ME 361A
Manufacturing Science and Technology

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Content

Manufacturing Processes Involving Solidification: Principles of solidification, Fluid flow and microstructure, Relevance to casting, welding, etc.

Casting

(A) Casting process - Overview

(B) Solidification transport phenomena: **solidification transport phenomena** involved in a casting process (mass and heat transfer, fluid dynamics, mushy zone).

- Defects analysis-causes and remedies, Understanding the **role of solidification transport phenomena** in the formation of these defects

(C) Casting design by controlling the accompanied heat transfer, fluid flow and solidification-shrinkage, feeding, gating, filling

(D) Case studies of some casting processes

Other applications of melting/solidification principles in manufacturing

Welding

(A) Welding process - Overview

(B) **Solidification transport phenomena** involved in a welding process

(C) Welding design, and some case studies

Fundamentals of 3d Printing

Lecture 1

Casting

(A) Casting process - Overview

Casting

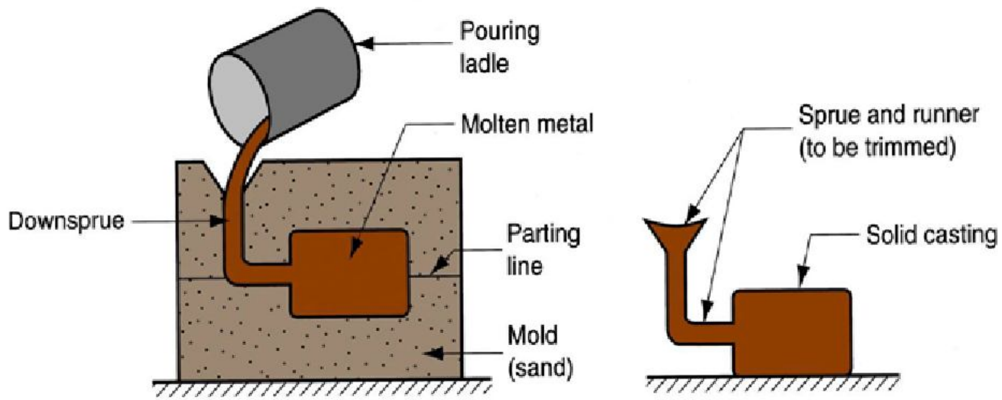
A shaping process in which molten metal flows by gravity or other force into a mold where it solidifies in the shape of the mold cavity

Solidification processes - starting material is a molten liquid or semi-fluid

- The term *casting* also applies to the part made in the process

- Steps in casting seem simple:

1. Melt the metal
2. Pour it into a mold
3. Let it freeze



- Casting is usually performed in a foundry

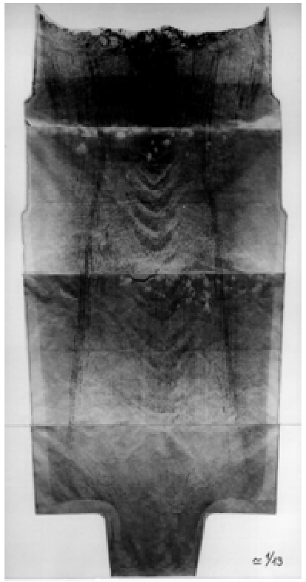
Foundry = factory equipped for making molds, melting and handling molten metal, performing the casting process, and cleaning the finished casting

- Workers who perform casting are called *foundrymen*

Foundry Engineering => Liquid Materials Engineering

Examples

Semi-finished or Finished products



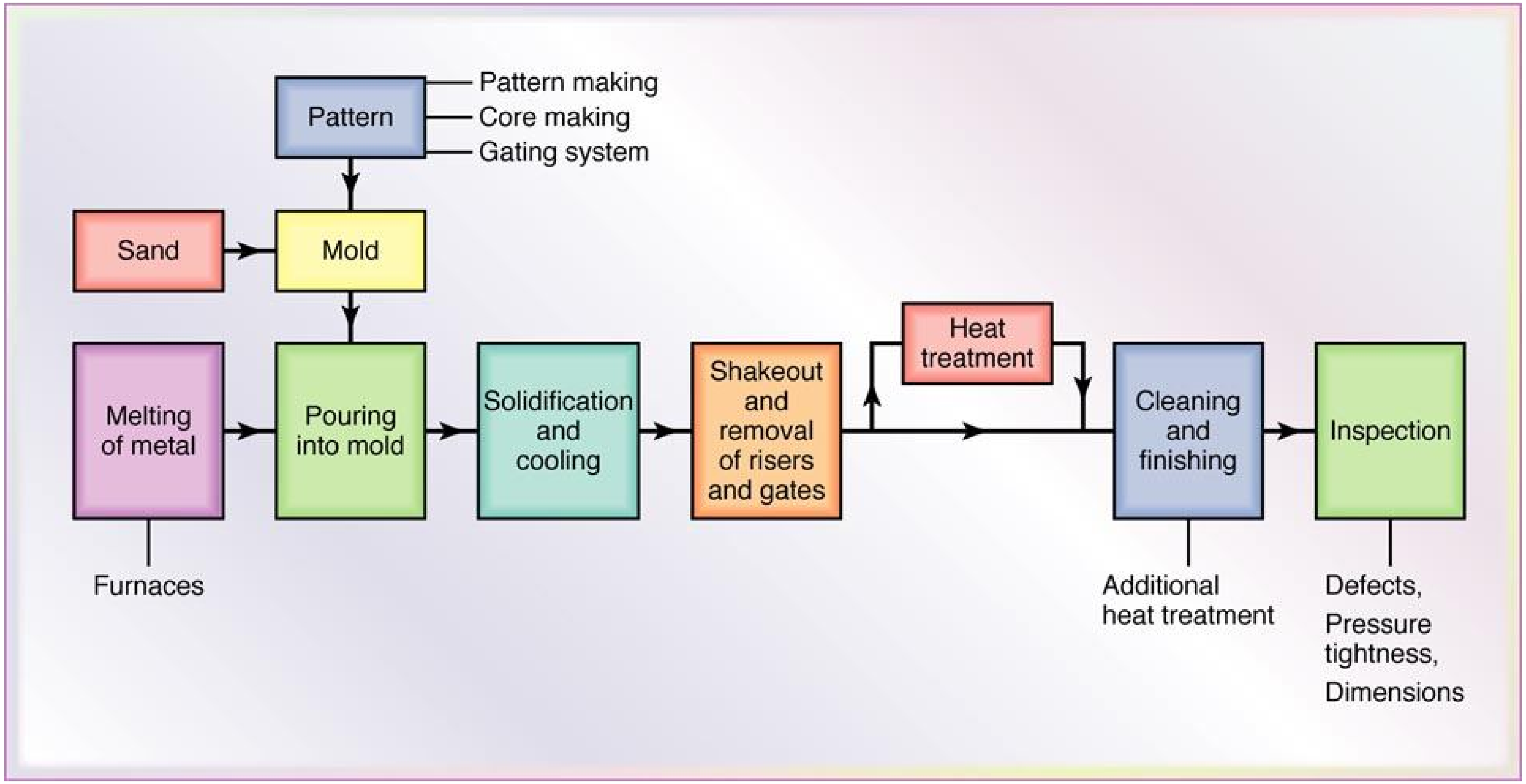
65 ton Steel Ingot: Feedstock raw material used for forging

Size: 2m height, 0.8m diameter

Aluminum piston for an internal combustion engine: (a) as-cast and (b) after machining

Finished shaped casting

Production Steps in Casting
(e.g. Sand Casting)



Materials

Casting alloys		Melting Temp. °C
	Zinc alloys	386 - 525
	Aluminium alloys	476 - 654
	Magnesium alloys	610 - 621
	Copper alloys	885 - 1260
	Nickel alloys Titanium alloys	1110 - 1454 1549 - 1649
	Cast iron (grey or ductile)	1148 - 1371
	Cast steel	1371 - 1532

Capabilities/advantages and disadvantages of casting

Capabilities and Advantages of Casting

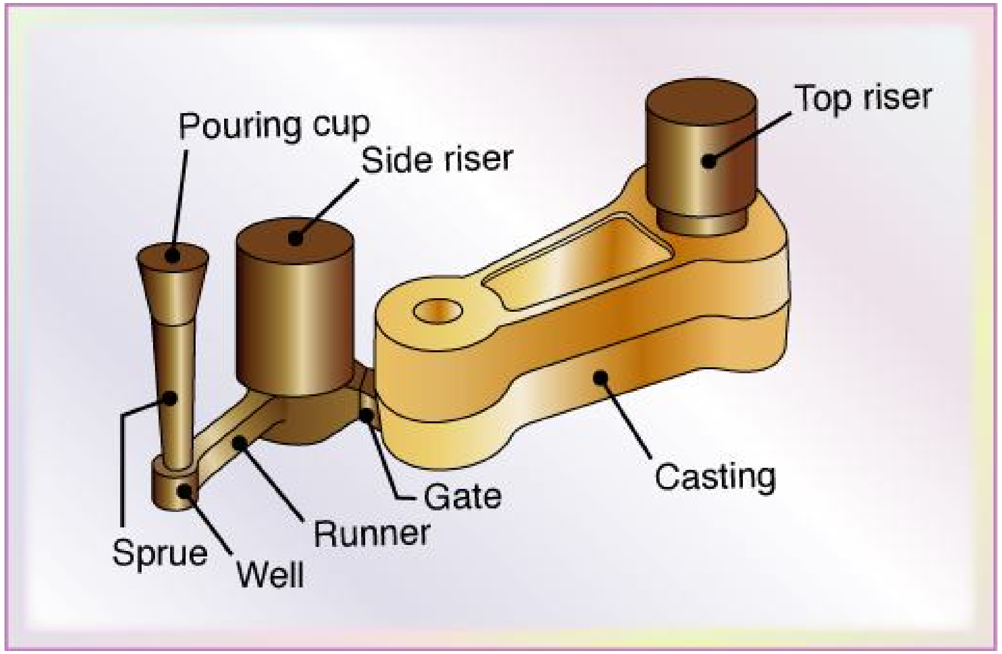
- Can create complex part geometries
- Can create both external and internal shapes
- Some casting processes are *net shape;* others are *near net shape*
- Can produce very large parts
- Some casting methods are suited to mass production

Disadvantages of Casting

- Different disadvantages for different casting processes:
  - Limitations on mechanical properties
  - Poor dimensional accuracy and surface finish for some processes; e.g., sand casting
  - Safety hazards to workers due to hot molten metals
  - Environmental problems

Parts Made by Casting

- Big parts: engine blocks and heads for automotive vehicles, wood burning stoves, machine frames, railway wheels, pipes, church bells, big statues, and pump housings
- Small parts: dental crowns, jewelry, small statues, and frying pans
- All varieties of metals can be cast, ferrous and nonferrous



Schematic illustration of a typical riser-gated casting. Risers serve as reservoirs, supplying molten metal to the casting as it shrinks during solidification

Casting System

- Pouring basin
- Sprue
- Runner
- Gate
- Mould cavity
- Feeders

Casting terms

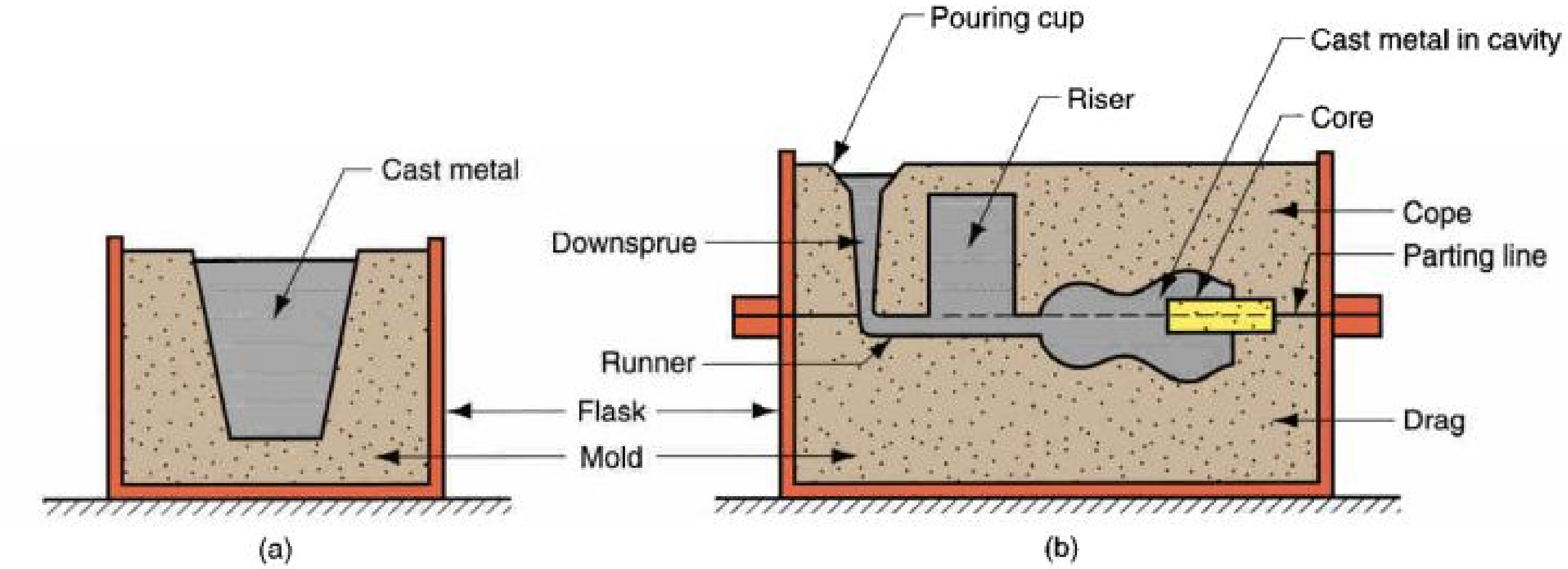


Figure 10.2 ‑ Two forms of mold: (a) open mold, simply a container in the shape of the desired part; and (b) closed mold, in which the mold geometry is more complex and requires a gating system (passageway) leading into the cavity

Fluid Flow during Casting Process

Laminar vs. turbulent flow $Re = \dfrac{\rho V D}{\mu}$

Re<2000	represents laminar flow
2000<Re<20000	laminar/turbulent flow
Re>20000	severe turbulence

1. During Mold filling

2. During freezing/solidification in the mold

Turbulence:

- is harmful to gating system
- causes air entrapment

Casting

(B) Solidification Transport Phenomena

- Three forms of energy transport:
  - conduction (diffusive transport),
  - convection (heat transmitted by the mechanical motion of the fluid) and/or
  - radiation (through space, material medium may not be needed)
- All three can be active during solidification of a casting
- Energy diffusion and convection occurs within the casting, at the metal/mold interface, and within the mold
- Energy is transported by convection and/or radiation from the mold to its environment, which is typically the air

3.2.1 Flux laws

Diffusive transport of energy, mass and momentum can be described through flux laws whose fundamental form is:

$$flux = \frac{flow\,rate}{area} = transport\ property \cdot potential\ gradient$$

The three laws describing diffusive transport are:

Energy: conduction: $q = -k\nabla T$ Fourier's law

convection: $q = h\left(T(t) - T(0)\right)$ Newton's law

radiation: $q = \varepsilon\sigma\left(T_1^4 - T_2^4\right)$ Stefan-Boltzman's law

prescribed temperature (Dirichlet problem): $T(0,t)=T_1$

insulated boundary (Neumann problem): $\frac{\partial T}{\partial x}(0,t) = 0$

known heat flux (Newton's law of cooling): $-k\frac{\partial T}{\partial x}(0,t) = h\left(T(t) - T(0)\right)$

where h is the heat transfer coefficient.

Mass (species): $J_A = -D_{AB} \nabla C_A$ Fick's law (3.9b)

Momentum: $\tau_{xy} = -\mu \dfrac{\partial V^y}{\partial x}$ Newton's law of viscosity (3.9c)

where q, J_A and τ_{xy} are the heat, mass and momentum flux, respectively, and V_y is the fluid velocity along the y axis. Analogous to mass diffusivity we can define the thermal diffusivity, $\alpha = k/(\rho\ c)$ and momentum diffusivity $\nu = \mu/\rho$. Hence, the flux laws can be written in their diffusion form as follows:

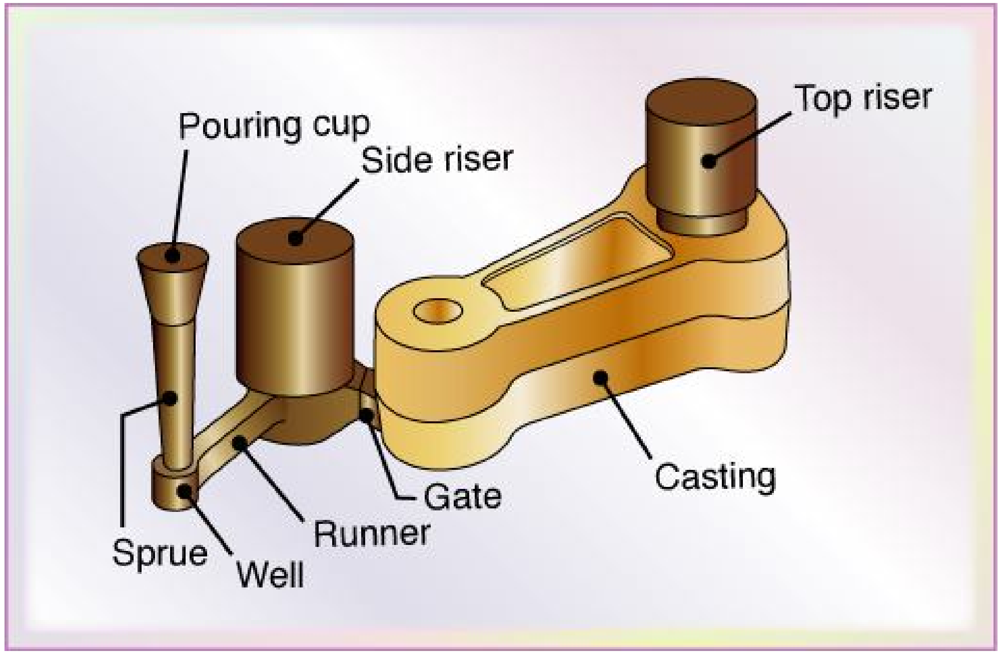
flux = - diffusivity · concentration gradient

Now the three flux laws for energy, mass and momentum transport can be written as:

Energy: $q = -\alpha \nabla (\rho c T)$ (3.10a)

Mass (species): $J_{Ax} = -D_{AB} \nabla C_A$ (3.10b)

Momentum: $\tau_{xy} = -\nu \dfrac{\partial (\rho V^y)}{\partial x}$ (3.10c)



Schematic illustration of a typical riser-gated casting. Risers serve as reservoirs, supplying molten metal to the casting as it shrinks during solidification

Casting System

- Pouring basin
- Sprue
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- Mould cavity
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Fluid Flow and Solidification Time

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

Mass continuity $$Q=A_1v_1=A_2v_2$$

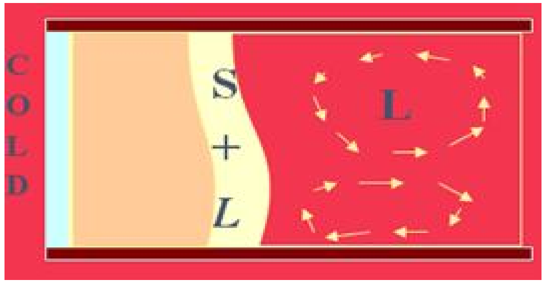
Sprue design $$\frac{A_1}{A_2}=\sqrt{\frac{h_2}{h_1}}$$

Reynolds number $$\text{Re}=\frac{\rho\,v\,D}{\eta}$$

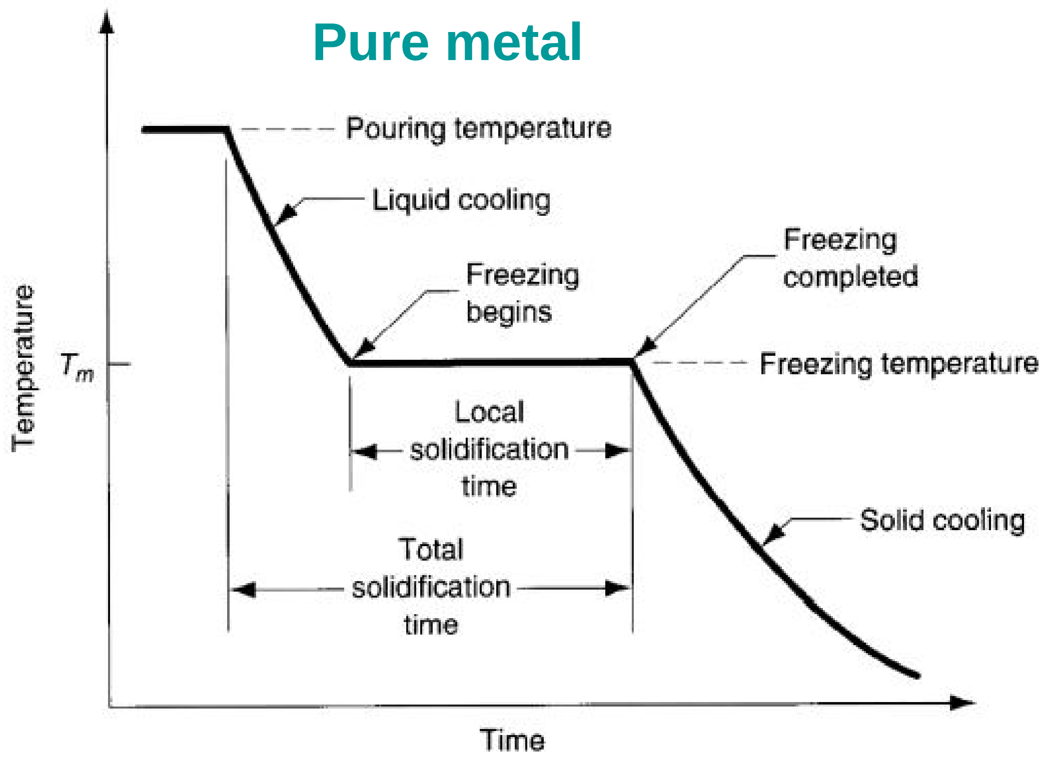
Chvorinov's Rule $$\text{Solidification time}=C\left(\frac{\text{Volume}}{\text{Surface Area}}\right)^n$$

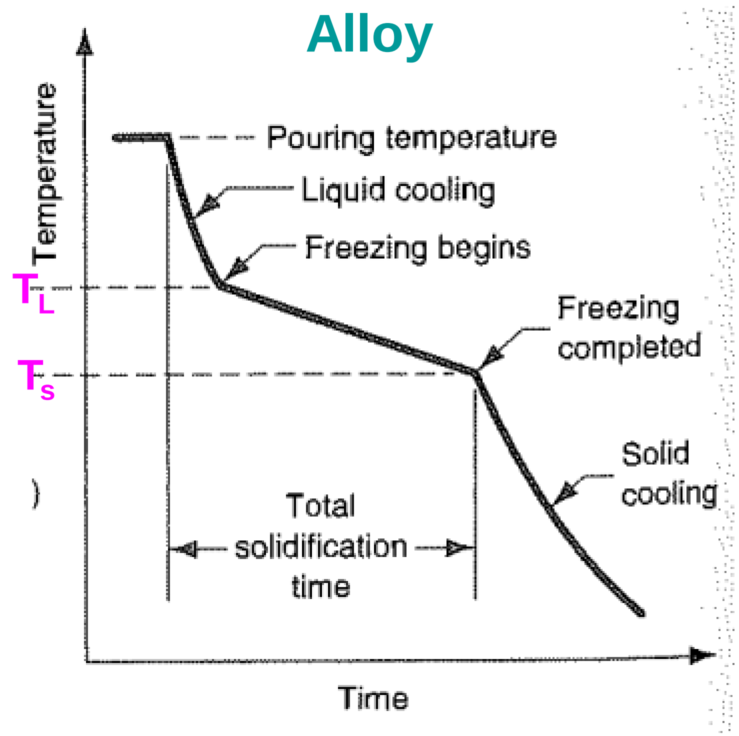
Phase change

- The phenomena of solidification and melting are associated with many practical applications. Metal processing, castings, welding and other solidification processes. In these processes, matter is subject to a change in its phase.
- Consequently, a boundary separating two different phases develops and moves in the matter during the process. Transport properties vary considerably between phases, which result in totally different rates of energy, mass and momentum transport from one phase to another.
- In these problems, the position of the moving boundary cannot be identified in advance, but has to be determined as an important constituent of the solution.



Freezing: pure metal and alloy

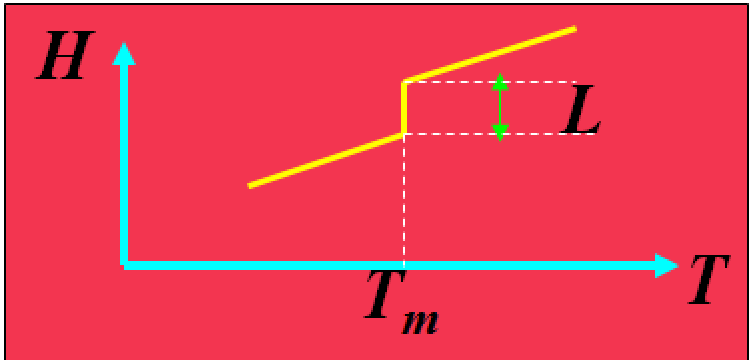




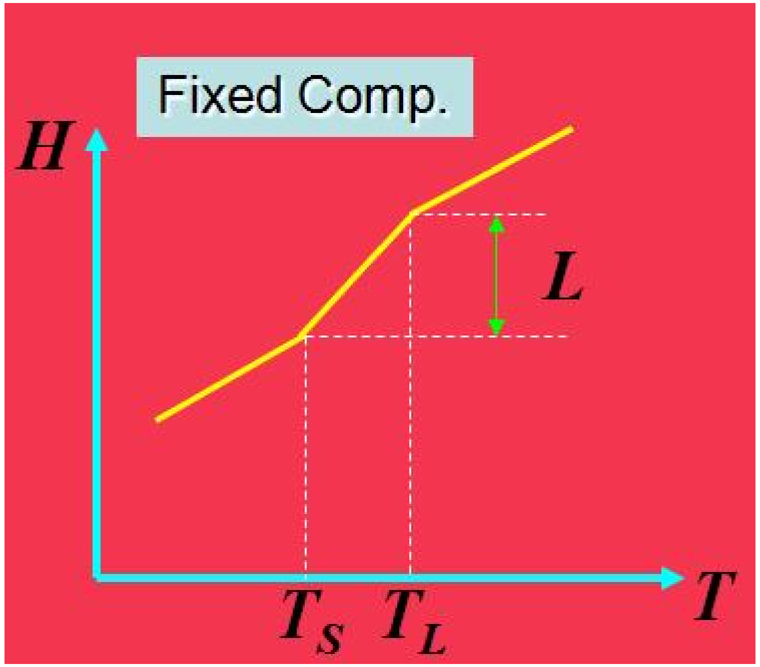
Note that the freezing takes place at a constant temperature

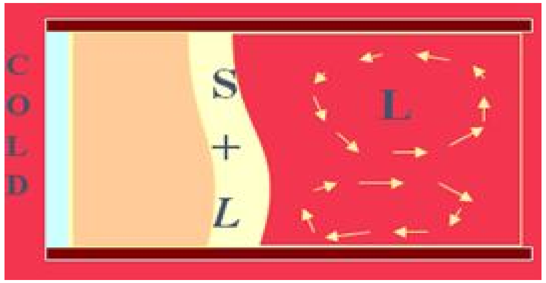
Note that the freezing takes place in a range of temperature (liquidus T_L and solidus T_S temperature)

PURE SUBSTANCE

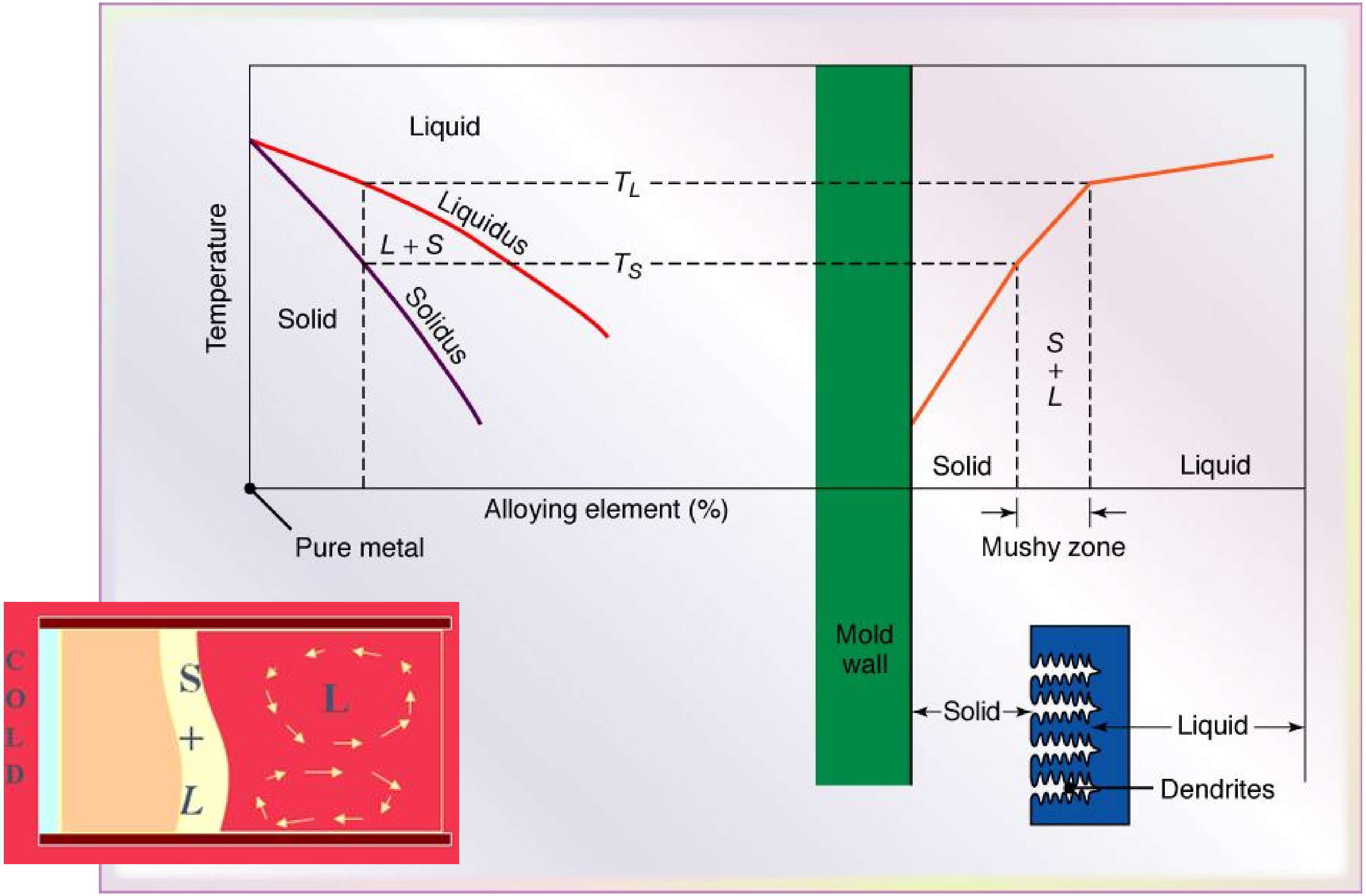


ALLOY



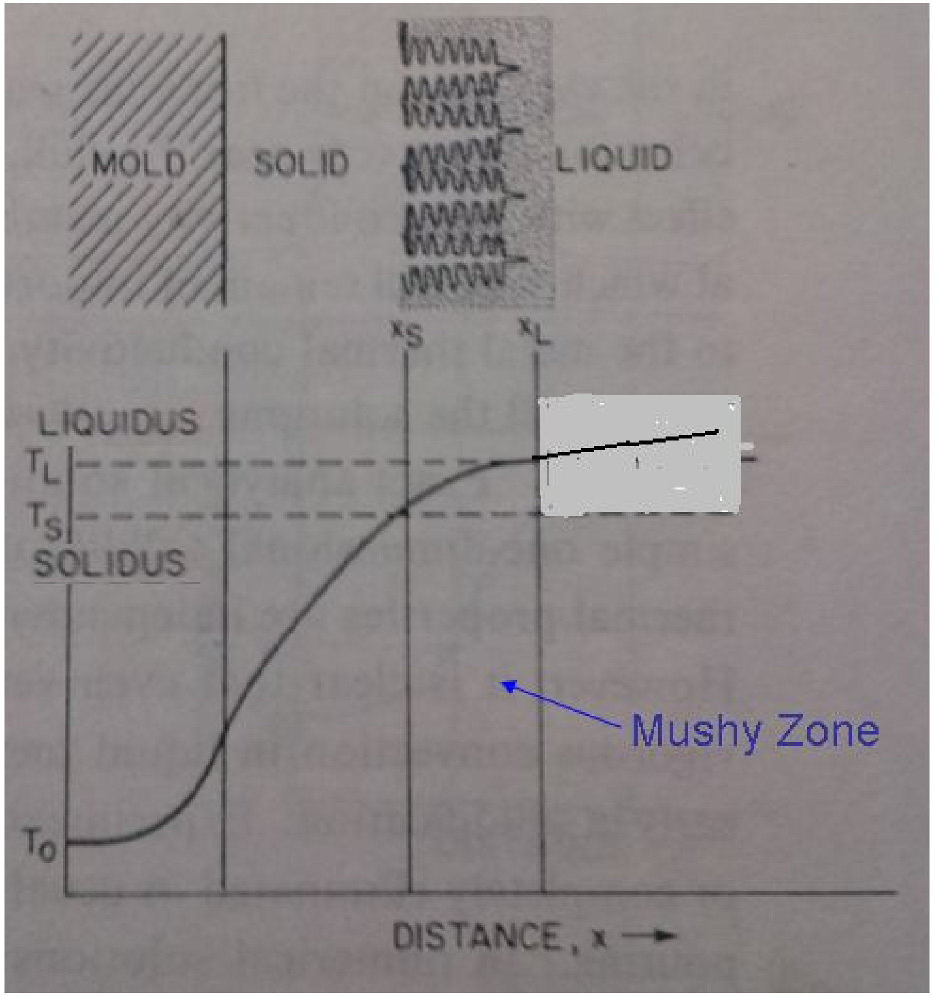


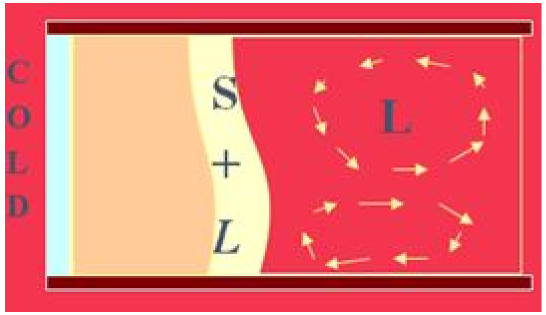
Alloy Solidification



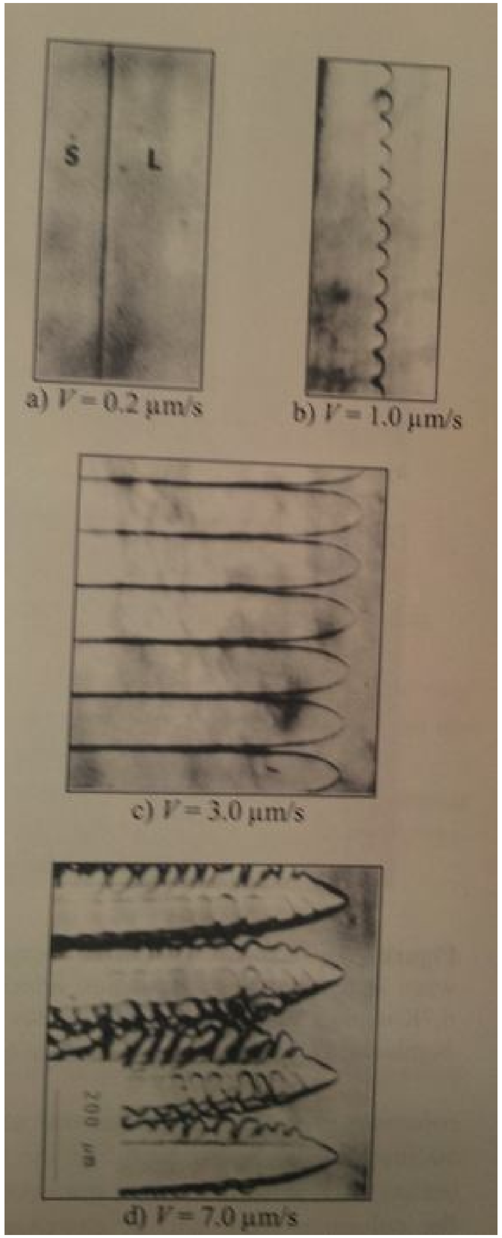
Schematic illustration of alloy solidification and temperature distribution in the solidifying metal. Note the formation of dendrites in the mushy zone.

Schematic of Alloy Solidification





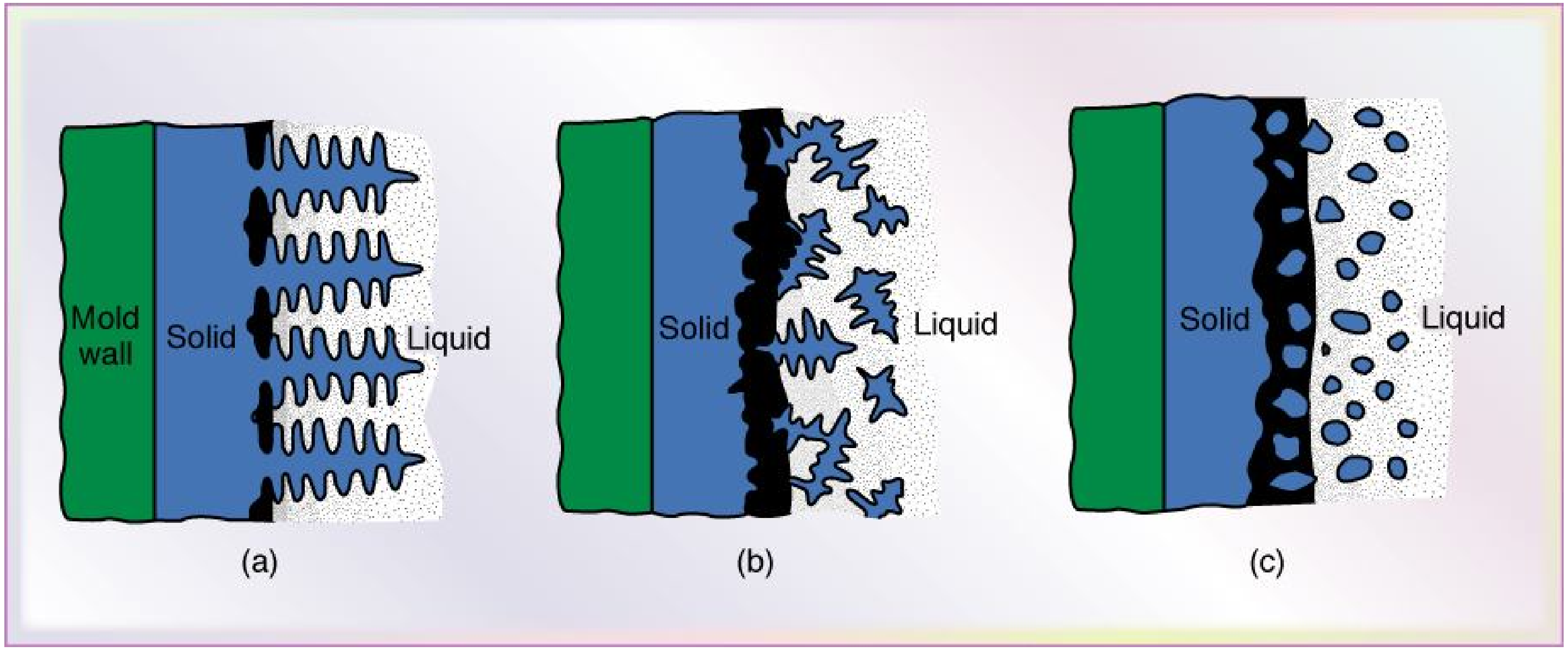
Solid-liquid Interfaces



Morphology for different interface velocity (*V*)

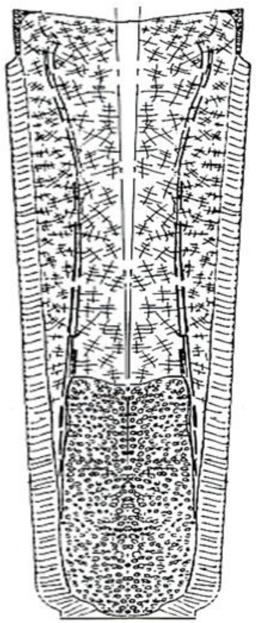
Planar to highly columnar dendritic

Basic Types of Cast Structures

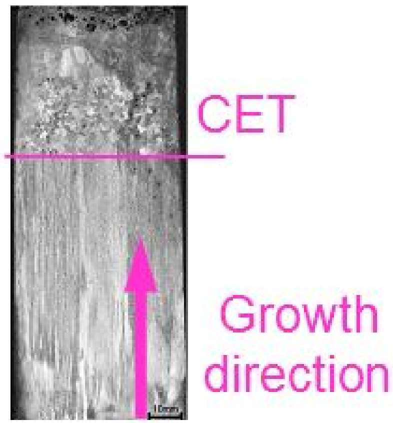


Schematic illustration of three basic types of cast structures: (a) columnar dendritic; (b) equizxed dendritic; and (c) equiaxed nondendritic

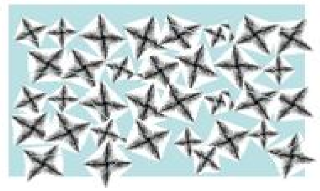
Basic Types of Cast Structures contd.



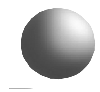
6 ton Industrial ingot

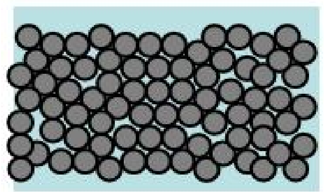


Mixed columnar-equiaxed

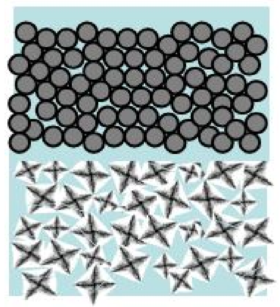


equiaxed dendritic



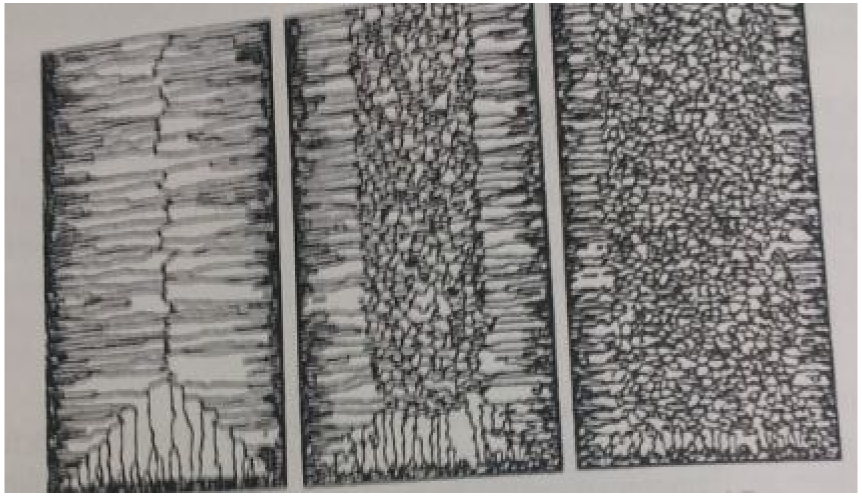


equiaxed nondendritic (globular)



Mixed equiaxed-globular

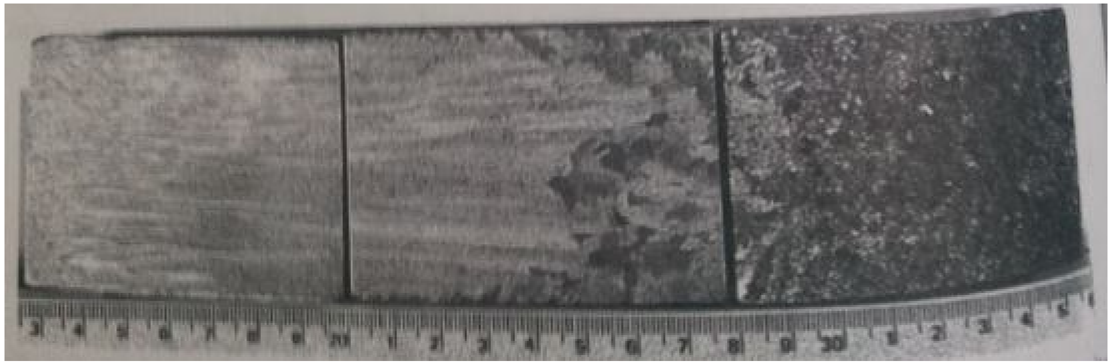
Columnar to Equiaxed Transitions



q

Mixed columnar-equiaxed

q



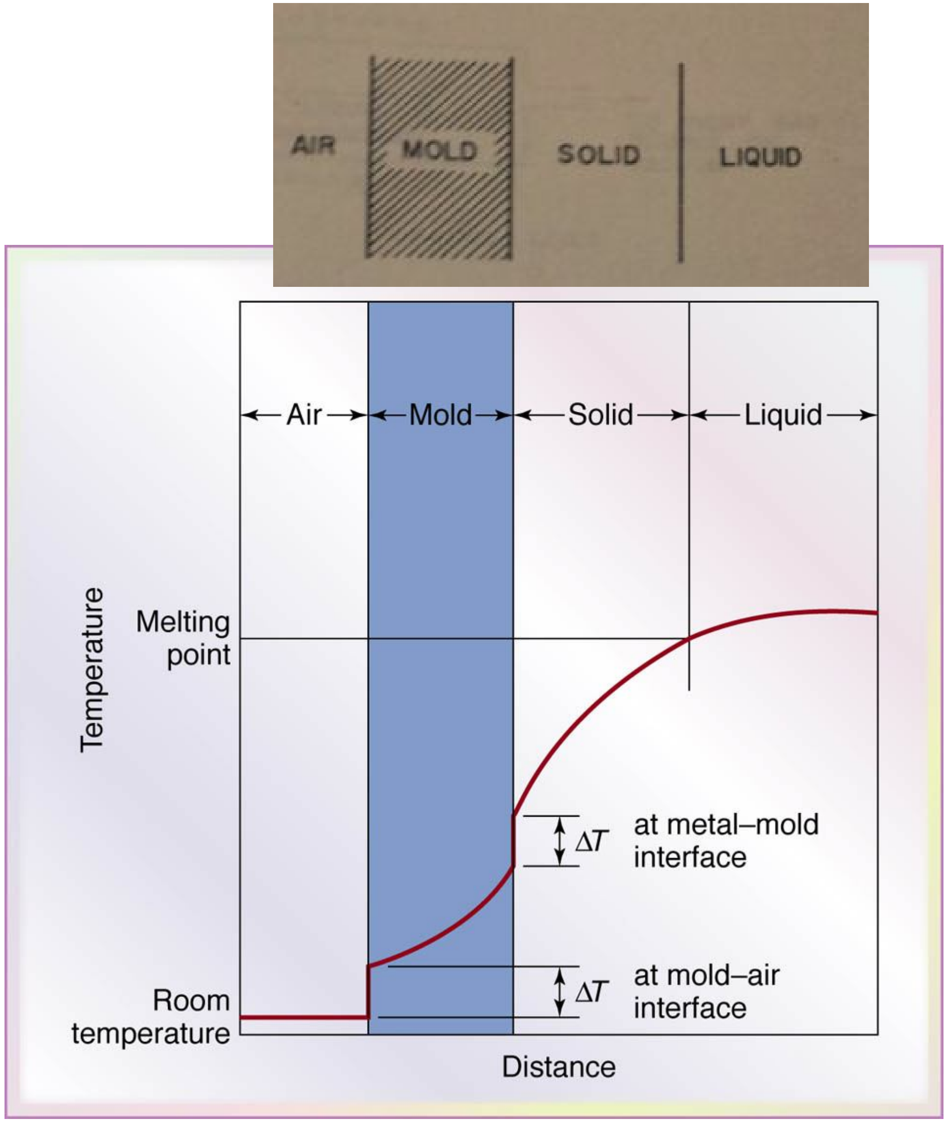
Mixed columnar-equiaxed

Lecture 3

ME 361A

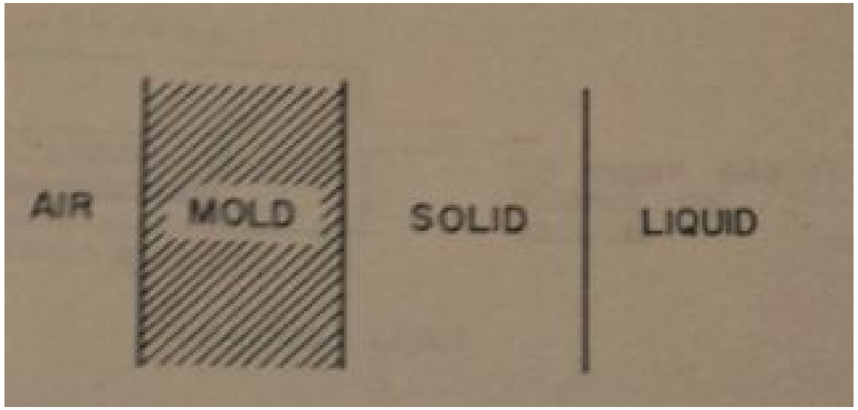
Heat transfer through mold

Temperature Distribution during Metal Solidification



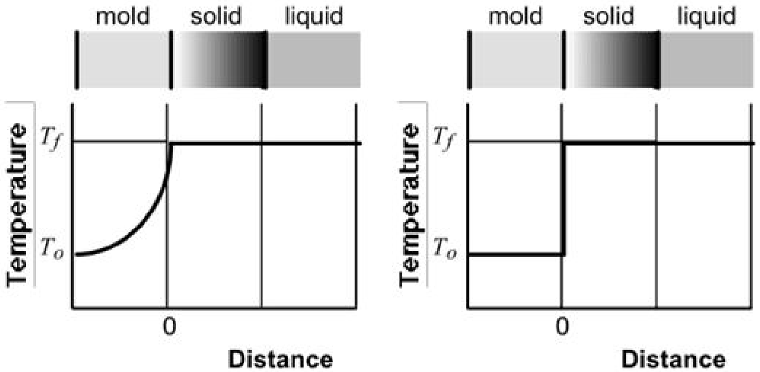
- **Generalized non-linear temperature profile due to temperature dependent thermal properties. tk, cp ~ *f* (*T*)**

- **If these thermal properties are constant, and convection is absent in liquid then the temperature profiles will be straight line**

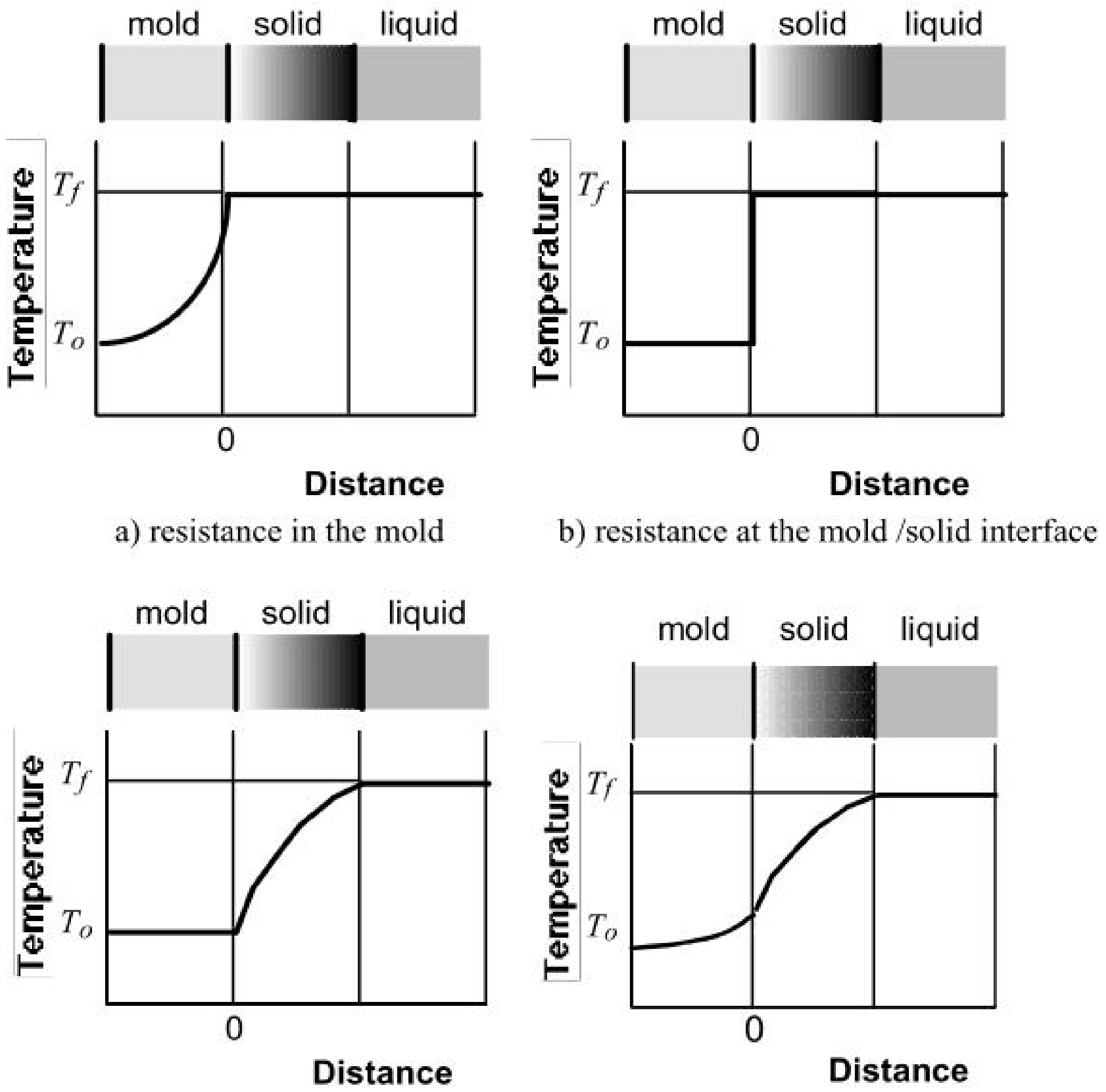


Assumptions on thermal resistance in a casting-mold system

Casting process	Figure 5.5	Resistance			
		In solid	At solid/mold interface	In mold	At mold/air interface
insulating molds	a	0	0	high	0
permanent molds	b	0	high	0	0
ingot molds	c	high	0	0	0
ingot molds	d	high	0	high	0



a) resistance in the mold b) resistance at the mold /solid interface



a) resistance in the mold

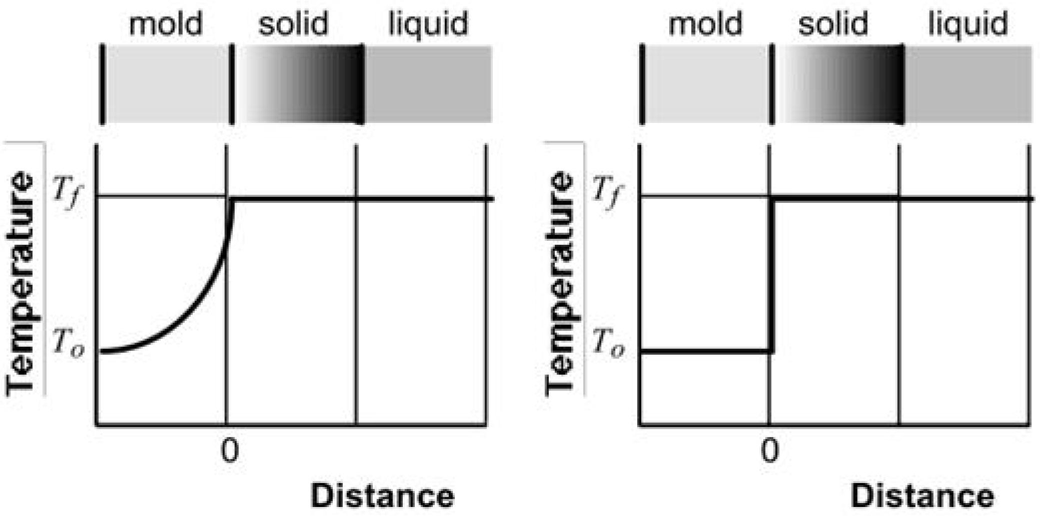
b) resistance at the mold /solid interface

c) resistance in the solid

d) resistance in the mold and in the solid

Temperature profile in the mold and in the casting for different assumptions.

Expression for solidification time for Fig. a) and b)



a) resistance in the mold   b) resistance at the mold /solid interface

Chvorinov's rule

Chvorinov's Rule

$$TST = C_m \left(\frac{V}{A} \right)^n$$

where *TST* = total solidification time; *V* = volume of the casting; *A* = surface area of casting; *n* = exponent usually taken to have a value = 2; and C_m is *mold constant*

A **is the surface area available for heat withdrawal**

Mold Constant in Chvorinov's Rule

- C_m depends on mold material, thermal properties of casting metal, and pouring temperature relative to melting point
- Value of C_m for a given casting operation can be based on experimental data from previous operations carried out using same mold material, metal, and pouring temperature, even though the shape of the part may be quite different

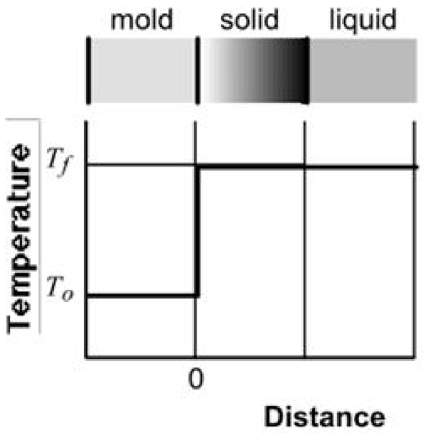
- C_m does not depend on shape and size of the casting
- TST does

What Chvorinov's Rule Tells Us

- A casting with a higher volume-to-surface area ratio cools and solidifies more slowly than one with a lower ratio
  - To feed molten metal to main cavity, *TST* for riser must greater than *TST* for main casting
- Since riser and casting mold constants will be equal, design the riser to have a larger volume-to-area ratio so that the main casting solidifies first
  - This minimizes the effects of shrinkage

Die casting

Consider that a thickness *dx* of the metal solidifies in a time interval *dt* when it is introduced in a water-cooled die at its melting temperature (i.e., zero superheat). The rate of heat loss during solidification of the element *dx* is



b) resistance at the mold /solid interface

$$A\rho L\left(\frac{dx}{dt}\right) = hA(T_f - T_0)$$

$$\frac{dx}{dt} = \frac{hA(T_f - T_0)}{\rho L} \qquad (2\text{-}37)$$

where h is the die–metal interface heat transfer coefficient, T_0 is the die temperature, maintained constant by circulating water, and T_f is the freezing or solidification temperature. The initial conditions are $x = 0$ at $t = 0$. Integration of the preceding equation yields the thickness, x, solidified as a function of time, t

$$x = \frac{h(T_f - T_0) \cdot t}{\rho L} \qquad (2\text{-}38)$$

Because the thickness solidified, $x =$ (volume/surface area), this equation can be rearranged to yield

$$t = \frac{\rho L}{h(T_f - T_0)} \cdot \left(\frac{V}{A}\right) \qquad (2\text{-}39)$$