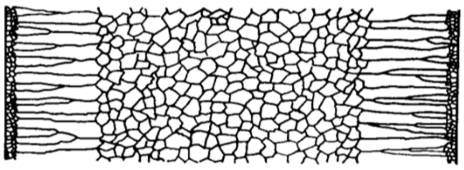
Casting Processing, MH2252, 6hp



Lecture 5-6
Structure and structure formation in cast materials. Micro-segregation and solidification processes in alloys. Macro-segregations

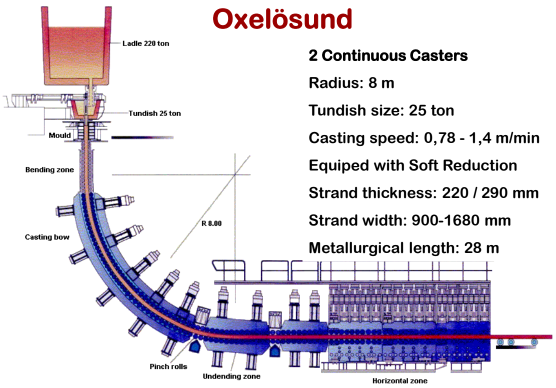
Lect.5-1

Today´s topics

- Repetition
  - The continuous casting process
  - Theory of Heat Transport in Casting -Permanent Moulds – poor contact models
- Structure formation in cast materials
  - Nucleation - Inoculation
  - Primary and Eutectic precipitation
- Microsegregation
  - The Lever rule
  - Scheil's segregation equation
  - Scheil's modified segregation equation
- Macrosegregation
  - A- and V- segregation
  - Positive and Negative segregation

Lect.5-2

The continuous casters in SSAB Oxelösund

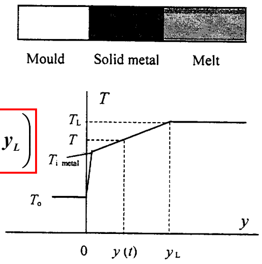


2 Continuous Casters
Radius: 8 m
Tundish size: 25 ton
Casting speed: 0,78 - 1,4 m/min
Equiped with Soft Reduction
Strand thickness: 220 / 290 mm
Strand width: 900-1680 mm
Metallurgical length: 28 m

Lect.5-3

Poor Contact Metal-Mould – Model 2

Note: High Conductivity in Mould, T_0 = const. = RT



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

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

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

Lect.5-4

Nussel's Number <<1 - Model 3

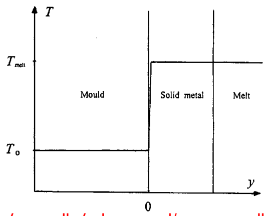
Note: Special case if Nu<<1

- Dimensionless number

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

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

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



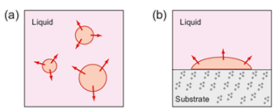
h : small, *k* : large and/or y_L : small *will give:* $T_i \approx T_L$

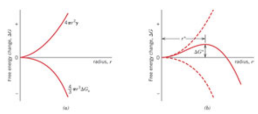
See chapter 4.4.5 Nussel´s Number. Temperature Profile of Mould and Metal at Low Values of Nussel´s Number

Lect.5-5

Structure Formation in Cast Materials - Nucleation

- Homogeneous
  - spontaneous process inside melt
- Heterogeneous
  - foreign particles act as nucleants



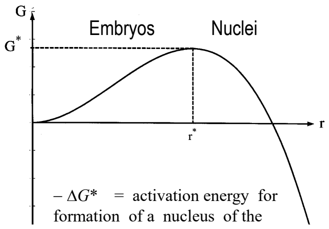


See chapter 6.2-6.4 Structure formation

Lect.5-6

Homogeneous Nucleation

Nucleation barrier



G = Free energy of embryo
G* = Critical free energy
R = Radius of embryo
r* = Critical radius

$$-\Delta G^* = \frac{16\pi}{3}\cdot\frac{\sigma^3 V_m^2}{(-\Delta G_m)^2}$$

$-\Delta G^*$ = activation energy for formation of a nucleus of the critical size r^*

$$-\Delta G_m = \frac{(T_M - T)}{T_M}\cdot\left(-\Delta H_m^{fusion}\right)$$

Note: pure alloys

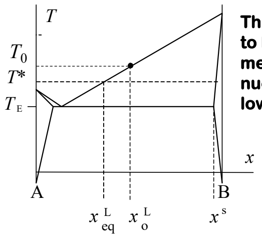
$$60\,kT^* = \frac{16\pi}{3}\cdot\frac{\sigma^3 V_m^2}{\left(\frac{(T_M - T^*)}{T_M}\cdot\left(-\Delta H_m^{fusion}\right)\right)^2}$$

$$-\Delta G^* = 60\,kT^*$$

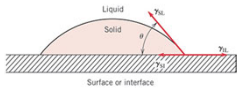
Note: T=T* = The critical temperature

Lect.5-7

Heterogeneous Nucleation - Presence of Small Amounts of Foreign Elements



The critical temperature *T is found to be much higher than that of pure metal melts (homogeneous nucleation) and corresponds to a low undercooling**



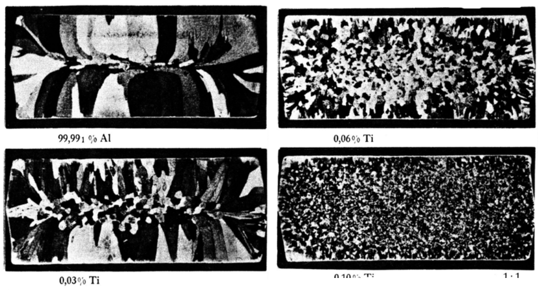
$$-\Delta G_m = RT^*\ln\frac{x_o^L}{x_{eq}^L}$$

The molar free energy of the melt at nucleation (solidification)

$$60\,kT^* = \frac{16\pi}{3}\cdot\frac{\sigma^3 V_m^2}{\left(RT^*\ln\frac{x_o^L}{x_{eq}^L}\right)^2}$$

Lect.5-8

Inoculation - Heterogeneous Nucleation

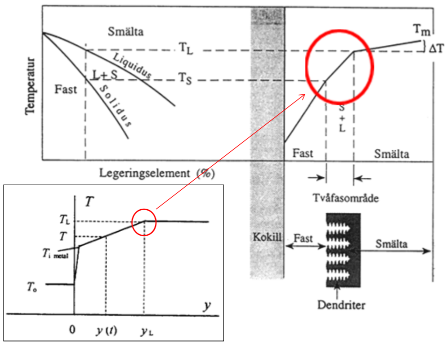


Small amounts of elements are added to the melt and small crystals are precipitated by homogenous nucleation. These crystals constitute the heterogeneities on which new crystals nucleate

Al inoculated with Ti

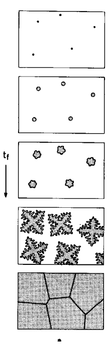
Lect.5-9

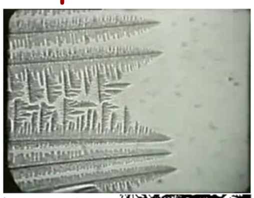
Solidification of alloys
Primary dendritic growth



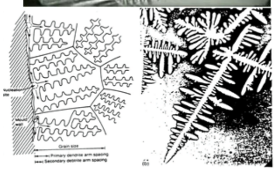
Lect.5-10

Primary Precipitation - Dendrites





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

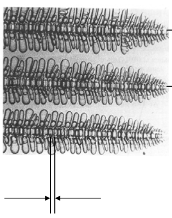


Dendrites – Grain structure

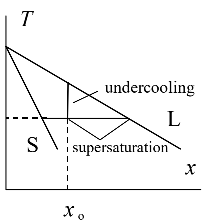
Process of dendritic solidification

Lect.5-11

Characterisation of Dendrites - Dendrite Arm Distance and Growth Rate



Drawing of a dendrite removed from a metallic melt

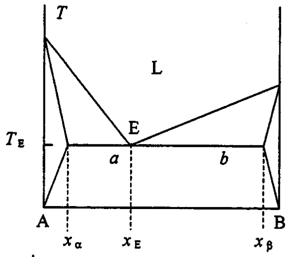


$$v_{growth} \cdot \lambda^2 = \frac{dy_L}{dt} \cdot \lambda^2 = const$$

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

Lect.5-12

Eutectic Solidification



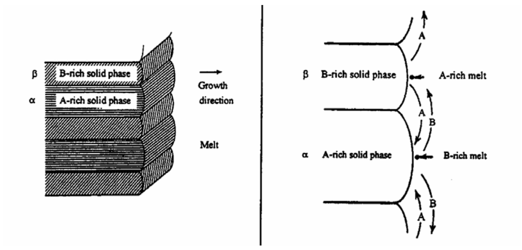
Reaction:

Liquid => $\alpha + \beta$

- Normal
  - growth in co-operation
  - growth rate equal
- Degenerated
  - one phase grows faster than the other

Lect.5-13

Lamellar Eutectic Growth



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

Lect.5-14

Eutectic Structures

Designation	Description
Lamella eutectic structure	The two solid phases are tied in separate planar layers.
Rod eutectic structure	One of the phases is precipitated as rods and is surrounded by the other phase.
Spiral eutectic structure	One of the phases is precipitated as spirals and is surrounded by the other phase.
Flake-like eutectic structure	One of the phases is precipitated as plates, separated from each other and surrounded by the other phase.
Nodular eutectic structure	One of the phases is precipitated as spherical particles and is surrounded by the other phase.

Figure 10 a.
Graphite crystal, which grows radially from a centre, forming a cell.

Figure 10 b.
Eutectic macrostructure of a large number of cells of the type shown in figure 10 a.

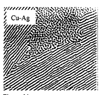


Figure 11 a.
Lamella and rod eutectic structure. Cu-Ag.

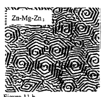
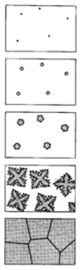


Figure 11 b.
Spiral eutectic structure. Zn-Mg-Zn_2.

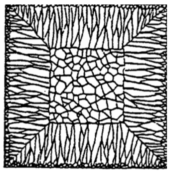
Figure 11 c.
Disk-shaped Si plates in a matrix of Al.

Lect.5-15

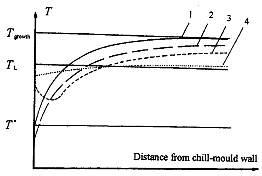
Macrostructure in cast materials



Still dendritic growth



Cross-section of a casting

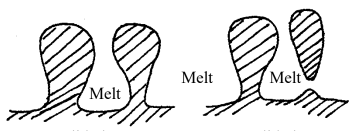


Temperature profiles close to mould wall at different times

See chapter 6.7 Macrostructure in cast materials

Lect.5-16

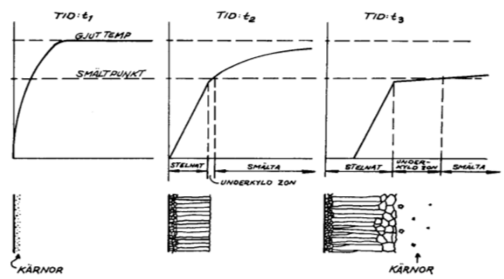
Crystal Multiplication - Heterogeneous Nucleation



1. Fragments are torn off in a purely mechanical way from the growing dendrite tips
2. Melting off dendrite arms

Lect.5-17

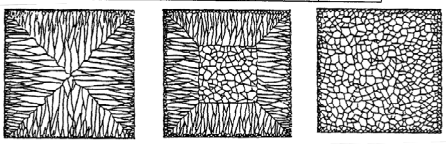
Formation of the different Crystal Zones



Lect.5-18

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

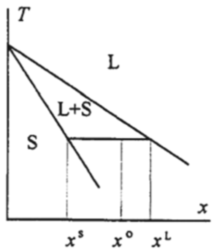
B: Medium cooling. Medium casting temperature

C: Weak cooling. Low casting temperature.

Lect.5-19

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

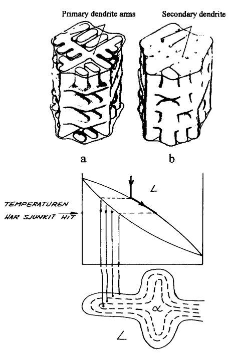
$k =$ partition coefficient (x^S/x^L) of the alloying element

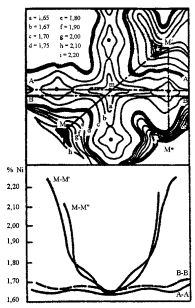
$D^S > 10^{-10}$ m²/sek

See chapter 7.3.2 The Lever rule

Lect.6-20

Microsegregation – concentration differences in solid material

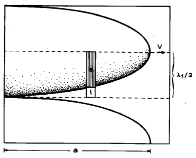


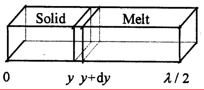


Lect.6-21

Scheil's Model

- f < 0.9 and low diffusion rate: *Scheil's model* valid
- There is an even composition in the melt at every moment
- The diffusion in the solid phase is neglectable
- There exists local equilibrium between solid and liquid phase can be described by the partition constant





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

$k = \frac{x^s}{x^L}$ the partition constant

$f = f_s$ = fraction solid

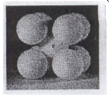
See chapter 7.3.1 Scheil´s Model for Microsegregation

Lect.6-22

Scheil's modified model

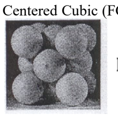
- Low diffusion rates: *Scheil's modified model* valid

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

θ = local solidification time

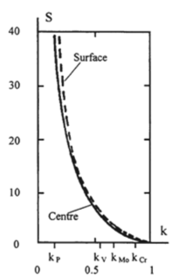
$$B = \frac{4D^s \theta k}{\lambda^2}$$

B<<1: Scheil´s model valid, B>>1: The Lever rule valid

See chapter 7.5.1 Scheil´s Modified Segregation Equation

Lect.6-23

Degree of Microsegregation



$$S = \frac{x^S_{max}}{x^S_{min}} = \frac{kx^L_{max}}{kx^L_{min}} = \frac{x^L_{max}}{x^L_{min}} = \left(\frac{B}{B+1}\right)^{-(1-k)}$$

$S =$ degree of segregation

$B =$ $4D^S\theta k/\lambda^2$

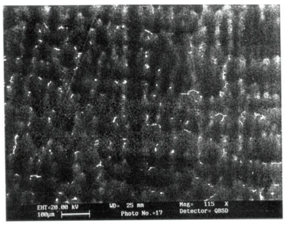
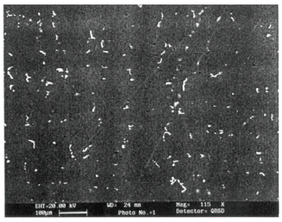
$k =$ partition coefficient (x^S/x^L) of the alloying element

S>1, i.e. high degree of microsegregation, when B<<1, i.e. D^s = low, θ: short, k: small, λ: large

Note: λ^2 and θ are in a relation to each other

Lect.6-24

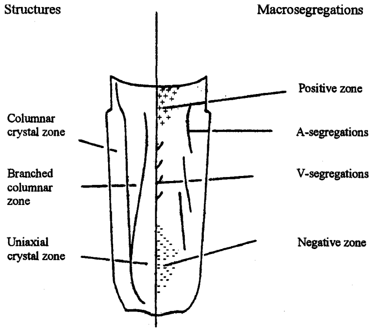
Microsegregation in IN624

As cast Heat treated

Lect.6-25

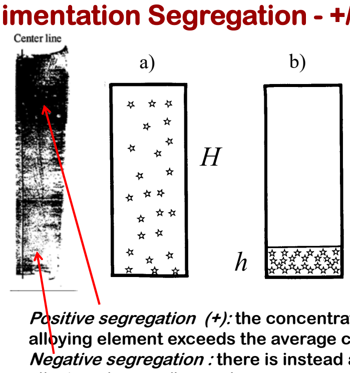
Macrosegregations in Ingots



See chapter 11.9 Macrosegregations in Steel Ingots

Lect.6-26

Sedimentation Segregation - +/- Segregation

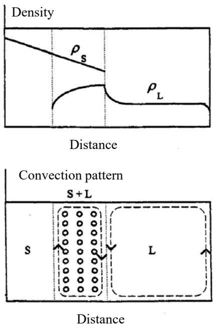


a) Equiaxed crystals in the melt before sedimentation.
b) Equiaxed crystals, including their associated melt, after sedimentation

Positive segregation (+): the concentration of the alloying element exceeds the average concentration.
Negative segregation : there is instead a lack of the alloying element (lower than average concentration)

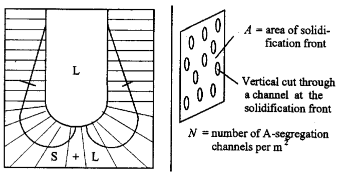
Lect.6-27

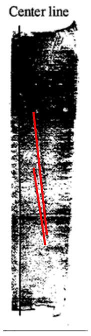
A-segregations – Ghost lines!



- The density of the melt increases linearly with decreasing temperature.
- The density of the melt within the two-phase region **decreases** due to **microsegregation of lighter alloy elements**.
- Natural convection in the melt and an **opposite convection pattern** in the two-phase region.
- Higher concentration of alloy elements will lower the liquidus temperature and cause **re-melting of solid structure**.
- Ghost-lines!

A-segregations - Freckles



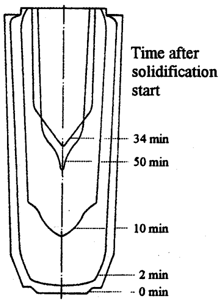


Channels (ghost lines/freckles) in castings are caused by natural convection due to concentration gradients in the two-phase region during the solidification process of an ingot.
The channels are created in the partly solidified two-phase region S+L.

Macrosegregation in IN624

V-segregation

- Vacuum, caused by the solidification shrinkage in the lower parts of the ingot.
- Cannot be filled by melt from above because the distance is long and the resistance from the dendrite arms is great.
- The pressure difference, which arises between the different parts of the ingot results in a general settling of the crystals in the middle zone.



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

Chapter:

- 6.1 – 6.11
- 7.1 – 7.9
- 11.1– 11.9