Overview on ECSC / RFCS research on sensors and measurement techniques for EAF process

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- Energy input
- Off gas/Emissions
- Liquid steel temperature
- Foam/Vibration
- Scrap/Steel analysis
- Purging/Cooling

Source: MPT Int. 1/14 Ferriere Nord steel work
“Necessity is the mother of invention” (Platon)

- Most important needs in the present research field of Electric arc furnace are:
  - Improvement of efficiency in energy
  - Improvement of efficiency in material
  - Improvement of quality
  - Improvement of safety

Source: Tenova State of the art in EAF technologies, 2nd VDEh-AIM Joint Meeting on Metallurgical Fundamentals
Evaluated RFCS research projects directly dealing with EAF sensor based process control

<table>
<thead>
<tr>
<th>Contract Report</th>
<th>Title</th>
<th>Participants</th>
<th>Date Start / End</th>
<th>Topic regarding sensors</th>
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<tbody>
<tr>
<td>No 7210-PR/204</td>
<td>Innovative continuous online determination of steel melt temperature by direct optical measurement in the melt</td>
<td>BFI, AG Dillinger Hütte, CRM, Aceralia</td>
<td>2000-07-01 to 2003-12-31</td>
<td>Based on a detailed analysis of the state of the art a fibre optical measurement technique was promising to meet the demands of the requested applications. The measurement principle is to feed a standard low cost optical fibre continuously into the steel bath and to analyse the radiation transmitted through the fibre for information on bath temperature.</td>
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<tr>
<td>No 7210-PR/271</td>
<td>In-situ, quick sensing system for measurements of critical components in steelmaking slags (INQUISS)</td>
<td>RWTH, Aceralia, Acerinox, Helliniki Halyourgia, ISQ, Univ. Malaga, Univ. Patras</td>
<td>2001-07-01 to 2004-06-30</td>
<td>Investigate and adapt a laser-based, online analytical tool for in-situ detection of a defined set of elements in steel metallurgical slags, Fe, Ca, Si, Al, Mg, to assist in process control and optimisation, to contribute to environmental strategies of the industrial branches and to support recycling measures of the industrial plants.</td>
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<tr>
<td>RFSR-CT-2004-00008</td>
<td>Control by camera of the EAF operations in airtight conditions (EAFCAM)</td>
<td>CSM, BFI, AM R&amp;D, CORUS UK, MORE SRL</td>
<td>2004-07-01 to 2007-12-31</td>
<td>To observe the scrap-melting process under slag-door closed conditions, a camera-based technology to observe furnace events during meltdown has been developed. The camera system is able to see through combustion gases by selecting its wavelength to be in the mid-infrared spectral band.</td>
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<tr>
<td>RFSR-CT-2006-00004</td>
<td>Improved EAF process control using on-line offgas analysis (OFFGAS)</td>
<td>RWTH, CRM, CSM, DEW, MH, Ori Martin, Tenova, TKN, BFI</td>
<td>2006-07-01 to 2009-06-30</td>
<td>To increase the efficiency of EAF oxygen injection and energy transfer to the scrap and melt. In expansion to short-term investigations using off-gas analysis to monitor energy flow rate of the off-gas, permanent on-line monitoring and control of the EAF process on the basis of off-gas analysis has been implemented.</td>
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### Ongoing RFCS research projects directly dealing with EAF sensor based process control

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<td>RFSR-CT-2013-00002</td>
<td>Determining process conditions for online monitoring of temperature and carbon content in the electric arc furnace to optimise end point control (MELTCON)</td>
<td>BFI, FERRIERE NORD S.P.A., POLITECNICO DI MILANO, SAARSCHMIEDE</td>
<td>2013-07-01 to 2016-06-30</td>
<td>Online measurement systems for continuous monitoring of the process status during EAF treatment and end point control will be developed and applied. At one furnace an accretion free melt access will be created for fibre-optical temperature measurement. At another furnace a measurement system for combined optical determination of carbon content and temperature will be developed using an lance access.</td>
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<tr>
<td>RFSR-CT-2014-00004</td>
<td>Adaptive EAF online control based on innovative sensors and comprehensive models for improved yield and energy efficiency (AdaptEAF)</td>
<td>BFI, GMH, Helmut Schmidt Universität</td>
<td>2014-07-01 to 2017-06-30</td>
<td>Novel sensors and measurement methods for online acquisition of bath level, steel and slag amount, and scrap melting behaviour will be applied. This additional process information will be used to enhance the performance and prediction accuracy of previously developed dynamic and statistical models for online monitoring of the process status.</td>
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Optical steel bath temperature sensors

- Immersed fibre-optical steel bath temperature measurement is:
  - Independent of emissivity
  - Continuous measurement of melt temperature during fibre feeding
  - Fast response time by optical measurement
  - No influence by melt bath surface or slag cover
  - Available also during heating operation, because insensitive against electromagnetic fields
  - Precise temperature control to reach the desired target temperature
Optical fibre temperature measurement based on lance/manipulator technique

Two flexible hoses connected to the probe (one for the fibre and shield gas, and one for cooling gas) and the lance / manipulator

Results:

- The probe withstood the harsh conditions inside the furnace during 11.5 minutes, i.e. much longer than the application period for liquid steel temperature measurement in the EAF (last 5 - 6 minutes of each heat);
- That the probe could have been used for an additional measurement;
- The measured temperature signal shows a clear trend up, as expected
BFI developed an optical temperature measuring system based on manual lances, especially in small-to-medium sized foundries.

Technical data of mobile, lance based optical temperature measurement system DynTemp® H:

- Temperature measurement range: 1250°C to 1800°C
- Reproducibility of detector: ± 0,1% + 1 K
- Response time: 0,5 s
- Device dimensions: 0,8 m x 0,8 m x 0,35 m
BFI has developed a robust continuous optical measurement system based on a consumable optical fibre fed through the bottom gas system into the liquid steel bath.

The system measures the actual steel bath temperature during the blowing process to determine accurately the required end of blowing.
Optical temperature measurement sensors (BOF)

Main benefits are:

- Short response time (< 0.1 s)
- Continuous online monitoring
- Easy application
- Improved process control
- Raising output
- Savings in oxygen consumption and time
Optical temperature measurement sensors (EAF)
RFSR-CT-2013-0002

Fibre-optical continuous temperature measurement (BFI DynTemp®) using

- Lance
- Bottom nozzle

- Monitor continuously the liquid steel temperature during the refining phase
- Determine process conditions to perform representative measurements in dynamic inhomogeneous melts
- Develop enhanced dynamic process control based on novel measurements
- Develop strategies and model-based set point calculations for exact determination of control parameters for accurate EAF end point control
- Evaluate availability, performance and limitations of continuous measurement
Optical temperature measurement sensors (EAF)

- Comparison between thermocouple spot measurements and the continuous optical fibre measurements.
- Initially the nozzles are operated with $N_2$ gas. During the process the tuyeres were switched to $O_2$ blowing.
- The time of switching can clearly be seen in the measured data by the step in temperature.
- During $O_2$ blowing the local temperature increases considerably due to the exothermic reaction of $O_2$ with the steel bath.
- The absolute numbers of 2200 up to 2500 °C seem quite realistic since it corresponds to measured temperatures in the hot spot of oxygen blowing converters.
The quick and online determination of the steelmaking slag analysis improve their overall metallurgical yield and their refractory performance.

The aim of the project was to investigate and adapt a laser-based, online analytical tool for in-situ detection of a defined set of elements in steel metallurgical slags, Fe, Ca, Si, Al, Mg, in order to assist in process control and optimisation in the steelmaking process.

Therefore the main objectives of the project were:

- Investigations of adaptation of LIBS to EAF
- Detection of Fe, Ca, Si, Al, Mg, Cr and Mn by LIBS
- Prove of the online feasibility of the quick detection system
The main components of the system include generally:

- Laser
- Optical system for focusing the beam
- Optical system of collecting the emission of the laser induced plasma
- Method of spectral resolution and detection
- An evaluation and control unit

The principal advantage of LIBS are minimal or no sample preparation, the ability to function in a hostile environment.

Limits of detection vary for individual elements and are typically 10 to 100 ppm with accuracy between 2 and 10%.
Conclusions

- The laser induced breakdown spectroscopy (LIBS) method was applied to metallurgical liquid and solid slags and it is possible to measure main chemical elements of steel plant slags like Ca, Si, Fe, Mg, and Cr in the rough environment of an EAF production facilities.

- Problems of focusing the laser beam to a wavy slag surface have been overcome by new submerged graphite nozzle into the liquid slag.

- The measurement LIBS system shows during this trial its ability of a real online analytic system. During the whole analyzing and alloying steelmaking process no problems like defect lenses or missing signals were encountered. The reduction of chromium during slag recycling was recognized clearly at all.

- For this development stadium the analytic system works in a good stabilized way so that there are no problems and barriers for a real industrial use.
The developed camera-based technology, is an infrared camera for observing the scrap melting process inside an EAF operate with a closed slag door.

- Recordings have provided new and interesting insights into the EAF melting process. Images showing:
  - the melting characteristics of different size scrap pieces; scrap-drop events; scrap melting completion
  - time; thermal contours after end-of-arcing; the extent and duration of slag foaming; and details of the tapping operation (including the size of the hot heel), have been demonstrated and these direct online views of operations inside the furnace would inevitably provide the operator with improved control of the process.
Detailed images of processing events were linked directly with furnace operating parameters.

Several images were selected within the EAF processing time, especially after particular events.

Processed image (based on the real thermal view) in order to provide a clearer picture.
Mass and energy flow rates at the EAF are not steady-state but time-dependent during a heat.

Some of the energy flow rates are precisely known for process control: electric energy input, heat transfer to the cooling system.

Other important EAF mass and energy flow rates are poorly known due to technical difficulty to achieve a reliable signal during long-term measurements: off-gas enthalpy, carbon mass flow rate in off-gas.

Since years offgas analysis systems based on infrared absorption are available for measurements at industrial furnaces, e.g. from ABB, Emerson Process Management, Goodfellow EFSOP™ system. New detector systems have been developed based on tuneable diode laser absorption techniques in-situ at the hot gas duct, e.g. the LINDARC™ system. Application of these systems at industrial EAFs is still rare.

Time-dependent process control is still restricted to control of electric power input. In this project, continuous analysis of EAF off-gas is used to reduce energy demand and thus to increase EAF productivity:

- implementation of on-line energy monitoring to increase energy efficiency
- monitoring of decarburization of the melt to increase oxygen efficiency
- decrease of oxygen lancing and injection time and, consequently, tap-to-tap time
Installation of measuring system

- shows a schematic of the EAF system layout at MH. The sampling of the off-gas was realized at point A using water-cooled probes.

- Therefore the off-gas sampling is carried out directly from the EAF off-gas stream at measuring point A with a LINDarc system.

- LINDarc is an a laser-based system for off-gas analysis, based on single-line spectroscopy in the near infrared (NIR) spectral range

- The detected shape and size of this single absorption line is used to calculate the kind and amount of gas

- Two lasers have to be used because the frequencies of CO and O₂ are too far apart to be covered by one laser.
**Conclusion**

- The response time of a laser based system is almost instantaneous and no sampling or sample conditioning equipment is needed. A disadvantage of the system is the proximity of the delicate optical and electrical systems to the furnace which leads to a potentially higher risk of damages to the analyser system.

- Direct laser-based off-gas measurement is a rather new technology by comparison and right now not for all desirable gas species a dedicated laser is available. So some interesting species like CO$_2$ cannot be measured with this system up to now.

- Nevertheless from Marienhütte point of view, the laser off-gas analysis is believed to be a key tool to drive the tuning of the EAF process, thanks to its real-time response.

- There is a particular interest in using the laser off-gas analysis as safety device.

- New developments of laser diodes enable the reading of the water content directly in order to detect dangerous water leaks inside the EAF.

- Additionally, the range of chemical species in the off-gas to be analysed expands steadily.
ongoing Pilot & Demonstration project, set up a new adaptive online control for the EAF.

Novel sensors and measurement methods for online acquisition of bath level, steel and slag amount, and scrap melting behaviour will be applied. This additional process information will be used to enhance the performance and prediction accuracy of previously developed dynamic and statistical models for online monitoring of the process status.

The online information on bath level, steel and slag amount, scrap melting progress and energetic behaviour will be used for model-based online control of scrap charging as well as chemical energy input via burners and oxygen injectors.
Two different measurement systems to assess the liquid bath level and the hot heel level after tapping will be installed and applied at the EAF of GMH.

Combining these two measurements provides reliable information on liquid steel and slag levels.

A dip sensor (Heraeus Delta Dist L) is applied to an existing manipulator.

The bath level and slag level/thickness will be registered by contacting the slag surface, and the crossing from slag to steel will be recognized by a small current-carrying coil inside the sensor.

As the characteristics of the current change dramatically by the presence of steel, the steel level and thus also the slag thickness can be detected by recording the position of the sensor.
EMLI-Furnace Bath Level
Non RFCS examples

- Principle of operation of dip sensor similar to Delta Dist L

- Bath level measurement is based on electromagnetic sensor detecting changes in the materials' conductivities passing through.

- Measuring system is automatically activated and shut off by immersion and withdrawal

- Power on / power off measurements possible.
A common slag door manipulator can be equipped with the sensor.

Measurements can therefore be done at only one fixed measuring position.

Data is recorded, computed/analysed by the EMLI software and displayed.
EMLI-Furnace Bath Level
Non RFCS examples Results

- Manual adaption necessary due to electrode noise affection.

- Steel level detection in the mm regime (bath surface turbulences are limiting)

-Apparently indication of slag level information possible

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<thead>
<tr>
<th>Time</th>
<th>Lance position (mm)</th>
<th>Comment</th>
</tr>
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<tbody>
<tr>
<td>20:56:14</td>
<td>809</td>
<td>Power on</td>
</tr>
<tr>
<td>20:57:20</td>
<td>794</td>
<td>Power on</td>
</tr>
<tr>
<td>20:59:21</td>
<td>801</td>
<td>Power off</td>
</tr>
<tr>
<td>21:00:26</td>
<td>805</td>
<td>Power off</td>
</tr>
</tbody>
</table>

Sensor position
Bath level detection
A camera-based bath level determination at open EAF furnace after tapping will be developed and applied. Three new cameras will be installed to monitor the furnace interior from the top in different angles of view. Software will be derived to determine the actual amount of hot heel.

Light conditions inside the furnace are often quite dark at the refractory side/wall and very bright in direction to the melt's surface. To get precise camera images and information about the bath level, the use of high dynamic range camera is necessary to adapt the light conditions.

Appropriate image processing and analysis tools will derive the absolute bath level.
Analysis techniques to continuously follow the scrap meltdown behaviour will be developed based on information captured by vibration and spectrometer sensors installed at the shell.

6 sensors will be installed at different positions on the outside of the shell of the EAF vessel to monitor the scrap meltdown behaviour from analysis of furnace vibrations.

The goal is to get conclusions of the remaining amount of not melted scrap inside the furnace. This will allow the detection of scrap pile collapses as well as a low foaming level.

Informations from the vibrations sensors will be compared to the camera imaging data.
Vibration sensors

- 3-axis Piezo elements are used as vibrations sensors
  - Frequency range (0.3 to 10000 Hz)
  - Max Temp. 100°C
  - Dust protection
  - Calibration

- Choice of filter and frequency analysing methods
  - FFT
  - Teraherz analysis

- Correlation vibration to process parameters
  - Effective power
  - Conclusions of the remaining amount of not melted scrap inside the furnace
EAF bottom gas purging systems

- Bottom gas purging provides cost benefits by:
  - Increased temperature homogeneity of the steel melt
  - Decreased melting time of scrap and DRI.
  - Increased heat transfer during the superheating period.
  - Decreased specific electrical energy demand.
  - Increased chemical homogeneity in the steel melt
  - Decreased oxygen consumption.

Conclusions

- Research and innovation is a key driver for energy and resource efficient EAF technology.
- Improved process control requires more sensor and measurement data.
- Until now, only few RFCS projects were directly related to sensors and measurement techniques for the EAF.
- Continuous measurement allows further improved understanding of actual process conditions also during fast processes such as heating or mixing.
- Online monitoring and real time sensors for improved EAF control is a requirement for future steelmaking.
- As in daily life, sensors become increasingly important to supply real time process information.
Thank you very much for your attention!

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