Sustainable steelmaking - resource efficient processes and new advanced steels

Claire Davis
Flexibility and Value - The Keys to Sustainability
Trends

• Energy sources vary in price and type
• Raw materials vary in price and quality
• In industrialized countries
  – Markets vary depending on global changes
  – Trained work force is limited
  – Tightening environmental regulations
There are also another concerns

• Availability of raw materials:
  – Coking (high quality) coals
  – High quality ore is becoming limited
  – High quality scrap is becoming expensive
Limits and Opportunities

Flexible Iron-Source
Gangue and scrap
Impurities
Flexible Reductant/Fuel
Reactivity and ash

Process
Productivity

Product Flexibility
Quality
By-products
Minimize and re-use

Work force
Trained but affordable
Strategy

Energy/Raw Material Flexibility

Hlsarna cyclone-smelter

Cleaner, high value Fe-C melt

Minimum Alloying/ refining

Cleaner Lean Chemistry Melt

Lower Energy Process

Strip casting

Lower Energy Processing and Innovative Micro-structures, Light weighting

Strip casting of new chemistries (e.g. Fe-Al)

Product diversification - Chemistry adjustment and coating including PVD

- Reactions in the cyclone
- CH$_4$ cracking on slags
- Metal drop slag reactions
- Carbonaceous feed reactions
- Hot slag heat recovery

P removal
High Strength Steels will be the dominant grades in 2030

Although steel will be partly replaced for certain automotive applications the consumption will grow

Advanced high strength steel (AHSS) and ultra-high strength steel (UHSS) will increase significantly in use

From 2015 North American Light Vehicle Aluminum Content Study
Examples of on-going research projects

Understanding Transient Trajectories

P removal in liquid steelmaking

Stephen Spooner and Professor Sridhar Seetharaman
In-situ observation for mechanism of P removal leading to optimisation of slag chemistry and process time for a given steel chemistry.

Fe-0.2% P drop immersed in slag:

<table>
<thead>
<tr>
<th>%CaO</th>
<th>%MgO</th>
<th>%SiO2</th>
<th>%FeO</th>
<th>%P2O5</th>
<th>CaO/SiO2</th>
</tr>
</thead>
<tbody>
<tr>
<td>36.64</td>
<td>7.08</td>
<td>16.98</td>
<td>33.56</td>
<td>1.66</td>
<td>2.16</td>
</tr>
</tbody>
</table>
The in-situ observations provide better understanding of the P removal with time during the oxygen blow:

\[ P + \frac{5}{2}O + \frac{3}{2}O^{2-} = PO_4^{3-} \]

\[ FeO = Fe + O \]

Examining the role of slag chemistry in combination with the steel composition on the droplet interfacial energies allows optimum processing to achieve clean steels for casting.
Examples of on-going research projects

Belt casting

Structure development and segregation behaviour

Dr Carl Slater and
Professor Claire Davis
Belt casting technology allows significant energy savings through casting to thinner section and removal of reheating stage.

Direct charging of as-cast steel strip (at 1100°C) to rolling process can save approx 1.25 GJ/t. Further saving of 2.0 GJ/t achieved in reduced energy for rolling to final thickness.
Belt casting involves mould-free casting with high cooling rates, which changes the resulting solidified steel structure and properties due to:

- interactions between the steel surface and gases giving different surface chemistries and potentially undesirable surface properties;
- significant variations in cast structure through thickness;
- complex micro-segregation behaviour and hence grain size development during hot deformation.

**Metallurgical challenges associated with belt casting**
Challenges associated with low density steels

The development of low density steels (LDS), particularly for the automotive industry, is desirable to give greater fuel efficiency: a 1.5 % density reduction is achieved per Al addition of 1 wt %.

However, there are processing difficulties with these steels due to crack sensitivity, mould flux interactions and large grain sizes in the ferritic LDS.

Ingot cast LDS (Fe-7Al-Ti) steel microstructure showing very large ferrite grain structure.
In-situ dynamic observation of LDS solidification and the effect of cooling rate on structure development, including segregation behaviour. Aim to define process windows for belt casting of advanced high strength steels.
Solidification trials and dendritic structure

It is known that the cooling rate \((C_R)\) during solidification affects the secondary dendrite arm spacing \((\lambda_2)\) with relationships of the form below developed:

\[
\lambda_2 = A C_R^{-n}
\]

Trials, carried out using a Gleeble 3500 thermomechanical simulator, for solidification of various steels, including stainless 303 and LDS, have confirmed the relationship.

Dendritic structures in 303 stainless at different cooling rates:

- \(\approx 100 \, ^\circ C/s\)
- \(\approx 8 \, ^\circ C/s\)
- \(\approx 1 \, ^\circ C/s\)
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Modelling segregation behaviour in LDS

Segregation during solidification with back diffusion. Concentration profiles of alloying elements such as Mn, shown below, Ti and Al can be determined.

After 0s
Peak Concentration = 1.33 wt%
Min Concentration = 0.38 wt%

After 1s cooling at 200 K/s
Peak Concentration = 0.66 wt%
Min Concentration = 0.43 wt%
Modelling segregation behaviour in LDS

Hence concentration profiles can be obtained based on the different cooling rates taking into account the SDAS. Hence, at high cooling rates the inhomogeneity in composition is over a smaller scale but is more intense in magnitude.
Solidification behaviour in LDS

The segregation levels also affect the local solidification characteristics. Direct dynamic observation of solidification allows the boundary velocity and solidification temperature ranges to be observed.

Time lapse images taken showing three secondary dendritic arm tips coarsening in a sample cooled at 50 °C/s
Solidification behaviour in LDS

The increased segregation levels at higher cooling rates, as back diffusion is limited, slows down the dendrite growth velocity and maintains a stable liquid phase to lower temperatures.
Solidification behaviour in LDS

As the segregation levels of Ti increase then there is a danger of TiC forming in the liquid prior to solidification giving undesirable coarse precipitates.

TiC precipitate forming in final interdendritic liquid during cooling at 1 °C/s
Examples of on-going research projects

In-line microstructural assessment

EM sensors

Dr Frank Zhou, Russ Hall and Professor Claire Davis
Phase transformation monitoring

Austenite is paramagnetic and ferrite / pearlite / bainite / martensite are ferromagnetic (below the Curie temperature, \( \approx 770°C \)).

Phase transformation can be clearly observed during controlled cooling experiments.

EM sensor output during cooling of 2 ¼ CrMo steel in a laboratory test (courtesy of Dr Xinjiang Hao)
Microstructural control during processing of high strength strip steels is essential to achieve the desired final properties. The required structure in dual and complex phase strip steels is achieved during cooling after hot rolling.

Relationship between magnetic permeability and ferrite fraction

COMSOL Multi-Physics simulations for mixed microstructures showing magnetic lines of flux.

Sensor positioned in a strip mill
Electromagnetic sensors

In-situ measurements of recrystallisation; signals are being correlated to the recovery and recrystallisation.

EM sensor signals have been related to tensile strength for dual phase steels offering the potential for on-line mechanical property assessment tools and strip mapping for homogeneity.
Enabling Technologies for cost effective A/UHSS manufacturing

- **Clean Iron**: Anticipated benefit related to mechanical integrity and Weldability. Need to accommodate varying quality raw materials.

- **Near Net Shape Casting**: Benefits in segregation control and improved isotropy and homogeneity.

- **Dynamic process feedback control**: producing the exact microstructures desired on processing.

- **Flexible Annealing**: Potential for use of leaner steels, grade consolidation, late differentiation and new differentiated products.
New Initiatives

Advanced Steel Research Centre at Warwick

Professors Sridhar Seetharaman, Claire Davis, Barbara Shollock
Assistant Professors Michael Auinger, Prakash Srirangam