ME361 Lab

Lab schedule: MTTh 14:00-16:00 (3 days a week)
Manufacturing Science Lab, Mechanical Engineering Department

Lab start date: 07 August (Monday)

List of experiments

Exp. No.	**Name**	**TA**
Experiment #1	Oblique cutting (turning) and identification of cutting force coefficients	Ankit Bansal
Experiment #2	EDM experiment	Bibeka Padhi
Experiment #3	Deep drawing of a cup	Govind Sahu
Experiment #4	Milling process cutting force coefficients identification	Mayank Gaur
Experiment #5	3D printing + Metrology	Arvind Chouhan, Jaiprakash Kumawat

Directives in the lab (MUST follow):

(1) Every student must come latest by 1:50 pm and should obtain a set of instruction sheet for every experiment from the Manufacturing Science Laboratory. Students arriving after 2:00 pm will be denied for that day.

(2) Every student has to carry a copy of the lab manual.

(3) For safety every student must come to the laboratory in shoes. For the same reason, do not wear loose garments. The Students should also ensure that floor around the machine is clear and dry (not oily) to avoid slipping.

(4) Instruments and tools will be issued from the laboratory to one member of the group. Every student must carry their identity card. Tools, etc. must be returned to the tool room on the same day.

(5) The student should take the permission of the Lab Staff /TA before handling any machine. The student should not lean on the machine when it is working.

(6) Students are required to clear off the chips from the machine and lubricate the guides etc. at the end of the session.

(7) Laboratory reports should be submitted in the format provided latest by 2:00 pm in the next week to the laboratory office to Mr. Sanjeev Verma. For example, students who finished their lab on Monday have to submit the report by 2:00 pm of next Monday. Lab reports without attendance on the lab day will not be graded.

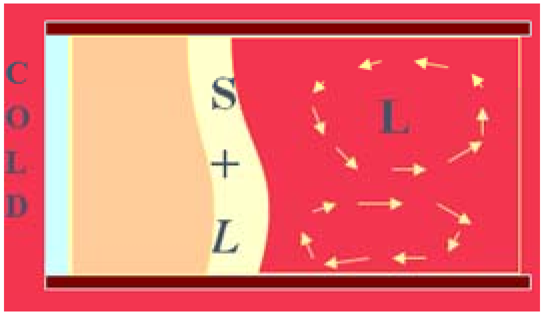
(8) Reports will not be returned to the students. Students may see the graded reports in the laboratory.

(9) One Make-up lab is planned towards the end of the course as mentioned in the lab schedule. Request for Make-up without proper justification will not be entertained. It has to approved by the course instructors

Lecture 4

ME 361A

Also follow blackboard discussions



Governing transport equations during solidification

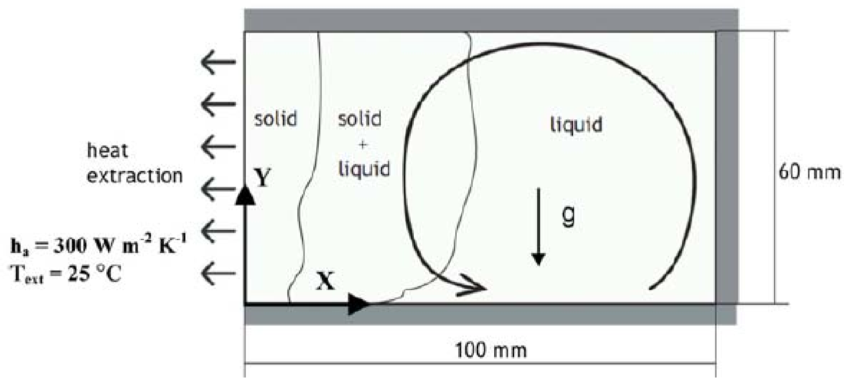
$$\frac{\partial(\rho\phi)}{\partial t} + \nabla\cdot(\rho\vec{\mathbf{V}}\phi) = \nabla\cdot(\Gamma\nabla\phi) + S \qquad (1.18)$$

You can get all the governing transport equations with suitable substitution of scalar and diffusivities

Table 3.1. Phase quantities, diffusivities, and origin of the source term.

Quantity	Mass	Energy	Species	Momentum
ϕ	1	H	C	$\vec{\mathbf{V}}$
Γ	0	k/c	D	μ

- <u>Continuum model</u>: It uses the classical mixture theory to develop a single set of mass, momentum, energy and species conservation equations, which concurrently apply to the solid, liquid and mushy regions. The numerical procedures for this model are much simpler since the same equations are employed over the entire computational domain, thereby facilitating use of standard, single-phase CFD procedures.



Continuum definition

$$g_l + g_s = 1,\ f_l + f_s = 1,\ f_l = \frac{g_l \rho_l}{\rho},\ f_s = \frac{g_s \rho_s}{\rho},\ \rho = g_l \rho_l + g_s \rho_s$$

$$u = f_l u_l + f_s u_s,\ k = g_l k_l + g_s k_s,\ D = f_l D_l + f_s D_s$$

Mathematical formulation

Continuity Equation

$$\frac{\partial}{\partial t}(\rho)+\nabla.(\rho\vec{u})=0$$

Momentum Equations

$$\frac{\partial}{\partial t}(\rho\, u)+\nabla.(\rho\vec{u}\,u)=\nabla\cdot\ (\mu\nabla u)-\frac{\partial p}{\partial x}-C\frac{(1-f_l)^2}{b+f_l^3}u$$

$$\frac{\partial}{\partial t}(\rho v)+\nabla.(\rho\vec{u}\,v)=\nabla\cdot\ (\mu\nabla v)-\frac{\partial p}{\partial y}-C\frac{(1-f_l)^2}{b+f_l^3}v+\rho_{ref}\,g\left[\beta_T(T-T_{ref})+\beta_S(C_l-C_{ref})\right]$$

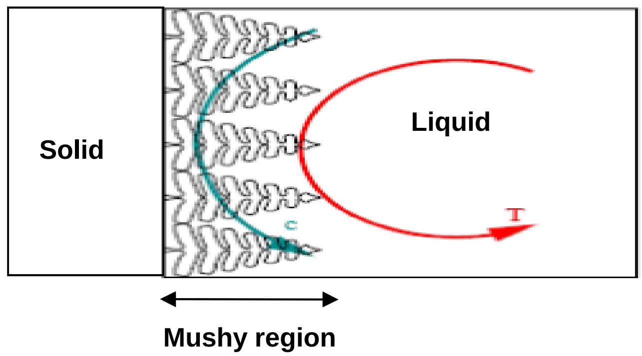
Continuum definition

$$g_l+g_s=1,\ f_l+f_s=1,\ f_l=\frac{g_l\rho_l}{\rho},\ f_s=\frac{g_s\rho_s}{\rho},\ \rho=g_l\rho_l+g_s\rho_s$$

$$u=f_l u_l+f_s u_s,\ k=g_l k_l+g_s k_s,\ D=f_l D_l+f_s D_s$$

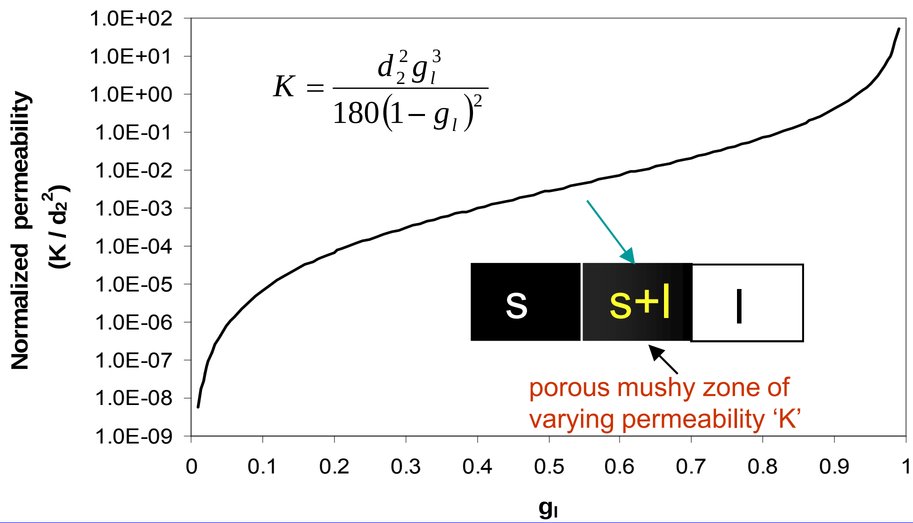
- **$C \sim 10^9$ (large no.), b = small no.**
- **Fully Solid: $f_l = 0 \Rightarrow$ large flow resistance $\Rightarrow$ Solution for u , v = 0**
- **Fully Liquid: $f_l = 1 \Rightarrow$ No flow resistance**
- **Mushy Region: $0 < f_l < 1 \Rightarrow$ Smooth variation of porous-medium resistance**

Flow in porous mushy zone and in liquid



Mushy zone permeability

Darcy equation $\boxed{\frac{\mu}{K}(g_l v_l) = -\nabla p}$



Modelling flow in the mushy zone

Darcy equation $\boxed{\frac{\mu}{K}(g_l v_l) = -\nabla p}$ $K = \frac{d^2 g_l^3}{180(1-g_l)^2}$

In x direction: $S_x = -\frac{\mu}{K}u = \boxed{-C\frac{(1-f_l)^2}{b+f_l^3}u}$

In y direction: $S_y = -\frac{\mu}{K}v + \rho_o g\left[\beta_C^o(C - C_o) + \beta_T^o(T - T_o)\right]$

$$= \boxed{-C\frac{(1-f_l)^2}{b+f_l^3}v} + \rho_o g\left[\beta_C^o(C - C_o) + \beta_T^o(T - T_o)\right]$$

$$\nabla T = m_l \nabla C \qquad N = \frac{|\beta_C|}{|m_L \beta_T|}$$

Mathematical formulation (Contd..)

Energy Equation

$$\frac{\partial}{\partial t}(\rho T)+\nabla\cdot(\rho\,\vec{u}\,T)=\nabla\cdot\{(g_S\,\Gamma_S+g_l\,\Gamma_l)\nabla T\}-\frac{1}{c_p}\left[\frac{\partial}{\partial t}(\rho\, f_l\,\Delta H)+(\nabla.\rho\vec{u}\,\Delta H)\right]$$

Liquid (1-solid) fraction is calculated by

$$f_l = 0 \qquad \text{if } T \leqslant T_{solidus}$$

$$f_l = 1 \qquad \text{if } T \geqslant T_{liquidus}$$

$$f_l = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \qquad \text{if } T_{solidus} < T < T_{liquidus}$$

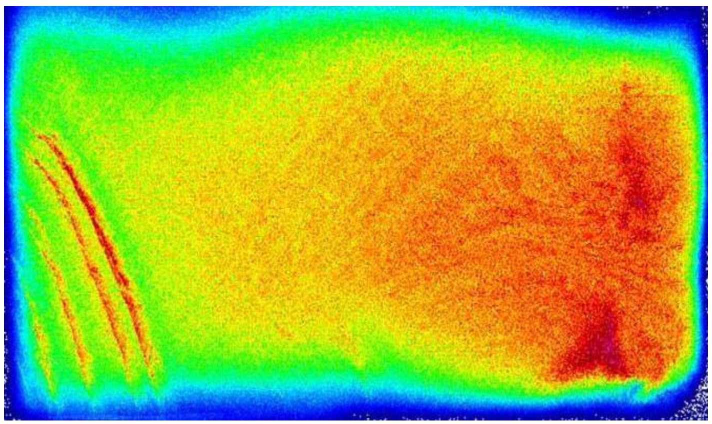
$T_{\text{liquidus}} - T_{\text{solidus}}$ = a small ΔT, *1-2 ºC for pure substance*

Species Equation

$$\frac{\partial}{\partial t}(\rho C_l)+\nabla.(\rho\vec{u}\,C_l)=\nabla.(D^{+}\,\nabla C_l)+\frac{\partial}{\partial t}\left[\rho\, f_S\, C_l\right]-\bar{C}_S\,\frac{\partial}{\partial t}(\rho\, f_S)$$

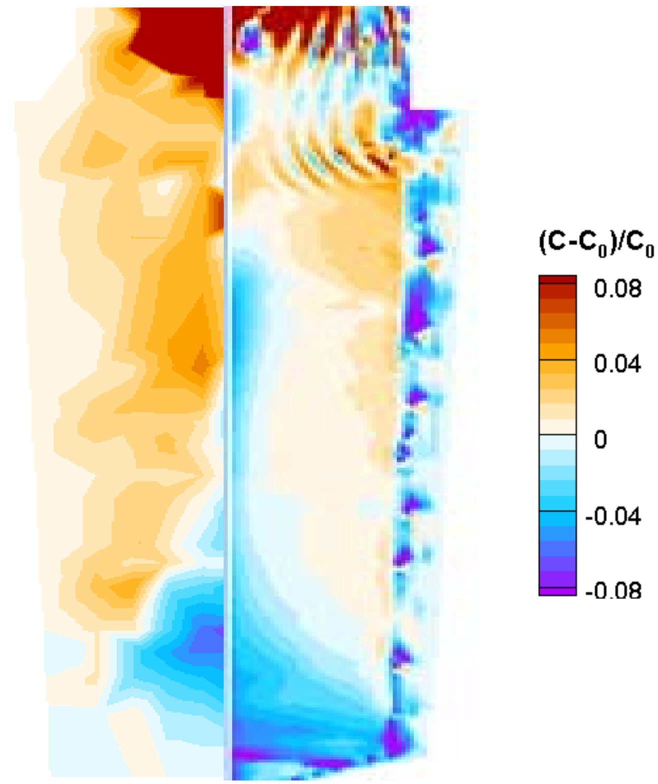
$$D^{+}=\rho\, f_l D_l$$

Macrosegregation defects in a representative industrial scenario



Laboratory casting

Industrial size casting
65 ton in weight
Experiment / Model



Macrosegregation
and mesosegregation

How Flow direction controls type of macro/ mesosegregation

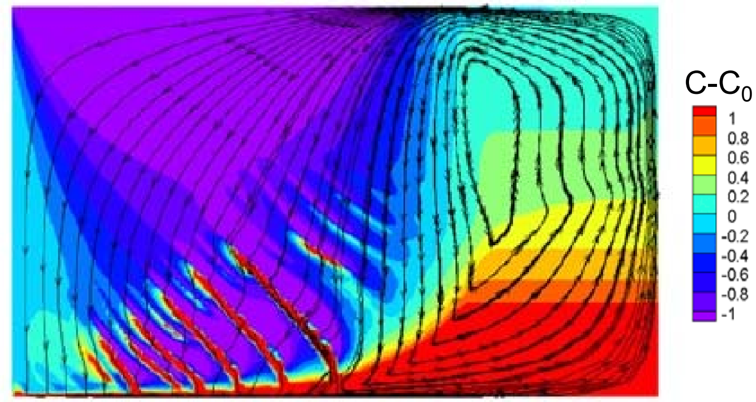
Species conservation equation

$$\frac{\partial}{\partial t}(\rho C) + \nabla \cdot (\rho C_L \mathbf{V}) = \nabla \cdot (\rho D \nabla C_L)$$

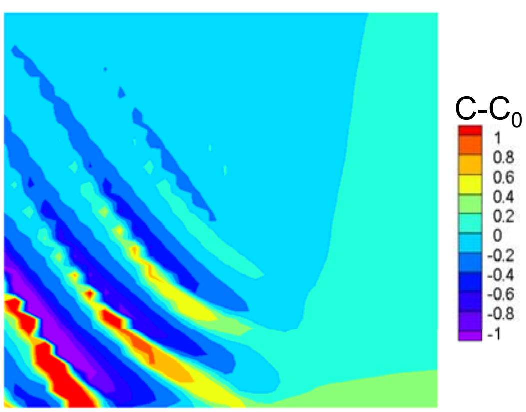
$$\frac{\partial C}{\partial t} = -g_l \langle \vec{v}_l \rangle^l \cdot \nabla C_l = -\frac{1}{m_L} g_l \langle \vec{v}_l \rangle^l \cdot \nabla T \sim \langle \vec{v}_l \rangle \cdot \nabla T$$

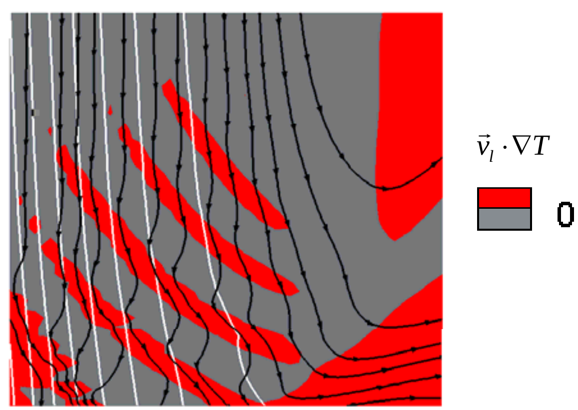
How Flow direction controls Macro/ mesosegregation

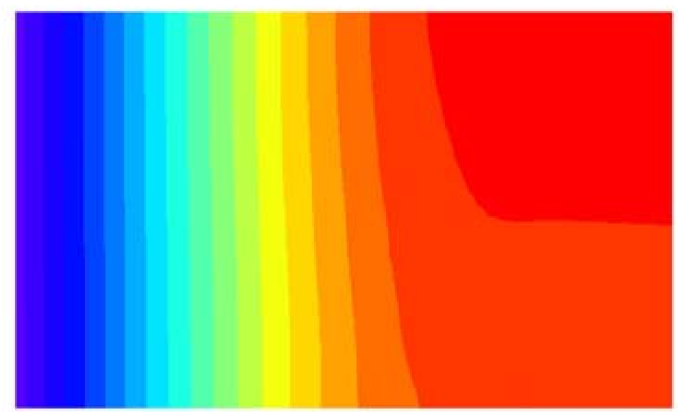
The nature of segregation is classical with respect to the direction of movement of liquid during solidification [5]. The dependence of segregation tendencies on the flow direction and the thermal extraction was elaborated in [8,9,17] according to $\partial C/\partial t = -g_l \vec{v}_l \cdot \nabla T/m$. In the areas where the velocity of the liquid is oriented to the temperature gradient, such that $\vec{v}_l \cdot \nabla T$ is positive, the tendency is to form a positive macrosegregation (note that the liquidus slope m is negative for the alloy considered) [8,9,17].



Concn + Flow streamlines

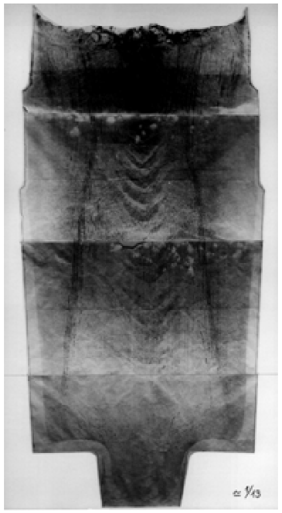






Temperature

Mesosegregation (channel) defects - freckles

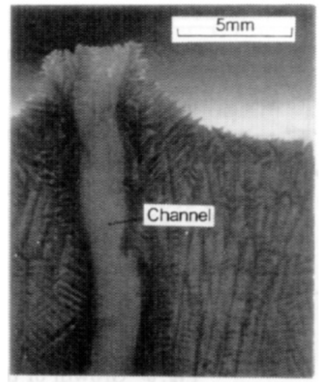


(a) Steel ingot

A.F. Giamei, UTRC

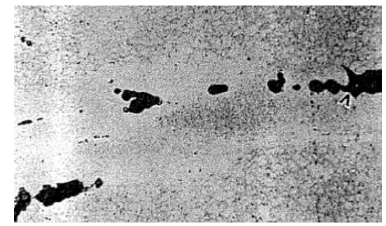
(b) Section of a turbine blade

T. Nishimura, Japan

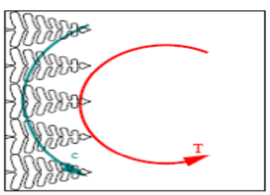


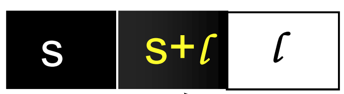
(c) Microstructure around meso segregates

R.C. Dorward et al., Aluminium, vol. 72



(d) Cracks in a test section under tension test (in the regions of meso segregates)





porous mushy zone of varying permeability 'K'

Can be controlled by controlling the fluid flow in the mushy zone

Example problem

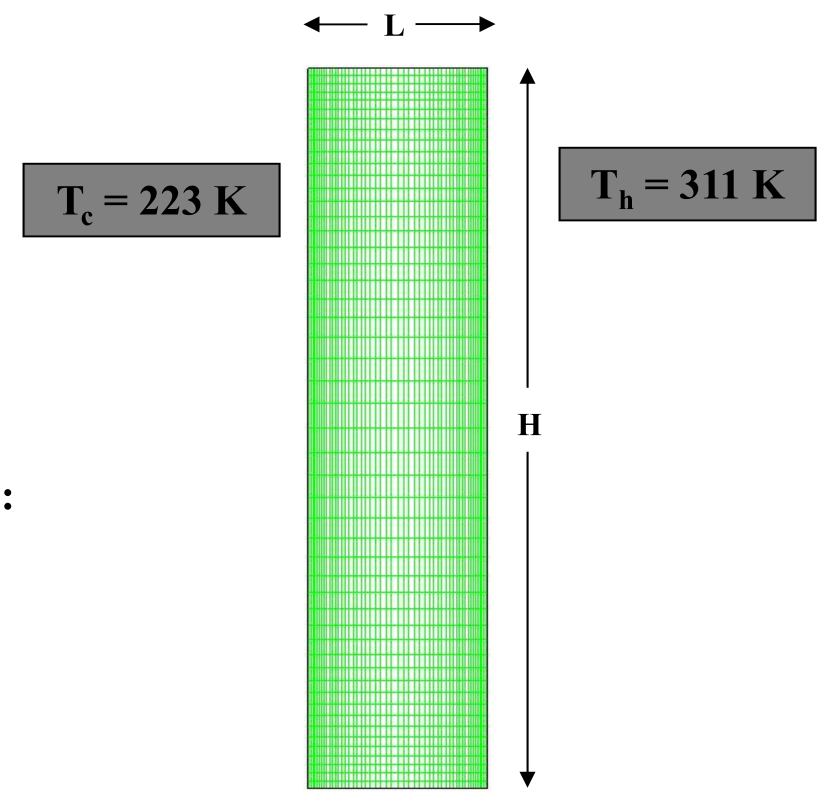
Ref: W.D. Bennon and F.P. Incropera, “A continuum model for momentum, heat and species transport in binary solid-liquid phase change systems – II. Application to solidification in a rectangular cavity”, Int. J. Heat Mass Transfer, vol. 30, No. 10, pp. 2171-2187, 1987.

Problem Description:

- **Rectangular domain filled with NH_4Cl-H_2O**
- **Initial condition**

  Mixture is fully liquid and at T_i = 311 K

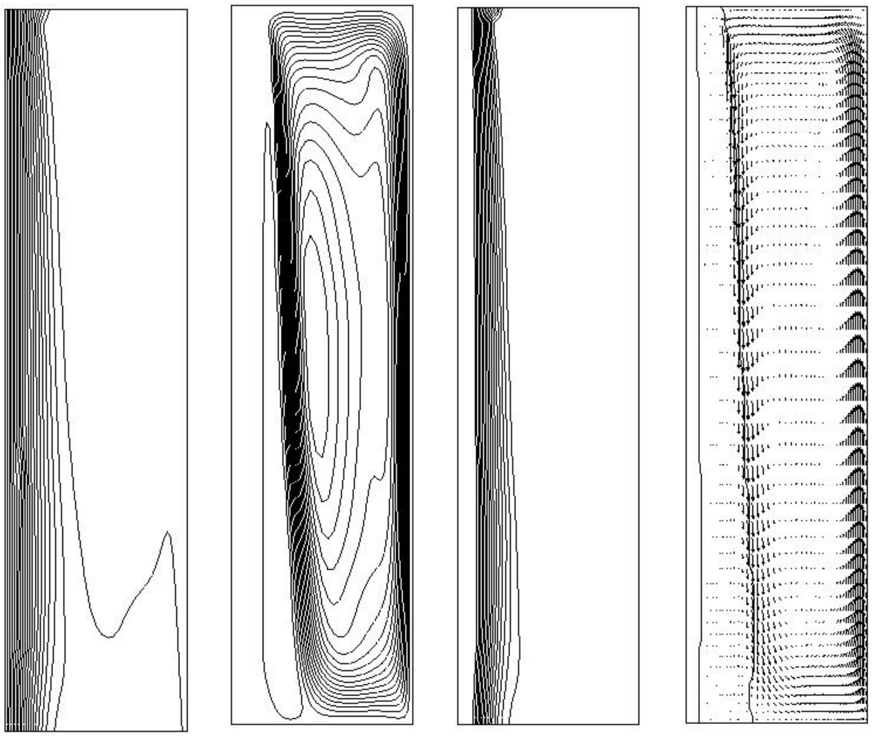
  Initial solute concentration is C_i = 0.7
- **Top and Bottom walls are insulated.**
- **L = 0.025 m, H = 0.1 m**
- **Numerical Simulation is shown for two case studies:**



Differentially Heated Side Walls

Left Wall: T_c = 223 K, Right Wall: T_h = T_i = 311 K

Example problem: differentially heated side walls 90 sec



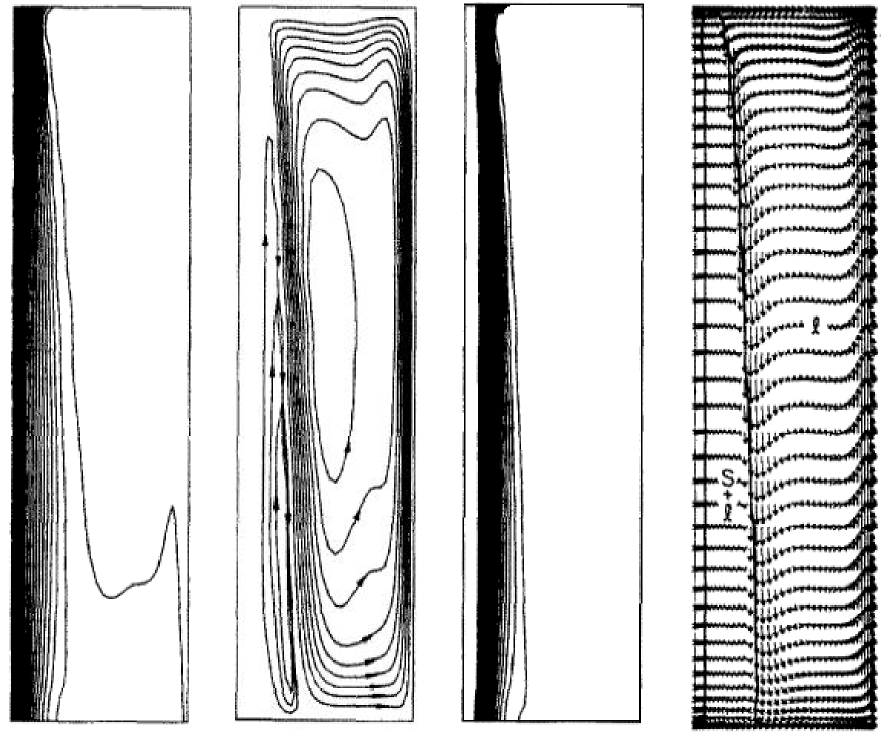
Isotherms $T_{max} = 311$ K $T_{min} = 223$ K

Stream Function $\psi_{max} = 0.016$

Species Concentration $C_l^{min} = 0.700$

Velocity Vectors $\rightarrow$ 5.8 mm/s

SIMULATION



Isotherms

Stream Function $\psi_{max} = 0.0153$

Species Concentration $C_l^{min} = 0.700$

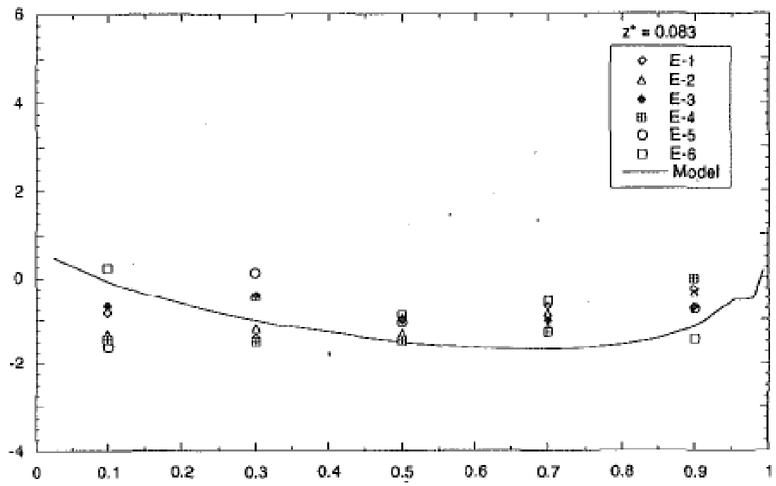
Velocity Vectors $\rightarrow$ 5.5 mm/s

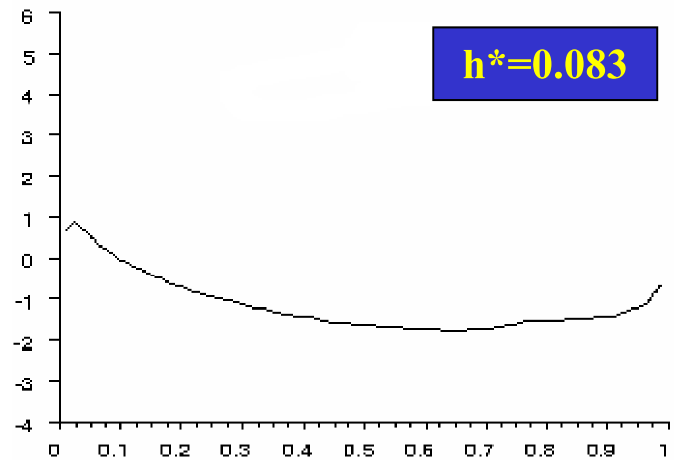
BENNON & INCROPERA Benchmark result

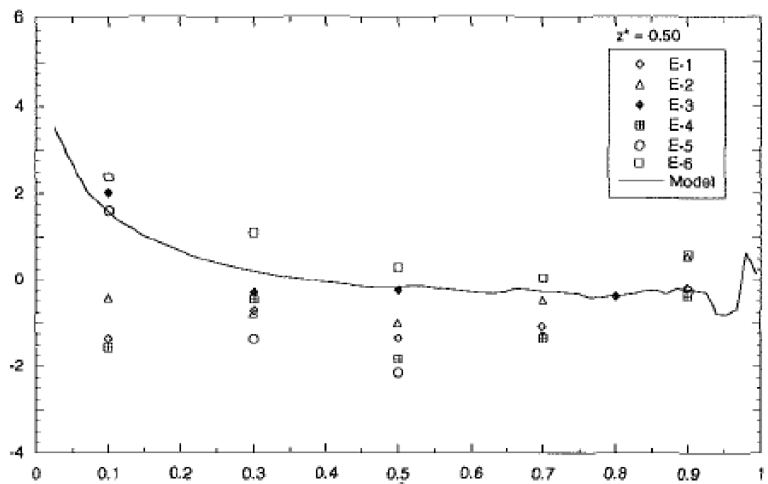
Final Macrosegregation Along Horizontal Direction

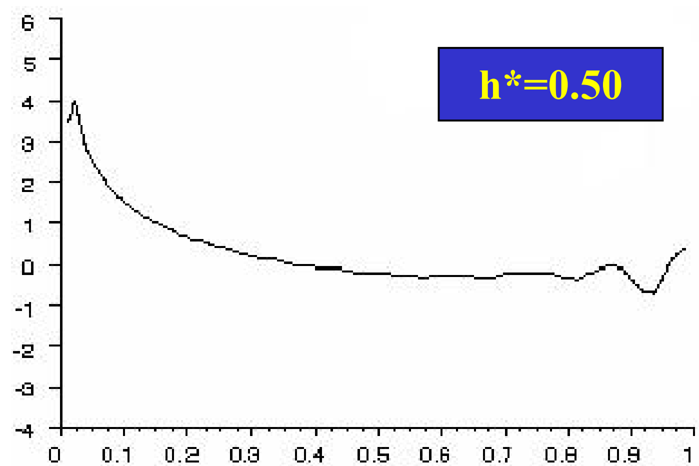
PRESCOTT *et al* (1994)

SIMULATION









Comprehensive casting modelling system

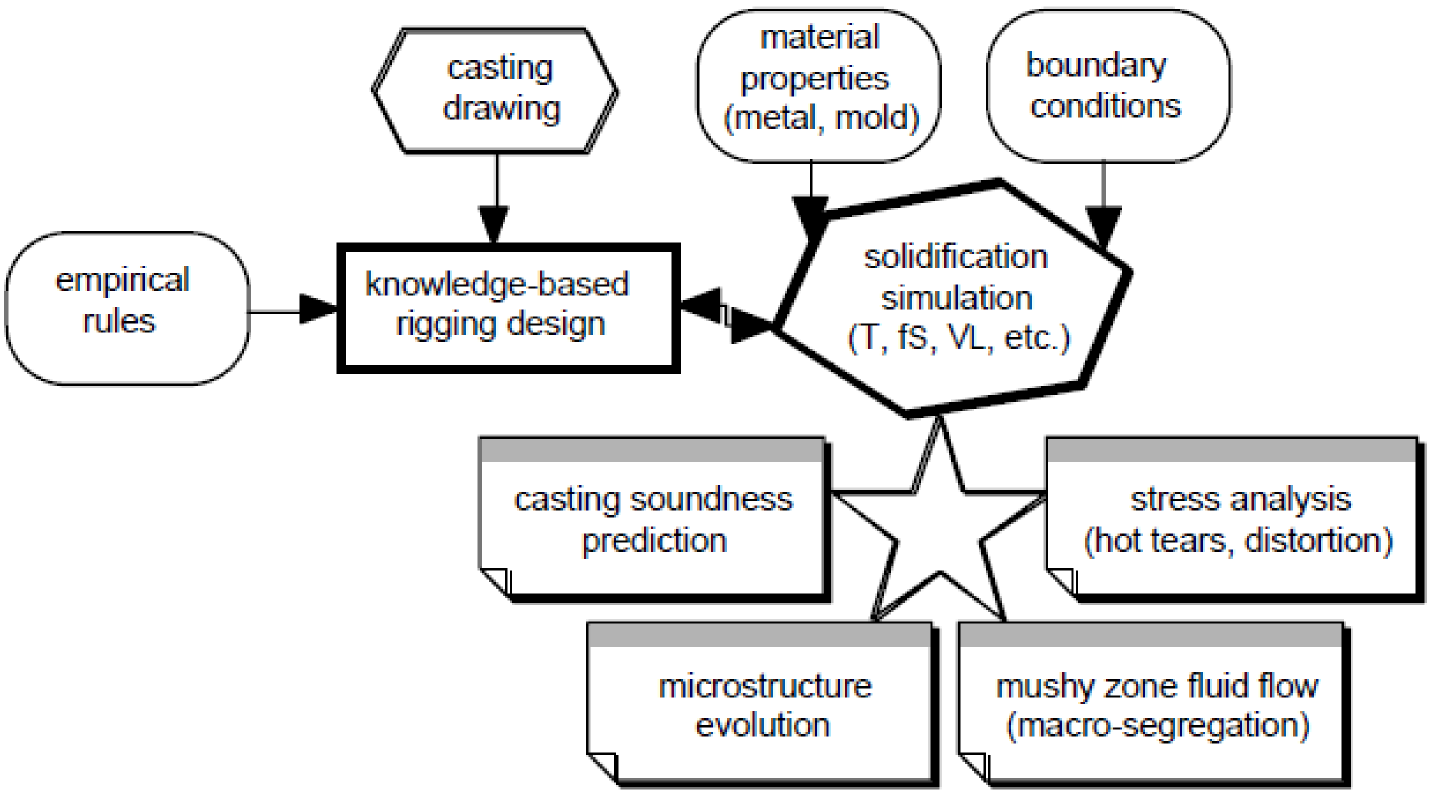
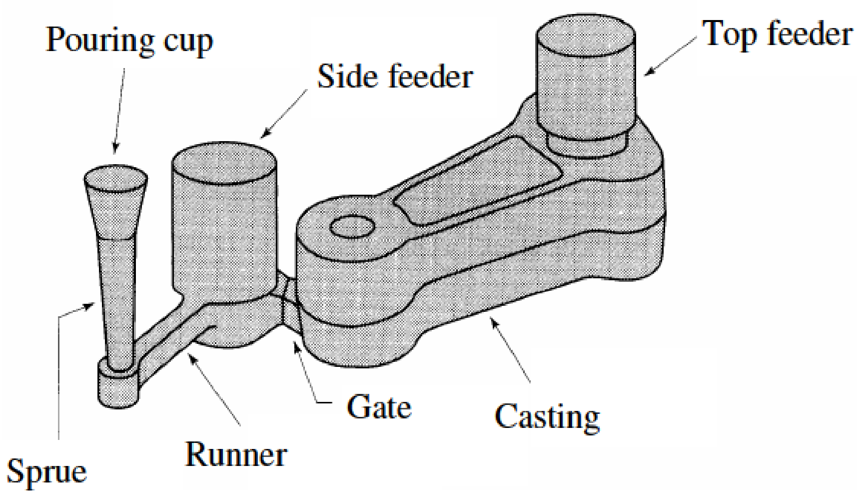


Table 6.2. Summary of foundry requirements and mold filling and solidification macro-models deliverables

Foundry objectives	Model deliverables	Calculations based on
casting soundness, surface quality		
macro-shrinkage	T, t_f, f_S, G, $\dot{T}$	criteria functions (Ohnaka 1986, Sahm 1991)
	volume deficit (Δv)	diffusive energy and convective mass transport (Jiarong et al. 1995)
micro-shrinkage/ porosity	T, t_f, f_S, G, $\dot{T}$, V_L, P	criteria functions (Niyama *et al*. 1982, Lee *et al*. 1990)
	pressure map	pressure balance (Bounds *et al*. 2000)
missruns, cold shuts	G, $\dot{T}$, $T_S > T_{min}$	criteria functions
	filling time	convective - diffusive, energy and mass transport
casting appearance - surface quality	penetration index	pressure balance at metal /mold interface and interfacial reactions (Stefanescu *et al*. 1996)
casting composition		
macro-segregation	composition map	convective - diffusive energy + mass transport (Mehrabian *et al*. 1970, Poirier *et al*. 1991, Schneider/Becker-mann 1995, Chang/ Stefanescu 1996)
casting dimensions - distortions	stress map	residual stress (Thomas 1993)
casting microstructure and mechanical properties		
fraction phase	C^{macro}, T, t_f, f_S, G, $\dot{T}$	criteria functions
SL interface stability	$G/V \geq \Delta T_{SL}/D$	criteria functions
phase transition	$\dot{T}$	criteria functions
columnar-to-equiaxed transition	$G_L < G_{min}$	criteria functions
dendrite arm spacing	$\lambda_I = ct.\cdot \dot{T}^n$, $\lambda_{II} = ct.\cdot t_f^{1/3}$, t_f: local solidif. time	criteria functions
gray-to-white transition in cast iron	$V < V_{max}$ or $\dot{T} < \dot{T}_{cr}$	criteria functions
mechanical properties of casting	C^{macro}, $\dot{T}$	criteria fct. based on composition and cooling rate
	C^{micro}, f_α, N, λ	criteria fct. based on microstructure

Nomenclature

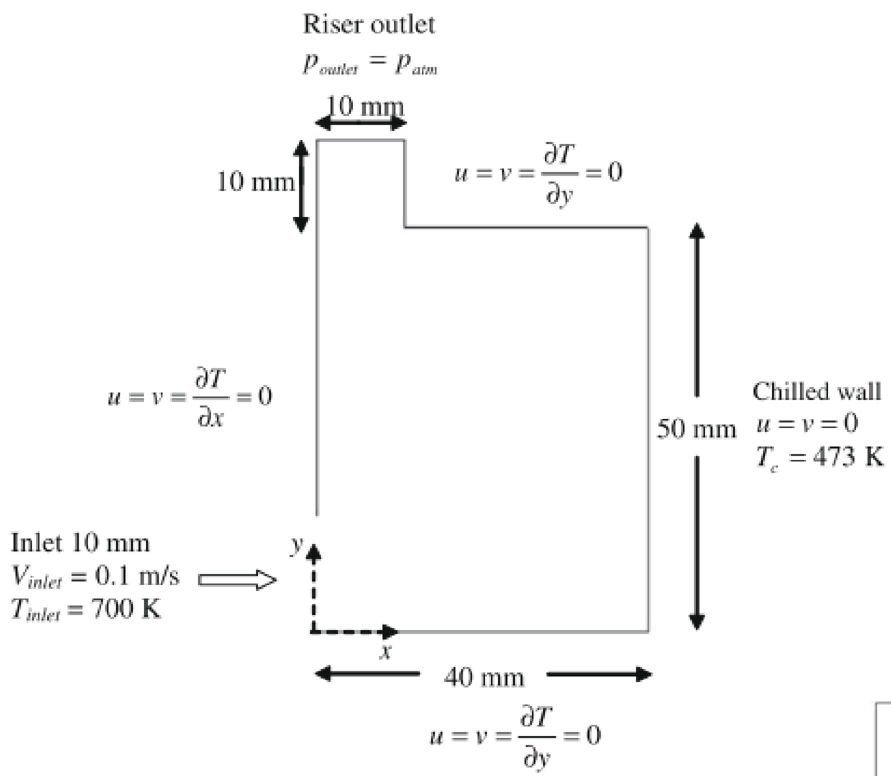
- C^{macro}: macro-scale composition
- C^{micro}: micro-scale composition
- f_α: fraction of phase
- G: temperature gradient
- N: number of grains per unit volume
- P: pressure
- t_f: final solidification time
- ΔT_{SL} : solidification interval
- Δv: total volume variation
- λ: phase spacing

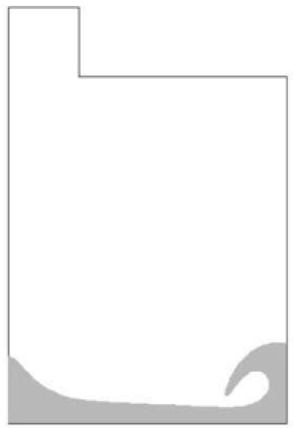


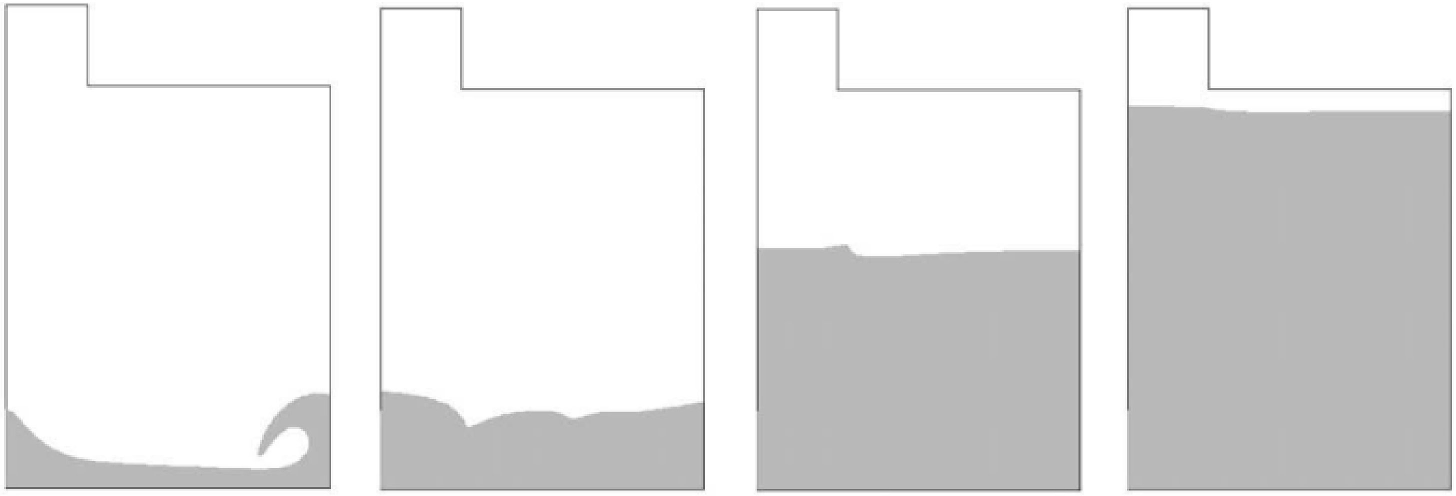
• It can be clearly seen that the filling and feeding systems are separate, which is appropriate since they perform completely different functions in the production of a casting.

• It might take ~ 10 seconds to fill the mould, whereas the feeding system would typically be operating for ~10 minutes as the casting solidifies.

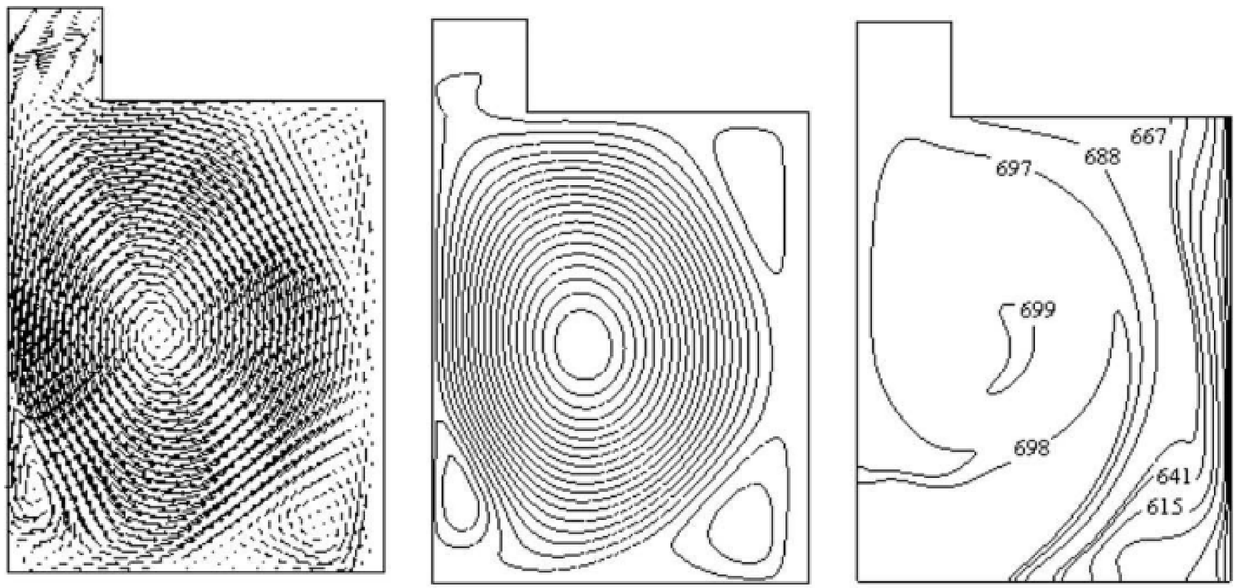
Example problem of mold filling







0.2 s　　0.4 s　　1.2 s　　1.9 s

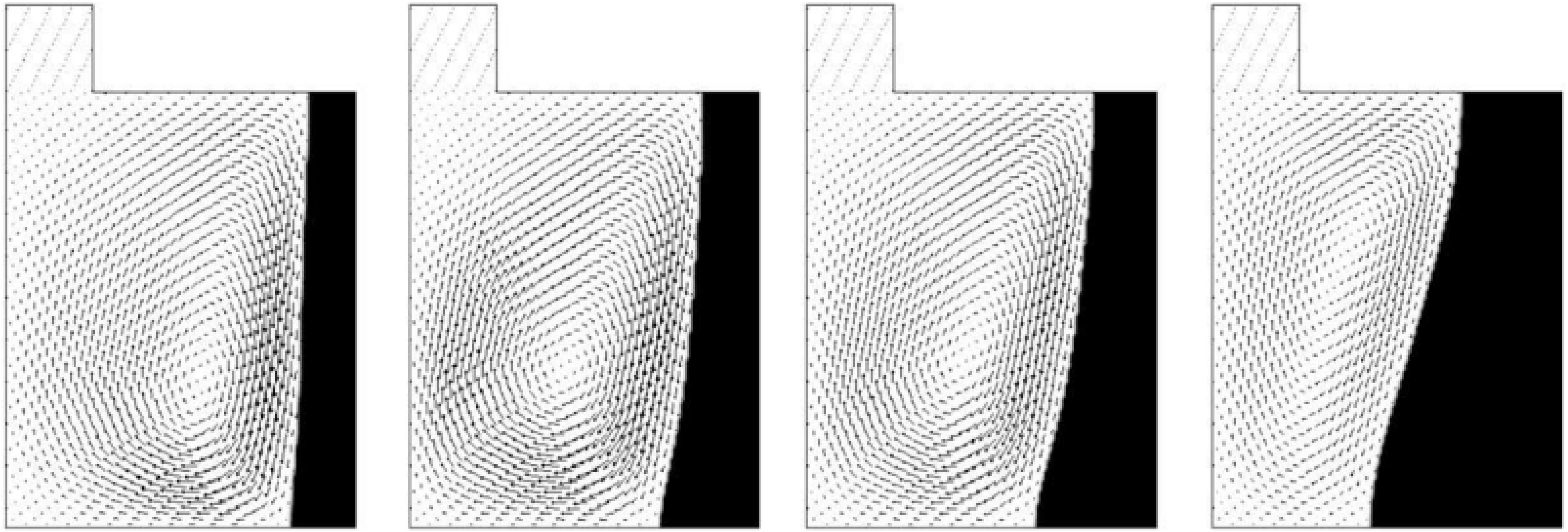


(a)　　(b)　　(c)

$V_{max} = 0.095$ m/s

$\psi_{max} = 14.184$ kg/s

$\psi_{min} = 1.182$ kg/s



$V_{max} = 0.0234$ m/s (a) 2 s

$V_{max} = 0.0244$ m/s (b) 4 s

$V_{max} = 0.0177$ m/s (c) 6 s

$V_{max} = 0.0089$ m/s (d) 13 s

Casting Quality

- There are numerous opportunities for things to go wrong in a casting operation, resulting in quality defects in the product
- The defects can be classified as follows:
  - Defects common to all casting processes
  - Defects related to sand casting process

Some common defects in any casting process

Misrun

A casting that has solidified before completely filling mold cavity

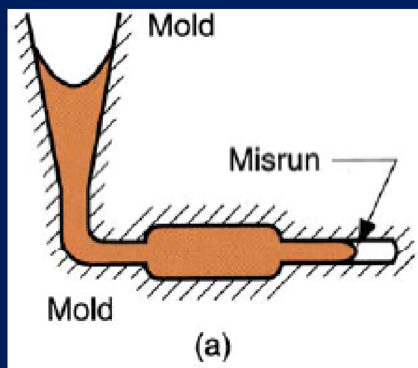


Figure 11.22 - Some common defects in castings: (a) misrun

Cold Shut

Two portions of metal flow together but there is a lack of fusion due to premature freezing

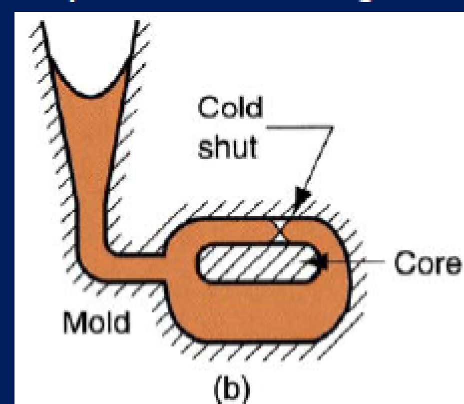


Figure 11.22 - Some common defects in castings: (b) cold shut

Cold Shot

Metal splatters during pouring and solid globules form and become entrapped in casting

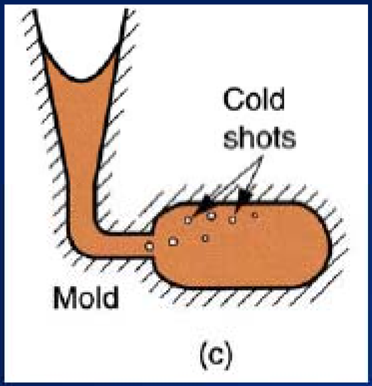


Figure 11.22 - Some common defects in castings: (c) cold shot

Shrinkage Cavity

Depression in surface or internal void caused by solidification shrinkage that restricts amount of molten metal available in last region to freeze

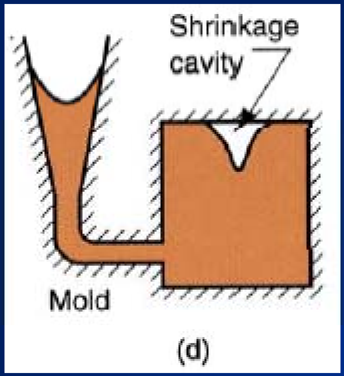
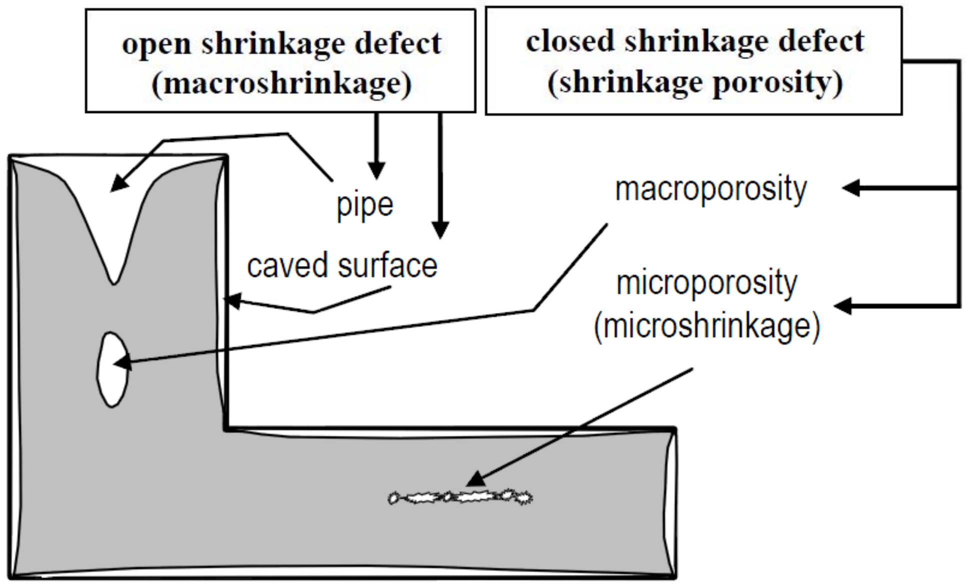


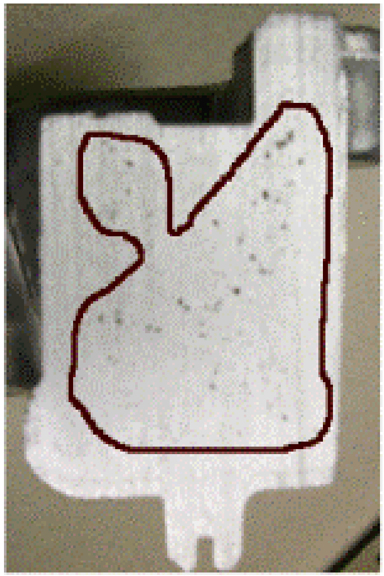
Figure 11.22 - Some common defects in castings: (d) shrinkage cavity

Lecture 5…

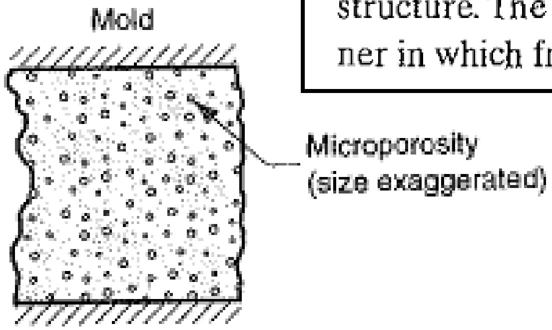
ME 361A

Also follow blackboard discussions





Microporosity



Microporosity consists of a network of small voids distributed throughout the casting caused by localized solidification shrinkage of the final molten metal in the dendritic structure. The defect is usually associated with alloys, because of the protracted manner in which freezing occurs in these metals.

Hot Tears in Castings

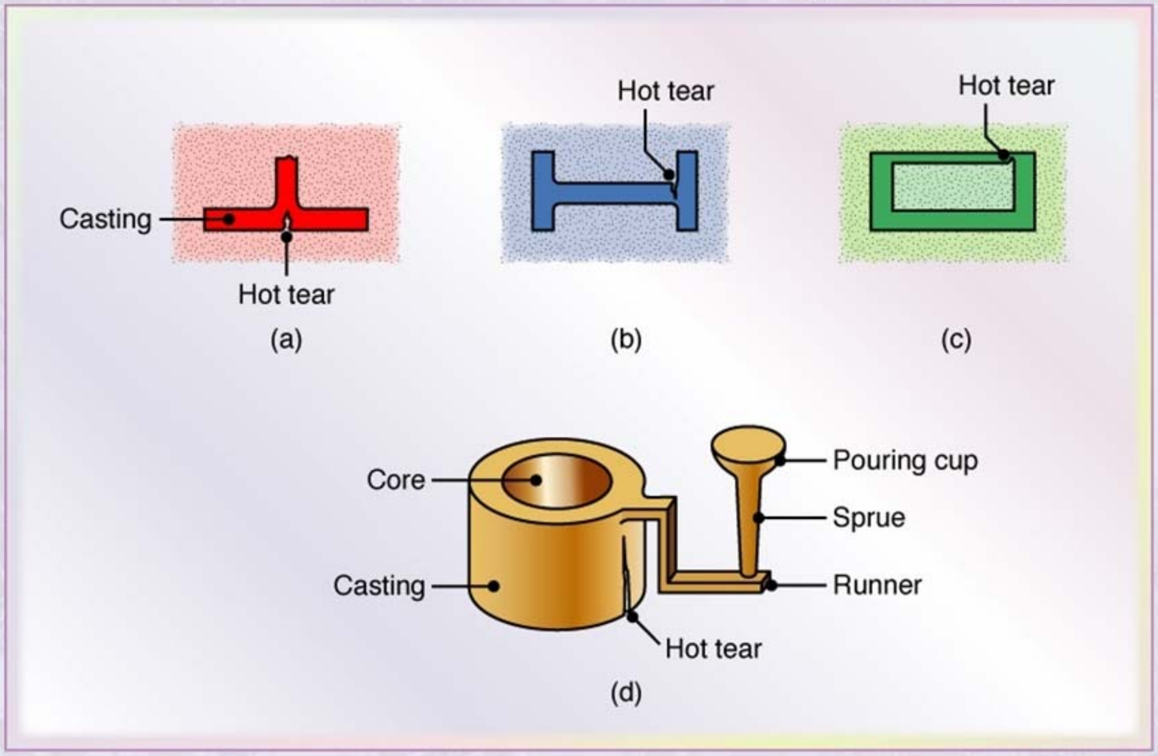
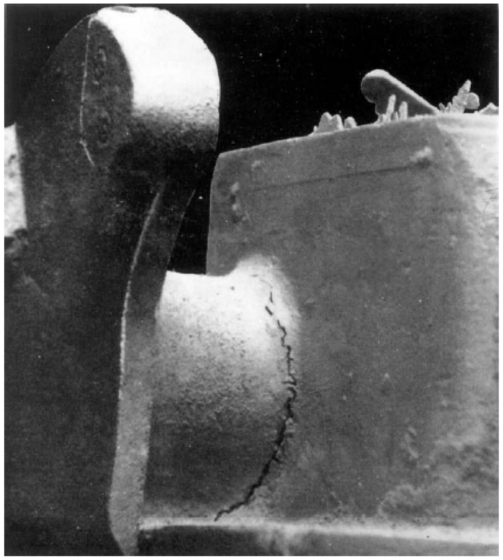


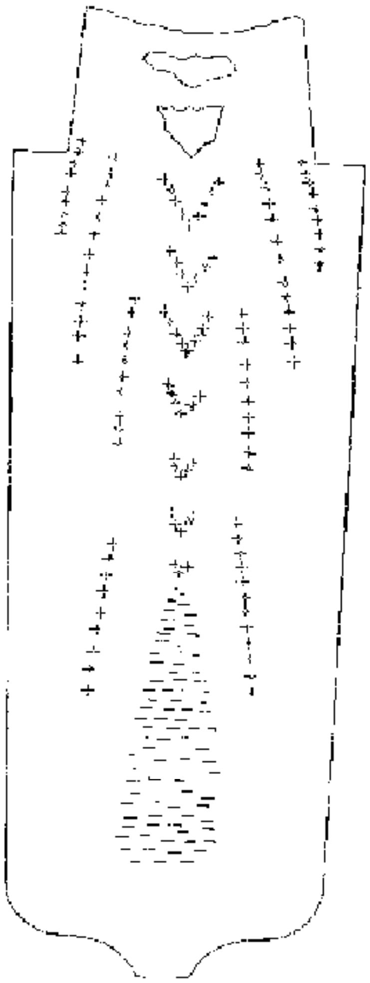
Figure 10.12 Examples of hot tears in castings. These defects occur because the casting cannot shrink freely during cooling, owing to constraints in various portions of the molds and cores. Exothermic (heat-producing) compounds may be used (as exothermic padding) to control cooling at critical sections to avoid hot tearing



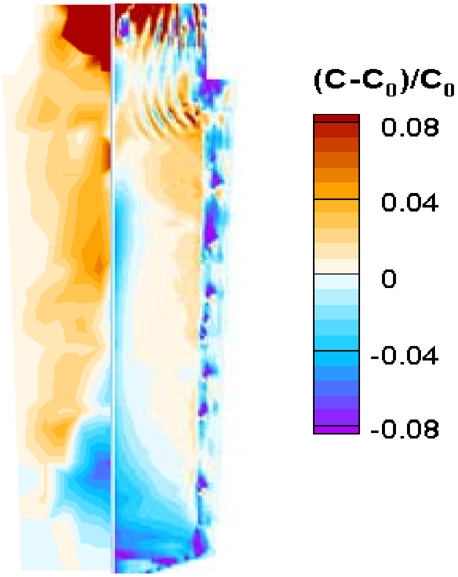
Typical hot tear at change of section

Hot tearing, also called ***hot cracking,*** occurs when the casting is restrained from contraction by an unyielding mold during the final stages of solidification or early stages of cooling after solidification. The defect is manifested as a separation of the metal (hence, the terms ***tearing*** and ***cracking***) at a point of high tensile stress caused by the metal's inability to shrink naturally. In sand casting and other expendable-mold processes, it is prevented by compounding the mold to be collapsible. In permanent-mold processes, hot tearing is reduced by removing the part from the mold immediately after solidification.

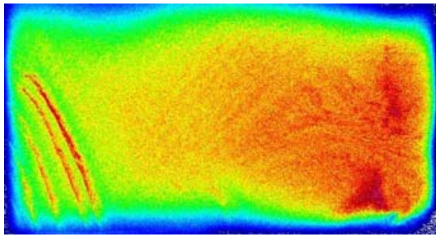
Macrosegregation defects in a representative industrial scenario



Experiment / Model

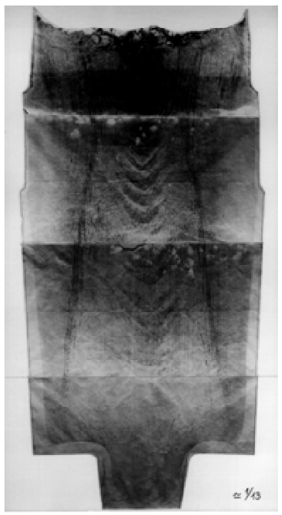


Macrosegregation
and mesosegregation



Laboratory casting

Mesosegregation (Channel) defects - freckles

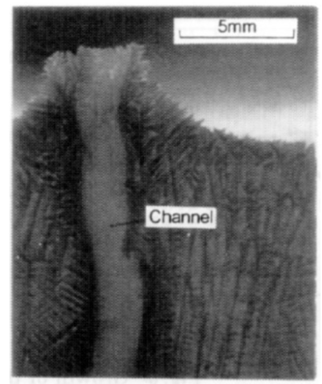


(a) Steel ingot

A.F. Giamei, UTRC

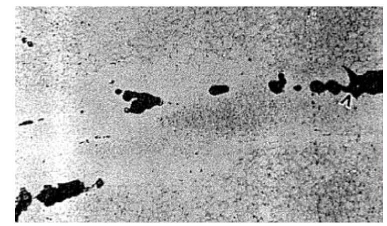
(b) Section of a turbine blade

T. Nishimura, Japan



(c) Microstructure around meso segregates

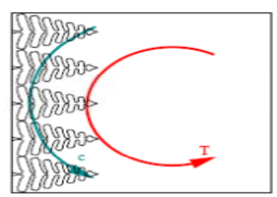
R.C. Dorward et al., Aluminium, vol. 72

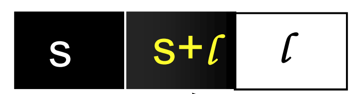


(d) Cracks in a test section under tension test (in the regions of meso segregates)

Mesosegregations

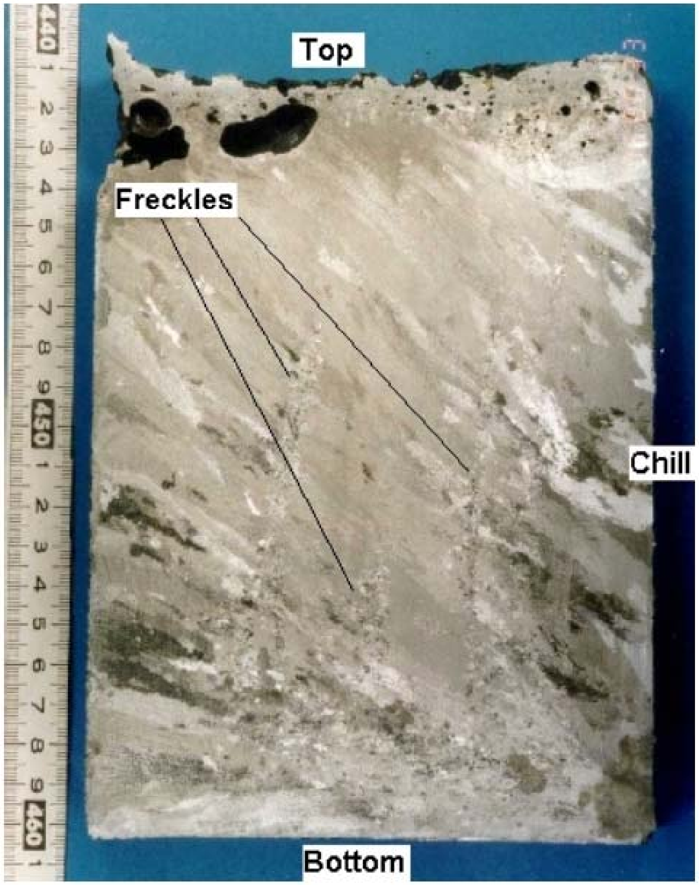
- Considerable variations in composition and microstructure
- Serious defects in industrial parts
- Difficult to detect
- Critical applications: nuclear, aviation

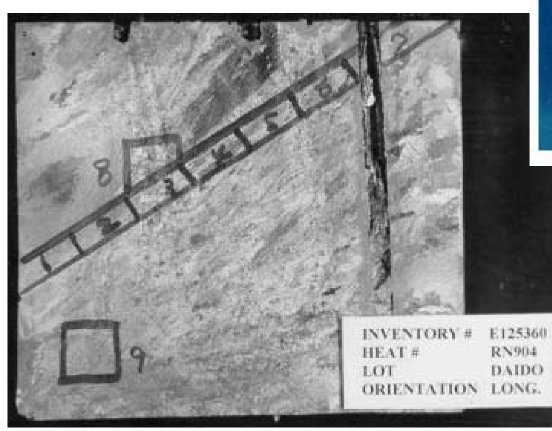


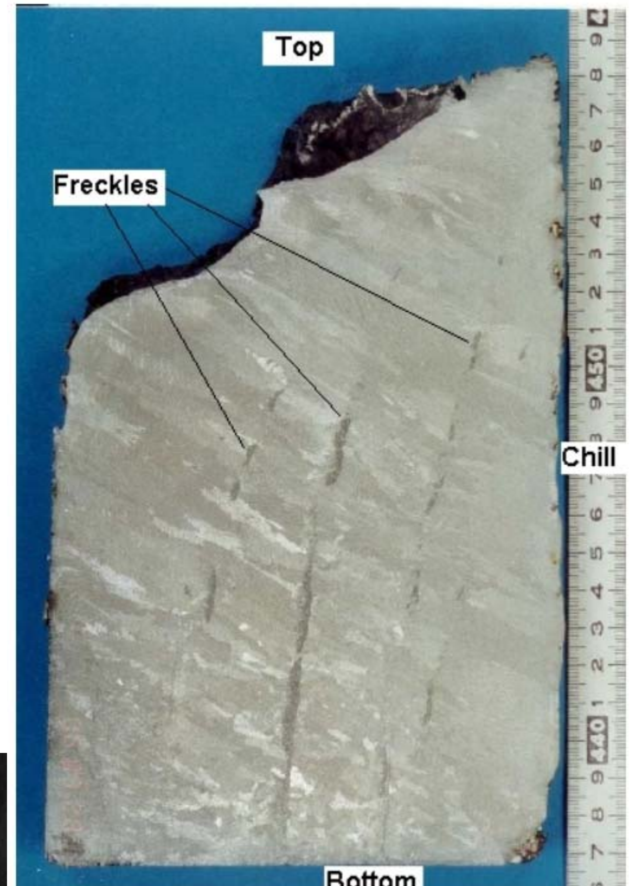


porous mushy zone of varying permeability ‘K’

Examples of mesosegregation (channel) defects - freckles







Macrosegregations due to convection of solid particles (grains)

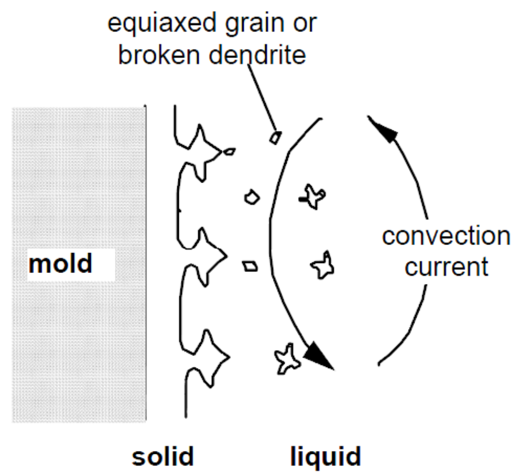
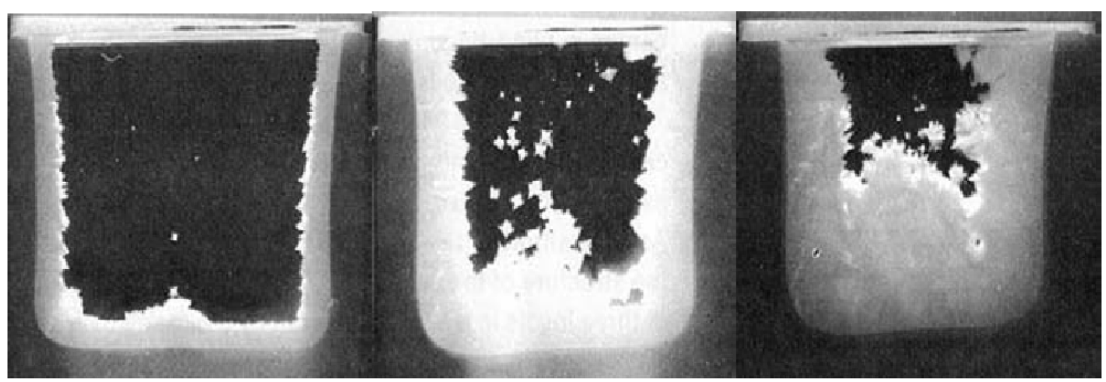


Figure 7.1. Schematic representation of thermal convection and displacement of dendrites from the wall to the center of the mold.

Figure 7.2. Equiaxed grain accumulation on a steel sieve inserted in a solidifying Al-2% Cu alloy (Ohno, 1987). With kind permission of Springer Science and Business Media.



a) 1 min after pouring b) 2 min after pouring c) 2.5 min after pouring

Figure 7.3. Broken dendrite branches transported in the center of the ingot by liquid convection in an NH_4Cl-H_2O system (T_L = 50°C) poured at 75°C (Jackson *et al.*, 1966).

Sand casting

Desirable Mold Properties and Characteristics

- *Strength* - to maintain shape and resist erosion
- *Permeability* - to allow hot air and gases to pass through voids in sand
- *Thermal stability* - to resist cracking on contact with molten metal
- *Collapsibility* - ability to give way and allow casting to shrink without cracking the casting
- *Reusability* - can sand from broken mold be reused to make other molds?

Foundry Sands

Silica (SiO_2) or silica mixed with other minerals

- Good refractory properties - capacity to endure high temperatures
- Small grain size yields better surface finish on the cast part
- Large grain size is more permeable, to allow escape of gases during pouring
- Irregular grain shapes tend to strengthen molds due to interlocking, compared to round grains
  - Disadvantage: interlocking tends to reduce permeability

Some common defects in sand casting process

Mold Shift

A step in cast product at parting line caused by sidewise relative displacement of cope and drag

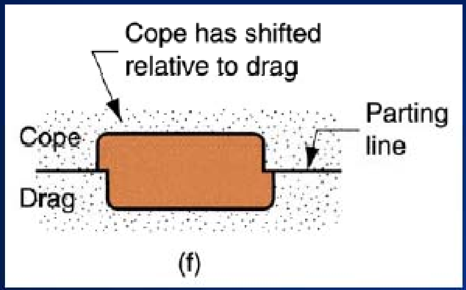


Figure 11.23 - Common defects in sand castings: (f) mold shift

Sand Blow

Balloon-shaped gas cavity caused by release of mold gases during pouring

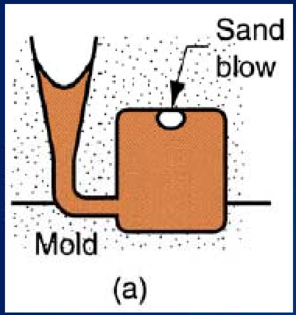


Figure 11.23 - Common defects in sand castings: (a) sand blow

Pin Holes

Formation of many small gas cavities at or slightly below surface of casting

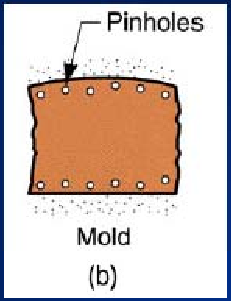


Figure 11.23 - Common defects in sand castings: (b) pin holes

Penetration

When fluidity of liquid metal is high, it may penetrate into sand mold or sand core, causing casting surface to consist of a mixture of sand grains and metal

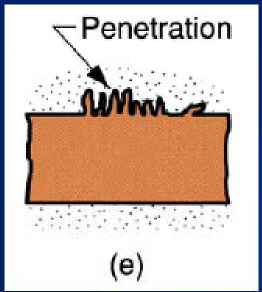
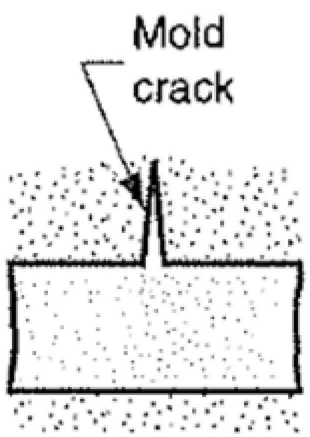


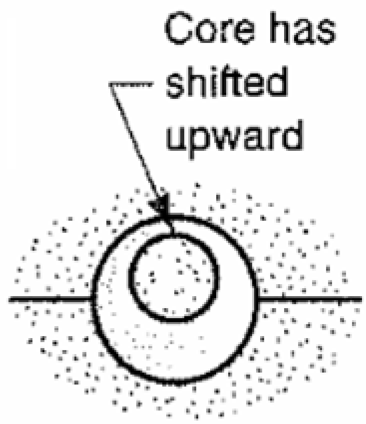
Figure 11.23 - Common defects in sand castings: (e) penetration

Penetration refers to a surface defect that occurs when the fluidity of the liquid metal is high, and it penetrates into the sand mold or sand core. Upon freezing, the casting surface consists of a mixture of sand grains and metal. Harder packing of the sand mold helps to alleviate this condition.



Mold crack occurs when mold strength is insufficient, and a crack develops, into which liquid metal can seep to form a "fin" on the final casting.

Core shift is similar to mold shift, but it is the core that is displaced, and the displacement is usually vertical. Core shift and mold shift are caused by buoyancy of the molten metal (Section 11.1.3).



Sand wash, which is an irregularity in the surface of the casting that results from erosion of the sand mold during pouring, and the contour of the erosion is formed in the surface of the final cast part.

Defects analysis: How to control them

Defects in casting: macro/ mesosegregation

- Redistribution of solute at the macro/ meso scale during solidification
- Redistribution caused by
  - diffusive transport
  - convective transport
    - natural convection
    - forced convection
    - Shrinkage driven flow
    - Marangoni convection (surface tension) driven flow

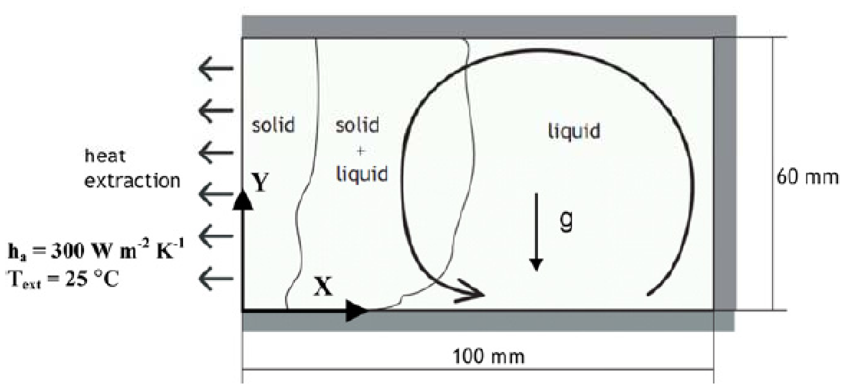


Table 1
Thermophysical data and parameters used in the 2D computation.

Parameter	Sn-5 wt% Pb
Phase diagram	
Initial mass fraction, wt% Pb	5.0
Melting temperature, °C	232.0
Eutectic temperature, °C	183.0
Liquidus slope, °C wt%$^{-1}$	−1.286
Eutectic mass fraction, wt%Pb	38.1
Partition coefficient, –	0.0656
Thermophysical data	
Specific heat, J kg^{-1} K^{-1}	260.0
Thermal conductivity, W m^{-1} K^{-1}	55.0
Latent heat of fusion, J kg^{-1}	61,000
Reference mass density, kg m^{-3}	7000.0
Reference temperature for mass density, °C	226.0
Thermal expansion coefficient, °C^{-1}	6.0×10^{-5}
Solutal expansion coefficient, wt %$^{-1}$	-5.3×10^{-3}
Dynamic viscosity, kg m^{-1} s^{-1}	10^{-3}
Computational parameters	
Initial temperature, °C	226.0
Heat transfer coefficient, W m^{-2} K^{-1}	300.0
External temperature, °C	25.0
Dimension of the cavity ($X \times Y$), m	0.1×0.06
Number of nodes, $X \times Y$ directions	150×150
Value of the representative size in the dendritic structure (in section 3.2), μm	100.0

Why is Dendrite Arm Spacing Important ?

The Dendrite Arm Spacing (DAS), *d,* is largely a function of the solidification time, t_S, and the relationship is of the approximate form:

$$d = k \cdot t_S^{0.3}$$

Effects on Mechanical Properties

As DAS decreases

- Tensile strength increases
- Ductility and elongation increase
- Hardness increases
- Shorter homogenisation heat treatment required

A small DAS also reduces the time required for homogenization heat treatments since the diffusion distances are shorter.

It is therefore beneficial to reduce the DAS as far as possible and since this is almost exclusively a function of the freezing time, any technique to reduce this will have a beneficial effect upon the DAS.

Solidification transport phenomena based predictive capability (modelling simulation) can be used to study/ to predict/ to explore means to control the **chemical heterogeneities and microstructure** in a solidification process

Hydrodynamic properties of the mushy zone

Benchmark lab expts and numerical solutions – validation with lab and industrial expt

Microstructure evolution

Chemical heterogeneities

Scalability to industrial manufacturing processes

Industrial applications – Actual product as large as 100 ton

Principal application: manufacturing processes

Process parameters → Transport phenomena → Chemical composition and structure formation → Properties of the product

Light metals, Steel, Si semiconductors

Casting defects such as those related to filling, solidification, stress, and microstructure can be predicted. As always, better understanding and accurate material properties, including mold materials, lead to improved predictive capabilities. Further development efforts should emphasize the enhancement of the accuracy of predicting various casting defects. Further coupling of heat treatment simulation with casting simulation can then predict the final mechanical properties of the part in service.

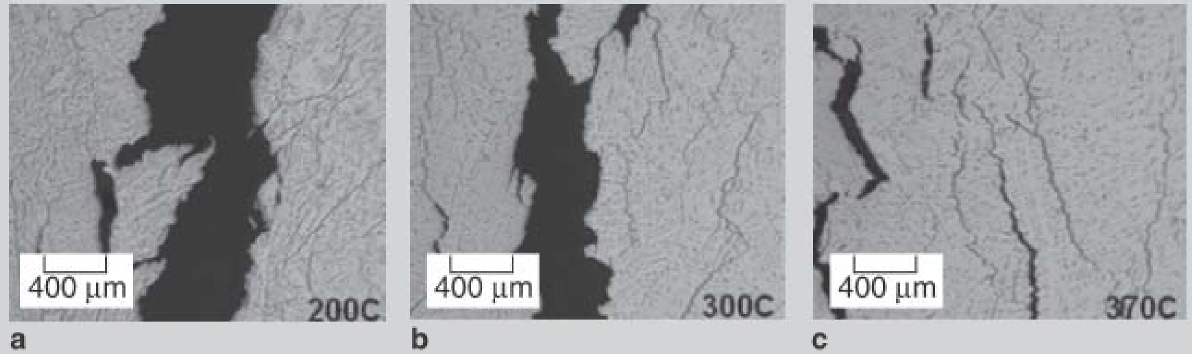


Figure 14. Hot tears in neck region for different mold temperature (a) 200°C, (b) 300°C, and (c) 370°C.

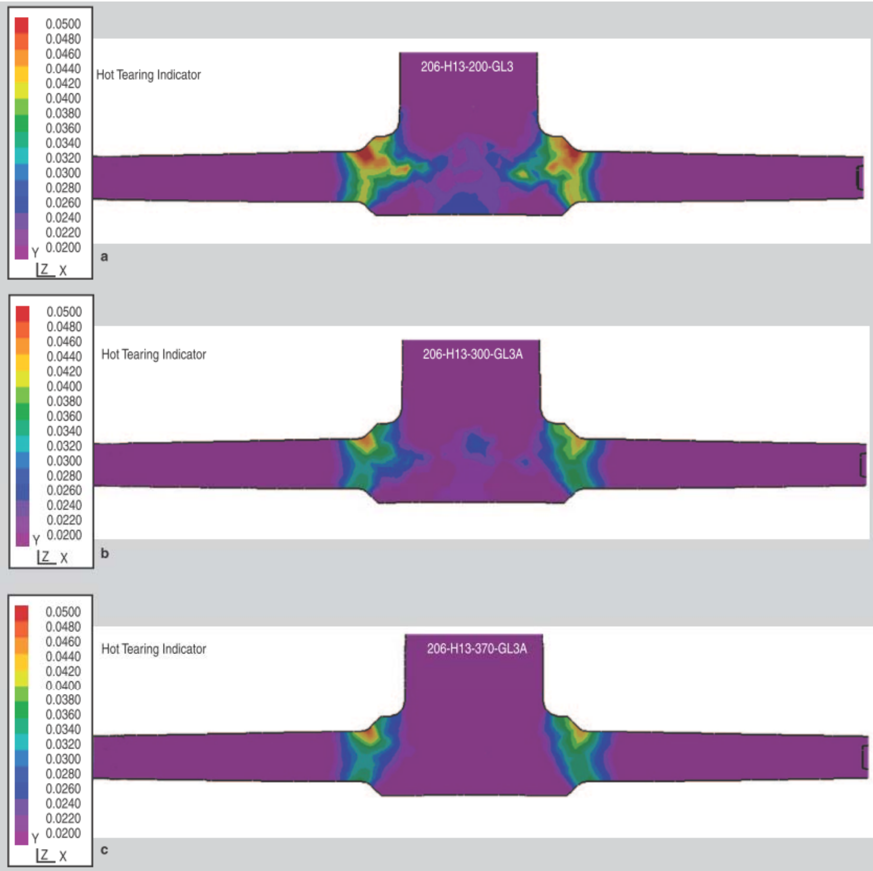


Figure 15. Predicted hot tearing indicator for mold temperature from top to bottom of (a) 200°C, (b) 300°C, and (c) 370°C.

Core

Full-scale model of interior surfaces of part

- It is inserted into the mold cavity prior to pouring
- The molten metal flows and solidifies between the mold cavity and the core to form the casting's external and internal surfaces
- May require supports to hold it in position in the mold cavity during pouring, called *chaplets*

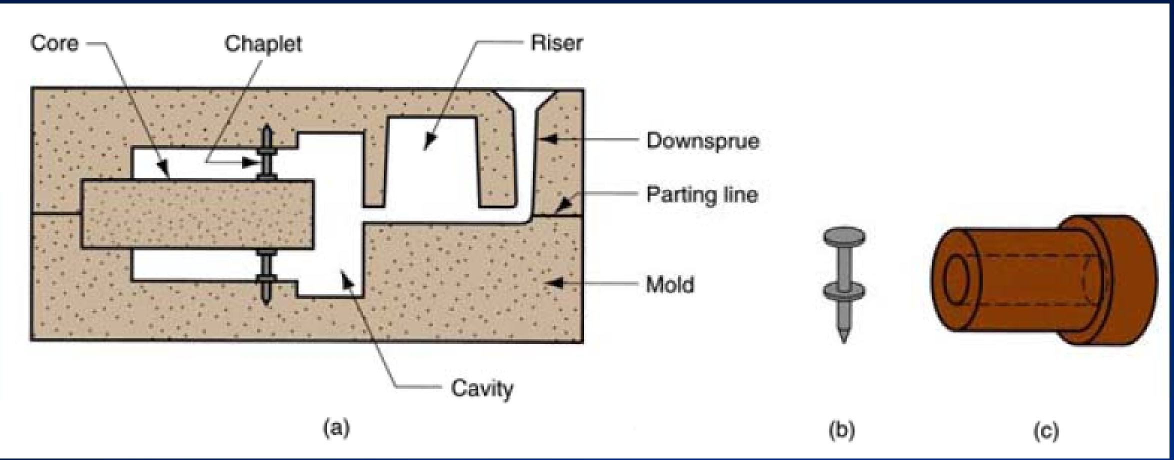
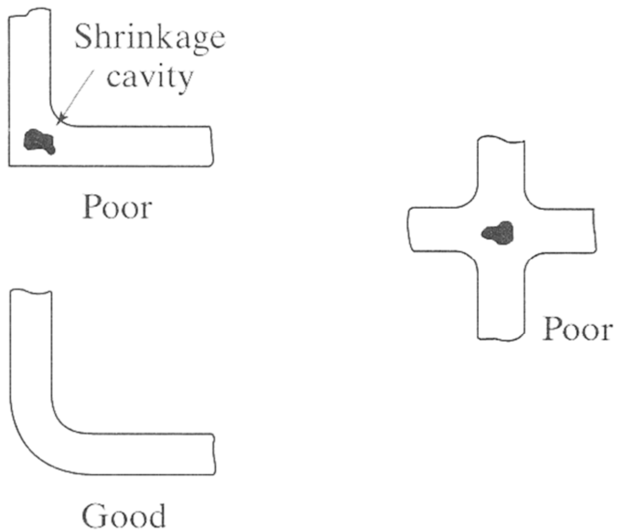


Figure 11.4 - Core held in place in the mold cavity by chaplets

(b) possible chaplet design

(c) casting with internal cavity

Specific geometry



Shrinkage Remedies:

- Feeders to provide enough liquid metal
- Chills to increase the rate of solidification in thicker sections