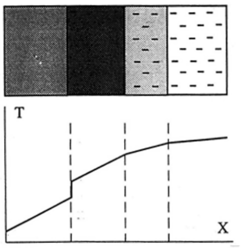
Casting Processing, MH2252, 6hp



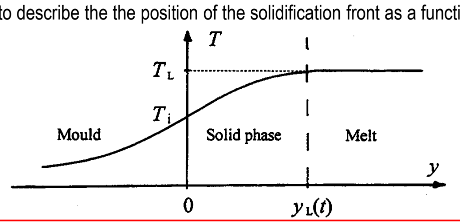
Lecture 4c
Heat Transport during Casting and Solidification

Today´s topics

- **Repetition**
  - Ideal Contact Model
  - Sand Mould Casting model
- **Continuous Casting**
  - The continuous casting process
- **Theory of Heat Transport in Casting**
  - Permanent Moulds
  - Continuous Casting

Ideal Contact Metal-Mould – Model 0

Find λ by iteration (guess a value) that satisfies the below equations, insert in $y_L(t)$ to describe the the position of the solidification front as a function of time



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

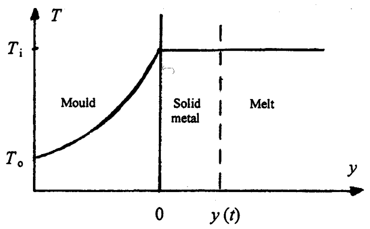
$$y_L(t) = \lambda\cdot\sqrt{4\alpha_{metal}t}$$

$$\frac{dy_L(t)}{dt} = \lambda\cdot\sqrt{\frac{\alpha_{metal}}{t}}$$

$$\alpha = \frac{k}{\rho c_p}$$

Sand Mould Casting – Model 1

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



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

$$y_L(t) = \int_0^t \frac{T_i - T_o}{\rho_{metal}(-\Delta H)} \cdot \sqrt{\frac{k_{mould}\,\rho_{mould}\,c_p^{mould}}{\pi}} \cdot \frac{dt}{\sqrt{t}}$$

The growth rate dy_L/dt *or solidification rate by the Sand Mould Model*

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Sand Mould Casting - Chvorinov's first assumtion

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

Sphere: $y_L = r/3$

Cube: $y_L = a/6$

Plate: $y_L = h/2$

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

- y_L = The solidification distance
- V_{metal} = Total volume of the casting (mould cavity)
- A = Total area of the interface between the mould and the metal (cooling interface)
- t_{total} = The solidification time of the casting

Lect.4-5

Sand Mould Casting - Chvorinov's Rule

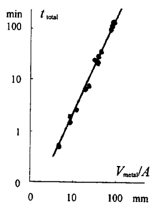
- Chvorinov's Rule
  - Every unit area of the mould absorb equal amount of heat
  - Experimentally verified

$$t_{total} = C\left(\frac{V_{metal}}{A}\right)^2$$

V=mould volume, *A*=cooling mould area

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

Only material properties of the melt and the mould!



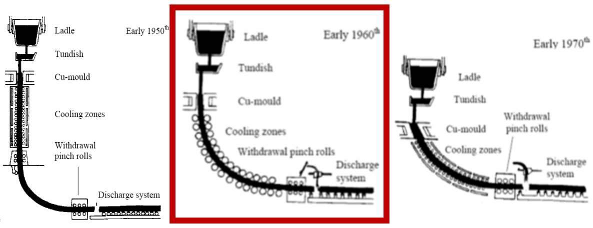
Note: Linear relation due to logarithmic diagram

Lect.4-6

Continuous Casting (repetition)

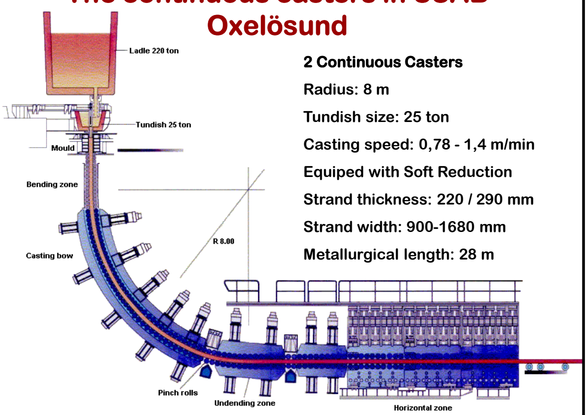
- Molten steel is solidified into a "semi-finished" shape. Slab, billet, bloom, or other shapes such as rounds, beam blanks etc.
- Compared to ingot casting the continuous casting has a **higher yield**, **better quality**, and is beneficial for **productivity** and **cost efficiency**.
- It is the most important method for production of iron base alloys in the world.
- A majority of the steel produced in the world is continuously cast, > 95%.

History of caster designs



- Today, most casters are built with a straight mould, and subsequent bending, normally reffered to as ”vertical-bending-machines”.

The continuous casters in SSAB Oxelösund



2 Continuous Casters

Radius: 8 m

Tundish size: 25 ton

Casting speed: 0,78 - 1,4 m/min

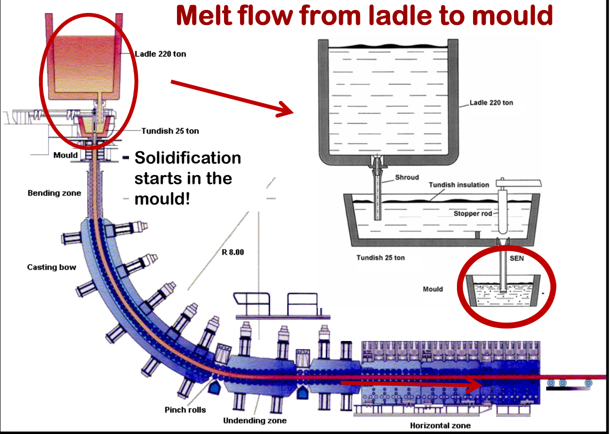
Equiped with Soft Reduction

Strand thickness: 220 / 290 mm

Strand width: 900-1680 mm

Metallurgical length: 28 m

Melt flow from ladle to mould

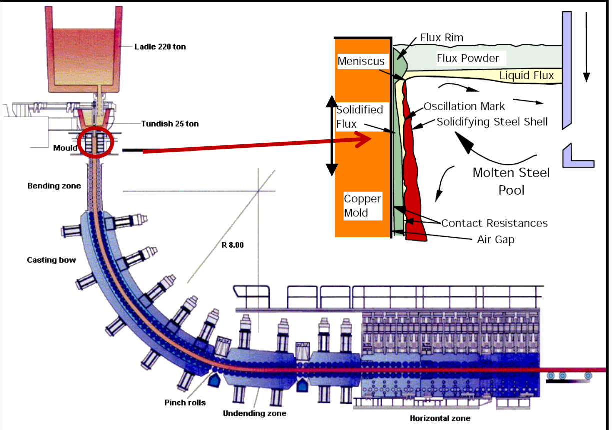


The continuous casting process

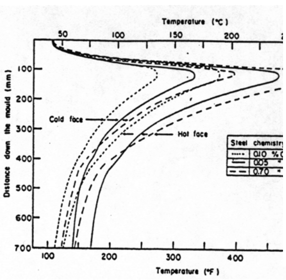
- Steel from the ladle is **bottom-poured** into a tundish
- The **tundish** regulates the steel flow to the water cooled mould where the actual solidification process starts.
- The steel is withdrawn from the mould as it **solidifies**. At mould exit the steel shell has to be strong enough to keep its dimensions.
- Below the mould the strand is contained by **rolls**.
- **Water spraying** on the steel surface between the rolls controls temperatures and further solidification. Known as secondary cooling.
- The steel strand is **bent** into a radius and later straightend during solidification in the secondary cooling zone.
- At the cutter the strand is **cut** into suitable length for further processing

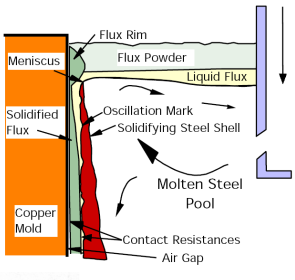
The mould

- It is in the mould the solidification starts!
- The shell that forms in the mould is the surface of the final product.
- The mould consist of water cooled copper plates in order to obtain a strong solid shell. Water temperature are normally in the range of 50-100 degrees C.
- Before the steel shell leaves the mould it has to be thick enough to withstand the ferrostatic pressure to contain the molten steel in the strand.
- To compensate for the shrinkage of the shell the mould is tapered.



Heat transfer in mould





What controls heat transfer in the mould?

- Fluid flow
- Casting speed
- Casting powder
- Oscillation
- Mould set-up

=> must be combined to get a solidified shell that is strong enough at mould exit.

Casting powder

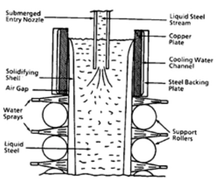
- Casting powder has several purposes:
  - Protection of the upper surface
  - Lubrication between mould and copper plates
  - Control the heat transfer from the steel
- Depending on steel grade and its crack sensitiveness, the powder is chosen to get a suitable cooling rate.

Mould oscillation

- Mould oscillation is vital for the continuous casting:
  - the mould will move with different speed than the shell preventing sticking between shell and copper plates.
  - helps feed molten casting powder into the gap between the shell and mould
- Due to the oscillation of the mould there will be oscillation marks on the steel surface

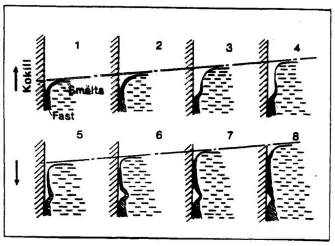
Principle of oscillation mark defects

SEN and Mould



SEN = Submerged Entry Nozzle

Oscillation marks

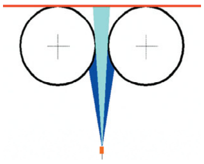


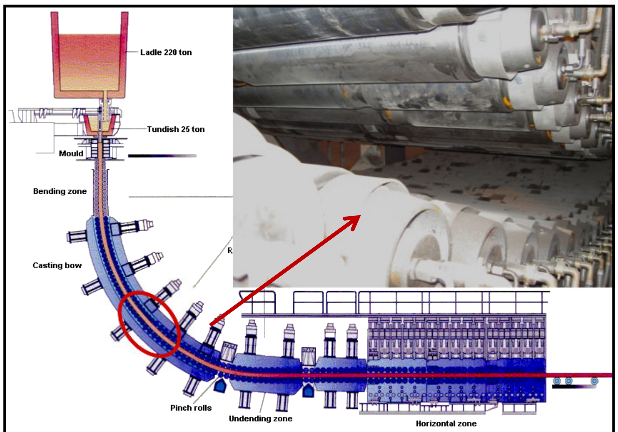
1-4: The mould are going up, streching the solid shell

5-8: The mould are going down, deforming the solid shell

Secondary cooling

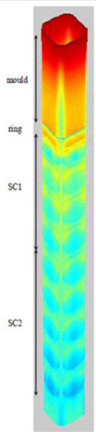
- Below the mould the steel shell is sprayed with water between the rolls.
- Cooling is dependent on amount of water.
- Water is also sprayed on the caster to keep it ”cool”.





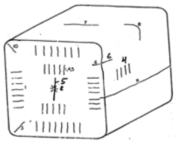
Why secondary cooling?

- The cooling must be designed so that solidification is complete at the end of the caster.
- Maintain a good surface temperature in order to avoid cracks in the solidified steel.
- The secondary cooling is divided into several different zones
  - Heat transfer is controlled depending on shell thickness
  - Decreasing cooling with distance from mould

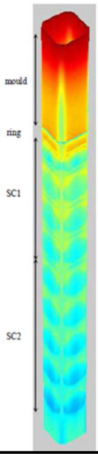


Possible defects due to wrong secondary cooling

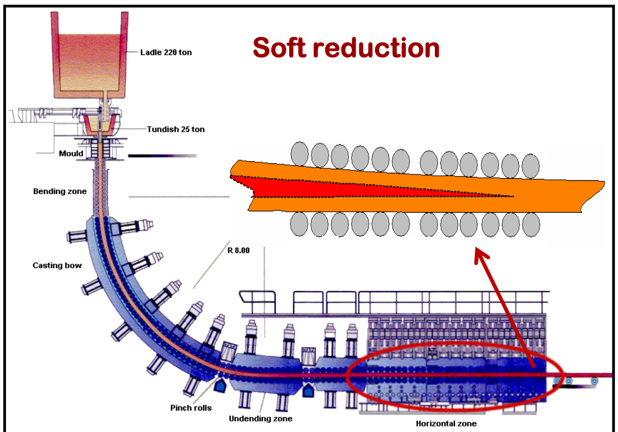
- Sudden changes in temperature caused by large changes in cooling water will cause internal cracks due to the thermal contraction.



- 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.

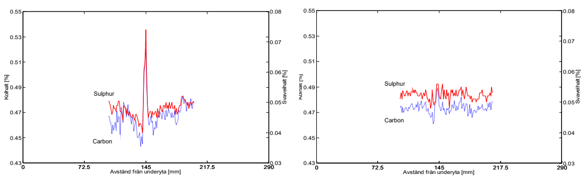


Soft reduction

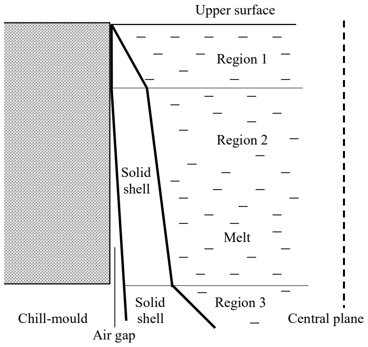


Soft reduction

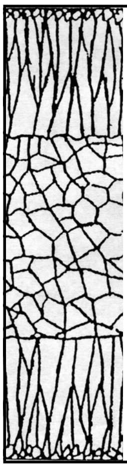
- Compression of the strand during the final solidification to compensate for the final solidification shrinkage.
- Eliminates centerline segregation.



Solidification Process in the Chill-Mould



Lect.4-25

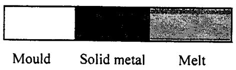


The solidified structure

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 sedimentation
- 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

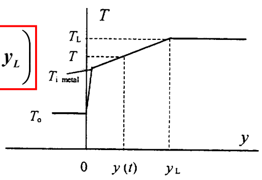
Poor Contact Metal-Mould – Model 2

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.4-27

Nussel's Number <<1 - Model 3

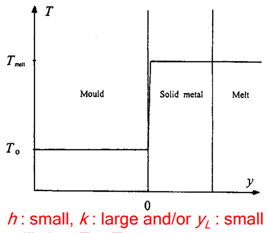
Note: Special case if Nu<<1

- Dimensionless number

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

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

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



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.4-28

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

Chapter:
- ❑ 4.1 – 4.4
- ❑ 5.1 – 5.7

Lect.4-29