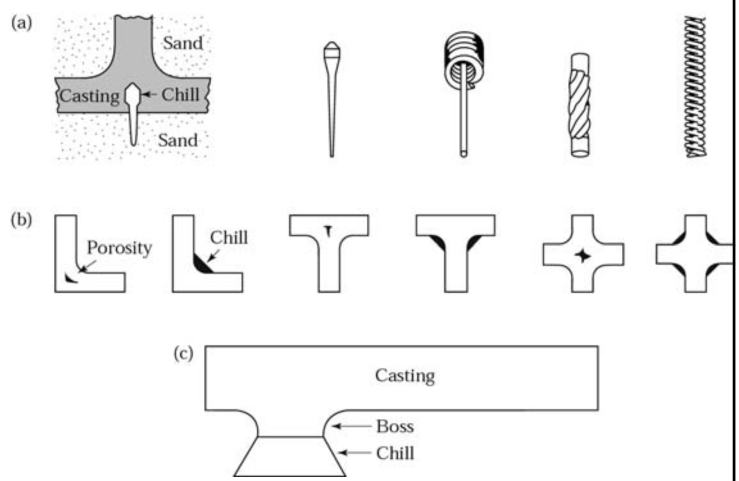
- In both cases, we need to be careful that the part does not freeze before filling the mold (short shot).

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 process toward the riser.
- Based on Chvorinov's rule, the section with lower V/A (volume-to-area) ratio should freeze first.
- Use 'Chills': Internal and External chills which encourage rapid cooling.

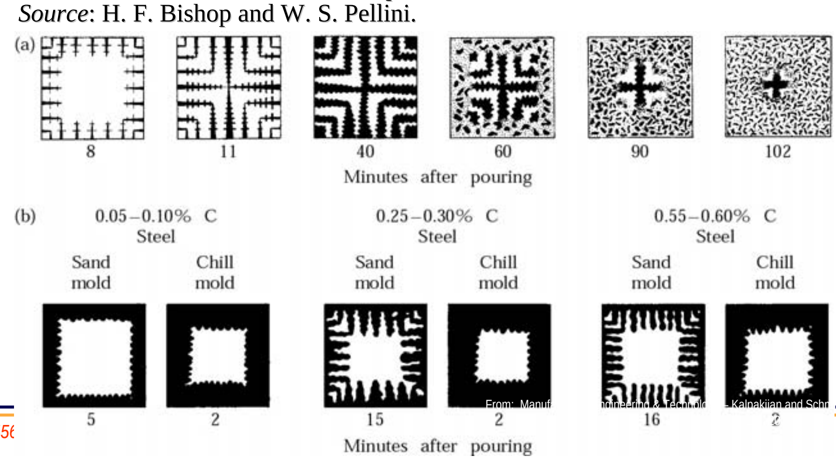
Internal and External Chills

Chills are used to increase rate of solidification. Various types of (a) internal and (b) external chills (dark areas at corners), used in castings to eliminate porosity caused by shrinkage. Chills are placed in regions where there is a larger volume of metals, as shown in (c).



Solidification Patterns

(a) Solidification patterns for gray cast iron in a 180-mm (7-in.) square casting. Note that after 11 min. of cooling, dendrites reach each other, but the casting is still mushy throughout. It takes about two hours for this casting to solidify completely. (b) Solidification of carbon steels in sand and chill (metal) molds. Note the difference in solidification patterns as the carbon content increases. *Source*: H. F. Bishop and W. S. Pellini.



Casting –
Defects and Design Issues

Solidification Effects - Defects

- Defects caused by
  - materials
  - part design
  - processing techniques
- No simple answers

Major Categories of Defects

- Projections
  - fins, flash, swells (massive), rough surfaces
- Cavities
  - internal, exposed, blowholes, pinholes
- Discontinuities
  - cracks, cold and hot tearing, cold shuts
- Defective surface
  - folds, laps, scars, adhering sand, oxide scale
- Incomplete casts
  - insufficient metal, leaky molds
- Incorrect dimensions or shape
  - improper shrinkage allowance, warping, etc

Major Issues in Casting

- Shrinkage
- Porosity
- Piping
- Microstructure

Solidification Effects - Shrinkage

- The metal shrinks as it cools
  - in the melt
  - as it solidifies as a solid (largest)

Volume Solid Contraction of some metals:

Aluminum	6.6%
Carbon Steel	2.5-3%
Copper	4.9%
Gray iron	-2.55

Kalpakjian p 279

Major Issues in Casting

Shrinkage

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

Impact of Shrinkage on Mold Design

- Dimensions of mold
- Molds must be constructed to be larger than the final product because the metal shrinks as it cools
  - Patternmakers ruler
- Warpage due to differential shrinkage
- Defects due to induced stresses
- Porosity

Major Issues in Casting

Shrinkage

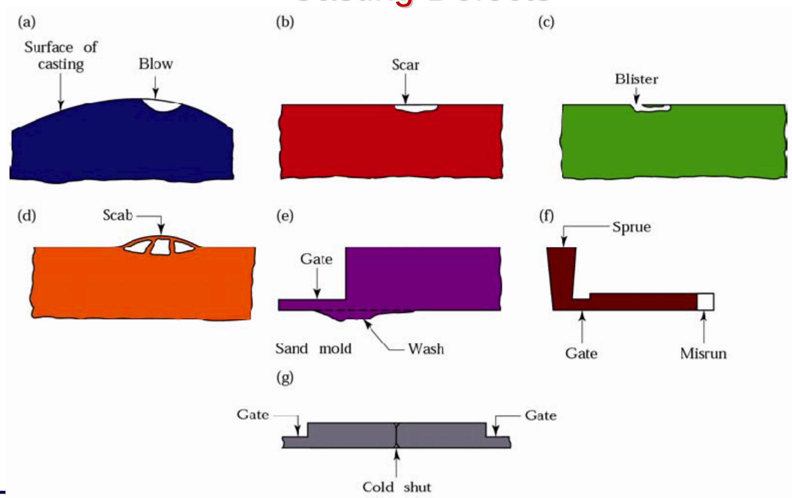
TABLE 5.1

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

Source: After R. A. Flinn.

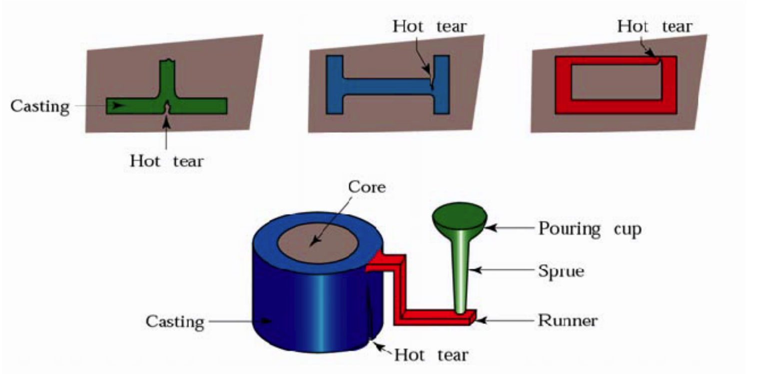
Major Issues in Casting

Casting Defects



Major Issues in Casting

Casting Defects – Hot Tears



Major Issues in Casting

Casting Defects – Porosity

- A special kind of cavity
- Caused by shrinkage or gases
- Detrimental to
  - the ductility of the metal
  - the surface finish
  - pressure integrity of the part
  - Etc.

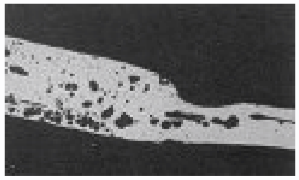
Major Issues in Casting

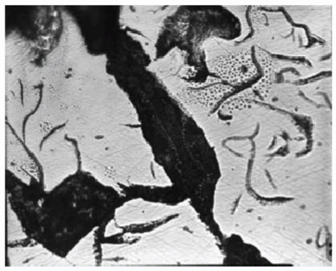
Casting Defects – Porosity

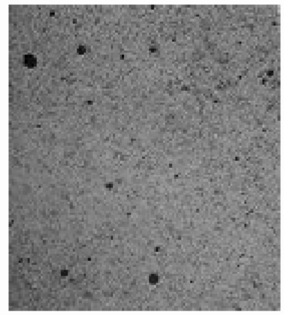
- Basically bubbles / voids
  - can lead to cracking
- Not a problem for ingots
  - parts that will be deformation processed
  - as long as it is not exposed to air (corrosion)
  - can be healed
- Types
  - due to gases
  - due to shrinkage

Major Issues in Casting

Casting Defects – Porosity







Major Issues in Casting

Casting Defects – Porosity due to Gases

- Liquid metals have greater solubility for gases than solid metals
- Any gas in the melt appears as spherical cavities
- Melt treatment must include various degassification processes
- Can also have gases arising from reactions (melt - mold)

Major Issues in Casting

Casting Defects – Porosity due to Gases

- Smooth bubbles
  - result from entrapped gases
  - solubility of liquid is high, 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

Major Issues in Casting

Remedies for Gas Bubbles

- Control atmosphere - vacuum
- Proper venting to let gases out
- 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 breakthrough)
    - .. little piping because gas doesn't escape

Major Issues in Casting

Casting Defects – Porosity due to Shrinkage

- Caused by differential cooling
- Thin sections cool faster than thick sections leading to too little material in the thick sections
- When the thick sections begin to solidify, porosity develops
- Mold designers avoid this by the use of chills and proper flow channels and riser placement

Major Issues in Casting

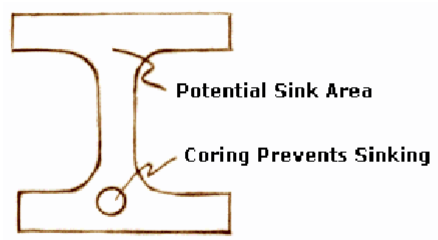
Casting Defects – Porosity due to Shrinkage

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

Major Issues in Casting

Casting Defects – Differential Cooling

• Transition between thicker and thinner sections can lead to porosity



Major Issues in Casting

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

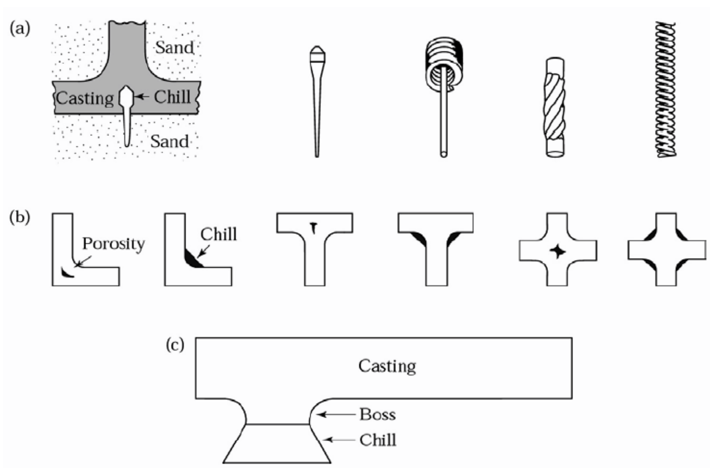
Major Issues in Casting

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

Major Issues in Casting

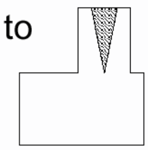
Chills



Major Issues in Casting

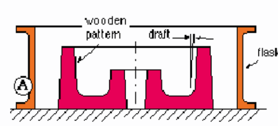
Pipe Defect

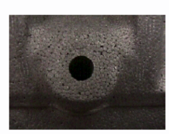
- Due to shrinkage giving rise to a funnel-like cavity
- Solutions
  - insulate top (glass wool)
  - heat top (exothermic mixture - thermit)



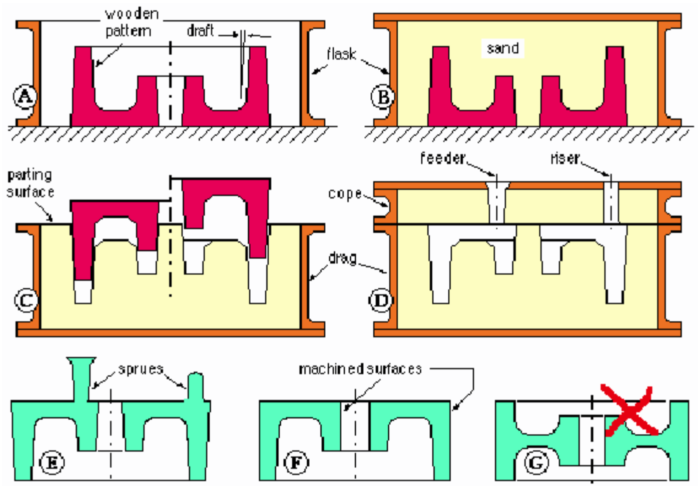
Design Rules Summary

- 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



Impact of all these factors on mold design

- Very complex
- Empirical
- Best left to experts !!!

Casting Fundamentals for Molten Material

- Factors affecting solidification characteristics from the molten state
  - Fluidity
    - Flow of molten material into the cavity
  - Heat transfer effects
    - During solidification and cooling
  - Solidification effects
  - The type of mold material

Influence of the Mold Material

- Mold material impacts:
  - The heat transfer rate
  - The surface finish
  - The number and hence grain size of the microstructure
- Selection of the mold material is strongly influenced by the process

Casting Economics

Economics Example

From: Manufacturing Engineering & Technology – Kalpakjian and Schmid, 4th Ed., 2001, Prentice-Hall

Economics Example

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

From: Manufacturing Engineering & Technology – Kalpakjian and Schmid, 4th Ed., 2001, Prentice-Hall

Economics Example

Alternatives Available

- Sand casting

- Low pressure casting
- Permanent mold casting

- Die casting

From: Manufacturing Engineering & Technology – Kalpakjian and Schmid, 4th Ed., 2001, Prentice-Hall

Economics Example

Cost Equation

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

- C = cost/part
- C_m = material cost
- C_c = capital cost
- C_L = labor cost
- n = number produced
- $\dot{n}$ = production rate

Economics Example

Process Costs

Process	Sand Casting	Low Pressure	Permanent Mold	Die Casting
Material, C_m ($)	1	1	1	1
Labor, C_L ($/hr)	20	20	20	20
Capital, C_C ($)	0.9	4.4	700	3000
Rate, $\dot{n}$ (#/hr)	6.25	22	10	50

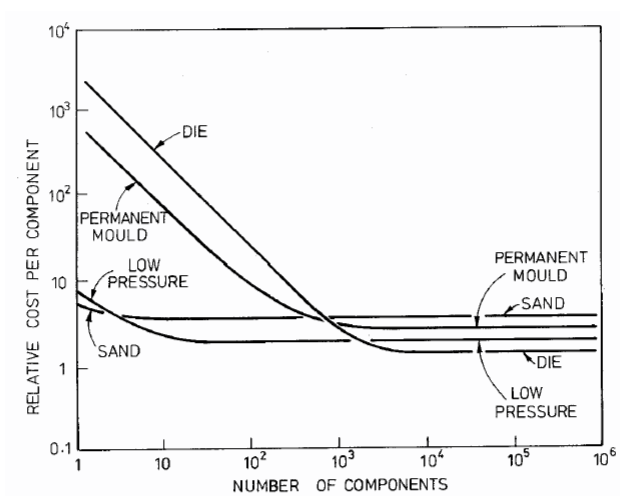
Process Economics

TABLE 5.10

Process	Die (Cost*)	Equipment (Cost*)	Labor (Cost*)	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.

Process Economics



Process Economics

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 Al Auto Parts

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