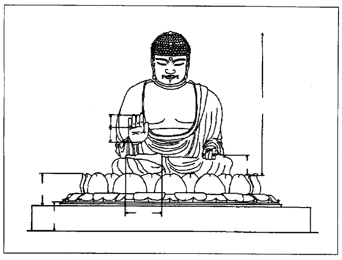
Casting Processing, MH2252, 6hp



Lecture 9
Repetition - Information about the exam

Lect.9-1

Today´s topics

- Study visit Scania AB
  - Seminar presentations
- Course Goals
- Information about the exam
  - Closed part – No help (calculator)
  - Opened part – Course literature allowed
- Repetition
  - Materials processing during casting

Lect.9-2

Seminar Presentation- Study Visit Groups – Scania AB

The presentations of the different tasks will take place:

14/10, 13-15, Blå

You should prepare and make a short presentation at a maximum of 10-15 minutes about your task (max 8-10 PowerPoint slides). Attendance at the presentations are mandatory!

Each presentation, should be handed in in Canvas before or latest at the presentation. All students should be involved and be at the stage. The groups are (max four members) - Subscribe in Canvas!

Group 1: Moulding - Materials and methods at Scania
Group 2: Cast Iron Parts in a Scania-truck, describe the different types of cast iron alloys and where they are used and why
Group 3: The technique of additive manufacturing is a growing technology that can be applied for manufacturing of cores. Discuss when/how this is a suitable process route.

Lect.9-3

Scania foundry 100 year

Scanias Gjuteri 100 år

Lect.9-4

Goals

The aim of the course is:

- To gives an overview of both component casting and processes such as ingot casting, continuous casting and direct casting
- Describe and explain the problems that can arise during casting of metals, solidification and cooling.

Intended Learning Outcomes

After passing the course the student should be able to:

- Give example of and justify for the use of **common casting processes** for manufacturing of components, as well as blanks/workpieces (TEN2)
- Apply and calculate **fluid dynamic processes for metal flow** at tapping and filling of a casting system for manufacturing of components, as well as blanks (TEN2)
- Explain principles and justify adopted **models for heat transport** at the moulding and solidification of metals (TEN2)
- Explain and justify for **structure and structure formation** in cast materials and the appearance of micro and macro segregations during solidification (TEN2)
- Explain the origin of **casting defects such as shrinkage, gas porosity**, slags, secondary phases and cracks and methods and processes to control and minimize these (TEN2)
- Dimension and simulate a casting system with the purpose of minimizing casting defects and maximizing yield, and present this in a scientific context (PRA1)
- Describe and give examples of the complexity of a real industrial process chain for casting of components or blanks and present this during a seminar (STU1)

Examination parts

STU1 – Study visit, 0.5 credits, grade scale: PF
TEN2 - Examination, 4.0 credits, grade scale: AF
PRA1 – Assignment/Lab, 1.5 credits, grade scale: P, F

Requirements for final grade:
Written examination (TEN2)
Computer assignment/Lab work (PRA1)
Study visit/seminar (STU1)

Examiner:
Anders Eliasson, anderse@kth.se

Written examination – TEN2

The examination are in **two parts**.
The **first part** is answered **without any aid**, while during the second part the use of course material is allowed. **"Summary" from the text book** Materials Processing during Casting, is allowed and handed out if you do not have a text book. Note, **no personal course literature** is allowed!

The questions are both fundamental ones about the different processes and some calculations (please do not forget a **calculator**). There are no time limits between the two parts. When you hand in the first part you will get the second one.

Note, **registration** in advance is needed to attend the exam!

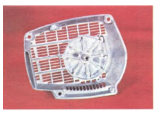
Old campus exams are found at the course page in Canvas.

Lect.9-8

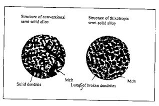
Industrial Casting – Component Casting

- Nonrecurrent Moulds
  - Sand moulding
  - Shell mould Casting
  - Investment Casting

- Permanent Moulds
  - High Pressure Die Castning
  - Die Casting (gravity die casting)
  - Low-Pressure Die Casting
  - Squeeze Casting

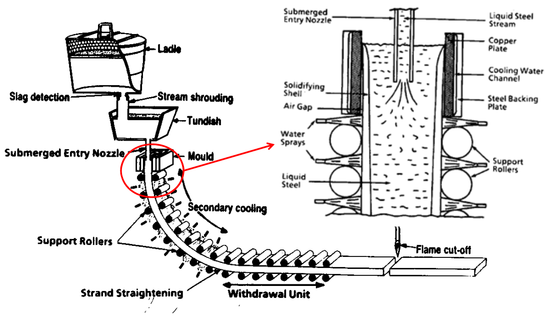


- Thixomoulding/Rheocasting

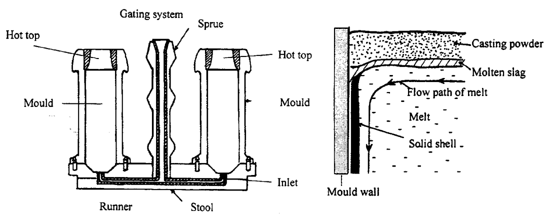


Lect.9-9

Continuous Casting

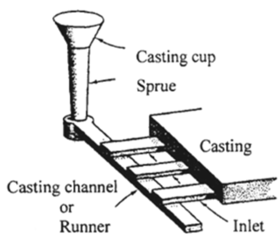


Ingot Casting - Uphill



Gating System

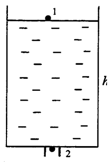
- Purpose
  - Provide the mould with melt at the proper rate
  - No unnecessary temperature losses
  - Without undesired gas and slag inclusions



Basic Hydrodynamics

- Bernoulli's Equation
  - Laminar flow

$$p_1+\rho g h_1+\frac{\rho v_1^2}{2}=p_2+\rho g h_2+\frac{\rho v_2^2}{2}$$



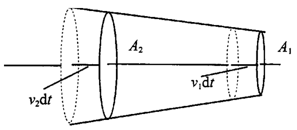
- Torricelli's law: $v = \sqrt{2gh}$
  - The first part: Pressure work
  - The second part: Potential energy
  - The third part: Kinetic energy

Used whenever you have a difference in height (potential energy change)

Lect.4-13

Basic Hydrodynamics

- Continuity Principle
  - Incompressible Liquid



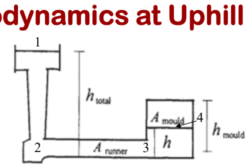
$$v_1A_1=v_2A_2$$

- No fluid appears or disappears during the flow
- The fluid flow volume is constant by time

Used whenever you have a change of area

Lect.9-14

Hydrodynamics at Uphill Casting



$v_2 = \sqrt{2g(h_{tot}-h)}$ — Melt velocity at point 2, from Bernouilli's eq.

$A_m dh = A_i\sqrt{2g(h_{tot}-h)}\cdot dt$ — Height (volume) change, *dh*, by the time *dt*, at point 4, by combining with the Principle of Continuity

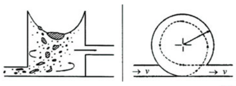
$\frac{A_i}{A_m}\int_0^{t_f} dt = \frac{1}{\sqrt{2g}}\cdot\int_0^{h_m}\frac{dh}{\sqrt{h_{tot}-h}}$ — Integrate

$t_f = \frac{2A_m}{A_i\sqrt{2g}}\cdot\left(\sqrt{h_{tot}}-\sqrt{h_{tot}-h_m}\right)$ — The filling time, t_f

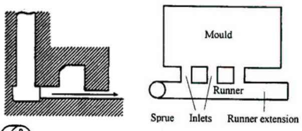
Lect.9-15

Inclusion Control

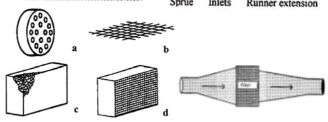
- Swirl trap



- Runner Extension Mechanical impurity trap

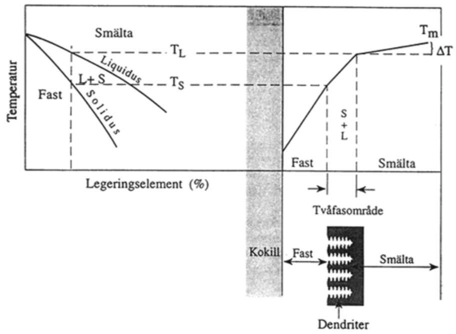


- Ceramic Filters



Lect.9-16

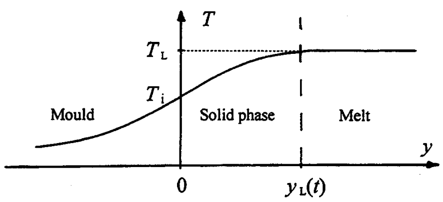
Modes of Solidification



- Relation between composition (solidification interval), cooling rate and dendrite structure

Lect.9-17

Ideal Contact Metal-Mould – Model 0



$$\frac{c_p^{metal}(T_L - T_o)}{-\Delta H} = \sqrt{\pi}\cdot\lambda\, e^{\lambda^2}\cdot\left(\sqrt{\frac{k_{metal}\,\rho_{metal}\,c_p^{metal}}{k_{mould}\,\rho_{mould}\,c_p^{mould}}} + \operatorname{erf}\lambda\right)$$

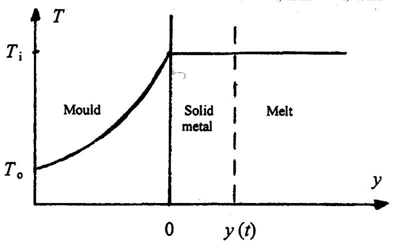
$y_L(t) = \lambda\cdot\sqrt{4\alpha_{metal}t}$ and $\alpha = \dfrac{k}{\rho c_p}$

See chapter 4.3.2 Theory of Heat Transport at Casting with Ideal Contact between Metal and Mould

Lect.9-18

Sand Mould Casting – Model 1

General Assumption: $T_i = T_{i,metal} = T_{i,mould} = T_L$



$$y_L(t) = \frac{2}{\sqrt{\pi}} \cdot \frac{T_i - T_o}{\rho_{metal}(-\Delta H)} \cdot \sqrt{k_{mould}\rho_{mould}\, c_p^{mould}} \cdot \sqrt{t}$$

See chapter 4.4.1 Temperature Distribution at Sand Mould Casting

Sand Mould Casting - Chvorinov's Rule

$$y_L = \left(\frac{V_{metal}}{A}\right)$$

Note: Every unit area of the mould absorb equal amount of heat

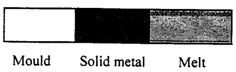
$$\frac{V_{metal}}{A} = \frac{2}{\sqrt{\pi}} \cdot \frac{T_i - T_o}{\rho_{metal}(-\Delta H)} \cdot \sqrt{k_{mould}\rho_{mould}\, c_p^{mould}} \cdot \sqrt{t_{total}}$$

$$t_{total} = C\left(\frac{V_{metal}}{A}\right)^2 \qquad C = \left(\frac{\sqrt{\pi}}{2} \cdot \frac{\rho_{metal}(-\Delta H)}{T_L - T_0} \cdot \frac{1}{\sqrt{k_{mould}\rho_{mould}\, c_p^{mould}}}\right)^2$$

- **V_{metal} = total volume of the solidified casting**
- **A = total area of the interface between the mould and the metal**
- **t_{total} = the total solidification time.**

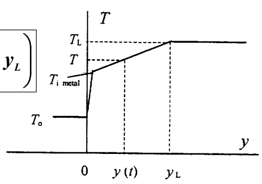
Poor Contact Metal-Mould – Model 2

Note: High Conductivity in Mould



$$t = \frac{\rho_{metal}(-\Delta H)}{T_L - T_0} \cdot \frac{y_L}{h} \cdot \left(1 + \frac{h}{2k_{metal}} \cdot y_L\right)$$

$$T_{i\,metal} = \frac{T_L - T_o}{1 + \frac{h}{k} y_L(t)} + T_o$$



See chapter 4.3.3 Theory of Heat Transport at Casting with Poor Contact between Metal and Mould

Nussel's Number <<1 - Model 3

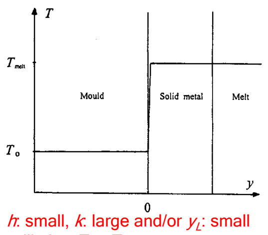
- Dimensionless number

$$\mathrm{Nu} = \frac{hs}{k} << 1$$

$$t = \frac{\rho_{metal}(-\Delta H)}{T_L - T_0} \cdot \frac{y_L}{h}$$

$$T_{\mathrm{i\,metal}} = \frac{T_L - T_o}{1 + \frac{h}{k} y_L(t)} + T_o = T_L$$

Note: Special case if Nu<<1

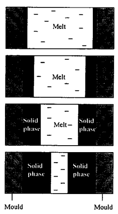


h: small, *k*: large and/or y_L: small *will give*: $T_i \approx T_L$

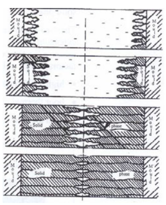
See chapter 4.4.5 Nussel´s Number. Temperature Profile of Mould and Metal at Low Values of Nussel´s Number

Lect.4-22

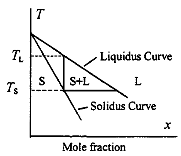
Modes of Solidification



- Pure metal or eutectic alloy
- Alloy with small ΔT and strong cooling

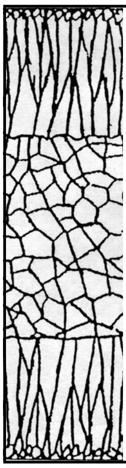


- Alloy with large ΔT
- Weak cooling



Solidification interval
$\Delta T = T_L - T_S$

Lect.9-23

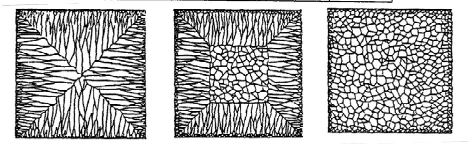


The solidified structure

Surface crystals
- Fast cooling in the mould gives small crystals
- Columnar crystals
  - The surface zone extends inwards with long crystals due to lower cooling
- Equi-axed crystals
  - Crystals forming in the liquid du to low temperature and sediments
- Centerline segregation
  - Segregated zone if soft reduction is not set properly
- Half way cracks (HWC)
  - Cracks between the columnar crystals, forms if cooling between zones are too different

Macrostructure - Different Cooling Conditions

Casting method	Cooling Rate	Growth Rate	Columnar Zone	Macro-structure
Continuous casting	very strong	high	long	Figure 37 a
Ingot casting	strong	medium	short	Figure 37 b
Sand mould	weak	slow	absent	Figure 37 c



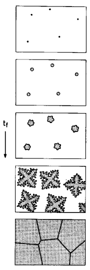
A: Strong cooling. High casting temperature

B: Medium cooling. Medium casting temperature

C: Weak cooling. Low casting temperature.

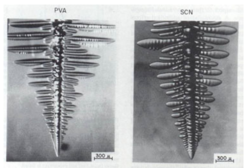
Lect.9-25

Primary Precipitation - Dendrites



Process of dendritic solidification

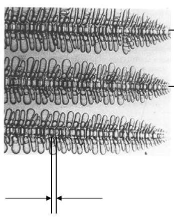
Drawing of a dendrite removed from a metallic melt

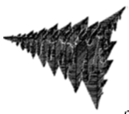


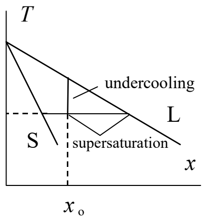
Dendrite morphologies in pivalic acid (PVA) and succinonitrile (SCN)

Lect.9-26

Characterisation of Dendrites - Dendrite Arm Distance and Growth Rate





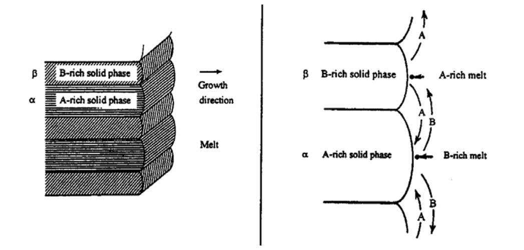


$$v_{growth} \cdot \lambda^2 = \frac{dy_L}{dt} \cdot \lambda^2 = const$$

$$v_{\text{growth}} = \mu \cdot (T_L - T)^n$$

Lect.5-27

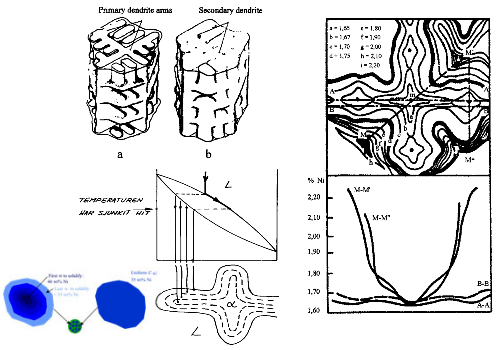
Lamellar Eutectic Growth



$$v_{growth} \cdot \lambda^2 = \frac{dy_L}{dt} \cdot \lambda^2 = const$$

Lect.5-28

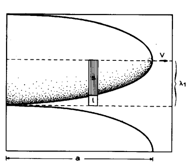
Microsegregation – concentration differences in solid material

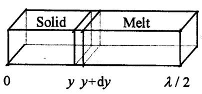


Lect.9-29

Scheil's Model

- <u>f < 0.9</u> and <u>low</u> diffusion rate: *Scheil's model* valid





$$x^L = \frac{x^S}{k} = x^0 \cdot (1 - f)^{-(1-k)}$$

$f =$ fraction solid

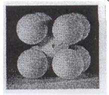
See chapter 7.3.1 Scheil´s Model for Microsegregation

Lect.6-30

Scheil's modified model

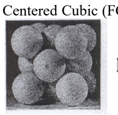
- <u>Low</u> diffusion rates: *Scheil's modified model* valid

Body Centered Cubic (BCC)



$D=10^{-11}$ m/s^2

Face Centered Cubic (FCC)



$D=10^{-13}$ m/s^2

Back diffusion in solid phase

$$x^L = x^0 \cdot \left(1 - \frac{\frac{2y}{\lambda}}{D^s \cdot \frac{4\theta}{\lambda^2} \cdot k + 1}\right)^{-(1-k)}$$

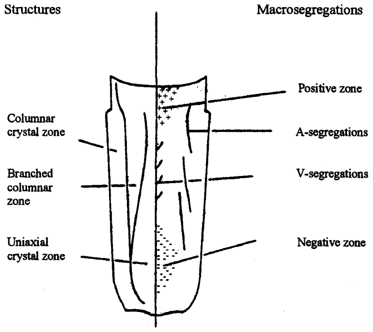
$f = 2y/\lambda$ = fraction solid

$$B = \frac{4D^s\theta k}{\lambda^2}$$

B<<1: Scheil´s model valid i.e. when D^s=low, θ:short, k:small, λ:large
B>>1: The Lever rule valid

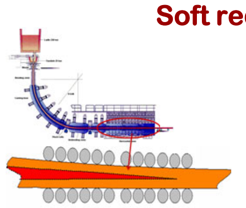
See chapter 7.5.1 Scheil´s Modified Segregation Equation Lect.7-31

Macrosegregations in Ingots

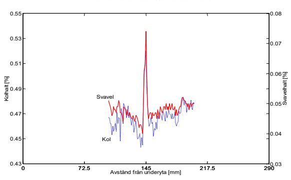


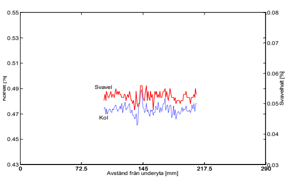
See chapter 11.9 Macrosegregations in Steel Ingots Lect.7-32

Soft reduction

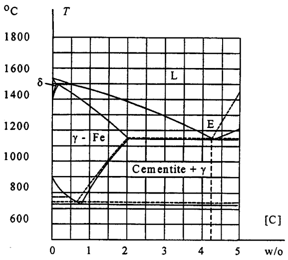


- **Compression of the strand during the final solidification to compensate for the final solidification shrinkage.**
- **Eliminates centerline segregation.**

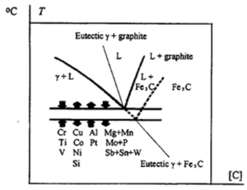




Cast Iron – Fe-Si-C



- Steel < 2% C
- Cast Iron > 2% C (2.5-4.3 %C)



Promotes Grey Iron
- Si
- Ni, Cu, Co
- Slow Cooling Rate
- Inoculation

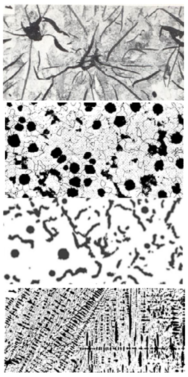
Promotes White Iron
- Cr, V, Ti
- High Cooling Rate

Lect.6-34

Cast Iron

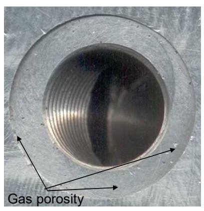
Defenitions
- Grey Cast Iron
  - A Flake Graphite
  - B Nodular Graphite (Ductile Iron)
  - C Compact Graphite (Vermicular Graphite)
  - D Undercooled Graphite (no picture)
- White Cast Iron

- Steel < 2% C
- Cast Iron > 2% C (2.5-4.3 %C)



Lect.9-35

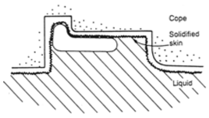
Shrinkage porosity - gas porosity



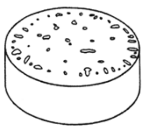
- Pores and porosity (micro / macro), cause surface defects and poor mechanical properties.
- Shrinkage porosity, arises because insufficient feeding of melt to the last solidified areas - Uneven surfaces!
- Gas porosity, gas entrapped during casting or resulting from precipitation of dissolved gas - Smooth surfaces!

Sources for Common Gases in Metals

- Entrapped Air
- From atmosphere
  - Oxygen, Nitrogen
  - Hydrogen from moisture
    $H_20+M=2\underline{H}+MO$ and $2\underline{H}=H_2(g)$
- In Steels and Iron
  - Carbon monoxide, $\underline{C}+O_2=2CO(g)$
- Reaction with mould materials
  - H_2 (moisture in sand), O_2, CO, CO_2,SO_2



Entrapped Air

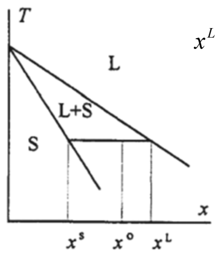


Precipitated gas porosity

Lect.8-37

The Lever Rule: Equilibrium Solidification

- High diffusion rates: ***Lever rule*** valid



$$x^L = \frac{x^S}{k} = \frac{x^0}{1-f(1-k)}$$

$x^0 =$ initial concentration of the alloying element

$f =$ fraction solid

$k =$ partition coefficient (x^S/x^L) of the alloying element

$D^S > 10^{-10}$ m²/sek

See chapter 7.3.2 The Lever rule

Lect.6-38

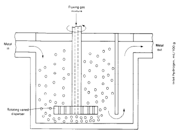
Pore precipitation in solidifying melts

1. $x^L = (\frac{x^S}{k}) = \frac{x^0}{1-f(1-k)}$ **The Lever Rule.**
   - Always valid for gaseous elements
   - f^S in relation to x^L
2. $[G]=const\sqrt{p_{G_2}}$ **Sievert's Law**
   - Valid for two atomic gas molecules
   - x^L in relation to $P_G{}^2$
3. $p_{gas} > p_{atm}$ **Condition for pore precipitation**
   - Simplified, close to the melt surface
   - $P_G{}^2$ in relation to P_{atm}
4. $k = \frac{x^s}{x^L}$ **The partition coefficient**
   - close to 1, low enrichment, << 1 large enrichment to the liquid

Lect.9-39

Methods of lowering the dissolved gas content in metal melts

- Solidification – re-melting
- Stirring
  - Subsonic stirring
- Lowering the partial pressure
  - Vacuum treatment
  - Inert gas bubbling
  - Active gas bubbling
- Desoxidation - precipitation of secondary phases



Rotating Impeller

Common gases

H_2: Hydrogen

N_2: Nitrogen

O_2: Oxygen

CO: Carbon monoxid

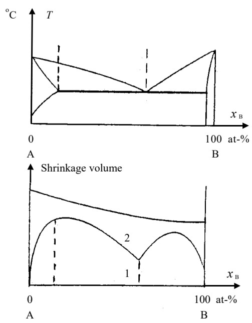
Slag Inclusions (Cinders)

- Slag:
  - Non-Metallic Inclusions in Metals
- Microslags:
  - Not detectable by naked eye (<0.1 mm)
  - Most often formed interdendritic during solidification
  - M+O = MO where M=desoxidation element (Si, Al etc.) Solubility Product $[M][O]=K_{MO}$
- Macroslags:
  - Visible by eye (>0.1 mm)
  - Formed in the melt before solidification
  - Reaction products from desoxidation elements
  - Refractory material from mould walls

oxide skin (Al_2O_3)

Slag Inclusions

Shrinkage Volume



$$\beta = \frac{V_L - V_S}{V_L} = \frac{\rho_S - \rho_L}{\rho_S}$$

Area 1: Shrinkage cavities – micro porosity

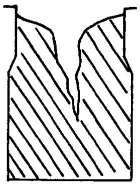
Area 2: Pipe – macro porosity

The shrinkage volume as a function of the composition of the alloy.

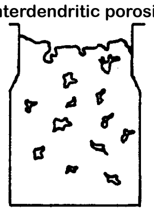
This is really important!

Different types of shrinkage Cavities

Macro Porosity
(Pipe)



Micro Porosity
(Interdendritic porosity)

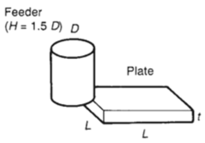


- Strong Cooling (chill mould)
- Small Solidification Interval

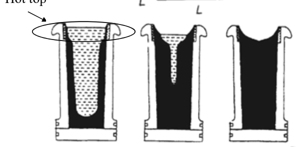
- Weak Cooling (Sand Mould)
- Broad Solidification Interval

Lect.8-43

Feeders and Hot Top



A feeder adds melt to the castings from an outside system.



A hot top is a better isolated part of an ingot and acts as a feeder for the rest of the ingot.

Feeding means to compensate the volume decrease of melt due to solidification shrinkage, with melt from an external system (feeder) such that the macro porosity (pipe) do not end up in the casting.

Three Conditions for Feeders

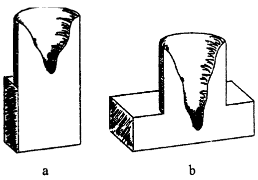
- Solidification Time
  - $t_{feeder} > t_{casting}$
- Volume
  - $V_{feeder\ total} - V_{solidified\ in\ feeder} > \beta\,(V_{feeder} + V_{casting})$

$$(1-\beta)\cdot\frac{V_f}{V_c} = \left(\frac{C_c}{C_f}\right)^{\frac{1}{2}}\cdot\frac{A_f}{A_c} + \beta$$

$$C = \frac{\pi}{4}\cdot\frac{\rho_{metal}^2(-\Delta H)^2}{(T_i - T_o)^2 k_{mould}\,\rho_{mould}\,c_p^{mould}}$$

- Placement of Feeder

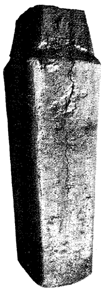
See chapter 10.4.1 Feeder System



The plate and the feeder has the same solidification time but in b, the plate volume is larger

Lect.8-45

Stresses and Cracking!!!



Local stress concentrations cause the ingot to crack

After solidification cooling continues;

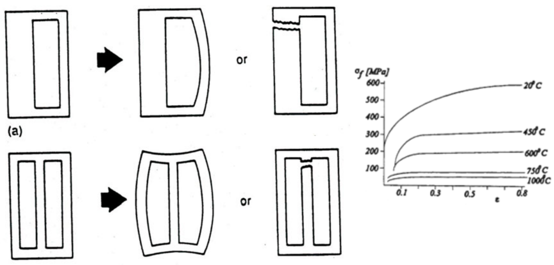
- Plastic deformation
- Tensions/stresses
- Cracking

$$\sigma = E \cdot \varepsilon$$

$$\sigma = -E \alpha \Delta T$$

Lect.8-46

The Shrinkage Harp

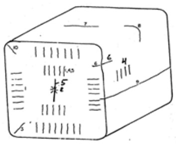


A thicker/more isolated part will take longer time to cool down but at the same time have a lower TS and might then be deformed. At low temperature stresses will occur och cracking

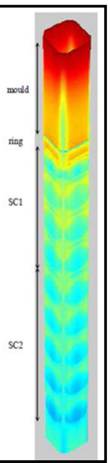
Lect.9-47

Possible defects due to wrong secondary cooling

- Sudden changes in temperature caused by large changes in cooling water will cause internal cracks due to the thermal contraction.

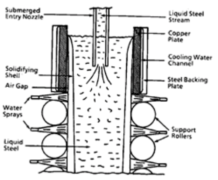


- Surface temperature on the strand surface must be controlled in order to avoid surface cracks during unbending. Steel is brittle in the range of 700-900 degrees and unbending must therfore be performed above this temperature.

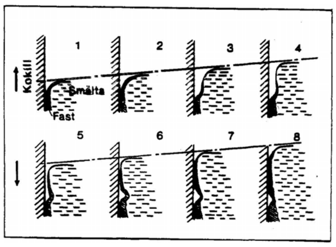


Principle of oscillation mark defects

SEN and Mould



Oscillation marks



Lect.4-49

Production of steel?!? in the film world

2. Casting. Unprotected casting, does it work? Yes, carbonaceous melts evolves CO that protects the melt from the influence of oxygen.

Recommended reading in "Materials Processing during Casting", by Hasse Fredriksson and Ulla Åkerlind

Chapters:

- 1.1 – 1.2
- 2.1 – 2.6
- 3.1 – 3.7
- 4.1 – 4.4
- 5.1 – 5.7
- 6.1 – 6.11
- 7.1 – 7.9
- 9.1 – 9.9
- 10.1 – 10.7

Lect.9-51