Modelling techniques for (semi-) continuous casting processes

Outils numériques appliqués aux procédés de coulée continue

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<table>
<thead>
<tr>
<th>Time Period</th>
<th>Project/Program Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996-2000</td>
<td>EU project EMPACT (European Modeling Program on Aluminium Casting Technology)</td>
</tr>
<tr>
<td>2000-2004</td>
<td>EU project VIRACT (Virtual Cast House)</td>
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<tr>
<td>2003-2006</td>
<td>project POST (Porosity and Stress)</td>
</tr>
<tr>
<td>2005-2006</td>
<td>Project Alcan Fund (Alufond)</td>
</tr>
</tbody>
</table>
1. General Overview of Continuous Casting

Sump depth as a function of ingot format and alloy properties:

\[ V = 1 \text{ mm/sec} \]
\[ 2w = 0.5 \text{ m} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>( k ) (W/mK)</th>
<th>density (-)</th>
<th>Sump depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>350</td>
<td>9000</td>
<td>0.62</td>
</tr>
<tr>
<td>Aluminium</td>
<td>200</td>
<td>2700</td>
<td>0.93</td>
</tr>
<tr>
<td>Steel</td>
<td>31</td>
<td>7850</td>
<td>10.13</td>
</tr>
</tbody>
</table>
1. Overview of the Al. semi-continuous casting process

- Convection
- Macrosegregation
- Exudation
- Grain movement
- Lateral faces pull-in
- Hot cracking
- Microporosity
- Butt curl
- Butt swell

Solid

S+L

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1. Overview of Copper Continuous Casting

- Copper: horizontal or vertical casting
- Coarse columnar microstructure
- Almost all macro and micro aspects similar to Al. but with different scales owing to different physical properties
1. General Overview of Steel Continuous Casting

- Computational Fluid Dynamics (CFD)
- Casting simulation
- Finite Element Structural Analysis

**Diagram:**
- Ladle
- Tundish
- Slag detection
- Stream shrouding
- Submerged Entry Nozzle
- Mould
- Secondary cooling
- Support Rollers
- Strand Straightening
- Withdrawal Unit
- Flame cut-off
2. Solidification Calculations: Evolution over 25 years

3 largest solidification simulations (number of nodes) reported in each volume of the MCWASP conference... follow Moore’s law (double every 16 months)!

2. Solidification Calculations

- Whatever the power of the computers, scientists and engineers are always going to use them at the “limit”.

- From simple thermal 2D computations done in 1980, we see nowadays complex multi-scale, multi-component alloys, multi-phenomena simulations.

- Although simulations are still limited by the computers performances, who could imagine of not using them?

- Simulation is saving money not only through direct cost but through a LEARNING process where concomitant phenomena can be separated.

- Validation and determination of model input parameters are really an important step to get confidence in the results and to prospect new directions

- When defining a strategy of simulation, Moore’s law should be accounted for (eg. molecular dynamic computations).
3. State-of-the-art and challenges at the macro scale

- Heat flow simulations do not pose any challenge, except maybe boundary conditions.

- Fluid flow and thermo-mechanical simulations are more delicate but can rely on advanced commercial software.

- There is no direct coupling between fluid flow in the liquid and stresses in the solid. But fluid flow changes the shape of the isotherms, and thus modifies thermal stress development.

  Combined heat-fluid-stresses calculations require mixed Lagrangian-Eulerian representations. Achieved only in few codes.

- Macrosegregation calculations are still very difficult: due to the various origins (convection, shrinkage, stresses, grain sedimentation) often very localised (e.g., in regions where \( v_l \cdot \nabla c \neq 0 \)).
Heat flux as a function of the distance to the top liquid level for an AA5182 alloy, as determined by inverse modeling.

A non uniform contraction of the whole ingot leads to distortions.

Thermo-Mechanical Aspects

Shrinkage between mould and ingot.

W. Schneider et al, in Continuous Casting Conf., Neu-Ulm, Ed. Mueller, 2005
Thermo-Mechanical Aspects

Ingot rolling faces pull-in

J.-M. Drezet, PhD thesis no. 1509, EPF-Lausanne, 1996
Thermo-Mechanical Aspects

Optimized mould shape

W. Schneider et al, in Continuous Casting Conf., Neu-Ulm, Ed. Mueller, 2005
Thermo-Mechanical Aspects

Measured and simulated contraction along the rolling faces of a 2200 × 600 mm² AA1050 slab cast at 60 mm/min.

Thermo-Mechanical Aspects

Thermal and deformation field within the mould (external view of ingot butt)

Deformation during the start-up phase including fluid flow, as calculated with Alsim/Alspen for an AA5182 alloy using a mixed Lagrangian-Eulerian approach.

Thermo-Mechanical Aspects

Measured and computed butt curl and curling speed (Abaqus).

Thermo-Mechanical Aspects: solid behaviour

Modified Ludwik’s law for as-cast behaviour: Gleeble tests

\[
\bar{\sigma} = K(T) \left( \varepsilon_p + \varepsilon_p^0 \right)^{n(T)} \left( \frac{\dot{\varepsilon}_p}{\dot{\varepsilon}_p^0} \right)^{m(T)}
\]

- \( K(T) \) alloy consistency (MPa)
- \( n(T) \) strain hardening coefficient
- \( m(T) \) strain rate sensitivity (-)
Fluid Flow

Velocities and temperatures at the surface and in the vertical symmetry-plane of an AA1050 DC cast billet as calculated with Fidap.

Thermo-Mechanical Aspects: cold and hot cracking

- Solidification cracking (hot tearing) during casting
- Cold cracking during ingot storage

Productivity and safety issues
Thermo-Mechanical Aspects: behaviour of the mush

Von Mises stress vs strain curves for an Al-2 wt pct Cu alloy, tested in simple compression in the fully solid state and in shear condition in the mushy state

Thermo-Mechanical Aspects: behaviour of the mush

\[ \dot{\varepsilon}_s^p = \frac{\dot{\varepsilon}_0}{(C_{S_0})^n} \left\{ -\frac{A_2}{3} \bar{P}_s + \frac{3}{2} A_3 S_s \right\} \left\{ A_2 \bar{P}_s^2 + A_3 \bar{\sigma}_s^2 \right\}^{n-1/2} \]

Compressible constitutive model with internal variables (cohesion).

Drained compression tests

Thermo-Mechanical Aspects: residual stresses

Ingot sawing operation are delicate for high strength alloys.

Saw pinching and ingot cracking are predicted using strain energy release and FE modeling.

Cracking might occur if lip tends to open and rate of energy release is higher than a critical value which depends on the fracture toughness of the alloy.

Thermo-Mechanical Aspects: residual stresses

Cold cracking after casting during storage ....

J-type crack (courtesy Alcan CRV)

Interaction of residual stresses with a given population of stress risers i.e. defects such as oxydes, particles, inclusions, microcraks, pores, ... (fracture mechanics)
Mixed Lagrangian-Eulerian description

Fixed mesh: Eulerian description

Moving mesh owing to deformation and/or transport of solid: Lagrangian description

Fluid flow and stress development

feeding velocity

casting velocity $v_c$
**Coupled fluid flow and solid deformation**

Automatic generation of the accordion domain. The thickness of the elements is set here to a small value to make the elements visible. One layer of elements of the accordion domain is already stretched (ProCAST).
Coupled fluid flow and solid deformation

Fluid flow and stress are computed simultaneously (ProCAST distributed by ESI, www.calcom.ch).
Macrosegregation

AA5182 alloy with 4.05 wt% Mg

4. State-of-the-art and challenges at the micro-scale

- Modelling of grain structure formation (i.e., nucleation/fragmentation, growth and transport) in Al and Cu casting is still a challenge.

- Modelling of microstructure formation can be coupled with phase diagram calculations. It is restricted to a small region (typically mm²) in 2D (Phase field, Pseudo front tracking, …). Remaining challenges: CPU time, nucleation of phases, kinetics of eutectics.

- Microporosity modelling, including pipe shrinkage and macroporosity, can now be predicted in 3D. Model being extended to multicomponent alloys and more than one gas. Challenge of the curvature contribution, … but hard to measure so hard to validate …….

- Hot tearing has made substantial progress over the past five years, thanks to the VIRCAST project. Two-phase approaches (i.e., deformation of the solid mush and liquid feeding) now exist, as well as an approach to coalescence for the prediction of bridging of the primary phase.
4. State-of-the-art and challenges at the micro-scale

In situ observation of columnar and equiaxed grain structure formation (X-Ray imaging at ERSF in Grenoble)

**FIG. 1.** Columnar dendritic growth of Sn crystals in an Sn–10 wt% Pb alloy. \( \partial T/\partial z \sim 19 \text{ K/mm} \), \( v_{\text{ave}} = 9.6 \text{ mm/s} \).

**FIG. 3.** Equiaxed dendritic growth of Pb crystals in an Sn–52 wt% Pb alloy. \( \partial T/\partial z \sim 29.5 \text{ K/mm} \), \( v_{\text{ave}} = 9.6 \mu \text{m/s} \).

As-cast Grain Structures

Calculation of nucleation, growth and transport of equiaxed grains using a granular approach.

H. Combeau et al, INPL-Nancy

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As-cast Grain Structures

Grain size distribution in a quarter section at the outlet of a DC casting

Cu as-cast grain structures: electromagnetic stirring

Influence of the position of the induction coil on the convection in the liquid as calculated for the BZ4 alloy (Cu-4wt%Zn-4wt%Sn-4wt%Pb)

Cu as-cast grain structures: electromagnetic stirring

Schematics of remelting (1) and fragmentation (2) of secondary dendrite arms to give birth to new nuclei (promotion of the CET).

Cu as-cast grain structures: electromagnetic stirring

Schematics of local fluid flow in the liquid, $u_l$, and in between the dendrites, $u_l^d$. Criterion for remelting.

$$C_R = \frac{u_{l,z}^d}{V_T} > 1$$
Cu as-cast grain structures: electromagnetic stirring

Optical micrographs of longitudinal cross-sections of the solidified C97 and BZ4 alloys without EMS ($P = 0\%$ at $V_c = 4$ mm/min) and with EMS ($P = 10$ and $30\%$ at $V_c = 4$ mm/min) for two inductor-liquidus distance, 23 and 13 mm.

As-cast Microstructures: Phase field methods

Calculated Mg concentration field at 27 mm from the rolling face.

Microstructure at 27 mm from the rolling face.

Microporosity

Two-phase approach to hot tearing, using the rheology of a compressible porous solid and a Darcy-type equation for liquid feeding.

*M. M’Hamdi et al, in Light Metals (TMS Publ., Warrendale, USA, 2004)*
Hot tearing

<table>
<thead>
<tr>
<th>Trial</th>
<th>Crack length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>entire ingot</td>
</tr>
<tr>
<td>2</td>
<td>58</td>
</tr>
<tr>
<td>3</td>
<td>214</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
</tr>
</tbody>
</table>

Hot tearing: coalescence and percolation

Evolution of a population of equiaxed grains from a continuous liquid film network to a fully coherent solid


Al - 1%Cu

600 °C

550 °C

500 °C

Red: wet grain boundaries

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Hot tearing: morphology of the liquid phase

In situ 3D investigation of solidification (Al -4%Cu)
Evolution of liquid morphology

ESRF-Grenoble

635°C (59%)  604°C (85%)  582°C (92%)  560°C (95%)

Conclusion

- **Macroscopic models** of solidification are fairly mature for Al. and steel casting (slightly less for Cu casting).

- **Macrosegregation** calculations are still a challenge for two reasons: difficulty to maintain the mass balance, various origins (shrinkage, convection, sedimentation, deformation).

- **Grain structure** modelling still a topic of active research.

- **Microstructure** modelling coupled with phase diagrams can be done for a small 2D domain.

- **Defect predictions** have really moved forward over the past 4-5 years.
  - **Porosity**: the challenge is to validate the model predictions by accurate comparison.
  - **Hot tearing**: the challenge is to combine coalescence, mechanical deformation and liquid feeding.