Evolution of Inclusion Characteristics in Calcium treated Ultra High Strength Steels

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Steelmaking process

- Aluminum-killed, calcium treated steel
- Oxygen blowing for decarburization
  - Dissolved oxygen increases
- Aluminum deoxidation
  - Aluminum oxides form
  - Dissolved oxygen decreases to 3–5 ppm
- Ladle treatments
  - Inclusions float into slag
  - Spinel (MgO·Al₂O₃) forms
- Calcium treatment
  - Liquid calcium aluminates (+CaS)
- Continuous casting
  - Temperature decreases
  - Solubilities decrease
  - Steel solidifies
  - CaS, MnS, and TiN are formed

SSAB Raahe steel melt shop
Inclusions

- Non-metallic compounds in steel
- Typically oxides, sulfides, and nitrides
  - Composite
- Analysis methods
  - Scanning electron microscopy (SEM) with EDS analyzer
  - Optical microscopy
  - Electrolytic extraction + SEM
  - OES-PDA
  - ...
- Accuracy – Resources – Duration – Price

Elemental map of a calcium aluminate – calcium sulfide inclusion (SEM + EDS)
Composition of oxides

- \(\text{Al}_2\text{O}_3\)-\(\text{CaO}\)-system
- Solid inclusions may clog the nozzle during continuous casting
- Calcium treatment
- Converts solid aluminum oxides into liquid calcium aluminates
Composition of oxides

- **Al$_2$O$_3$–CaO–MgO-system**
- Presence of MgO widens the liquid window (1550°C)
- **Calcium treatment**
- Converts solid aluminum oxides into liquid calcium aluminates
Composition of inclusions

- Component fractions are calculated based on the elemental analysis of inclusions
  - $\text{Al}_2\text{O}_3$, CaO, MgO, CaS, MnS, TiN
- Compatibility triangles 1–7
- Oxide phase fractions calculated according to the lever rule
- Typically compound inclusions

![Diagram of oxide phase fractions](image-url)
Evolution of inclusions during continuous casting

Composition change of oxide (+CaS) inclusions in the continuous casting mould and hot-rolled product

- CaS
- Ca-aluminate
- CaS + Ca-aluminate
- CaS + Al₂O₃
- Back-modification
Evolution of inclusions

- Risk of back-modification reduces with decreasing sulfur content in steel
- Reaction
  \[(Al_2O_3) + 3(CaS) = 3(CaO) + 2[Al] + 3[S]\]
- Equilibrium constant
  \[K = a_{[Al]}^2a_{[S]}^3\]
Elongation of inclusions

- Oxide(+CaS) inclusions in hot rolled products
- Aspect ratio: Length/Breadth
- Elongation tendency in compatibility triangles
Oxide–sulfide stringers

- Inclusions are elongated and fragmented into stringers during hot rolling

Schematic view of stringer formation

Stringer detected in a steel sample
Oxide–sulfide stringers

- MATLAB script developed to locate and identify stringers
- Input: Excel spreadsheets imported from Oxford Inca Feature software (SEM inclusion data)
- **Adjustable parameters**
  - Distance between inclusions
  - Composition
  - Orientation
  - Etc…
- **Output:**
  - Total length
  - Thickness location on product
  - Phase fractions
  - Oxide composition
  - Estimated original inclusion size & composition
Oxide–sulfide stringers

Example output of a detected stringer, showing oxide compositions, phase fractions and a geometrical visualization of the stringer.
Oxide-sulfide stringers

- Overmodification with calcium makes inclusions more prone to elongate and to form stringers
- Inclusions in stringers highlighted
Summary

- Data handling is needed in order to find out actual phases in inclusions
- In aluminum-killed, calcium treated steels, inclusions are typically compounds comprising $\text{Al}_2\text{O}_3$, CaO, MgO, CaS, MnS, and TiN components
- Sulfur contents lower than 10 ppm are recommended to avoid back-modification of calcium aluminates into $\text{Al}_2\text{O}_3$ (or $\text{MgO. Al}_2\text{O}_3$) during continuous casting
- Excess calcium treatment makes inclusions prone to elongate and to form stringers