In-Line measurement and Control for Metal Processing

IOM3 Conference, Warwick University, 6-7 Dec 2017.
Chairs: Didier Farrugia, Tata Steel and John Hinton, Primetals Technologies.

The presentations were significantly focussed on steelmaking plants due to the organizers background, but the techniques are applicable elsewhere. A number of sensors for measurements and cameras for observation are installed on steelmaking and steel processing lines for continuous monitoring of the state of the equipment and, more and more, of the product itself. The same is true, to a lesser extent, on Al processing lines. The conference provided an important review at a time where microstructure and chemical composition measurement technologies are becoming mature for in-line implementation in the most severe environments (high temperature, corrosive gases, water vapour, high speed…).

The main measurements technologies addressed are:

- continuous and non-contact in-line chemical analysis:

- Laser-Induced Breakdown Spectroscopy for all kinds of elemental analyses.
- measurement of oxygen concentration in furnaces.
- Glow Discharge or Inductively Coupled Plasma emitted light analysis for liquid analysis of e.g. waste water and effluents.

- continuous and non-contact in-line microstructure evaluation

- Electro-Magnetic Spectroscopy (EMSpec®)
- Laser US

- IR Pyrometers (pointwise as well as line scanner) for continuous temperature monitoring

- optical measurement:

- Interferometric oxide thickness measurement
- IR absorption for oil film thickness measurement
- automatic image analysis for defect detection by inspection cameras
- shape measurement (from roughness to flatness defects) by line projection

The principles of some specific techniques which appear in several presentations are first sketched here for more clarity:

- Laser-Induced Breakdown Spectroscopy vaporizes surface material into a plasma, the radiation of which is analysed by a spectroscope. It is applied to Al scrap sorting for recycling, to agglomeration ahead of the blast furnace, to strip carbon / iron fines cleanliness, to zinc bath analysis), i.e. all along the steelmaking process line.
- EMSpec® exploits the response to electromagnetic induction: eddy currents induced by an excitation coil create retro-induction in measuring coils. The frequency response of the complex impedance of the sensor (detected voltage / current input) is addressed, hence “spec” for “spectroscopy”. The impedance depends on the presence of steel below the sensor, its magnetic permeability and electrical conductivity. EMSpec® currently measures the advancement of γ (paramagnetic) $\rightarrow$ α (ferromagnetic) transformation on many Hot Strip Mills through the “Zero Crossing

Frequency (ZCF)”, i.e. the frequency at which the real part of the impedance is zero. But a number of microstructural features impact the response and might be accessible in the future, at a greater modelling expense hence not real time as needed for on-line application - yet.

- In Laser US technology, a high power Laser creates US waves which propagate into the metal and are reflected from the opposite side of a product; a second Laser detects the movement of the surface as the US wave reaches it. This allows measuring either the thickness (of a strip, a tube wall) by Time-of-Flight, the grain size via its influence on the sound wave velocity, texture through its direction-dependence… This technique is already available on mills for the geometrical measurements but still at development stage for the microstructural measurements.

Next comes a survey of the presentation, with a flavour of the discussion, technique by technique

EMSpec®

P. Hunt (Primetals Technologies, 1st worldwide rolling mill manufacturer):
EMSpec® in Tata Steel Ijmuiden

After the presentation of the sensor principle, performance and implementation constraints, the discussion addresses the capacity to distinguish ferrite from bainite or martensite (all ferromagnetic) in case of faster cooling. These phases have different permeabilities and conductivities indeed, and they have indeed an influence, together with microstructural features, on the ZCF and more generally the EMSpec® signal. Direct computation shows this, the problem is that the inverse computation from the measured ZCF does not have a unique solution. One should exploit the complete complex impedance curves, and maybe scan not only frequency but excitation intensity (one stays well below saturation field). This would be too costly to be done in-line but is feasible in the laboratory, at low temperature and keeping the sample fixed in the sensor frame; movements, vibrations introduce noise which makes the inverse identification impossible.
Another key point is the capacity to address heterogeneity, in particular skin / core, maybe using frequency range and the skin effect. However at present, the sensor installed on Run-Out Tables to detect α from γ is designed to average over the thickness (2-5 mm), this is what is required in the first place. Some attempts are made in the laboratory, playing also with the sensor design, they are described next.

J. Shen, L. Zhou (Warwick U.)

Two lectures show a complete analysis of the EMSpec® concept, using 3D electromagnetic FEM at the scale of the sensor and at the microstructure scale. At sensor scale, the impact of the design (dimensions, coils characteristics, manufacturing defects, strip thickness or movement) can be estimated in order to optimise precision and robustness. At the microscale, reconstructing the grain (and potentially subgrain) structure from EBSD, entering the two main parameters conductivity $\rho(T)$ and permeability $\mu(T)$, the effect of the microstructure is shown. Concentration of dislocation near grain boundaries are modelled with a grain boundary thickness with specific ρ and μ, introducing e.g. the effect of strain on the measured quantity. It is claimed that e.g. perlites with different interlamellar distances will give distinguishable answers – in the direct model. Grain size, second phase particles and precipitates also have an impact on ZCF. The topology of the phases, e.g. the existence of a percolation path of α phase in a γ matrix, has a strong importance in case of large difference of μ between the two phases. In steels, this difference decreases at higher temperatures so that the topology effect becomes less.

Laser – UltraSound

M. Malmström (SWEREA KIMAB)
Texture study by Laser – UltraSound sensor.

In LUS sensing, a first, pulsed Laser creates US waves, a second one reads the surface movement, namely the echoes of the initial pulse. At low Laser energy, simple dilatation creates an elastic strain whereas at high energy, a shock wave is generated (but ablation may create a mark on the product). The distance between the two Lasers is fixed. Echoes are observed after either a single reflection on the opposite strip surface or multiple reflections. As the angles at which these waves have traversed the material differ, this gives a subtle view of the anisotropy of wave speed (time lag between echoes) and attenuation (exponential decay vs number of reflections) as a function of the direction. This tells us about microstructural anisotropy, more precisely here morphological texture, detecting if deformed grains have recrystallized (→ equiaxed) or not. Ray tracing and elastodynamics FDM models have been tested to interpret these differences, the FDM has been found more efficient.

P.J. Krauth (AMMR)
Development of a mobile LUS sensor

The work is devoted to grain size measurement via signal attenuation of successive echoes. The sensor can be moved from interstand to interstand for short duration R&D studies (for longer measurement times, lens are degraded by heat). The excitation and detection Lasers aim to the same point, generally the strip on top of an interstand looper for better positional stability. First tests match well the grain size *prediction* by WS18, a well-established metallurgical model of restauration, recrystallization coupled with precipitation.
The question of measuring gradients of microstructure is raised again by D. Farrugia.

M. Choquet (TECNAR)

The chanter of Laser-US, here applied to tube wall thickness measurement, measuring the ToF of the echo on the inner surface of the wall after excitation on the outer surface. On a tube, circularity and eccentricity are essential, this is why a rotating transducer has been installed at the exit of a tube rolling line. This basic application shows however a first case where the technique is indeed routinely and continuously working with success, paving the way for more ambitious applications.

Magnetic measurements

A. Martinez de Guerenu (CEIT)
Magnetic Hysteresis loop & Magnetic Barkhausen Noise measurements of Dual Phase steels

Barkhausen "noise" in ferromagnetic materials is due to the reorganisation of the Bloch walls after a magnetic pulse. The changing permeability map creates eddy currents which, input in a microphone, give a characteristic sound. As the magnetic domains are influenced by

microstructure, Barkhausen noise is connected with the latter and is ultimately a way to check mechanical properties – for a given material after careful calibration.
The complete measurement of Magnetic Hysteresis loop is a more complex, but more precise measurement of the same properties. It is applied to detection and measurement of martensite in DP steels: martensite give a much broader hysteresis loop and the evolution is continuous as a function of the % of martensite in the ferrite matrix.
Hysteresis loops are also sensitive to decarburization e.g., which can be considered either as a perturbation of the measurement, or a way to measure decarburized layer thickness (in-line?). Moreover, the loop width and shape depends also on the state of the martensite, namely its %C or its tempering. Again, the question is if analysing local features of the loop can give access to all this information of if it makes the inverse problem ill-posed.

Surface sensors, surface inspection

G. Moréas (CRM)
A survey of surface sensing

A few examples of problems to control and related visual measurement systems:

- Continuous Annealing Line: Advanced High Strength Steels (AHSS) typically contain Cr, Al and Si which may readily oxidize and degrade surface properties, in particular in view of galvanizing. One remedy is to promote fast oxidation by a powerful oxidizing medium in the first part of the furnace: formation of FeO_x thus dominates (remember that Fe diffuses towards the surface to be oxidized). In the second part of the furnace, a reducing atmosphere is introduced, resulting in a porous Fe surface which covers the Cr et al. oxides. This porous Fe layer also acts as an adhesion layer for zinc. The development of the Fe oxide is monitored by interferometric thickness measurement (interference colour) through the furnace.

- still in the continuous annealing furnace, a strip waviness can be created by the movement of the hot strip under tension over rollers, which can result in folds and unevenness. A sensor has been developed to monitor the shape in situ in the furnace by a line projection technique: a straight light beam is shone on the strip, the reflected image becomes wavy if the strip is.

- the same kind of technique may be used after air wiping at exit of the galvanizing bath, in order to check the evenness of the zinc layer thickness; it is also used as a continuous, on line roughness estimate (claimed range: from Ra = 0.3 µm up).

- quantitative image analysis (QIA) is used for surface defect detection and identification of their origins (using e.g. periodicity = roll mark for instance etc.). For instance, among the Zn-Fe phases formed during galvannealing, the ζ phase raises concerns for coating adhesion. Thanks to it visual signature on the surface, its spurious formation may be monitored in line by cameras assisted by AI image recognition techniques. Immediate detection allows correction by changing process parameters.

P.J. Krauth (AMMR)
Visual detection of roll marks

Roll defects print on the strip surface and degrade its aspect (roll marks). Monitoring the strip surface allows detecting these defects and trigger roll change. They are often very faint,

difficult to detect except after “stone brushing”; yet they may reveal much more clearly after galvanizing, so that early detection is essential. The detection of these “indents, bumps, scratches” is made possible by their quasi-periodic character since they print at each roll revolution: the algorithms look for repeated features. Yet as the reduction or forward slip may vary slightly, the period is not rigorously constant, so that a larger field must be searched.
The technique consists in illuminating and “looking” (with cameras) under different incidence angles, as one would do by eye. The combination of Bright Field, Dark Field and Side Light images (the latter mainly for longitudinal or oblique scratches) allows identification; chatter (mill vibration) marks, grinding defects are detected as side-products. The difficulty comes from geometrical unevenness (flatness defects, vibrations), from oil residuals (often digitated) on the strip; remedies are image accumulation to improve the signal-to-noise ratio and filtering. In line testing since 2013 results in 80% of the defects detected at mill exit, with < 10% false alarms.

LIBS

Montfort (CRM)
LIBS for cold rolled strip cleanliness

Cleanliness contains two items: surface carbon contamination and detachable iron fines. Techniques to enhance their detection by LIBS are described. For carbon, working under pure N_2 atmosphere (in the laboratory) forms C-N bonds under UV illumination: as a result, the plasma emits in the blue range, facilitating detection with simple (and cheap) spectrometers. The calibration quantification is based on the ratio of C-N / N_2 emission peaks.
For iron fines, 345 peaks from Fe are exploited, 60 000 ratios of peak intensities! Iron of the “bulk” strip and iron from the detachable particles provide measurably different signals. A tentative explanation is based on the following idea: “bulk iron” conducts heat so that the emitting plasma is at lower temperature, compared with Fe in a quasi-separated particle: the high energy / low energy peak intensity ratios are impacted. Anyway, using these ratios, a good correlation is found with “scotch tests” in which an adhesive tape is applied on the surface, then detached and the amount of iron entrained measured by different means: particle counting, colorimetry (grey level), dissolution and chemical measurement of iron…

In the discussion the author mentioned that strip roughness is not detrimental since it does not seem to impact the correlation. And yes, the measurement is very local (a few μm^2) compared with the scotch test (cm^2), but with high frequency lasers, thousands of shots can be used.

J. Petersson (SWEREA KIMAB)
LIBS to sort metallic scraps on running conveyor belts in view of recycling

The detection is associated to a robotic arm to put each scrap piece in the relevant bin. To be fast enough, the algorithms (Principal Component Analysis PCA, Neural Networks NN…) must be taught the most relevant peaks for each element, the ratios of which allow the best (and fastest) quantitative analysis. Comparison with in-laboratory XRF measurement is performed to validate the in-line method. One difficulty is with coated metals (e.g. galvanized steel) for which the LIBS penetration depth, 3-4 µm, may be insufficient.

Hofmann (SECOPTA) shows that LIBS can be used throughout the processing line,
- at ore agglomeration, coal control and sintering for blast furnace charge control,

- for recycled steel scrap identification with two-stage ablation: first, high power to clean the surface from dirt, coatings…, then LIBS scrap identification properly speaking,
- refractories, slag composition at exit of the blast furnace or in converters,
- checking liquid steel composition,
- checking slab grade before the hot strip mill, or at exit of the cold mill, in relation with the production schedule…

In the laboratory, further possibilities can be exploited such as µm-scale elemental mapping, but other techniques are available.

M. Choquet (TECNAR) has also presented LIBS analysis of the zinc bath at the galvanization line, measuring the concentration of Al addition, the amount of dissolved Fe which can lead to the dross defect…

M. Malmström (SWEREA KIMAB) presents an alternative analytical technique, Solution Cathodic Glow Discharge, by which a spark between a liquid and an anode creates a plasma of which optical spectroscopy is performed. A portable device is being developed for in-line flowing liquids chemical analysis.

Pyrometer-based temperature measurement.

P. Drögmöller (AMETEK)

IR pyrometry may seem a routine technique but application in a harsh environment remains tricky: reflection from the environment perturb the measurement, emissivity is varying. On the one hand, stray emissions may be shielded. But another technique is possible in certain cases, which also fixes the emissivity problem: wedge measurement. It consists in targeting the corner between a strip and e.g. a guiding roll. Due to the tight wrapping, the detected IR signal is in fact the result of multiple reflections and this is equivalent to measuring from a surface with $\varepsilon=1$. This is a technique we have used on CEMEF’s rolling mill in the 90s to measure strip temperatures close enough to the bite exit (B. Rizoulières’s PhD).
Furthermore, the trend is to line scanning rather than pointwise measurement, for better temperature control of the process. The possibility of combining scanning mode and wedge measurement is demonstrated ; of course the scanned line must be perfectly aligned with the strip / roller contact line.

J. Niemi (SWEREA MEFOS)
Simultaneous measurement of O_2 concentration and temperature in a Walking Beam Furnace

The topic is important to control product oxidation. Unfortunately the sensor is at patenting stage and no technical detail could be given. For any reason which was not found convincing by the audience, the team developed a storage in the cloud for this “small data” application, maybe just to set up the structure and demonstrate feasibility for other, “big data” applications.
Note by the way that mill manufacturers now offer distant storage of the hundreds of signal continuously recorded at high frequency on the mills. These data are available for the manufacturer to perform maintenance, and to the mill owner for any statistical analysis in view of improved traceability and quality insurance.

Strip thickness and contact length measurement

T. Holdich, Sheffield U.
Roll bite measurement by Ultra Sound Time-of-Flight

This work had begun during the RFCS project “Roll Gap Sensors” coordinated by AMMR (N. Legrand). The Sheffield group (R. Dwyer-Joyce) is at the tip of application of US sensing to tribology problems. They used it to try and measure in-bite oil film thickness in the sub-micrometer range, in the mixed lubrication regime, based on US interface reflectivity. Only a side-product of this work is presented here, the application to geometrical measurement by the detection of US successive reflections from top and bottom surfaces.

Oil film thickness measurement

S. Schöner (EMG Automation GmbH)
The SOLID sensor

Two variants of the SOLID sensor exist. The first one is based on absorption of an IR beam reflected from a steel surface by the oil film; the Beer-Lambert law is used to determine the oil film thickness. For more robustness, the measurement is performed at 4 wavelengths. The calibration depends on surface type (galvanized or not) and roughness. The second one is based on UV fluorescence; this time the emitter is the lubricant itself so that strip surface properties have little impact. The thickness is determined through the fluorescence intensity, which makes it on the contrary sensitive to impurities in the oil. Both sensors are able to measure oil film thickness either at the exit of a rolling mill, after the oiling line or in the press shop for sheet metal forming. The mapping capacity allows checking deposition of non-uniform film thickness in order to promote differential friction whenever needed. It may also be used to detect oil residues (“wax additive residues on rubber” which disappear after propanol cleaning…).

The same manufacturer provides in-line ultra-fast optical roughness measurement (SORM3PLUS sensor) and the IMPOC in-line sensor for mechanical properties based on measurement of the residual magnetic field after a magnetic impulse. The latter is used to check strip mechanical properties of the high speed running cold rolled strip thanks to calibrated but mysterious correlations between mechanical properties and the answer of magnetic domains and walls to a magnetic field impulse, maybe through the grain size effect on magnetic properties on the one hand and the Hall & Petch relation on the other hand (I have never read anything clear about this).