Pilot scale simulator based on liquid metal to study flow related issues on continuous casting

Pavel E. Ramirez Lopez
SWERIM AB
pavel.ramirez.lopez@swerim.se
Flow pattern in the mould

Definitions

The molten metal flow pattern inside the mould is one of the main factors controlling the casting process. This pattern is produced by the molten steel exiting the nozzle ports, which creates a variety of flow structures within the mould such as discharging jets, standing waves, rolls and biased flows.
# Flow instabilities = cracking & defects

## Defects in CC

<table>
<thead>
<tr>
<th>DEFECT</th>
<th>CAUSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longitudinal cracking and longitudinal corner cracking</td>
<td>4% difference in thermal shrinkage coefficient between $\gamma$ and $\delta$-ferrite causes stresses in the shell, which can only be relieved by cracking. Particularly severe in MC grades. Nozzle misalignment, biased flows and immersion depth changes.</td>
</tr>
<tr>
<td>Star cracking</td>
<td>Irregular heat transfer at bottom of mould due to breaking of slag film</td>
</tr>
<tr>
<td>Deep Oscillation Marks</td>
<td>decreases with increasing , stroke, slag rim thickness, superheat and frequency.</td>
</tr>
<tr>
<td>Transverse and corner cracks</td>
<td>Associated with large’s. Particular problem in ULC. where small $\gamma$ to $\delta$-Ferrite shrinkage causes: Excessive taper and low powder consumption. Sometimes related to deep Oscillation Marks</td>
</tr>
<tr>
<td>Sticker breakouts</td>
<td>Lack of lubrication. Formation of low-melting shell through C contamination, which does not heal in (particularly HC grades). Often involves blockage of liquid slag channel. Strong level fluctuations</td>
</tr>
<tr>
<td>Slag entrapment</td>
<td>High turbulence and high interfacial velocities between slag and steel</td>
</tr>
<tr>
<td>Gas entrapment, “pinholes”, “pencil pipe”</td>
<td>Gas bubbles trapped in meniscus. Prevalent wide slabs of LC and ULC steel. Metal flow takes bubbles too far (bubbles entrapped in the shell). Inclusion attaches to bubble (not welded shut). Foam near flux attaches to the SEN “sliver”</td>
</tr>
<tr>
<td>“silver”</td>
<td>$\text{Al}_2\text{O}_3$ particles freed from SEN trapped by shell; prevalent in LC and ULC.</td>
</tr>
<tr>
<td>Depressions</td>
<td>a) Associated with large mould level variation- probably due to increased pressure and bending forces on shell as liquid slag enters the rim.</td>
</tr>
<tr>
<td>a) Longitudinal</td>
<td>b) Mould and starter fluxes mix forming a sinter (&quot;rope&quot;), which forms a template for depressions as mould rises.</td>
</tr>
<tr>
<td>b) Transverse</td>
<td>c) This stops liquid slag flow, the rope melts and is captured by the shell.</td>
</tr>
<tr>
<td>c) Off-corner</td>
<td></td>
</tr>
<tr>
<td>Carbon pick-up</td>
<td>Particular problem in LC and ULC grades due to either pick-up from C-rich slag rim or steel poking into powder.</td>
</tr>
<tr>
<td>SEN erosion</td>
<td>Erosion of Z band by flux, promoted by low viscosity flux Attack of CaO stabiliser for $\text{ZrO}_2$ by CaF$_2$ and SiO$_2$ and high metal flow velocities.</td>
</tr>
</tbody>
</table>
Continuous Casting Simulator (CCS) with liquid metal
• Designed and built between 2004-2007 through RFCS–FLOWVIS project. The model was originally focused in the submerged entrenozzle (SEN).

• Between 2011-2014; RFCS DDT (Direct Defect Toolbox) allowed updating of control and heating systems, solving operational issues with dross and developing probes for velocity and metal level measurements (Vivés, ultrasound, light beam, etc.)

• Results of the revamped Continuous Casting Simulator were used to validate numerical models and expand process knowledge.

• Lately, VINNOVA–FLOWFLEX (2014-2016) focuses on nozzle design allowing installation of new industrial ceramic nozzles and a secondary Argon line.
Why using Bismuth-Tin alloy?

The properties of MCP-137 (Bi 58%-Sn 42%)

### Electrical conductivity

<table>
<thead>
<tr>
<th></th>
<th>$\sigma$ (1/$\Omega$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCP-137 (solid)</td>
<td>1.7*10^6</td>
</tr>
<tr>
<td>MCP-137 (liquid)</td>
<td>1.0*10^6</td>
</tr>
<tr>
<td>Steel (solid)</td>
<td>0.8*10^6</td>
</tr>
<tr>
<td>Steel (liquid)</td>
<td>0.7*10^6</td>
</tr>
</tbody>
</table>

### Kinematic viscosity

<table>
<thead>
<tr>
<th>Material</th>
<th>$\eta$ [Ns/m$^2$]x10^{-6}</th>
<th>$\rho$ [kg/m$^3$]</th>
<th>$\nu$ [m$^2$/s]x10^{-6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel(1600°C)</td>
<td>~6.3</td>
<td>7000</td>
<td>~0.9</td>
</tr>
<tr>
<td>MCP-137(150°C)</td>
<td>~10.7</td>
<td>8580</td>
<td>~1.25</td>
</tr>
<tr>
<td>MCP-137 (170°C)</td>
<td>~8.6</td>
<td>8580</td>
<td>~1</td>
</tr>
</tbody>
</table>
Continuous Casting Simulator (CCS-1) at SWERIM
Real refractories in CCS

SENs and stoppers and diverse measurements

All the tests and measurements can be carried out with industrial ceramic nozzles and stoppers.

Measurements include:

- Velocity just below metal level (electromagnetic Vivés probe)
- Mould Level fluctuations (Light beam)
- High-speed imaging to capture argon bubble size and number released through stopper and SEN porous plugs.
Measurement techniques
Velocity measurements

Electromagnetic (VIVES probes) and ultrasound.
Velocity measurements

Electromagnetic (VIVES probe)

• Postprocessing
  • Averaged over 5 s
  • Derivatives above $5 \cdot 10^{-8} \frac{dV}{dsample}$ and absolute values above $17.5 \cdot 10^{-5}$ V treated as noise
  • Each peak was matched with velocities
  • Linear equation fit to the data

• Results
  • Voltages directly translated to velocities
  • Data not useable
    • No verification
    • Considerable disturbance of surface during trial
Mould level measurements

Optical probes

- Light beam
  - Chromatic confocal type
  - Working distance 76.5 mm
  - Working range 25 mm

- Blue laser line scanner
  - Laser triangulation type
  - Working distance 240 mm
  - Working width 100 mm
Mould level measurements

Light beam installation
Mould level measurements

casting speed = 1.5 m/min
Mould level measurements

Blue laser installation
Mould level measurements

Blue laser

Surface profile at $u_{cst} = 0.7\ m/min$, $q_{arg} = 2\ dm^3/min$

Surface profile at $u_{cst} = 0.8\ m/min$, $q_{arg} = 2\ dm^3/min$
Pressure in flow regulation zone
Pressure in flow regulation zone

Measurements in argon line vs stopper
Research projects
Test variables

- Casting speed, 0.6 to 1.2 m/min
- Argon flow rate, 0 to 8 liters/min
- Stopper position, closed to 17 mm
- Immersion depth: variable
Increased process knowledge

Change in vc from 1.0 to 1.4 m/min

Metal level fluctuations
Finding the right amount of Argon for a caster

casting speed 1.2 m/min
and argon=4 lt/min

casting speed 1.2 m/min
and argon=5 lt/min
Finding the right amount of Argon for a caster

4 lt/min

5 lt/min
Mould level stability
(Light Beam Sensor)
Mould level stability

(Light Beam Sensor)

- Asymmetry due to bubble bursting effect
- Stable behaviour
- Bad behaviour
- Bad behaviour
Mould level stability
Nozzle frequency signatures

CCS-1.5 - Experimental data

Frequency (Hz)

Velocity sweep - Model data

Amplitude (mm/Hz)

1.0 m/min
1.1 m/min
1.2 m/min
Nozzle frequency signatures

H. Barestrand and T. Forslund. [Link](http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-59847)
Flow characterization in stopper-SEN

Pressure measurements

- **Postprocessing**
  - Filtered by using moving average over 12.5 s, points with high rate of change set to adjacent points value
  - Graph split into different setup numbers
  - Pressure averaged over each setup number and matched with test variables
  - Single variable regression for each flow condition
  - Highest contributing variables used in a multiple variable regression

- **Results**
  - High $R^2$ pressure model

*J. Eck. Development of systematic measurement on liquid metal. [http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-75347](http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-75347)*
Possible cavitation?

Pressures of a few mBar

Cavitation damage in metallic stopper?

Diagram illustrating the separation area, argon supply, cavitating gas layer, SEN wall, and build up.
Other pilot facilities at SWERIM
Pilot Trials – Full Scale
Pilot trials of secondary cooling
EU-RFCS Research Highlights
EU research highlights

Improvement in cast product quality by the visualisation and control of the steel flow pattern in the tundish pouring nozzle (SEN/SES)

Report EUR 21247 en
Flowvis: measurement, prediction and control of steel flows in the casting nozzle and mould
Development of a toolbox for direct defect prediction and reduction through the characterisation of the meniscus-slag bed behaviour and initial shell solidification in CC (DIRECT DEFECT TOOLBOX-DDT)
EU research highlights

Improvement to steel cleanliness, castability and surface quality through the application of magneto-hydrodynamics during pouring and solidification (Magnetohydro)

Figure 2.2.79 (Tata Steel). Time-dependence of the stopper rod position, of the fluid level in the tundish, of the distance of the meniscus from the upper edge of the mould, of the pressure in the Argon supply tube, as well as of 2x4 measured induced magnetic fields for six representative runs with different stirrer rotation rates between 0 and 50 Hz. The numbers of the magnetic field signals correspond to the flux-gate sensors indicated in Fig. 2.2.77.
Thanks for the attention!

Stay informed

http://valcra.eu/

https://www.linkedin.com/company/european-continuous-casting-network

VALCRA linkedin group (linkedin.com/groups/13794289/)